



Geological evaluation for the seismic acquisition programme for SCAN areas H (West-Friesland) and I (Noordoostpolder)

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Inleiding en duiding

Voor u ligt één van de geologische evaluaties van het SCAN programma, zoals deze in maart 2019 is vastgelegd. Deze inleiding en duiding is later toegevoegd om de actualiteit te kunnen toevoegen en duiding te geven aan het rapport.

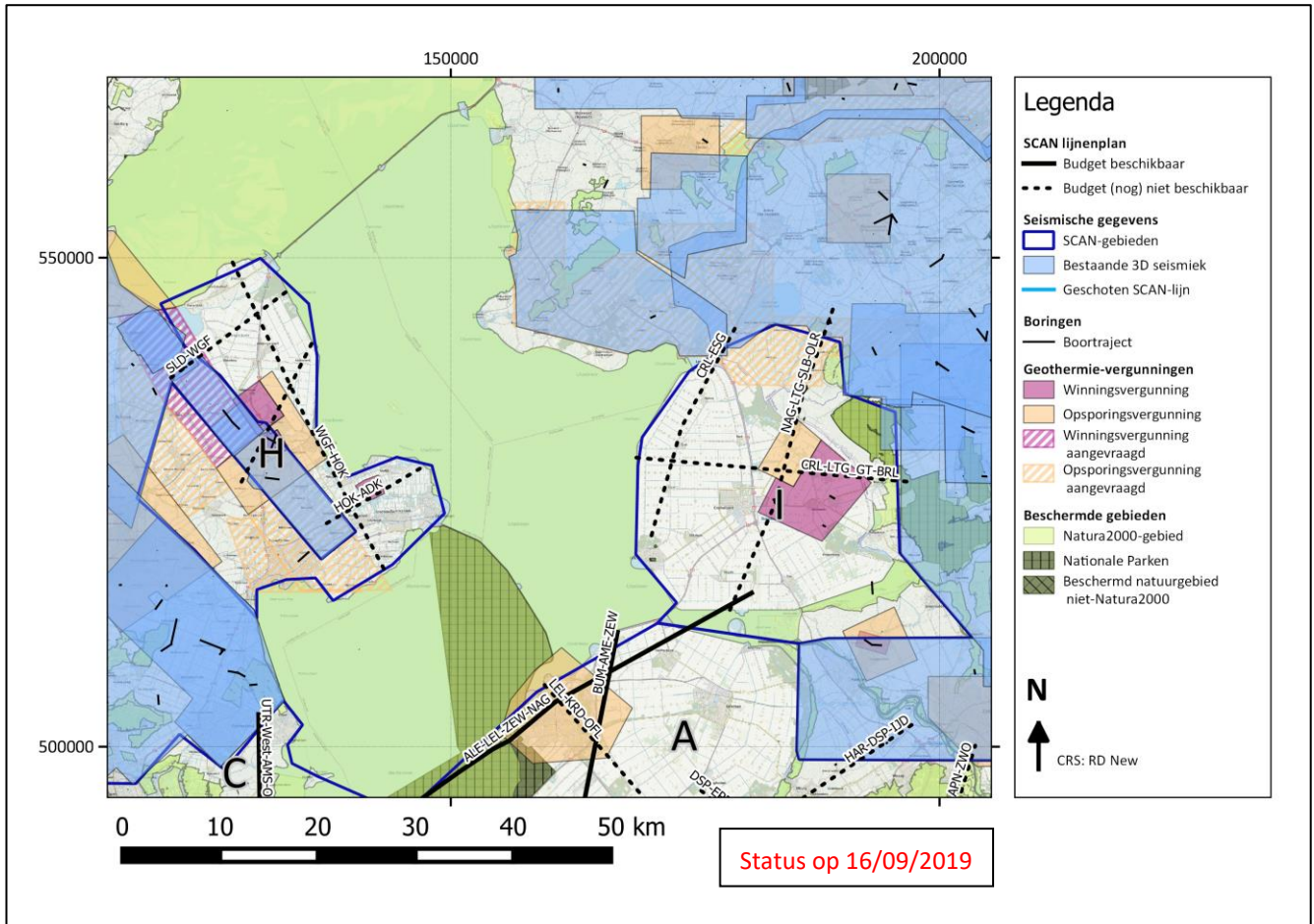
Om het acquisitieplan voor de SCAN 2D seismische lijnen te kunnen bepalen zijn door geologen en geofysici ondergrondse evaluaties gemaakt van de verschillende SCAN-gebieden. Hierbij is gelet op welke delen van de ondergrond de beste kansen bieden voor geothermische projecten en welke informatie nog ontbreekt voor een goede evaluatie. Per (mogelijk) geothermische play is aangegeven welke gegevens en werkprogramma's nodig zijn om vast te stellen of de betreffende play al dan niet een interessant doel kan zijn voor geothermische boringen. Bij het opstellen van deze plannen en voorgestelde werkprogramma's is in eerste instantie vooral gekeken naar de technische bruikbaarheid en noodzakelijkheid, en minder naar een kosten-baten analyse van deze plannen. Voor elk SCAN-gebied (of combinatie van SCAN-gebieden) is op deze wijze een 2D seismisch lijnenplan gemaakt dat het beste de lacunes in de huidige 2D seismisch dataset, zowel in kwaliteit als kwantiteit, zou kunnen opvullen. Het rapport hierover en het voorgestelde acquisitieplan is vervolgens voorgelegd aan geologen en geofysici van EBN en TNO, die niet direct bij de evaluatie van het SCAN-gebied betrokken waren geweest. Op basis van de opmerkingen en aanvullingen van deze peer-reviewers zijn de plannen en rapporten waar nodig aangepast en afgerond. Het onderliggend rapport voor gebied H&I is het resultaat zoals dat op 20-03-2019 was afgerond. Om de informatie voor zoveel mogelijk geïnteresseerden toegankelijk te maken zijn de rapporten in het Engels geschreven, wat de meest gangbare taal is voor het geologische/geofysische vakgebied.

Nu alle rapporten en plannen afgerond zijn kan het totaal van de aanbevelingen hierin als "Best Technical Programme" worden gezien. Het Best Technical Programme is het acquisitieplan dat het meeste kans heeft om alle openstaande geologische vragen te beantwoorden. Echter, voor de 2D seismische acquisitie van het SCAN-project is er een beperkt budget beschikbaar bij het Ministerie van Economische Zaken en Klimaat. Op basis van de (veronderstelde) kosten van de seismische acquisitie is de verwachting dat voor het beschikbare budget niet het gehele "Best Technical Programme" kan worden uitgevoerd.

Om te bepalen welke seismische lijnen prioriteit hebben is een ranking van alle lijnen verricht. Deze ranking is onder andere gebaseerd op de volgende parameters: aantal mogelijk aanwezige primaire en secundaire plays, de dichtheid en kwaliteit van de seismische data in het gebied, de aanwezigheid van warmtevragers en de inpassing van lokale seismische initiatieven. Op basis van deze ranking wordt bepaald welke seismische lijnen met het beschikbare budget kunnen worden geacquireerd, terwijl de andere lijnen alleen zullen worden geacquireerd bij meevallende kosten of als aanvullend budget beschikbaar komt.

Na de acquisitie in het voorjaar van 2019 van een testlijn tussen Utrecht en Almere (deel van lijn EVD-UTR-BLA) om de acquisitieparameters in detail te bepalen, is besloten het programma verder te vervolgen in het oostelijk deel van SCAN gebied C. Op basis van de daar uitgevoerde terreinonderzoeken zijn enkele voorgestelde lijnen deels aangepast. Ook in sommige andere gebieden zijn er enkele kleinere aanpassingen gemaakt ten opzicht van het voorgestelde lijnenplan en ook in de toekomst zullen andere aanpassingen volgen nadat lokaal terreinonderzoek is verricht.

Op de kaart op de volgende bladzijde is de status van het lijnenplan van SCAN gebied H&I van heden weergegeven met inbegrip van de ranking van de lijnen. Op de website van SCAN (www.scanaardwarmte.nl) kan de status van de opname van de lijnen worden gevolgd.



Kaart met de status van het lijnenplan in de SCAN-gebieden H&I op 16/09/2019. Voor de lijnen die in doorgetrokken streep zijn weergegeven is met de huidige kostenverwachting budget voor acquisitie beschikbaar, voor lijnen die gestreept zijn weergegeven is met de huidige kostenverwachting geen budget beschikbaar.

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1. Introduction to the SCAN project

In order to achieve the goals of the Paris Treaty and limit global warming a shift from fossil towards renewable energy resources is required. Geothermal energy is a proven and promising renewable energy resource. To successfully and safely plan, fund and execute geothermal projects subsurface data is essential. Presently producing geothermal projects in the Netherlands are generally located in areas where abundant subsurface data is available (Figure 1).

Although subsurface data availability in the Netherlands is excellent, the data is not well distributed over the country; data coverage is poor in roughly half of the country, including major residential and industrial areas with high heat demand (Figure 1). As a result, effective and economically feasible development of geothermal projects is not possible under the current circumstances in these areas. A framework study was carried out to identify what data acquisition is required to overcome this limitation (EBN–TNO-AGE, 2017). Subsequently, EBN and TNO-AGE have been asked by the Ministry of Economic Affairs and Climate to embark on a geothermal exploration program (SCAN: ‘*Seismische Campagne Aardwarmte Nederland*’) to decrease the subsurface uncertainty and hence shape the conditions needed for the successful development of geothermal projects in these areas.

The most important subsurface parameters that need to be known for the successful development of a geothermal project are permeability, thickness and depth of the aquifer. These parameters can be derived from seismic and well data (Table 1) (EBN – TNO-AGE, 2017). The SCAN project will therefore comprise acquisition of new 2D seismic data, reprocessing of vintage seismic data and drilling of new wells in areas with relatively low data availability. Nine such areas have been identified (Figure 1). The areas were prioritized based on the expected future heat demand. Area H, which comprises the city of Hoorn and some large greenhouse complexes, was identified as an area of normal priority. Area I, which includes the city of Emmeloord and a large greenhouse complex near Luttelgeest, was identified as an area of normal priority as well. This report discusses both areas H and I, which have been evaluated together since their geological history and make-up is quite comparable, even though they are located on either side of the Texel-IJsselmeer High. The combined area will be called ‘area H&I’ in this report.

This document outlines the geological objectives and design criteria (position and orientation) for the 2D seismic acquisition (“Acquisitieplan” in the tentative planning, EBN, TNO-AGE, 2017, appendix 6). More potential future work other than the seismic acquisition is presented in this report. This includes geological and geophysical studies, seismic reprocessing and the drilling of exploration wells to test the stratigraphy and/or sedimentology. It should be noted that this work will be subject to further detailed review but is presented here only to give the proper setting for the 2D seismic acquisition plan.

Information	2D-Seismic data	3D-Seismic data	Well
<i>Economical evaluation: presence and quality of aquifer, temperature</i>			
Presence, continuity, depth and thickness aquifer	+	++	+++
Porosity	–	+/-	+++
Permeability (transmissivity)	--	--	+++
Temperature	+	+	+++
<i>Safety, well planning and regional geological knowledge</i>			
Regional geological model	++	+++	++
Presence of faults	+	+++	+/-
Character of overburden on well trajectory	+	++	+
Risk-assessment of presence of hydrocarbons	+	++	+/-
Water composition	--	--	++

Table 1 – data-acquisition methods and information resulting from these methods. Legend: --: produces no or inaccurate information, +++: results in much, accurate information.

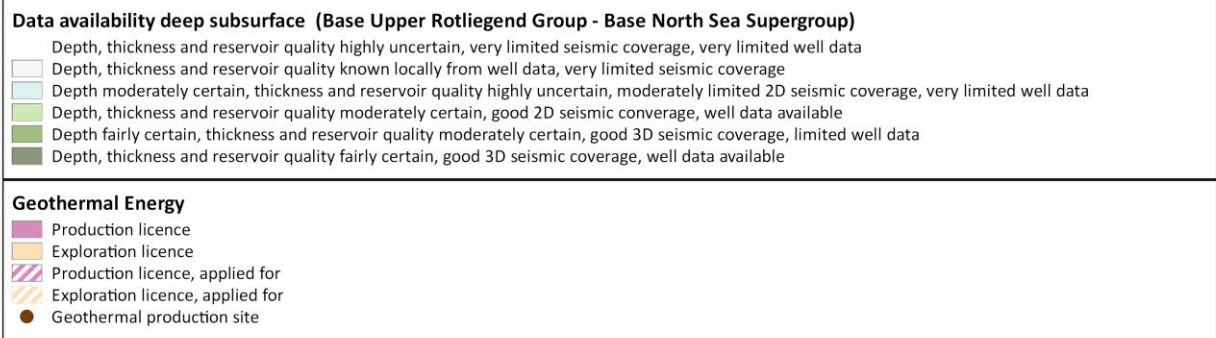
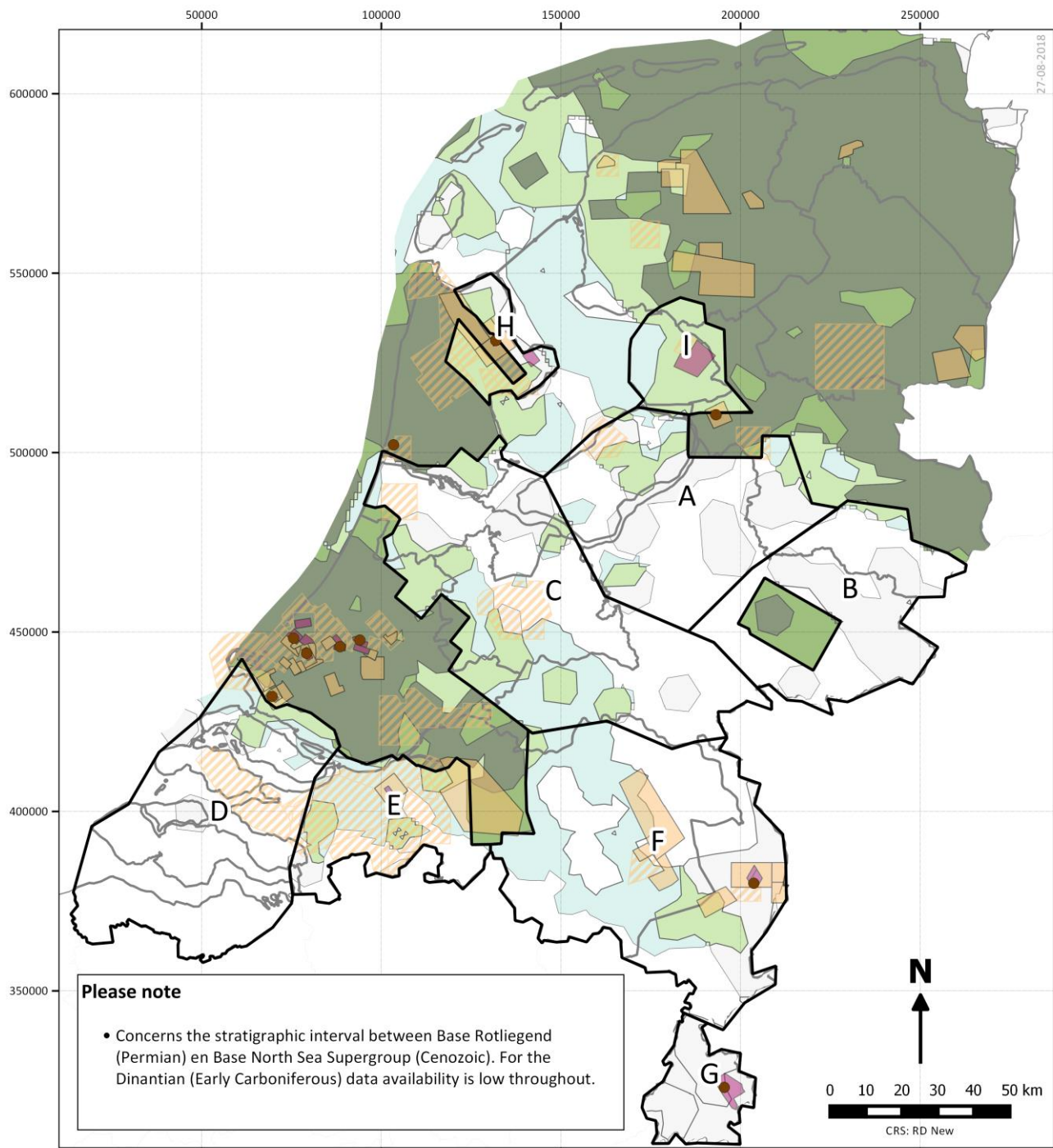


Figure 1 – SCAN areas, geothermal licenses and producing geothermal installations (after EBN -TNO-AGE 2017).

2. Geological overview of SCAN area H&I

The stratigraphic interval of interest ranges from Lower Carboniferous (Dinantian) carbonates at a depth of approximately 4500–6000 m to Cenozoic sands as shallow as 700 m below ground level. The by far most important target for geothermal projects in this area is the Rotliegend sandstone. Other primary targets are provided by the Lower Carboniferous carbonates and the Brussels Sands of the Lower North Sea Gp. (Figure 2). Secondary targets include the Lower Cretaceous sandstones, Triassic sandstones and Zechstein carbonates.

Within area H&I the following structural elements can be distinguished for the Jurassic–Cretaceous tectonostratigraphic evolution of the area (Kombrink et al. 2012, Figure 3):

- The Texel IJsselmeer High (TIJH) forms the central structural element, where the interval between Rotliegend and Upper Jurassic has been largely eroded below the Base Cretaceous Unconformity (BCU)
- Located east of the TIJH in area I is the Friesland Platform (FP), where the Triassic to Upper Jurassic has been eroded below the BCU
- The area west of the TIJH in area H is called the Noord-Holland Platform (NHP), where the Jurassic is largely absent below the BCU

Another important structural element is the Cenozoic Zuiderzee Low (Figure 3). This feature is associated with a thick development of the North Sea Groups in contrast to the eroded Middle and Lower North Sea Groups of the Kijkduin High.

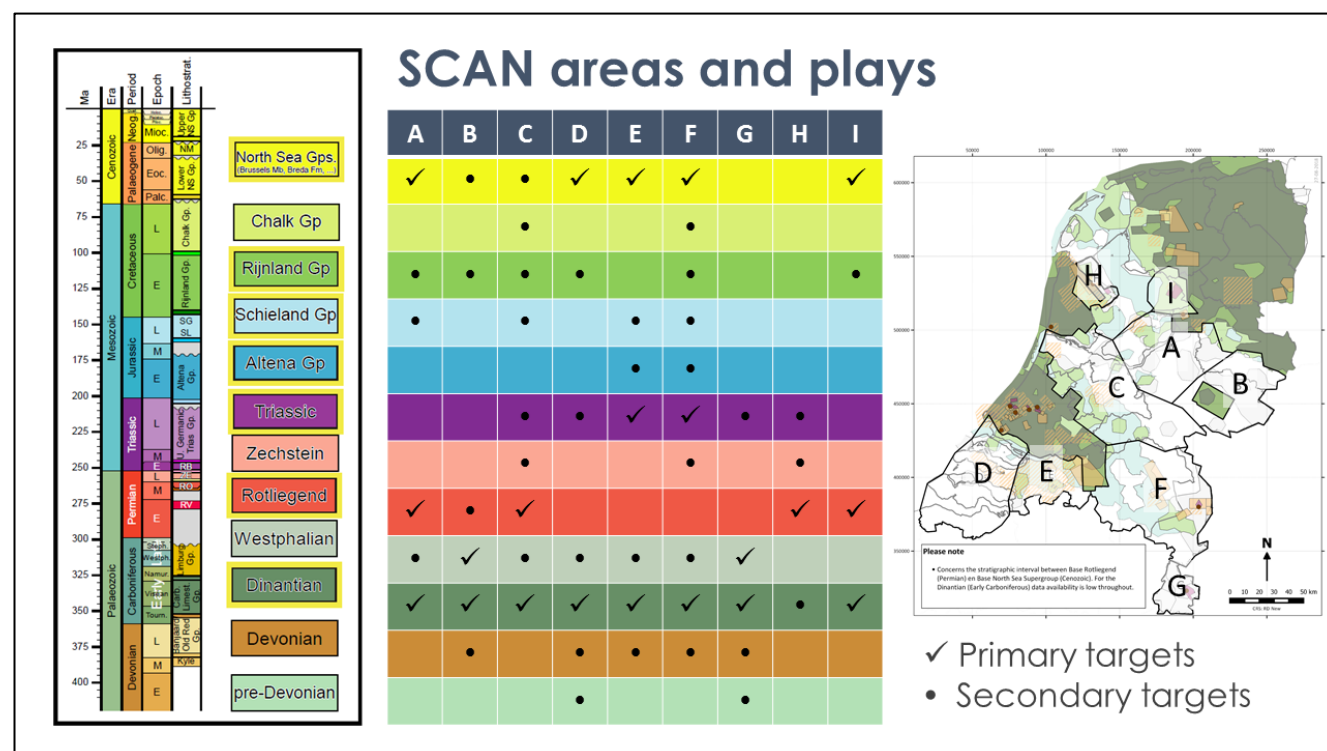


Figure 2 – Overview of the primary and secondary targets in the SCAN areas.

2.1 Stratigraphic Section

From old to young the stratigraphy (Van Adrichem Boogaert & Kouwe, 1993–1997) relevant to geothermal projects in area H&I is expected to consist of:

- A siliciclastic Devonian section. The oldest interval drilled in area H&I is a Devonian (Famennian) claystone section with interbedded sandstones in well LTG-01. This well penetrated only the top 45m of this formation, so detailed evaluation of the Devonian potential is not possible.
- Lower Carboniferous (Dinantian) carbonates (Figure 5). In well LTG-01 a 767m thick section of limestone and dolomite was drilled in what, on 2D seismic data, can be identified as a reefal build-up structure. The thickness of the formation outside this build-up is probably much lower, but this has not been ascertained by seismic interpretation.
- An Upper Carboniferous siliciclastic sequence (sandstones, claystones and coal) (Figure 4 & Figure 5; Limburg Group). The top of the Upper Carboniferous sequence was eroded during the Variscan orogeny resulting in a significant time gap between the Carboniferous and overlying Permian sediments represented by the Base Permian Unconformity (BPU). In most of the area a relatively claystone-rich interval of Westphalian A age is present below the BPU. In area I the Carboniferous interval locally contains several intrusions, most a few meters thick.

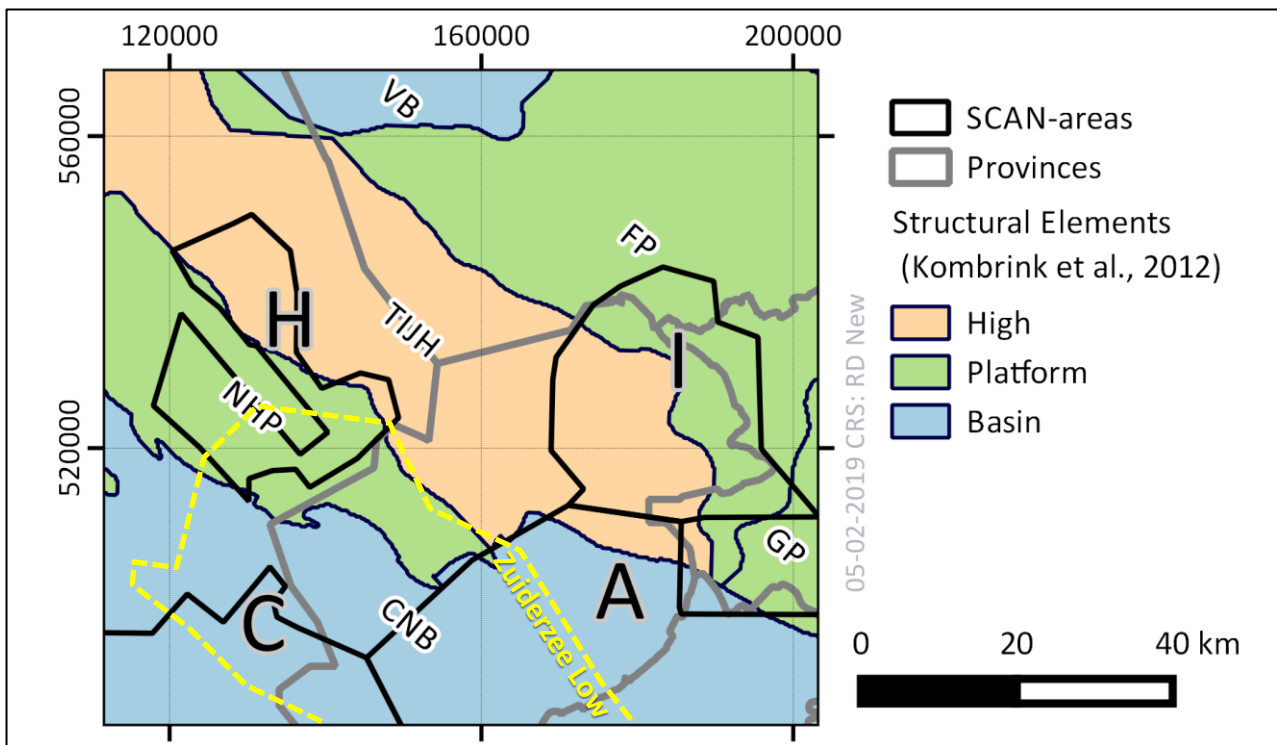


Figure 3 – Late Jurassic – Early Cretaceous structural elements in and around SCAN area H&I after Kombrink et al. (2012), CNB – Central Netherlands Basin, FP – Friesland Platform, GP – Groningen Platform, NHP – Noord Holland Platform, TIJH – Texel IJsselmeer High, VB – Vlieland Basin. Indicated in yellow dashed line is the Cenozoic Zuiderzee Low.

- The Permian Rotliegend Slochteren Sandstone interval (Figure 4 & Figure 5; Upper Rotliegend) covers the BPU. In area H&I the Rotliegend sandstone is (partly) eroded on the Texel-IJsselmeer High. In area H the Rotliegend has a thickness of around 200m, whereas in area I the Rotliegend is thinner ranging between 50-100m.
- The Permian Zechstein interval (Figure 4 & Figure 5, Zechstein Group) is developed mainly in a platform facies in area H&I, characterized by anhydrite, dolomites and limestones. No salt intervals are present in this area.
- The Lower Germanic Trias Group (Figure 4 & Figure 5) comprises the Lower Buntsandstein Formation and the Main Buntsandstein Subgroup and is preserved in area H. The Lower Buntsandstein Fm. consists of a regional uniform lacustrine claystone with thin interbeds of oolitic limestone. The Main Buntsandstein has a sandstone interval at its base whereas the remaining section is composed of claystones.

- The interval between of the Upper Germanic Trias Group to Upper Jurassic Schieland Gp. has been eroded (or was not deposited) in areas H&I (Figure 4 & Figure 5, Upper Germanic Trias Group, Altena Group and Central Graben Group).
- The Lower Cretaceous Rijnland Group in area H&I (Figure 4 & Figure 5) is present over the whole of area H&I. However, it is thin (50-100m) in area I, where mainly the marls of the Holland Fm. are present and the underlying Vlieland shales are absent. In area H the thickness of the Rijnland increases to 400m in the west, where more Vlieland claystones are present.
- The Upper Cretaceous Chalk Group (Figure 4 & Figure 5). The Chalk Group is present over most of area H&I, however the Chalk is progressively eroded below the Base North Sea Unconformity towards the south of area H.
- The Lower and Middle North Sea Groups (Figure 4 & Figure 5, not subdivided). This interval consists primarily of unconsolidated sands, sandstones and claystones. The interval is thinned towards the west of area H due to erosion below the unconformity below the Base Upper North Sea Gp.
- The youngest sediments, the Upper North Sea Group (Figure 4 & Figure 5; not subdivided). These consist mainly of marine sands and claystones. The interval is thickening in the south of area H into the Zuiderzee Low.

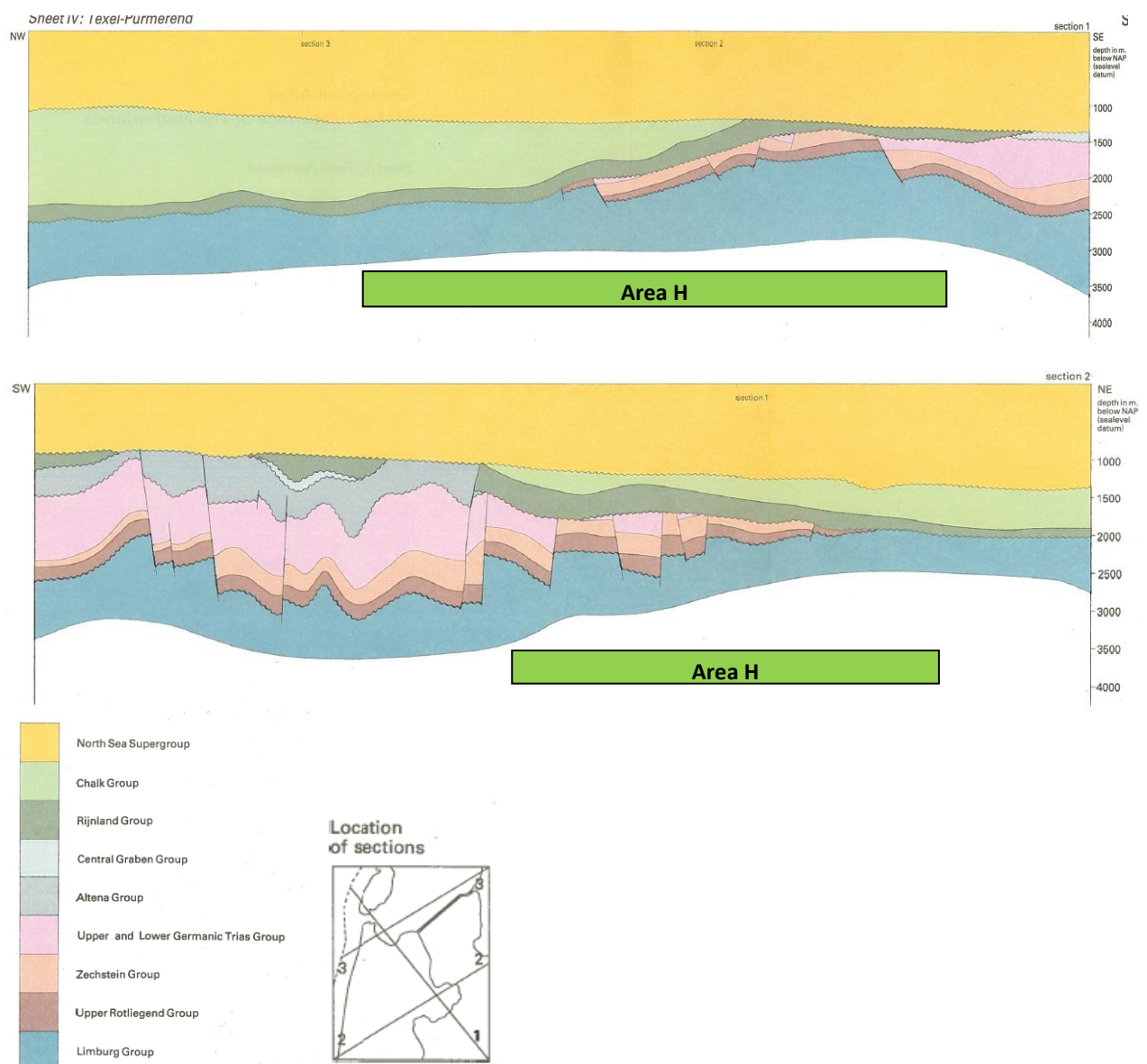


Figure 4 - Cross sections (sections 1 and 2) through area H (RGD, 1993a).

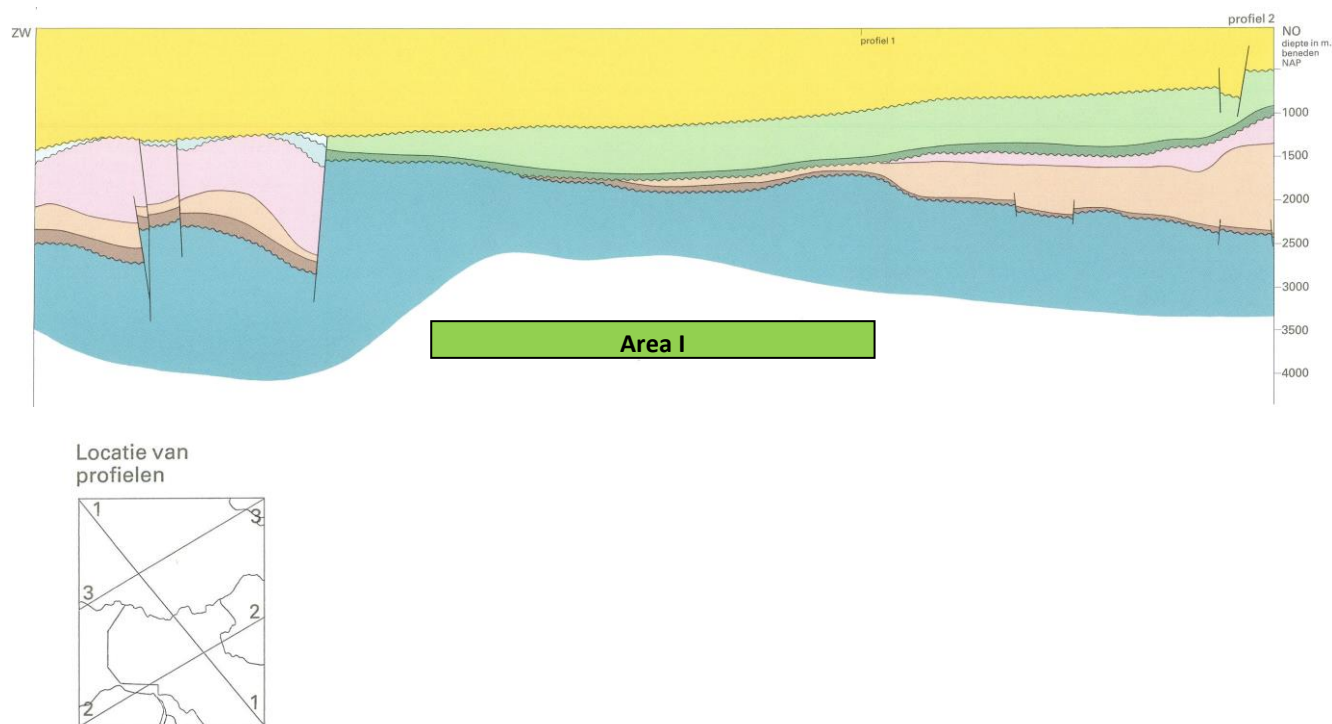


Figure 5 - Cross section (section 2) through area I (RGD, 1993b).

2.2 Structure

The sequence of tectonic events, also applicable to area H&I, from Devonian times onwards is well summarised in De Jager (2007). The main NW-SE structural trend is interpreted to originate from the Caledonian tectonic event of mid-Palaeozoic times. The structural style at that time is considered to be a horst and graben configuration in an overall NE-SW extensional setting. The horsts and grabens were separated by major NW-SE trending normal fault systems with significant throw, which are expected to root in the basement.

These Caledonian fault systems were reactivated during Variscan and Alpine orogenic events, and in intermediate rifting events; each event under different stress-regimes: in orientation, strength and nature (compressive or extensional). For example, in the period from Mid/Late Jurassic until Late Cretaceous times, in the last phase of Pangean breakup, an extensional to transtensional regime resulted in the formation of the Mesozoic Basins (Broad Fourteens Basin, West Netherlands Basin, Roer Valley Graben) and intermediate platforms and/or highs. The subsequent Alpine tectonic events in which the Alpine stress regime forced oblique-slip movement along the old Caledonian faults resulted in, amongst others, thrust faults and flower structures in the Late Palaeozoic to Cenozoic sedimentary overburden.

For the development of geothermal systems and hazard assessment it is of utmost importance to have a good understanding of the structural evolution and architecture of the subsurface of area H&I, in an adequate detail. This requires a detailed interpretation of the structural and stratigraphic framework, for which control from seismic and well data is essential. These constraints are needed at least down to the top of the Dinantian, which is to be expected at a depth of 4 to 6 km in area H&I.

From regional maps it appears that the structural architecture of area H&I below the Base Cretaceous Unconformity is dominated by NW-SE trending normal faults. However, the current fault mapping is simplified by the fact that connecting faults using only 2D data is difficult and is prone to aliasing.

From the 2D seismic data that is available in area H&I it can be inferred (Figure 4 & Figure 5) that in this area:

- 1) The Cenozoic is essentially unfaulted and is deepening to the south into the Zuiderzee Low. The Lower and Middle North Sea Groups, however, are progressively eroded towards the Kijkduin High to the southwest of area H.
- 2) Inversion tectonics at the end of the Cretaceous to earliest Paleogene in the Central Netherlands Basin, located just south of area H, is characterized by uplift and erosion and local folding and reversal of fault movements. In area H itself these effects are limited, when compared to the Central Netherlands Basin. Especially the Slootdorp-

Middenmeer-Hoogkarspel (SLD-MDM-HOK) structure shows clear inversion phenomena, such as oblique-slip faults and a thinned Chalk section. In area I no significant inversion tectonics have been observed.

- 3) In the Triassic to Upper Carboniferous interval a NW-SE trending fault system is present and locally horsts and grabens can be observed, suggesting more faults with oblique orientations to the main trend. Since the interval between the Base Cretaceous Unconformity and the Base Permian Unconformity is quite thin in area H&I correlating faults is hampered by lack of clearly identifiable markers in this section.
- 4) In the LTG area a Dinantian carbonate build-up structure can be recognized on the better quality 2D lines. No other similar structures have been recognized on the current 2D seismic data of area H&I.

2.3 Primary targets

2.3.1 Rotliegend sandstones

In area H&I the Upper Permian Rotliegend reservoir (Slochteren Fm.) is the most important geothermal reservoir. A significant number of wells has penetrated this interval, which resulted in good information on the depth, thickness, porosity and permeability of the Rotliegend reservoir. The depth of the top of the formation ranges between 1800-2500m TVDss. The thickness of the (non-eroded) formation (*Figure 6*) ranges from 12m in the northeast of area in well BRL-01 to 207m in well LKM-01 in area H. In general, the thickness in area I is smaller (12-123m) than in area H where the thickness varies between 164-207m. It is important to note that on the Texel-IJsselmeer High, the Rotliegend has been partly and sometimes completely eroded below the Base Cretaceous Unconformity (BCU). Only in wells NAG-01 in area I and in well BRG-01 (Den Burg-1) on the island of Texel north of area H the Rotliegend is completely absent. In well WGF-01 in area H and in wells EMO-01 & LTG-01 the Rotliegend has been partly eroded.

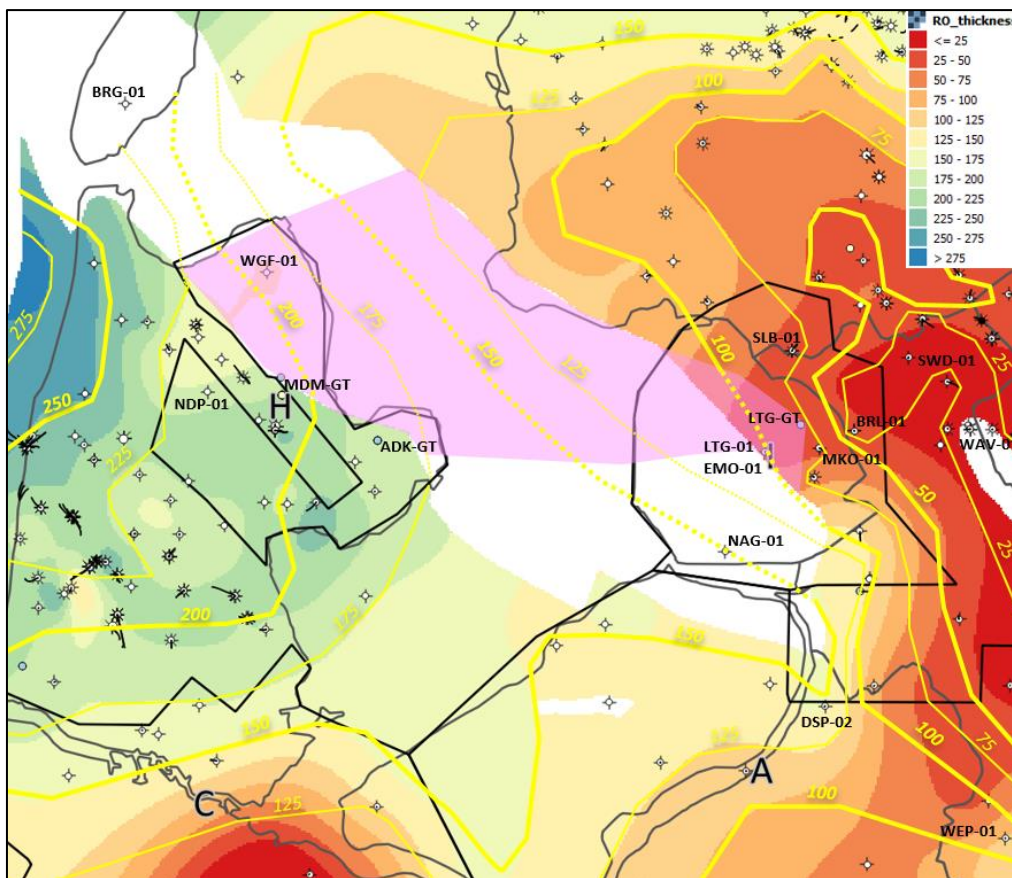


Figure 6 – Rotliegend isopach map (in m): in color the TNO 2014a map, in yellow lines adjustments were made to remove wells with unrepresentative thicknesses due to erosion, faulting or well deviation. The isopach lines are dashed where the Rotliegend can be partly eroded below the Base Cretaceous Unconformity. The pink polygon shows an area where the quick-look interpretation shows local presence of fault blocks with partly eroded Zechstein and Rotliegend. In the white areas the Rotliegend is thought not to be present. Well names indicated for wells mentioned in report text.

From density data in well logs and core porosity data it is clear that in a large number of wells the Rotliegend reservoir has an average porosity higher than 20%. The core permeability is often higher than 100mD, which in most cases is high enough to warrant good flow rates in geothermal wells. Possibly the short distance to the BCU or even exposure at the BCU has had a positive effect on the Rotliegend reservoir quality, leaching the sandstone when it was exposed to (fresh) ground water. Only well BRL-01 has a much thinner reservoir (12m) and logs indicate a poor reservoir quality. Based on the available data it is not clear why the Rotliegend is of poor quality here. High quality 2D may constrain the area around BRL-01 with poor reservoir quality by mapping the reservoir with help of seismic inversion. Igneous rocks of Early Permian age have been found directly below the Rotliegend in this well (Sissingh 2004). These harder rocks may have formed cuesta-type of topography resulting in a thinned accommodation space for the Rotliegend sandstone. In wells to the east (e.g. WAV-01 and SWD-01) this effect can also be postulated.

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In area H two geothermal projects have been initiated: the Middenmeer (MDM-GT) project and the Andijk (ADK-GT) project, whereas in area I the Luttelgeest (LTG-GT) project was recently drilled. Only for the MDM-GT project public data is available. This data together with the news coverage of the other projects in media and on the projects' websites indicate that the wells have been successfully drilled and tested.

Above the Rotliegend reservoir a package of Zechstein anhydrites and carbonates is present. These hard and fast Zechstein layers generally give a good reflectivity on the seismic data and can be mapped well on 2D data, thereby also permitting the mapping of the underlying Rotliegend. The base of the Rotliegend generally has a small impedance contrast which makes seismic mapping of the Base Permian Unconformity (BPU) more difficult, often the depth map of the base of the Rotliegend is constructed by isochoring downwards from the Base Zechstein depth map. Only where underlying high-reflective coals subcrop the Rotliegend with an angular unconformity, the BPU can be picked with confidence on the seismic data. If the Zechstein has been eroded and only Rotliegend sandstone is underlying the BCU the identification and mapping of the Rotliegend is more difficult. Since only an interval of 50-150m of seismically opaque Rotliegend is present above the BPU it is hard to ascertain if a Rotliegend interval is present, or if only Carboniferous rocks are present below the BCU. The coal intervals are the best criterion to positively identify the Carboniferous. Inverting the seismic data may help to discriminate between Rotliegend and Carboniferous. Another option would be to do gravity modelling to distinguish between fault blocks with Rotliegend sandstone or Carboniferous claystones.

A quick-look interpretation of the seismic data indicates that in some parts of the Texel-IJsselmeer High the high-impedance Zechstein carbonates/anhydrites can be positively identified to be present below the BCU by their bright seismic response. This leads to the conclusion that most likely also Rotliegend is present at those locations. In other areas of the Texel-IJsselmeer High an opaque section, like in well WGF-01, is seen to subcrop the BCU underlain by high-reflective coals. These opaque intervals can be interpreted as the Rotliegend interval, which is characterized by a homogeneous section without impedance contrasts. The quick-look interpretation indicates (*Figure 6*) that (partly eroded) Rotliegend fault blocks may be present over a larger area the Texel-IJsselmeer High than indicated in the regional TNO maps (TNO 2014a). Only in the NAG-01 area no Rotliegend was seen below the BCU in the quick-look evaluation.

At some locations in area H&I edits on the TNO 2014a isopach map of the Rotliegend are possible (*Figure 6*). It seems that for this map locally wells have been used that have an anomalous isopach due to faulting, erosional truncation and well deviation and dip. Removing these suspect wells leads to a higher isopach in area H&I near wells NDP-01 in the west of area H and near wells MKO-01 and SLB-01 in the centre of area I. These adjustments also result in higher expected non-eroded isopachs for any preserved Rotliegend on the Texel-IJsselmeer High (e.g. near wells WGF-01 and LTG-01).

It is important to note that no evidence is found for the theory that the Texel-IJsselmeer High was a syn-sedimentary high during the deposition of the Rotliegend sediments. The thickness trend of the Rotliegend (*Figure 6*) does not show a consistent thinning of the Rotliegend towards the TIJH, fault blocks on the TIJH show presence of Rotliegend on the TIJH and the fluvial facies and in wells WEP-01 and DSP-02 in area A&B shows the presence of a fluvial channel towards the TIJH. However, a syn-depositional high may have been present east of area I in the north of Overijssel and the south of Drenthe.

To reduce the risk of geothermal projects in the Rotliegend of area H&I the following activities are proposed:

- Reprocessing of existing 2D data (if field data is available).
- Perform a test to assess if a seismic inversion project may help to seismically predict areas of good reservoir quality
- Perform a gravity data modelling test to distinguish between fault blocks with Rotliegend sandstone or Carboniferous claystones
- Acquisition of new 2D seismic data across the eastern part of area H and the western part of area I to highlight fault blocks with Zechstein or partly eroded Rotliegend not identified on the TNO maps, and to map the area of poor and thin reservoir quality around well BRL-01.
- Acquire 3D seismic data to better map Rotliegend fault blocks in order to ascertain their size and investigate if compartmentalization or well interference may be an issue. 3D seismic may be an alternative to 2D acquisition if it is felt that the Rotliegend eroded fault block play is sufficiently proven in area H&I. However, 3D seismic acquisition is beyond the scope of the SCAN project.

2.3.2 Cenozoic sands

The sands in the Cenozoic section are a relatively new target for geothermal exploration and production. Since the Cenozoic is in general not buried deeper than 1.5 km the temperature in these sands is relatively low (30-45 °C). The application of this heat is called in Dutch: Lage Temperatuur Aardwarmte (LTA). An LTA doublet has recently been drilled in SCAN area E near Zevenbergen. The reservoir here consists of the Brussels Sand Mbr. of the Dongen Fm. in the Lower North Sea Gp. located at a depth of around -600m. In area H&I the Brussels Sands are thought to have potential for geothermal energy projects as well.

Since the Cenozoic was of nearly no interest to oil and gas exploration in the Dutch onshore, very limited reservoir information is available. Additionally, the interval was usually not covered by an extensive logging suite in hydrocarbon exploration wells. The wells of the Zevenbergen doublet have not been released yet, however, some information is available on the website of the operator and in media coverage.

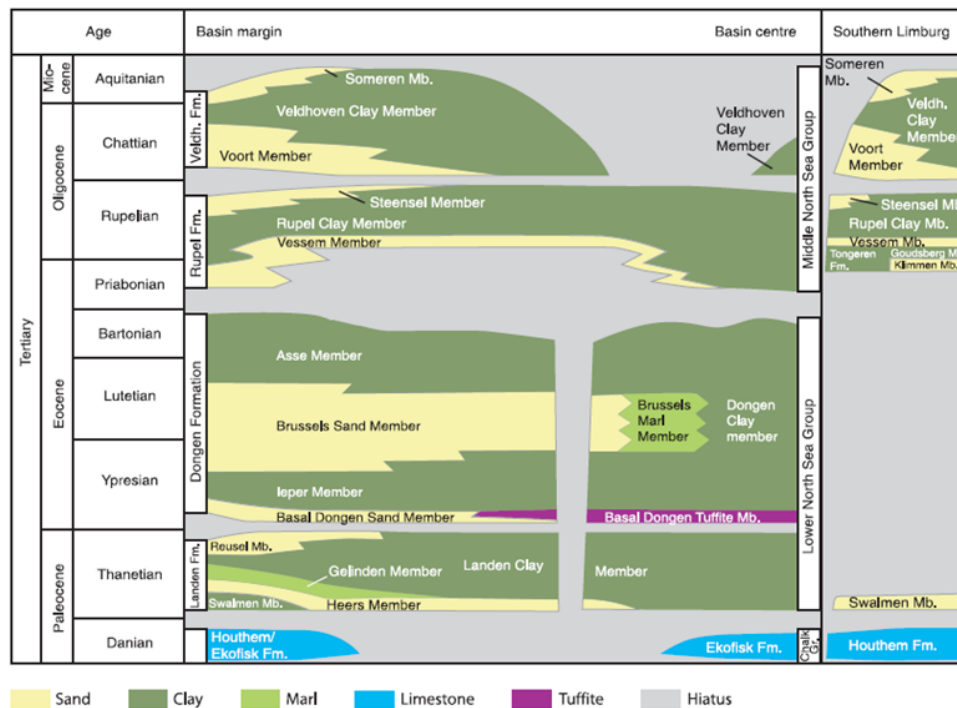


Figure 7 – Stratigraphic scheme of the Lower and Middle North Sea Groups in the Netherlands (Wong et al 2007).

The Lower North Sea Group (Figure 7) consists mainly of marine claystones with interbedded sandstones. In general, the thickest sand interval is the Middle Eocene Brussels Sand Mbr. of the Dongen Fm. Other Lower North Sea Gp. sand intervals are the Heers Mbr. at the base of the Landen Fm. and the Basal Dongen Sand Mbr. at the base of the Dongen Fm. However, in area H&I, which is located further basinwards than area D&E, only the Brussels Sand Mbr. is a viable reservoir. The Brussel sands have been eroded just south of area H, where the Lower North Sea Group is truncated below the Middle North Sea Group.

According to Van Adrichem Boogaert & Kouwe (1993-1997) the Brussels Sand Mbr. can be characterized as a succession of green-grey, glauconitic, very fine-grained sands with, mainly in the upper part, several hard, calcareous sandstone layers of some decimetres thickness (leading to high-resistivity peaks). Towards the base of the unit the clay content increases, and the calcium carbonate content and amount of glauconite decreases. A minor amount of mica occurs. The upper part with the cemented, calcareous sandstone layers is very rich in fossil fragments, abundant Nummulites, shells (including Pecten) and Echinodermata, indicating a near-shore environment. The member is deposited in an inner-neritic to near-shore environment. In general, the water depth appears to be shallowing upwards, with a possible exception for the uppermost part of the unit.

The Eocene formations are found in outcrop in Belgium. It should be noted that the Dutch Brussels Sand Mbr. is not equivalent to the Belgian Brussels Fm. The upper half of the Dutch Brussels Sand Mbr. is more or less time-equivalent to the

Belgian Lede Fm., whereas the base can be correlated to the Belgian Brussels Fm. In the Gobertange area (east of Brussels) the sandy limestones of the Brussels Fm. are mined for building use (Gullentops & Wouters, 1996). The tight layers form up to 20cm thick hard banks consisting of 73-87% carbonate. Some of the layers are seen to be continuous in the quarry, whereas there are also smaller discontinuous concretions. These hard carbonate banks are expected to be analogous to the calcareous sandstone layers described in the Dutch lithostratigraphy and seen in well logs (Figure 6) in the top part of the formation. In well WYK-12, 20km east of area I the Brussels Sands have been completely cored (297-375m MD). Core analysis data shows that the upper 25m of the formation is mostly tight, however the basal 50m section has porosities between 35-45% and permeabilities between 150-1000 mD, except in occasional tight streaks.

Based on the higher Gamma Ray response and the cuttings descriptions the Brussels Sands in area H seem to have a lower reservoir quality than in area I (Figure 8). A quick-look seismic interpretation of area I of the Top and Base Brussels Sands shows these markers can be interpreted on the existing 2D seismic data. In area I the Brussels Sands have a thickness of around 90m, thickening to the north to around 110m. The depth of the Top Brussels increases from 700m in the east of area I to around 800m in the west. With well MKN-01 a gas accumulation has been found in the Basal Dongen Tuffite Mbr. This field, operated by Tulip Oil, has not been developed yet since its discovery in 1983. In this same well a dropout of the sonic log in the Brussels Sands could point to gas saturations in this formation. However, the saturations could be quite low.

In the southern part of area H, in the Zuiderzee Low, the Upper North Sea Gp. consists of a sand-rich section with its base at a depth of 750m (e.g. well HOK-02). These sands may provide additional geothermal potential. The aquifers may also be used to seasonally store excess heat.

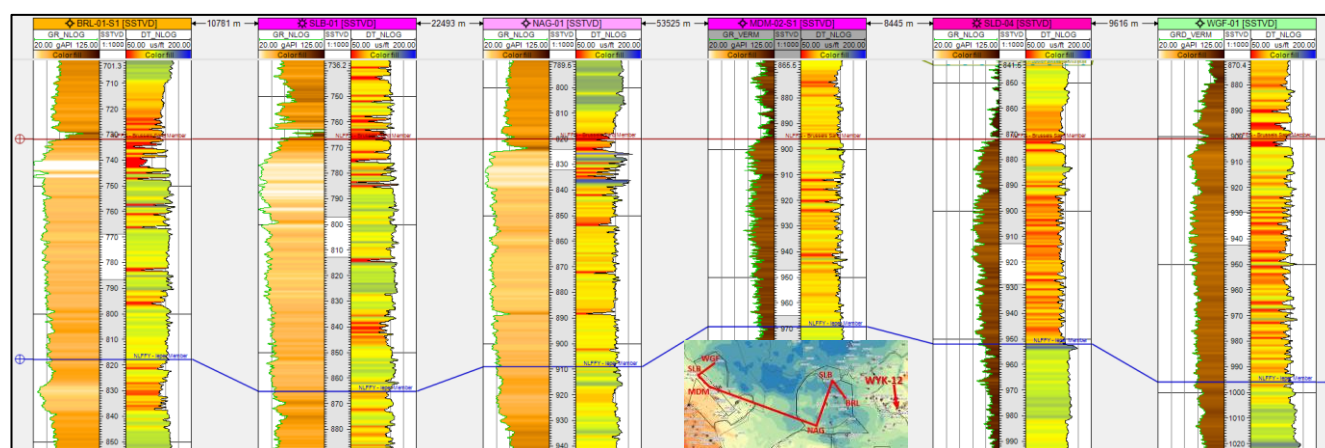


Figure 8 – Log Correlation (GR-DT) Brussels Sand Mbr. wells BRL-01-S1, SLB-01 & NAG-01 in area I and wells MDM-02-A1, SLD-04 & WGF-01 in area H. Note the low DT tight streaks in all wells and the much higher GR response in the wells of area H.

For a more comprehensive evaluation of the Cenozoic geothermal plays the following activities are recommended:

- Drill well(s) to obtain good core and log coverage and well testing of the Brussels Sands in area I to evaluate the reservoir properties and sedimentological environments. In area H coring the Brussels Sands is not advantageous in view of the poor perceived reservoir quality, however, an extensive logging program in a well to a deeper target may be useful for both the Brussels and the Upper North Sea aquifers.

In preparation of this well the following work is recommended:

- Perform a petrophysical analysis of the North Sea reservoirs
- Seismic reprocessing of relevant seismic data (if field data available)
- Perform a detailed seismic interpretation
- Use new seismic data to be acquired for deeper targets to further refine the interpretation
- Test seismic inversion on North Sea reservoirs

2.3.3 Lower Carboniferous (Dinantian) carbonates

In area H&I one well (LTG-01) has been drilled into the Dinantian carbonates (*Figure 9*). The well was drilled by Total in 2004 for hydrocarbon exploration in this reservoir. The location of the well was determined on 2D seismic data, where a build-up structure with around 500m relief was seen. The well was positioned near the western edge of the platform, which is the steepest side of the structure. The platform is elongated and has a length of around 10 km in the west-east direction and 4 km in the north-south direction. The well found a 767m thick limestone and dolomite section of Dinantian age. Below this reservoir a 45 m clastic Devonian section consisting of Famennian claystones and some sandstones was drilled down to the TD of the well. During the drilling of the Dinantian several kicks and flows from the formation were observed. High Gamma Ray log responses (up to 130 API) point to fractures filled with clay and other radioactive minerals. Also, the borehole image logs (FMI) point to significant fracturing in the Dinantian. The matrix of the carbonates is mostly tight with less than 5% porosity. The reservoir temperature was around 200°C, higher than the expected 150°C, based on a normal geothermal gradient. The Limburg Group showed an elevated temperature above the Dinantian reservoir. Lipsey et al. (2016) modelled the temperature development of the LTG structure and concluded that convection through a fractured reservoir could explain the elevated temperatures observed. Pressure testing found a formation pressure of 605 bar in the station (4604.7m MD) with the highest mobility (6.3mD/cp), which is around 145 bar above hydrostatic pressure. The LTG-01 well was plugged and abandoned after a well test over a 40m reservoir interval did not result in flow to surface.

Since the normal matrix permeability of Dinantian carbonates is very low, geothermal plays in this reservoir will depend on secondary permeability. Three subplays on enhanced permeability can be identified: related to faulting and fracturing (e.g. the Californië project), karstification of the reservoir during the Dinantian/Namurian (e.g. Loenhout UGS in Belgium) and karstification below the Base Permian or Base Cretaceous Unconformity (e.g. KTG-01 well). This last subplay is not present in the H&I area.

In the context of the SCAN Dinantian studies the LTG-01 well will be the subject of more detailed evaluations, as the LTG structure could serve as an analogue for other UDG projects, especially the ones in the north of the Netherlands, where more build-up structures have been observed on (3D) seismic data. At this moment there are no plans to use the LTG structure for geothermal purposes. However, one or two high quality 2D lines with deep penetration and a connection to the 3D seismic surveys to the north and east of the area I could help to better tie the top and base of the Dinantian and may help to highlight the internal structures in the build-up. Extensive acquisition of 2D seismic data over the LTG structure, in addition to the existing data is not seen as advantageous at this moment.

It has been suggested by Boxem et al. (2016) that more platforms could be present on the Texel-IJsselmeer High (*Figure 9*) if this high is a long-lived structural feature, which was already present during Devonian/Dinantian times. TNO 2014b mapping (*Figure 10*) shows the presence of a top Dinantian high just below well NAG-01. This well was drilled to a TD of 4300m in Lower Namurian claystones of the Geul Subgroup. The mapping also indicates a high in the east of area H near Enkhuizen. A regional deep seismic section shot by Delft Geophysical in 1987 across the Texel-IJsselmeer High at the location of the Afsluitdijk shows local good and deep penetration of the seismic energy into the Carboniferous section. However, no potential build-ups of Dinantian age can be seen on this section. Since the field data of this line is lost, reprocessing of the data to enhance the Carboniferous section is not an option. The seismic acquisition proposed for a Rotliegend target in area H&I could also help to image the deeper Carboniferous section, provided the acquisition parameters allow for this deep penetration.

To reduce the risk of geothermal projects in the Dinantian of area H&I the following activities are proposed:

- Detailed seismic interpretation and depth mapping of the Dinantian (in progress, part of SCAN Dinantian)
- Reservoir study of the Dinantian (in progress, part of SCAN Dinantian)
- Acquisition of deep-penetration 2D seismic data across the LTG and NAG structure and connect these to the surrounding 3D seismic data
- Acquisition of deep-penetration 2D seismic in area H over the Texel-IJsselmeer High in conjunction with the Rotliegend acquisition program

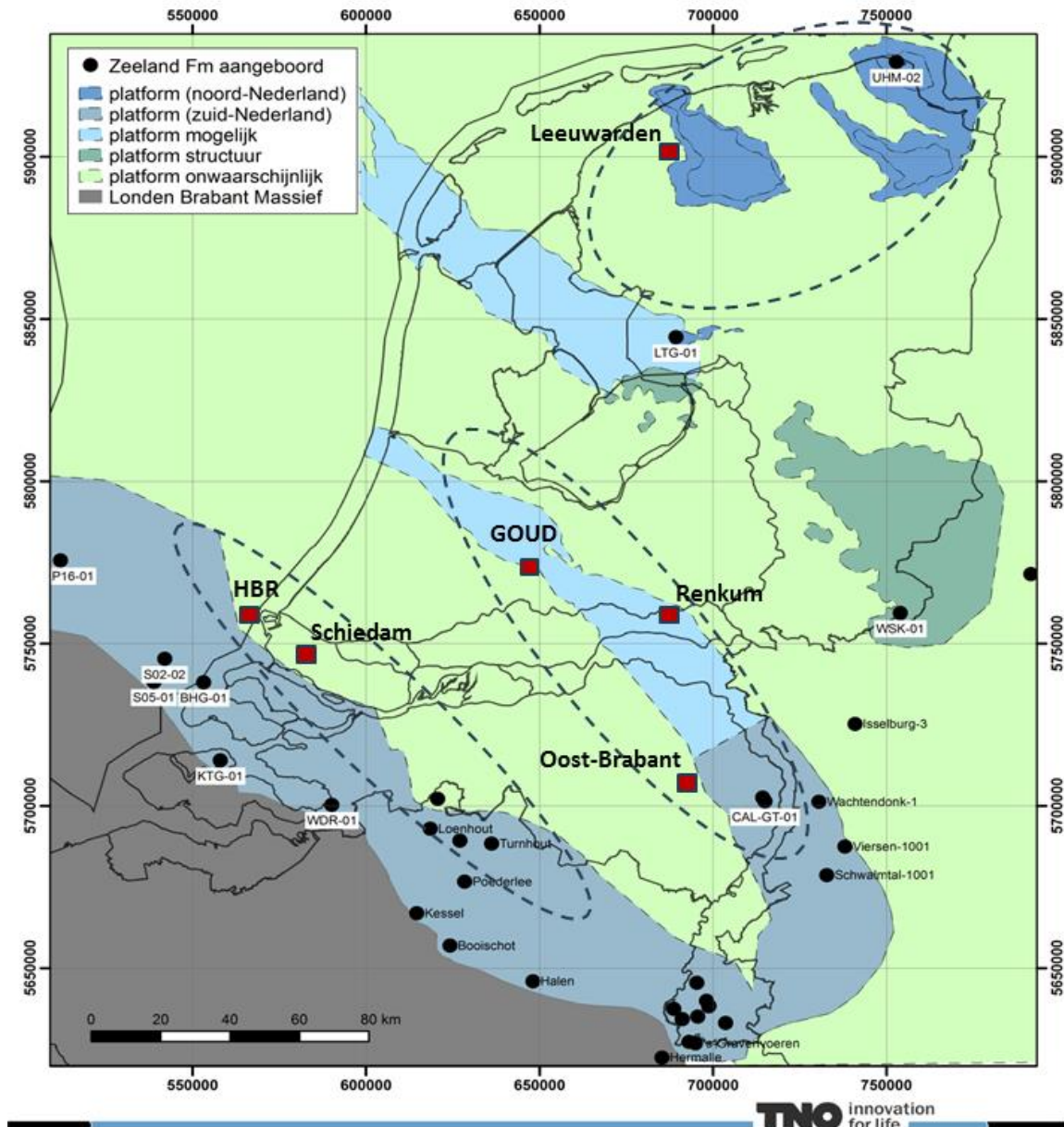


Figure 9 – Facies map of the Dinantian (Early Carboniferous) from Boxem et al. (2016). “Platform mogelijk”: platform possible, “Platform structuur”: platform structure, “Platform onwaarschijnlijk”: platform unlikely, “Zeeland Formatie aangeboden”: Zeeland Fm encountered in well. NB: This map may be outdated as it does not reflect the ongoing SCAN Dinantian work.

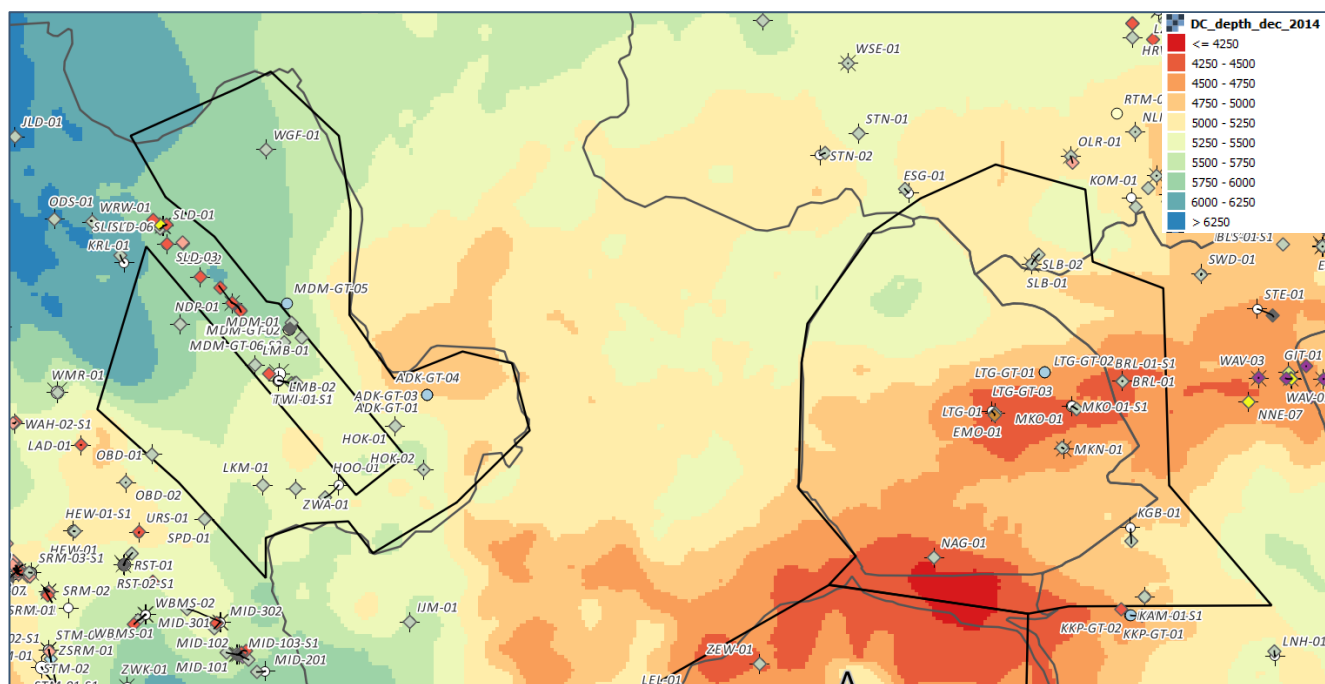


Figure 10 – Depth map of Top Dinantian horizon, as provided in Dinoloket (TNO 2014b)

2.4 Secondary targets

2.4.1 Lower Cretaceous sandstones

On the Friesland Platform to the north of area I locally the Vlieland Sandstone (Friesland Mbr.) is a hydrocarbon reservoir. The Vlieland sandstone has not been encountered in wells in area H&I, but just north of area I, in well KOM-01, a 18m water-bearing sandstone was found. Pressure tests in this sandstone interval found relatively low mobilities (0.51-9.38 mD/cP). The locations on the Friesland Platform, where Vlieland sandstones have been found, are generally areas where the total Rijnland isopach is larger than the surrounding areas. Regional TNO maps show the Rijnland to thicken from well KOM-01 into a small syncline in the north of area I. Here the Vlieland may be developed in thicker and better reservoir quality facies than in well KOM-01. These potential reservoir trends may also be evaluated using seismic inversion. It should be noted that in general the reservoir quality of the Vlieland sandstone of the Friesland Platform is not as good as in other basins. Permeabilities are typically lower than 100 mD. Based on the limited potential in area H&I, this play type can probably be better tested in areas where 3D seismic is available.

Proposed work for the Lower Cretaceous play in area H&I:

- Acquire 2D seismic lines over the target area, to be used for seismic inversion

2.4.2 Triassic sandstones

The Triassic has been eroded in completely in area I and in most of area H. However, in several wells in area H the Lower Buntsandstein claystone has been found below the Base Cretaceous Unconformity (BCU). TNO mapping of the thickness of the Triassic section shows that in some locations in the south of area H the preserved thickness is more than 300m. This is more than the typical Lower Buntsandstein thickness in this area. At these locations the Lower Volpriehausen sandstone can be expected to be present below the BCU. Since it is located below an unconformity the reservoir of the Volpriehausen sandstone may have an enhanced reservoir quality due to leaching. The thickness of the Lower Volpriehausen sandstone is not known in area H, however in wells to the west (URS-01 and RST-01) a thickness of 25 and 28m was found respectively. The presence of a permeable Volpriehausen sandstone across the bounding fault may have caused the Twisk (TWI) Rotliegend structure to be dry. Due to the small area where the relatively thin Volpriehausen sandstone is present, the potential of this play is limited. To make further progress with this play 3D seismic and a well penetration would be needed. The Volpriehausen sandstone may serve as a secondary target in a well to the Rotliegend reservoir.

Proposed work for the Triassic play in area H&I:

- Acquire 3D seismic over the target area in area H. This is, however, beyond the scope of the SCAN project.
- Propose to penetrate the Volpriehausen sandstone as a secondary target to wells to the Rotliegend reservoir

2.4.3 Zechstein carbonates

In the Slootdorp (SLD) and Middenmeer (MDM) field gas has been produced from the Zechstein Z2 and Z3 carbonates, in addition to the Rotliegend sandstone reservoir. In these fields these limestone/dolomite reservoirs are located just below the BCU. Leaching at the time of the formation of the unconformity has probably enhanced the reservoir quality. Also, north of area I the Oldelamer (OLR), Sonneg- Weststellingwerf (SOW) and De Blesse (BLS) fields produce gas from, probably leached, Z2 and Z3 reservoirs. What seems to be an impediment for geothermal applications of the Zechstein is the relatively low permeability of these reservoir. The permeability is generally below 100mD, probably too low for any commercial applications. For exploration of the Z2/Z3 carbonates it is crucial to find a good subcrop location for these reservoirs below the BCU, in addition to tectonic fracturing/faulting. Probably 3D seismic would be needed to map out these sweet spot areas. This would be most relevant for area H, since in area I the Zechstein has been mostly eroded down to the Z1 Anhydrite.

Proposed work for the Zechstein play in area H&I:

- Acquire 3D seismic over the area H, which is beyond the scope of the SCAN project

3. Seismic survey design

In the previous chapter proposals were made for the further geological and geophysical evaluation of area H&I. These proposals have been reviewed and ranked on their respective potential impact of the play (w.r.t. expected areal extent and reservoir quality) and their estimated chance of success in delivering on the objectives of these projects. Figure 11 graphically summarizes the most important proposed work items and their ranking. These considerations are the starting point for defining the location and goals for the planned seismic acquisition. Additionally, next to the geological objectives (3.1) the new seismic survey design should meet a number of essential technical criteria (3.2).

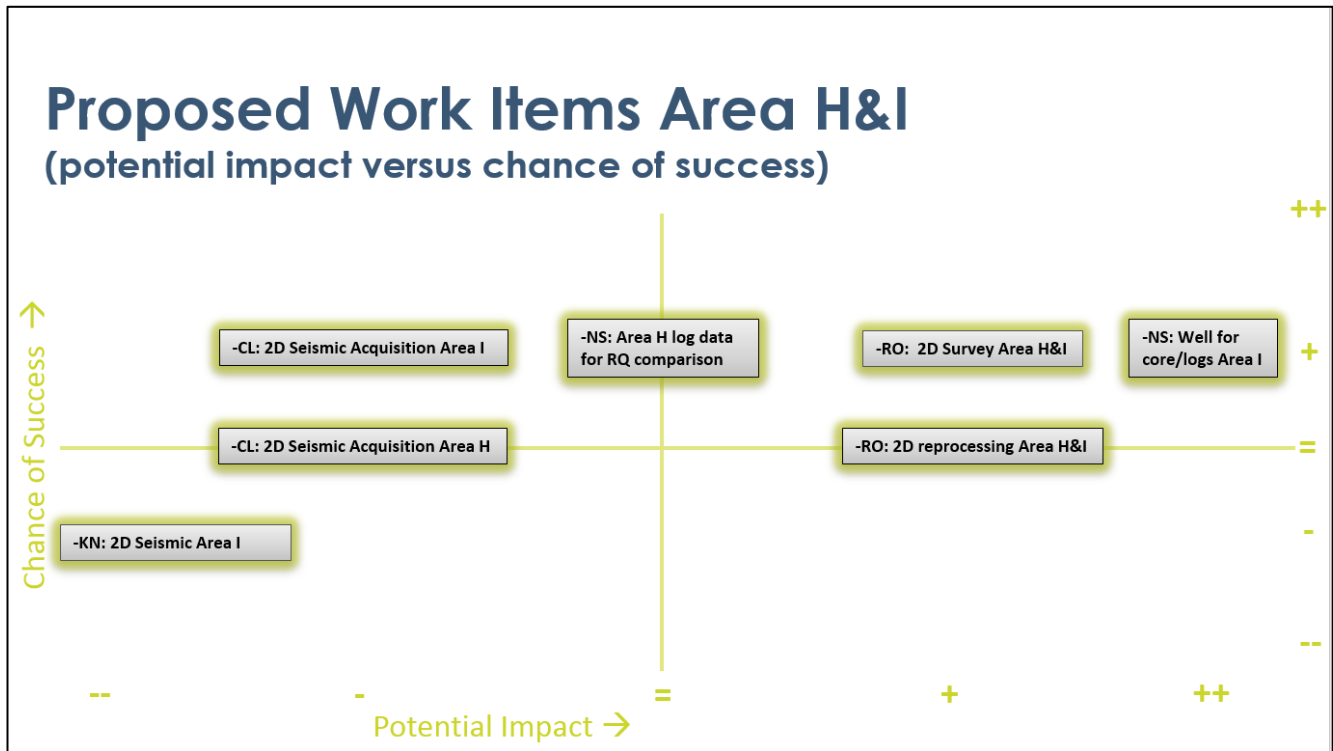


Figure 11 – Cartoon showing the main proposed work items for further evaluation of area H&I ranked according to potential impact of the play and estimated chance of success

3.1 Geological objectives of the seismic survey

The geological objectives of the seismic acquisition are summarized from high to low impact:

- Provide core and log data from area I where a thick and potentially good Brussels Sand is present. This may open a potentially significant new play over an extensive area.
- Provide new high-quality 2D seismic data on the Texel-IJsselmeer High (both in area H and area I) where there is a potential for good quality Rotliegend reservoir below the BCU, which is currently not highlighted in the TNO mapping. Inversion of the seismic data may help to highlight the presence of the Rotliegend. A line over the BRL-01 well may help to explain why the Rotliegend is thinned in this well and how the isopach develops between the LTG-GT wells and BRL-01. 3D seismic to better map the (eroded) Rotliegend pods may be an alternative to 2D acquisition, if it is felt that the Rotliegend eroded fault block play is sufficiently proven in area H&I. Obviously this would come at a higher cost than 2D acquisition, so this would require additional budget.
- Reprocessing of existing 2D data may highlight the presence of the (eroded) Rotliegend reservoir in area H&I. In area I a large dataset of potentially suitable 2D data is present. The legacy seismic in area H seems less promising. Inversion of the reprocessed seismic data may help to map the eroded Rotliegend
- The Brussels sand reservoir in area H seems to be of lesser reservoir quality compared to area I. In order to better compare the reservoir development between the two areas an extensive logging of the Brussels aquifer and the Upper North Sea sands in a well with a deeper target in area H is proposed.

- On existing 2D data the LTG build-up can be recognised but mapping internal structures or the base of the formation is difficult. One of two new 2D lines with deep penetration may be helpful, as is a good tie to the 3D seismic data of Friesland, Drenthe and Groningen. As there are no plans for commercial geothermal use of the LTG-structure and the LTG-01 well has been plugged and abandoned, more seismic acquisition is not seen as advantageous.
- The seismic quality in area H is in general too poor to image the Top Dinantian, so any build-up like LTG cannot be seen on the seismic data. New 2D seismic data with a Rotliegend target may also give information on the Dinantian. However, it should be evaluated if deep penetration (dynamite) acquisition is worth the cost over Vibroseis acquisition.
- Acquiring 2D seismic data over the Vlieland sandstone area in the north of area I is not seen as attractive because of the limited potential.

3.2 Criteria for design of the seismic survey

The positions and orientations of the lines were designed to meet as many of the criteria listed below as possible.

- De-risk of the geological issues and uncertainties described in sections 2 and 3.1.
- Take into account heat demand and active geothermal projects.
- Perpendicular to the regional NW-SE structural trend, where possible.
- Straight, long (>20 km) lines.
- Well ties for wells penetrating relevant stratigraphic levels, preferably by choosing the line trajectory over / nearby an existing well location.
- Tie to 2D line to 3D seismic data.
- Minimize complications from near-surface geology: push moraines, swamps, lakes, etc.
- Individual lines of survey cross each other.
- Avoid Natura2000 and other protected areas.
- Avoid mixing of land and water seismic.
- Synchronized with data acquisition plans (local seismic surveys, project locations) of active projects.
- Budget and time planning.

The acquisition parameters of the survey should take into account the following geological objectives:

- Have sufficient recording time and penetration energy to properly image Dinantian limestones at 5 sec TWT if the Dinantian is seen as a target for the line. If the Dinantian is not a target, it should be considered if Vibroseis acquisition is a cost-effective option.
- Be acquired with parameters that results in good imaging of subtle details as unconformities and karst-zones and permits quantitative interpretation reservoir properties. This would mean prestack data with dense source and receiver sampling in time and space and with long offsets. With this data special seismic processing/analyses should be possible such as: AVO, seismic inversion, Full Waveform Inversion, diffraction imaging and broadband processing.

3.3 Survey design

Figure 12 shows the proposed line locations covering area H&I which do conform to the above listed geological objectives and design criteria. The geological goals for each of the lines are given in Table 2 and further highlighted per line in geological cross-sections in Appendix 5.1. A buffer of 2 km is drawn around the ideal trajectory to accommodate alternative routing; field scouting may lead to significant changes to the design.

In EBN& TNO-AGE (2017) the length of the lines required for area H was estimated at 62 km, whereas 60 km was foreseen in area I. The current design amounts to 78 + 84 km (Table 3). It is therefore plausible that it may not be possible to acquire all proposed lines and it is therefore necessary to decide which lines have the highest priority. To facilitate this, a scoring system has been developed to assess how well they meet the design criteria. To indicate how the 2D seismic acquisition fits within the overall planning of the SCAN project an indicative planning of the main activities in SCAN area A&B is given in Appendix 5.2. It is possible that if good results are obtained with seismic reprocessing, acquisition of some new lines may not be necessary.

Line	Goals
SLD-WGF	Image Rotliegend and Dinantian. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Dinantian presence, facies and depth. Tie to wells SLD-01 and WGF-01. Provide tie Slootdorp 3D.
LMB-MDM	Image Rotliegend and Dinantian. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Dinantian presence, facies and depth. Tie to wells LMB-01 and MDM-GT-05. Provide tie Slootdorp 3D.
HOK-ADK	Image Rotliegend and Dinantian. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Dinantian presence, facies and depth. Tie to wells HOK-01 and ADK-GT-02/04. Provide tie Slootdorp 3D.
WGF-HOK	Image Rotliegend and Dinantian. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Dinantian presence, facies and depth. Map presence and depth Volpriehausen sandstone. Tie to wells WGF-01, HOK-01 and HOK-02. Provide ties to 2D lines.
NAG-LTG-SLB-OLR	Image Rotliegend and Dinantian. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Dinantian facies of LTG structure. Map depth and presence of Vlieland sandstone. Tie to wells NAG-01, LTG-01, SLB-01/02 and OLR-01/02. Provide tie Friesland 3D. Connection to line ALE-LEL-ZEW-NAG.
CRL-LTG_GT-BRL	Image Rotliegend and Dinantian. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Dinantian depth and facies of LTG structure. Tie to wells LTG-GT-01 and BRL-01. Provide tie Schoonebeek West 3D.
CRL-ESG	Image Rotliegend. De-risk Rotliegend reservoir quality, depth and thickness. Provide data for seismic inversion project in Rotliegend. Tie to well ESG-01. Provide tie Friesland 3D.

Table 2 – Geological goals for the proposed lines

Line	Total Length (km)	Comment
SLD-WGF	14.8	
LMB-MDM	16.0	
HOK-ADK	11.5	
WGF-HOK	35.4	
NAG-LTG-SLB-OLR	33.4	Connection to line ALE-LEL-ZEW-NAG
CRL-LTG_GT-BRL	27.9	
CRL-ESG	22.9	
Total length	161.9	

Table 3 – Length of the proposed lines. **Please note that line lengths may change if lines are updated**

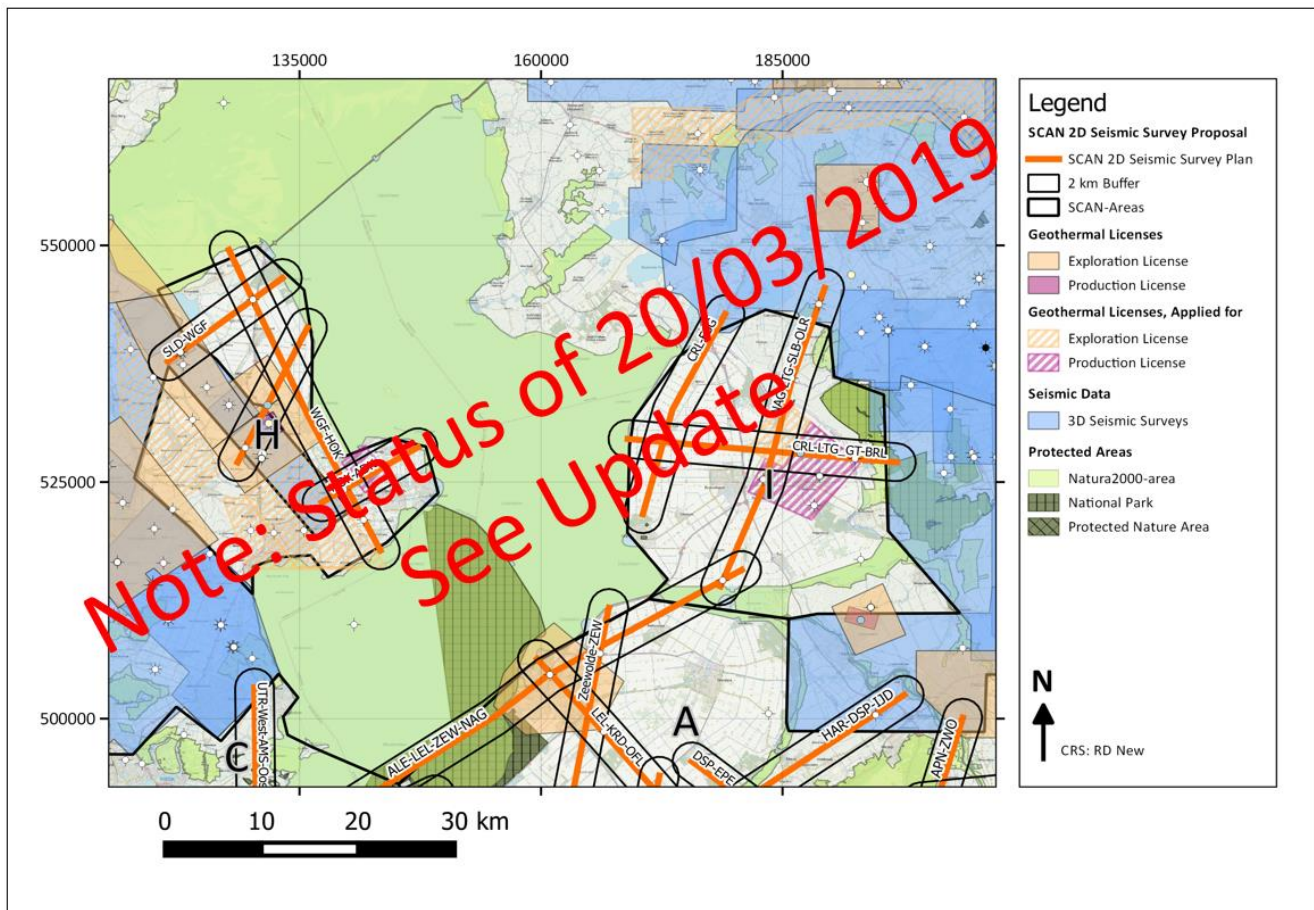


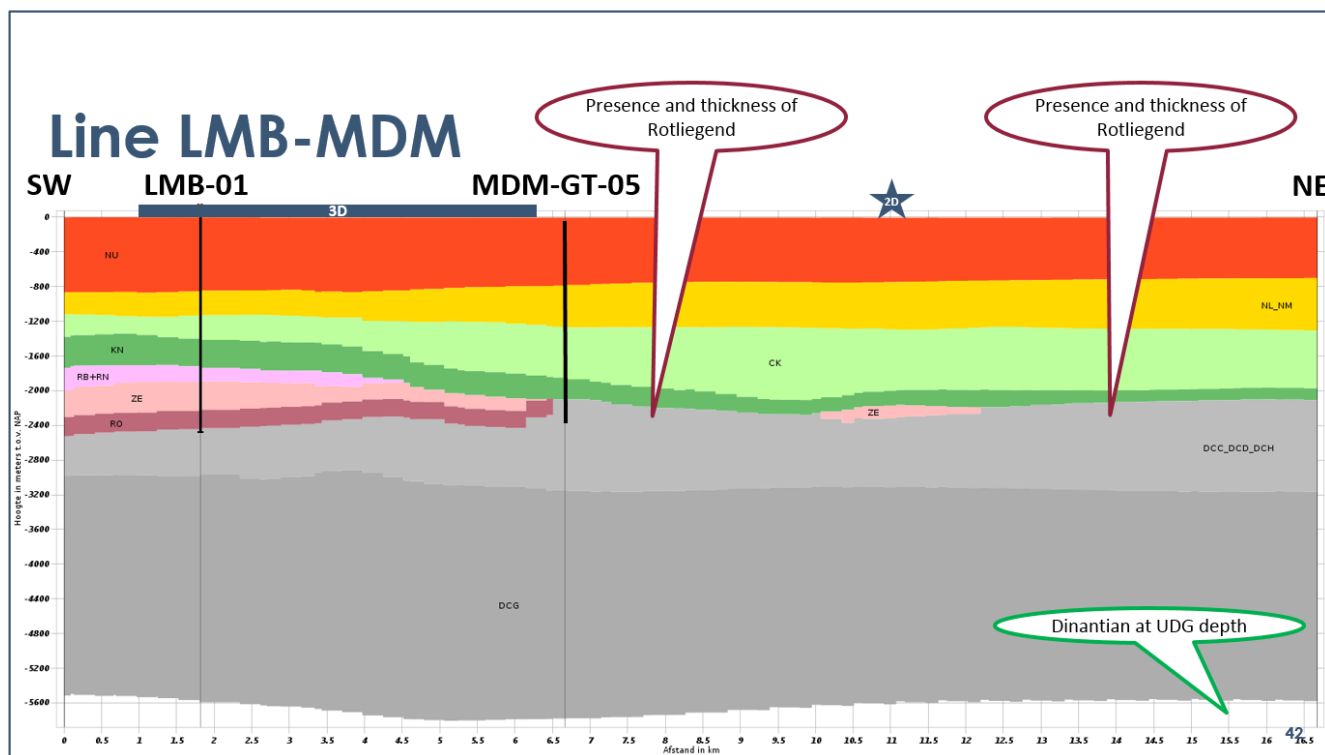
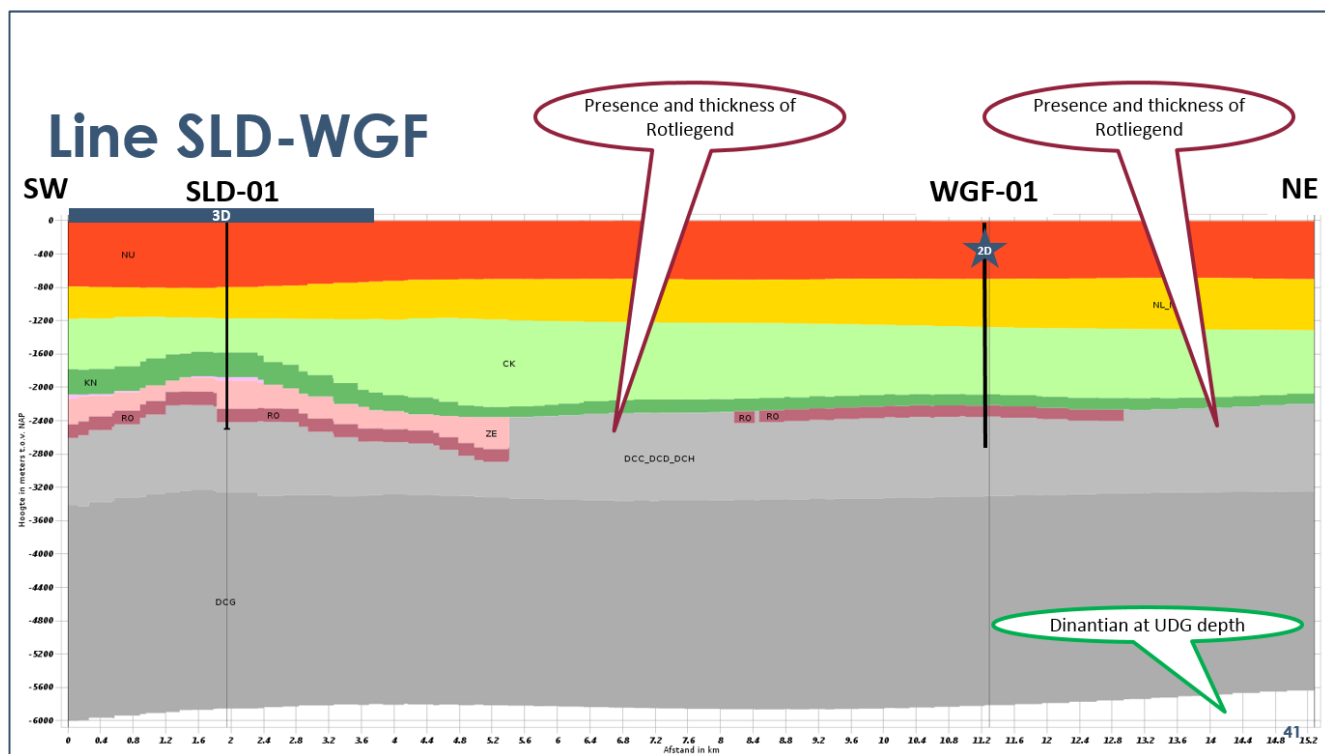
Figure 12 – Seismic survey design for SCAN area H&I. The outlines show the area where full-fold coverage is required. Note: the actual acquisition of these lines is subject to ranking and budget appropriation. **Please note that this figure displays the status of 20/03/2019, an updated map can be found on page 6 of this report**

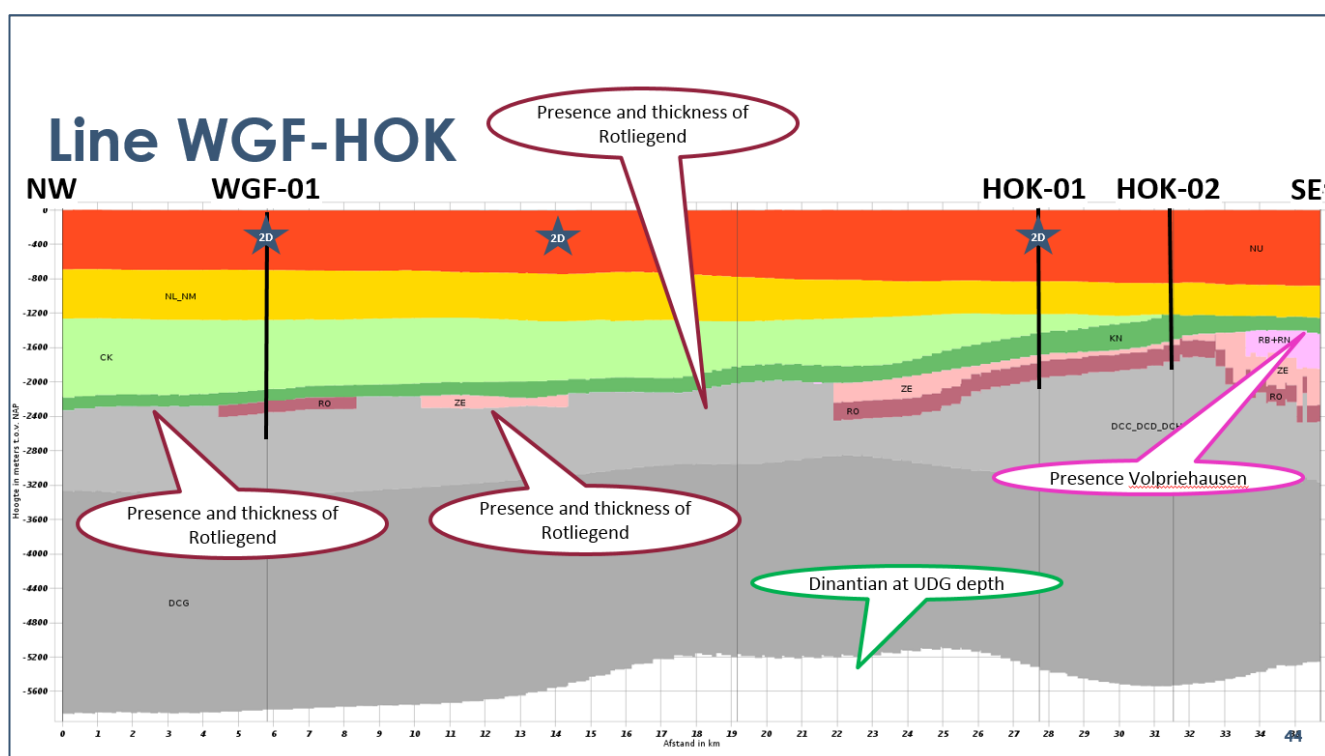
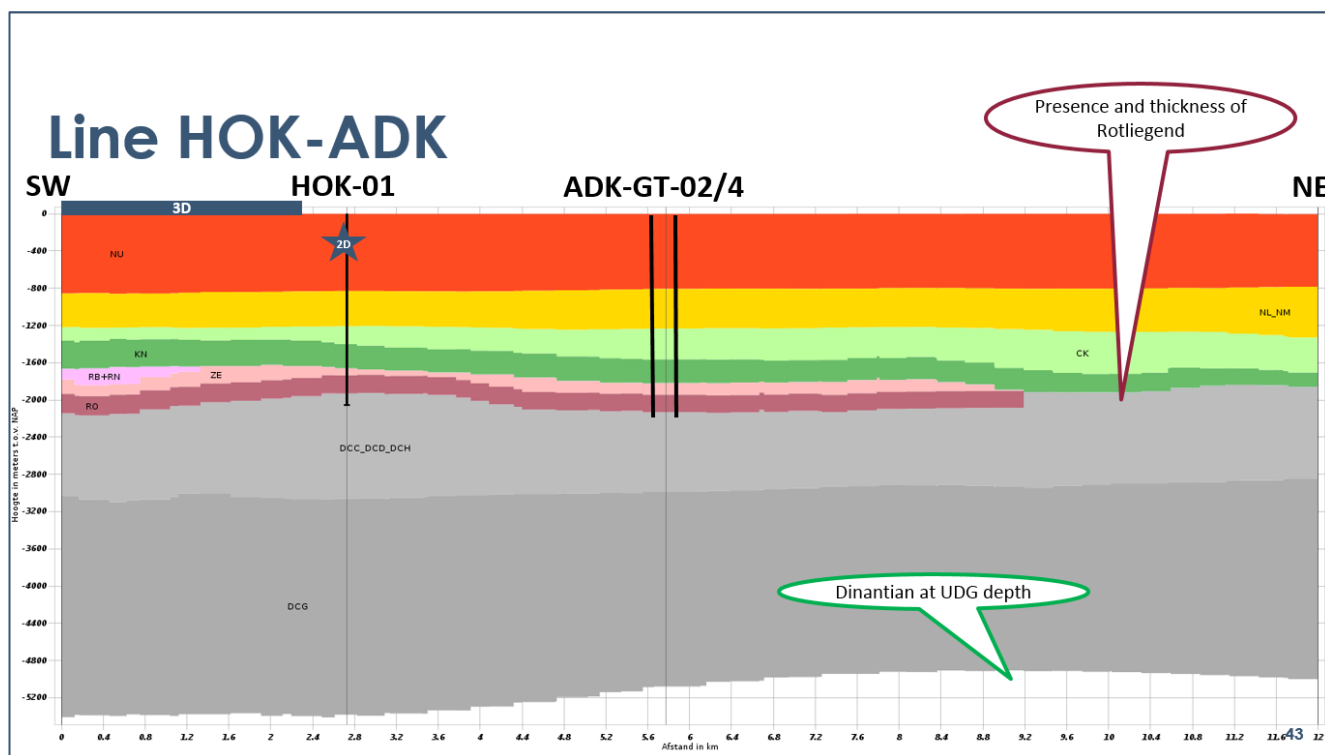
4. References

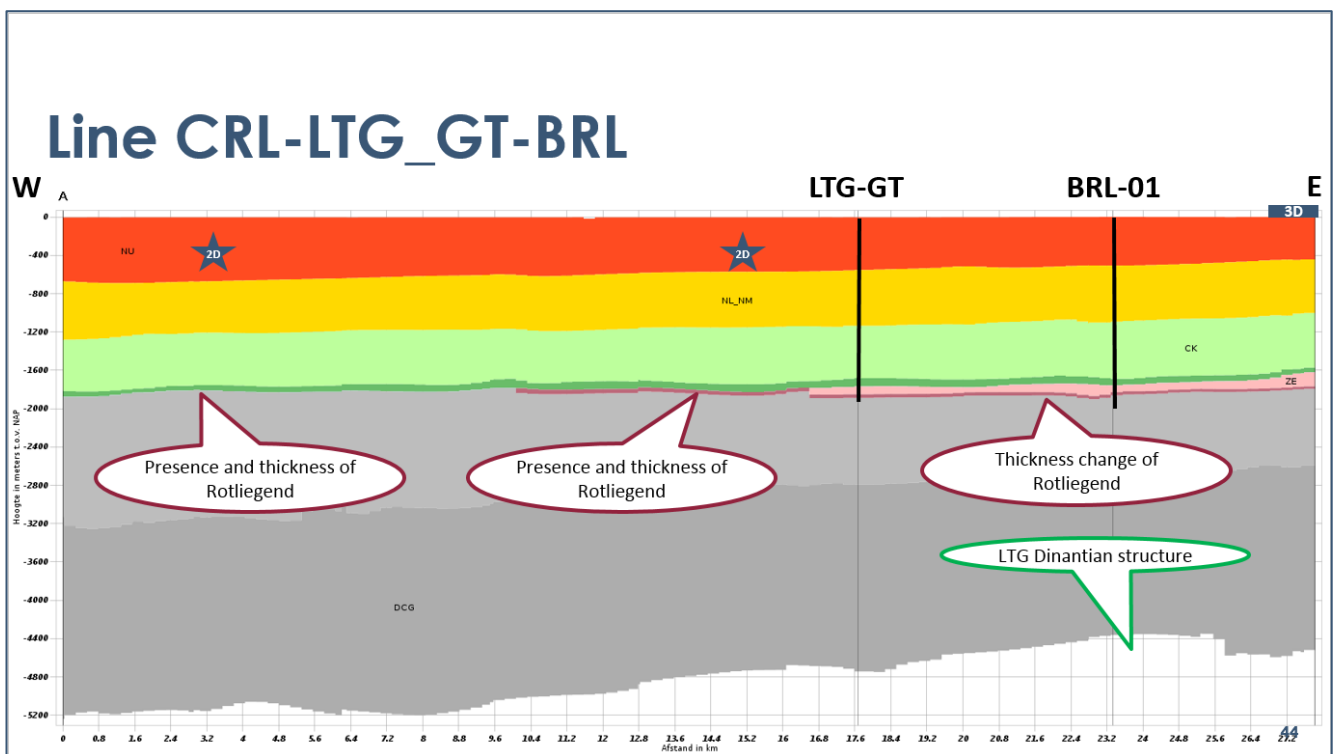
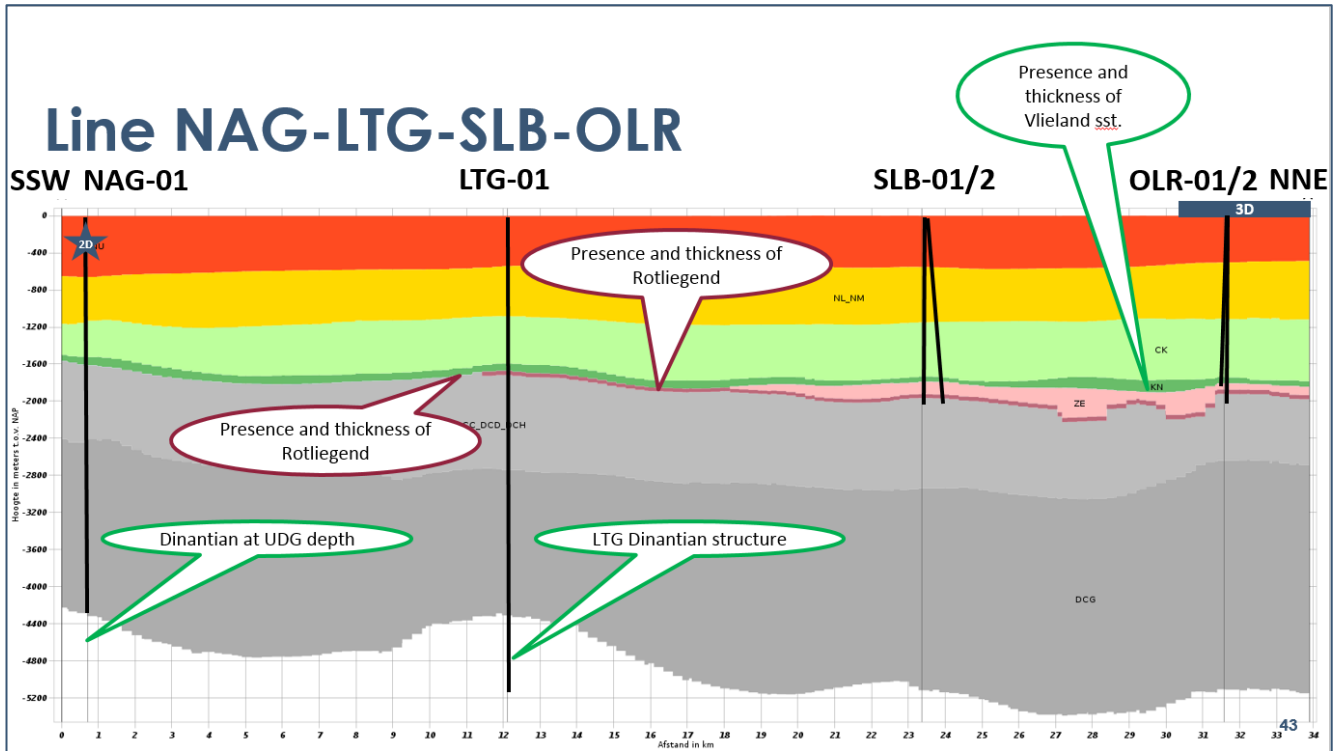
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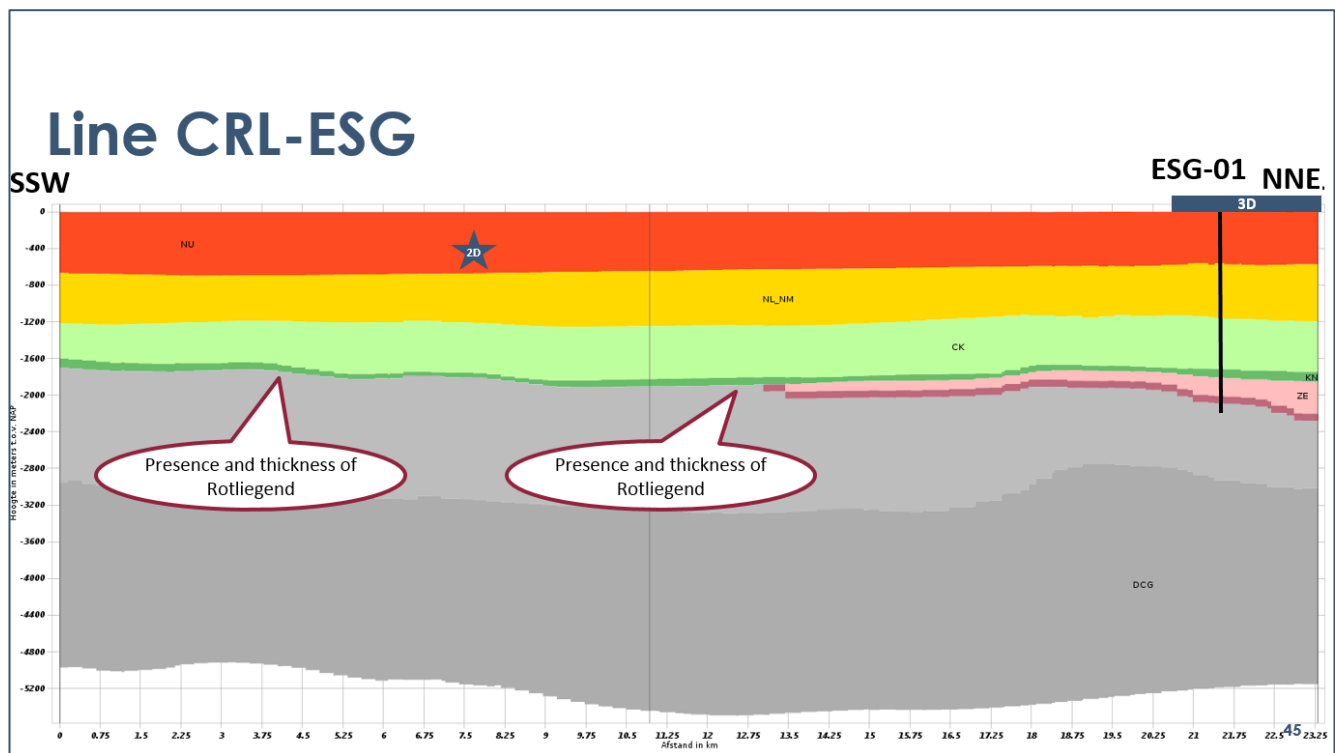
5. Appendices

5.1 Depth sections from DGMdiep v4.0 in Dinoloket over proposed seismic sections SCAN area H&I

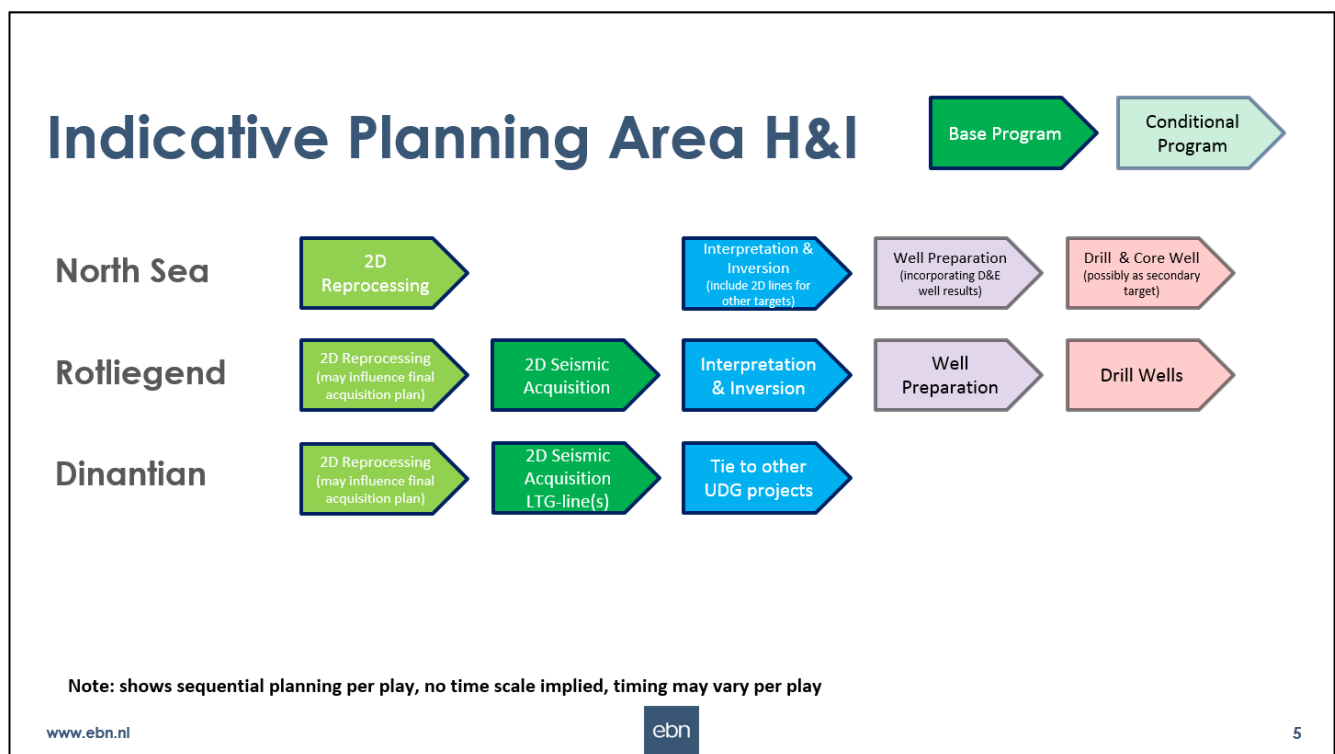








5.2 Indicative planning SCAN area H&I



Onderzoek in de ondergrond voor aardwarmte