Geological evaluation for the seismic acquisition programme for SCAN areas D (Zeeland and Zuid-Hollandse Eilanden) and E (West-Brabant)

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Dit rapport is een product van het SCAN-programma en wordt mogelijk gemaakt door het Ministerie van Economische Zaken en Klimaat

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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.

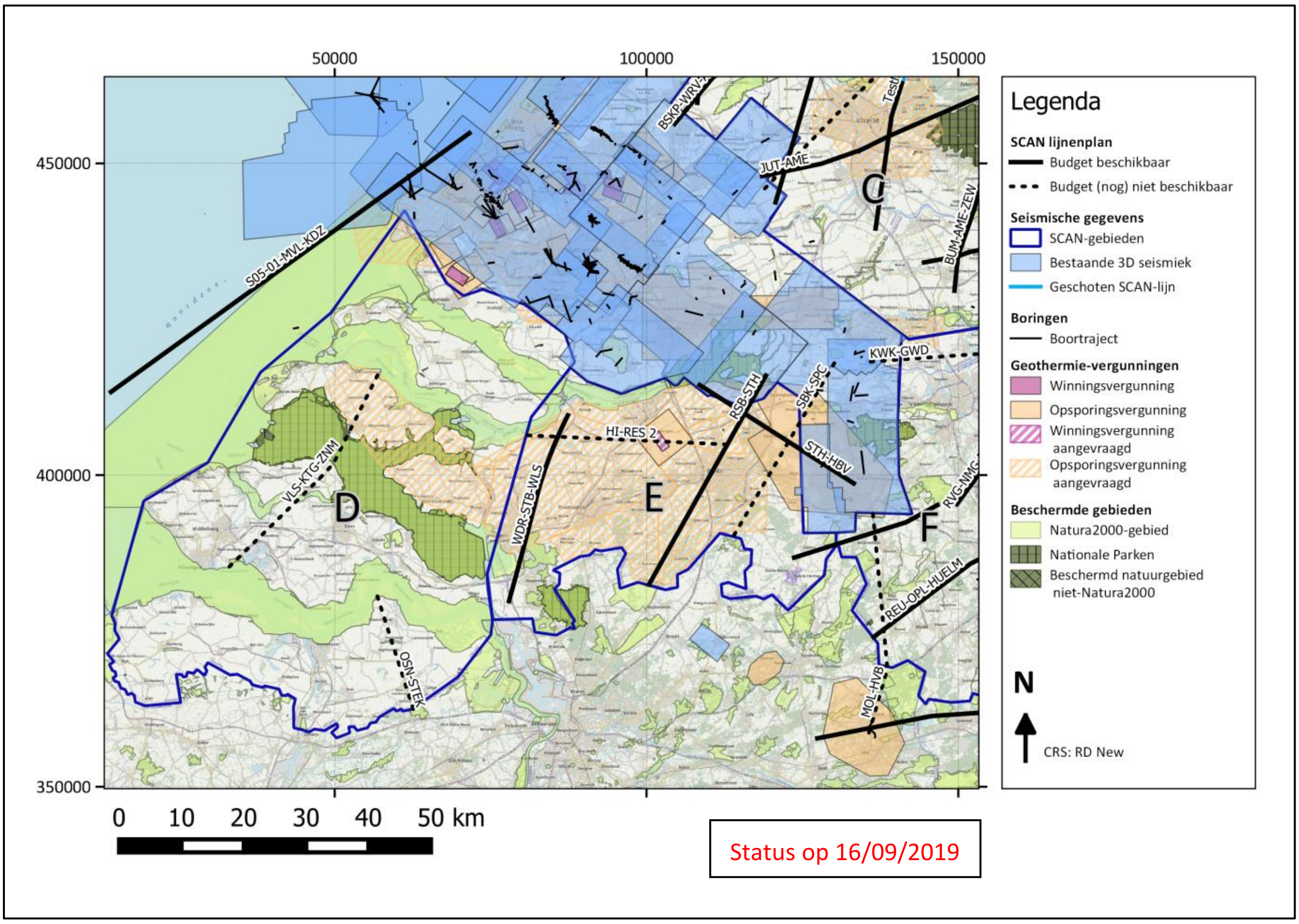
Om het acquisitieplan voor de SCAN 2D seismische lijnen te kunnen bepalen zijn door geologen en geofysici ondergrondevaluaties gemaakt van de verschillende SCAN-gebieden. Hierbij is gelet op welke delen van de ondergrond de beste kansen bieden voor geothermische projecten en welke informatie nog ontbreekt 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 D&E 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 D&E 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 D&E 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.

Contents

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 E, which comprises major urban centers such as Breda, Roosendaal and Bergen op Zoom, was identified as an area of the highest priority. Area D covers the cities of Middelburg, Vlissingen, Goes and Zierikzee, however initial assessment prognosed a lower subsurface potential than area E. This report discusses both areas D and E, which have been evaluated together since their geological history and make-up is quite comparable. The combined area will be called 'Area D&E' 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 reviews but is presented here only to give the proper setting for the 2D seismic acquisition plan.

Information	2D-Seismic data	3D-Seismic data	Well
Economical evaluation: presence and quality of aquifer, temperature			
Presence, continuity, depth and thickness aquifer	+	++	+++
Porosity	–	+/–	+++
Permeability (transmissivity)	– –	– –	+++
Temperature	+	+	+++
Safety, well planning and regional geological knowledge			
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.

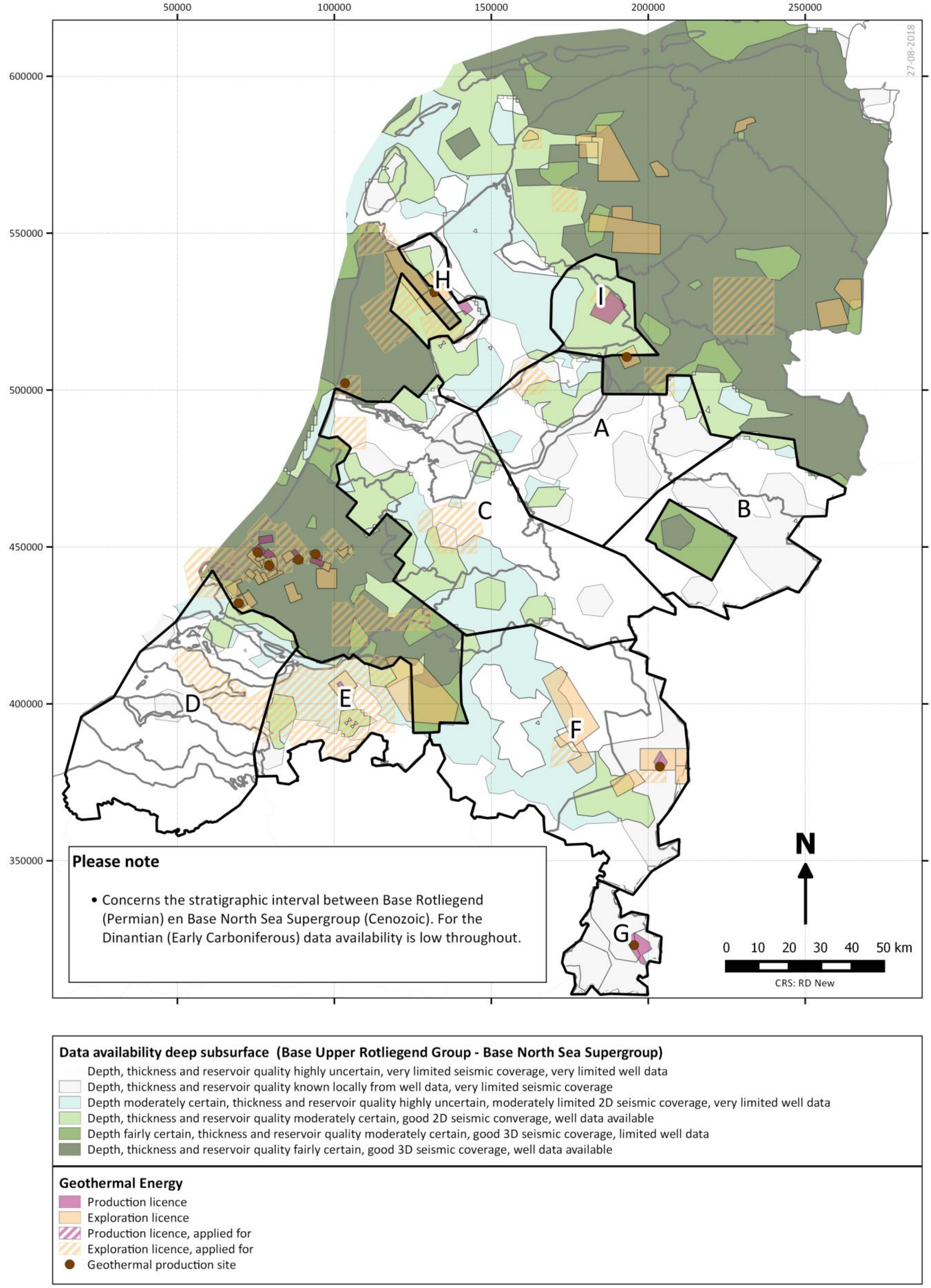


Figure 1 – SCAN areas, geothermal licences and producing geothermal installations (after EBN -TNO-AGE 2017).

2. Geological overview of SCAN area D&E

The stratigraphic interval of geothermal interest ranges from Lower Carboniferous (Dinantian) carbonates at a depth of approximately 4500–6000 m to Cenozoic sands as shallow as 300 m below mean sea level. In the south of Zeeland even older Paleozoic rocks (Devonian to Ordovician) are close to surface (TNO-NITG, 2003) and could form a fault/fracture or EGS (Enhanced Geothermal System) play. The primary targets for geothermal projects in the area are provided by Lower Carboniferous carbonates and Triassic Röt and Buntsandstein sandstones (*Figure 2*). Cenozoic sands may prove a primary target for low temperature geothermal systems and/or high temperature storage applications. Secondary targets include Upper Jurassic and Lower Cretaceous sandstones, Upper Carboniferous sandstones and the pre-Dinantian interval.

Within area D&E the following structural elements (Van Adrichem Boogaert & Kouwe, 1993–1997) can be distinguished for the Mesozoic–Cenozoic tectonostratigraphic evolution of the area (*Figure 3*):

- The southern edge of the West-Netherlands Basin (WNB);
- The western edge of the Roer Valley Graben (RVG);
- An intermediate area named the Oosterhout Platform (OP);
- The southern area called the Zeeland High (ZH).

Another important structural element is the Paleozoic London Brabant Massif, which dominated the geological development from Dinantian to Cretaceous times and of which the northern flank is also named the Zeeland High in literature. During the Paleogene the asymmetric Voorne Trough developed in the North of area D&E. The Voorne Trough has its steeper flank to the north where is bounded by the Kijkduin High.

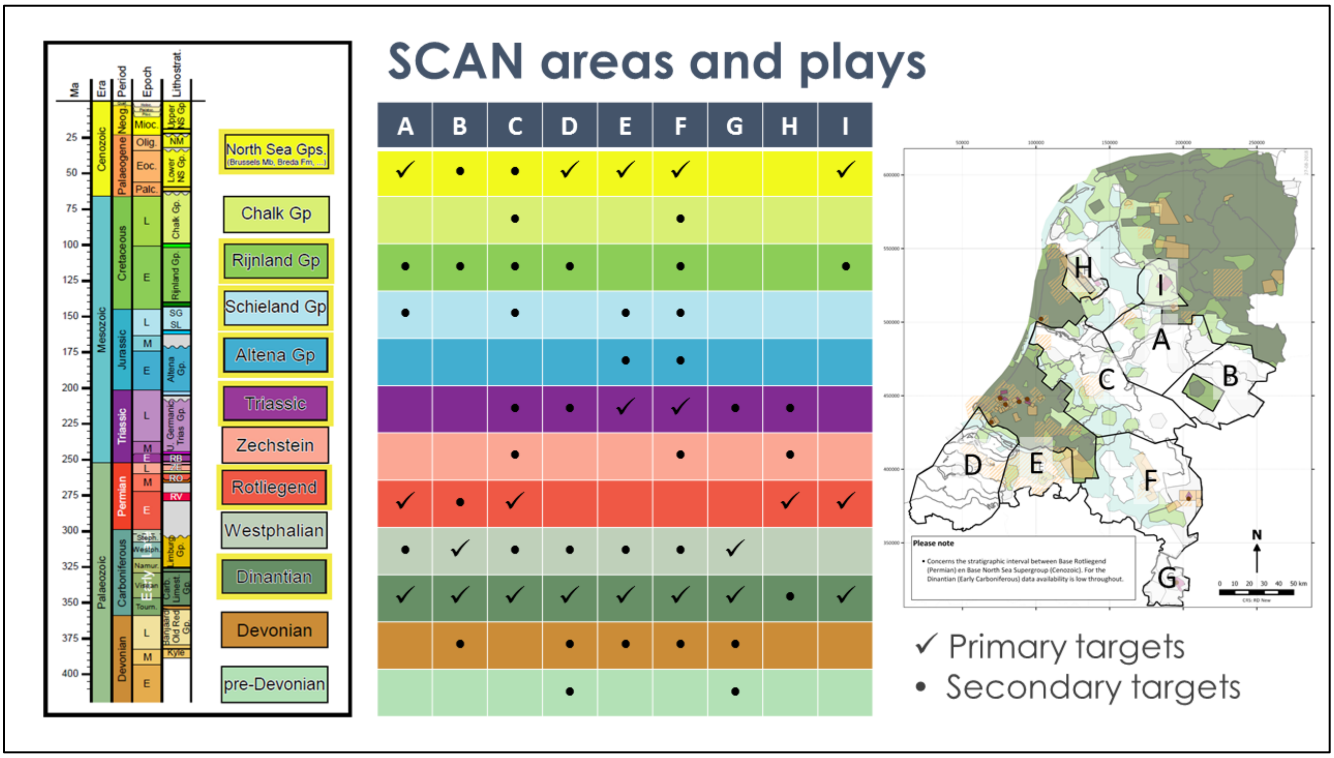


Figure 2 – Overview of the primary and secondary targets in the SCAN areas.

2.1 Stratigraphic Section

From old to young the stratigraphy relevant for geothermal projects in area D&E is expected to consist of:

- A Pre-Cambrian Basement below the London Brabant Massif of which nearly no information is available since it is not penetrated by wells (André 1991).
- A thick (>13km) Early Paleozoic section which consists of Cambrian to Silurian rocks (Figure 4; Ordovicium and Siluur), which form the core of the Brabant Massif, as known from the Belgian outcrops and subsurface data (Herbosch & Verniers 2015). These rocks are present at shallow depths (550-1000m) below Zeeuws Vlaanderen and Walcheren/Zuid Beveland. In Dutch offshore well O18-1 the Silurian section is characterized by black shales interbedded with fine grained to silty turbidites
- On top of the Caledonian Unconformity Devonian (Figure 4; Devoon) sandstones and carbonate reefs are known from Belgian outcrops. In well KTG-01 and O18-1 Devonian sandstones are found to be present in and around area D&E.
- Lower Carboniferous (Dinantian) carbonates (Figure 4; Kolenkalk) and shales. On the seismic data of area D&E the top of the Dinantian limestone can often be well recognized. The Dinantian is partly eroded below the Cretaceous in well KTG-01 at a depth of around 1km and dips gently to the north to a depth of more than 6km north of Breda.
- An Upper Carboniferous siliciclastic sequence (sandstones, claystones and coal) (Figure 4; Limburg Groep). 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 the south of area D&E the Base Cretaceous Unconformity (BCU) cuts down into the Upper Carboniferous.

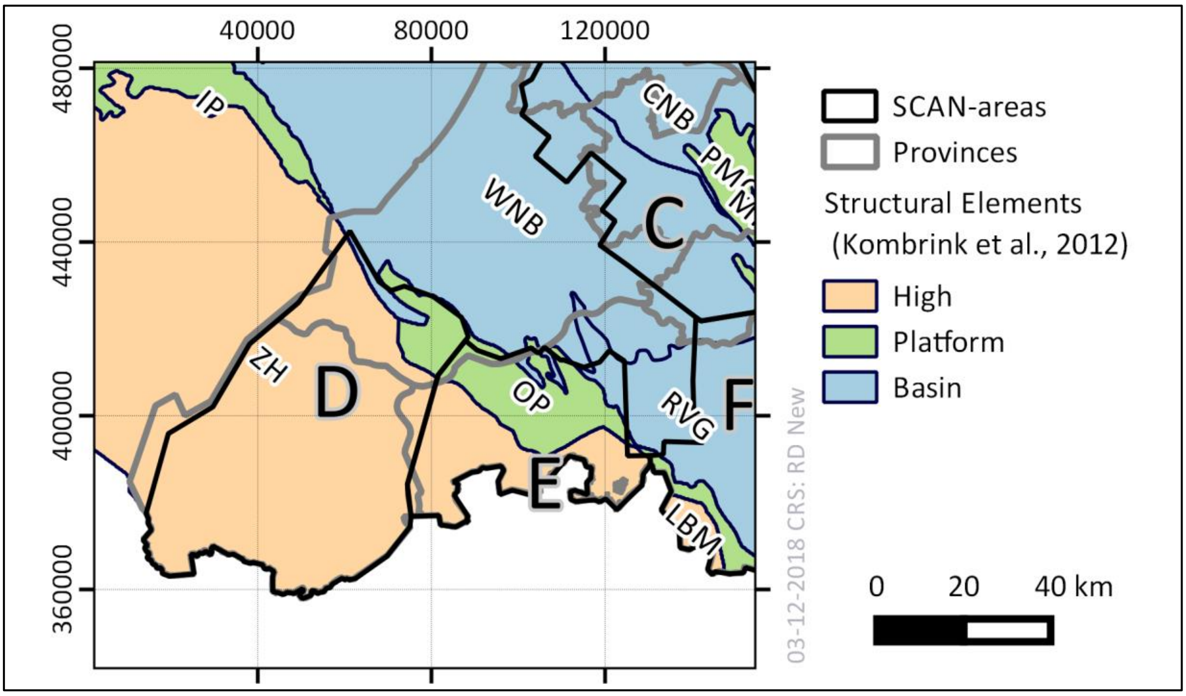


Figure 3 – Late Jurassic – Early Cretaceous structural elements in and around SCAN area D&E after Kombrink et al. (2012), CNB – Central Netherlands Basin, IP – Indefatigable Platform, LBM – London–Brabant Massif, OP – Oosterhout Platform, PMC – Peel-Maasbommel Complex, RVG – Roer-Valley Graben, WNB – West Netherlands Basin, ZH – Zeeland High

- The Permian Rotliegend Slochteren Sandstone interval (Figure 4; Boven Rotliegend) overlies the BPU. In Rotliegend times the D&E area was located at the very basin edge, consequently the Rotliegend sandstone interval is very thin (up to max 14m).
- During the Permian Zechstein interval (Figure 4) the D&E area was also situated at the basin edge resulting in the presence of typical basin fringe facies comprising dominantly sandstones and shales.
- The Lower Germanic Trias Group (Figure 4; Onder Germaanse Trias) comprises the Lower Buntsandstein Formation and the Main Buntsandstein Subgroup. The Main Buntsandstein consists of a thick package of sandstones inter-bedded by some claystones. The Lower Buntsandstein, here located at the southern basin edge, has a sandier facies compared to the common lacustrine claystone and thin oolitic limestones present further to the north.

- The Upper Germanic Trias Group (Figure 4; Boven Germaanse Trias) comprises sandstones, claystones, carbonates and evaporites (predominantly anhydrites). The Röt interval does not contain the evaporites, which characterize Röt sediments further towards the north, but here at the basin fringe a sandstone of good reservoir quality is found.
- In area D&E the claystones of the Lower Jurassic Altena Group (Figure 4) are present in the Roer Valley Graben only.
- In the northeastern corner of area D&E, in the Roer Valley Graben, a thick package of sandstones and claystones are present of the Upper Jurassic Schieland Group (Figure 4), which unconformably overlies the section below. These sediments are also present in the West Netherlands Basin, but hardly extend into the northwestern corner of area D&E.
- The Lower Cretaceous Rijnland Group is, in area D&E, only present at the southern edge of the West Netherlands Basin. At this location the interval consists of sandstones and clayey sandstones.
- The Upper Cretaceous Chalk Group (Figure 4) consists, as the name suggests, almost exclusively of Chalk. It thickens gradually from south to north in area D&E. However, in the Roer Valley Graben the basin was tectonically inverted, and no Cretaceous Chalk is present, only a relatively thin Danian Chalk interval is found in the Roer Valley Graben.
- The Lower and Middle North Sea Groups (Figure 4) consist primarily of unconsolidated sands, sandstones and claystones. This interval thickens significantly in the Voorne Trough.
- The youngest sediments, the Upper North Sea Group, comprise marine and fluvial sands. The interval is relatively thin in area D&E compared to the much more expanded section in the Roer Valley Graben.

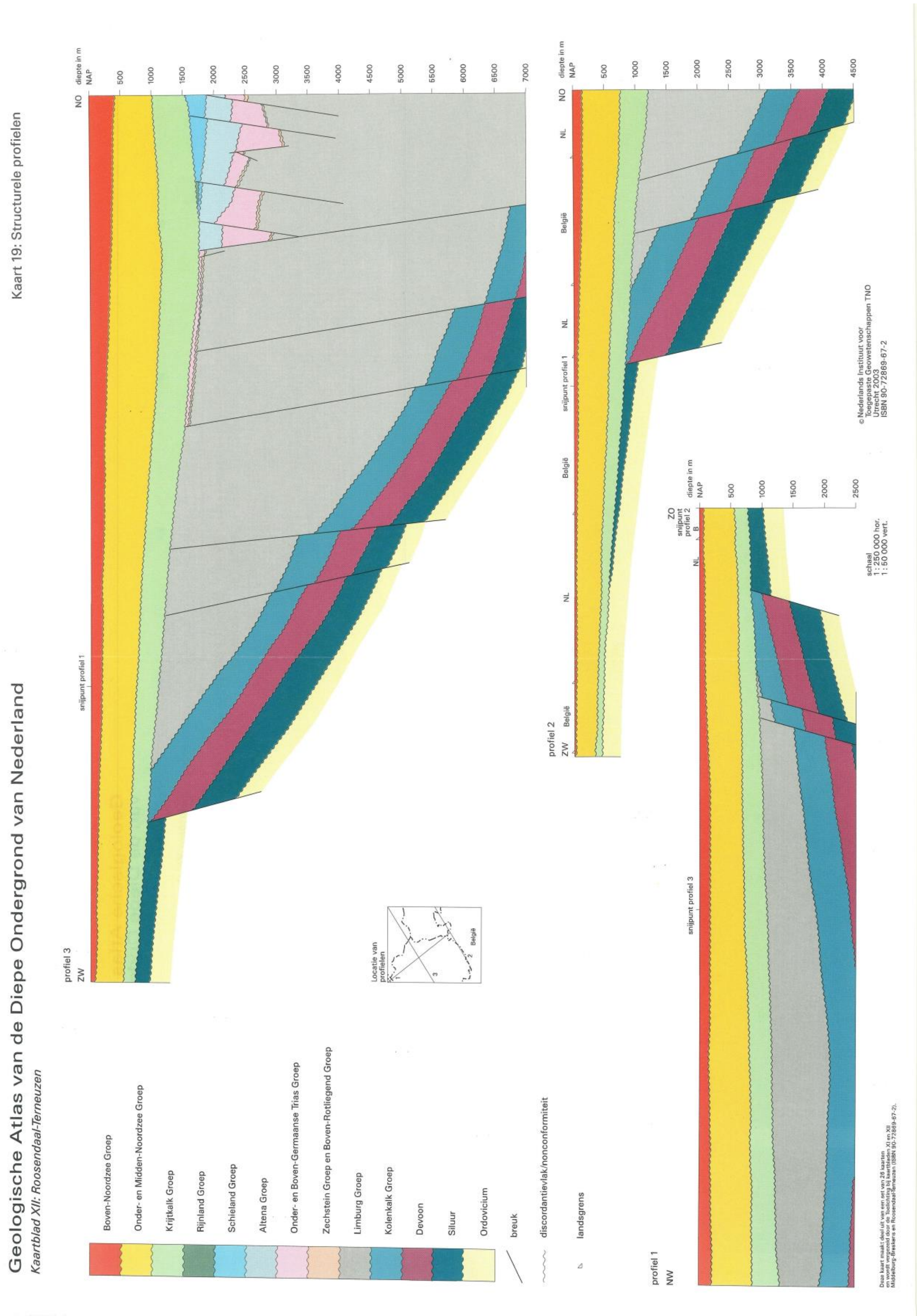


Figure 4 - Cross sections through area D&E (TNO-NITG, 2002).

2.2 Structure

The sequence of tectonic events, also applicable to area D&E, 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, Central Netherlands Basin and 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 D&E, 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 expected to be present at a depth of 1 to 6,5 km in area D&E.

The structural configuration of area D&E is relatively clear even though the naming varies between authors (e.g. Doornenbal & Stevenson 2007 use the name Zeeland Platform for what Van Adrichem Boogaert & Kouwe 1993-1997 and Kombrink et al., 2012 called Oosterhout Platform), however these areas are all considered to be the north flank of the London-Brabant Massif in this report.

From regional maps it appears that the structural architecture of area D&E is dominated by NW-SE trending horst and graben faults. However, the current fault mapping is simplified by the fact that correlating faults using only 2D data is difficult and is prone to aliasing.

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

1) The Cenozoic and Chalk intervals are largely unfaulted.
2) The pre-Cretaceous of the southern West Netherlands Basin and Oosterhout Platform is crosscut by WNW-ESE to NNW-SSE trending faults, creating horst and graben structures with a spacing between faults of hundreds of metres to kilometres.
3) Mainly northwards dipping NW-SE trending normal faults are present in the Limburg Group and the Dinantian on the north flank of the London-Brabant Massif.
4) A prominent NNW-SSE fault, the Rijen Fault, forms the boundary between the Oosterhout Platform (*Figure 3*) to the west and the Roer Valley Graben to the east. In the Roer Valley Graben near the Rijen Fault the prominent fault trend is N-S oriented. This fault trend also had a significant impact on the thickness distribution of sediments of Upper Jurassic age and younger. During the Upper Jurassic thick paralic and fluvial sediments were deposited in the Roer Valley Graben, which are absent on the adjacent north flank of the London Brabant Massif. Whereas during the Late Cretaceous inversion and uplift any Rijnland and Cretaceous Chalk deposits present in the Roer Valley Graben were eroded. In the Paleogene, the Roer Valley Graben area had a thinner development than the London-Brabant Massif. The character of the Rijen Fault dramatically changed again during the Neogene, when the Roer Valley Graben rapidly subsided, resulting in a thick package of Neogene and younger sediments.

2.3 Primary targets

2.3.1 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 low temperature heat is called in Dutch: Lage Temperatuur Aardwarmte (LTA). An LTA doublet has recently been drilled in area E near Zevenbergen. The reservoir here is the Brussels Sand Mbr. of the Dongen Fm at a depth of around -600m. Since this target was of no interest to oil and gas exploration in the Dutch onshore very limited reservoir information is available. Also, the formation was usually not covered by an extensive logging suite in hydrocarbon exploration wells. Given the information on the website of the operator it is clear that the injector and producer wells were drilled horizontally in the Cenozoic reservoir after first drilling a vertical pilot hole. The wells of the Zevenbergen doublet have not been released yet, so no information further of these wells was available. In D&E area recently a large number of licence application were filed by the Zevenbergen operator Visser, Smit Hanab suggesting exploration efforts for the Cenozoic targets

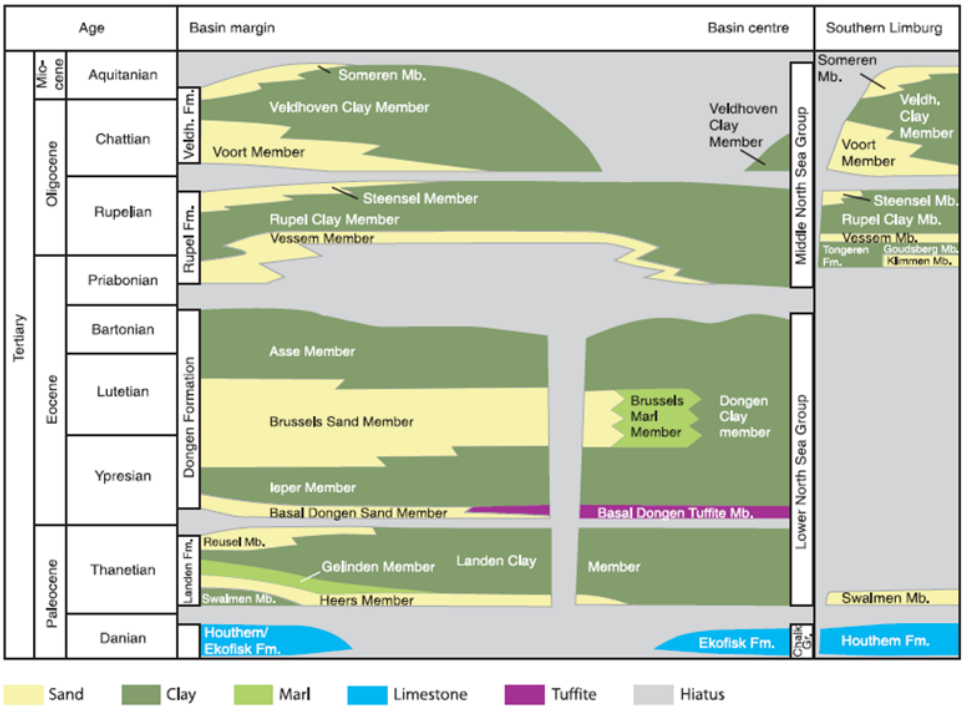


Figure 5 – Stratigraphic scheme of the Lower and Middle North Sea groups in the Netherlands (Wong et al 2007).

The Lower and Middle North Sea Group (*Figure 5*) in area D&E consists mainly of claystones with interbedded sandstones and unconsolidated sands. 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. The Heers and Basal Dongen sands are generally relatively thin (around 10m) in area D&E. The Vessem Mbr. of the Rupel Fm. can be another potential geothermal target. It has a thickness of 20-50m in area D&E and is a transgressive sand on top of the unconformity at the base of the Middle North Sea Gp.

The Brussels Sand seems to have the best geothermal potential of the Middle and Lower North Sea Gps. interval. A small section has been cored in the Brussels sands in nearby well DON-01. The average core porosity value of this 1 m core interval is around 33% and with an average permeability around 2000mD. 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 sand 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 to the south 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. The tight layers form up to 20cm thick hard banks consisting of 73-87% limestone. 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 lithostratigaphy and seen in well logs (*Figure 6*).

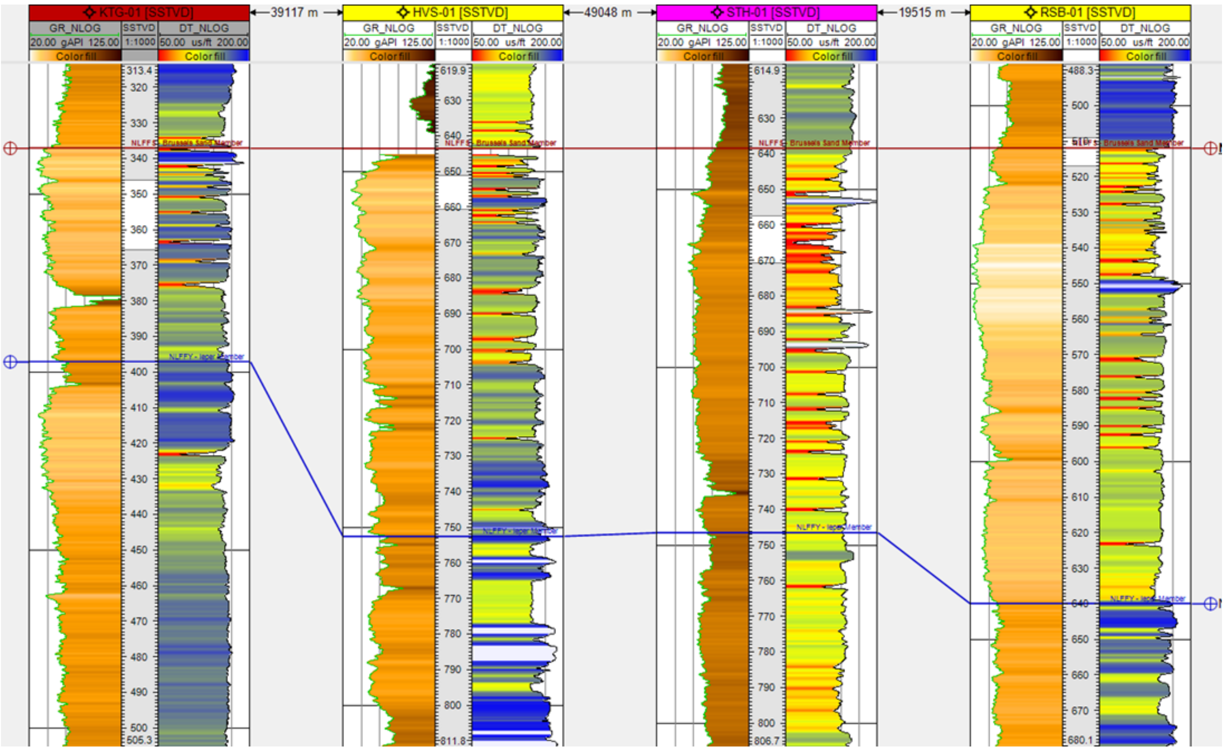


Figure 6 – Log Correlation (GR-DT) Brussels Sand Mbr. wells KTG-01, HVS-01, STH-01 and RSB-01. Note the low DT tight streaks in the top of the formation.

The thickness (*Figure 6*) of the Brussels Sand Mbr. in area D&E varies between 60m in well KTG-01 to 128m in well RSB-01. It is present over the whole of area D&E and the top of the reservoir varies in depth from around -650m in the north to around -300m near wells KTG-01 and WDR-01. On the current seismic dataset, it is possible to make a preliminary isochron map (*Figure 7*) of the Brussels Sands. A more detailed depth and isopach map could be obtained if: 1) a proper mistie analysis was performed on the current seismic data, 2) a depth conversion model was made and 3) the seismic data was reprocessed.

For a more comprehensive evaluation of the Brussels Sands geothermal play the following activities could add value:

- Drill well(s) to obtain good log and core coverage of the Brussels Sands Mbr. and well test data to evaluate the reservoir properties and sedimentological environments
- Retrieve relevant outcrop data from Belgium
- Perform petrophysical analyses of the Brussels Sands Mbr. in existing wells
- Seismic reprocessing of relevant seismic data (if field data available)
- Pending on well results and geological studies acquire a high-resolution test line to better image the internal reservoir architecture and thickness distribution. The seismic line should be tied to wells to demonstrate if inversion of the seismic data will help to map reservoir quality
- Build a detailed reservoir model to evaluate how the tight reservoir layers influence the flow in the aquifer and what the optimal well configuration is in this reservoir

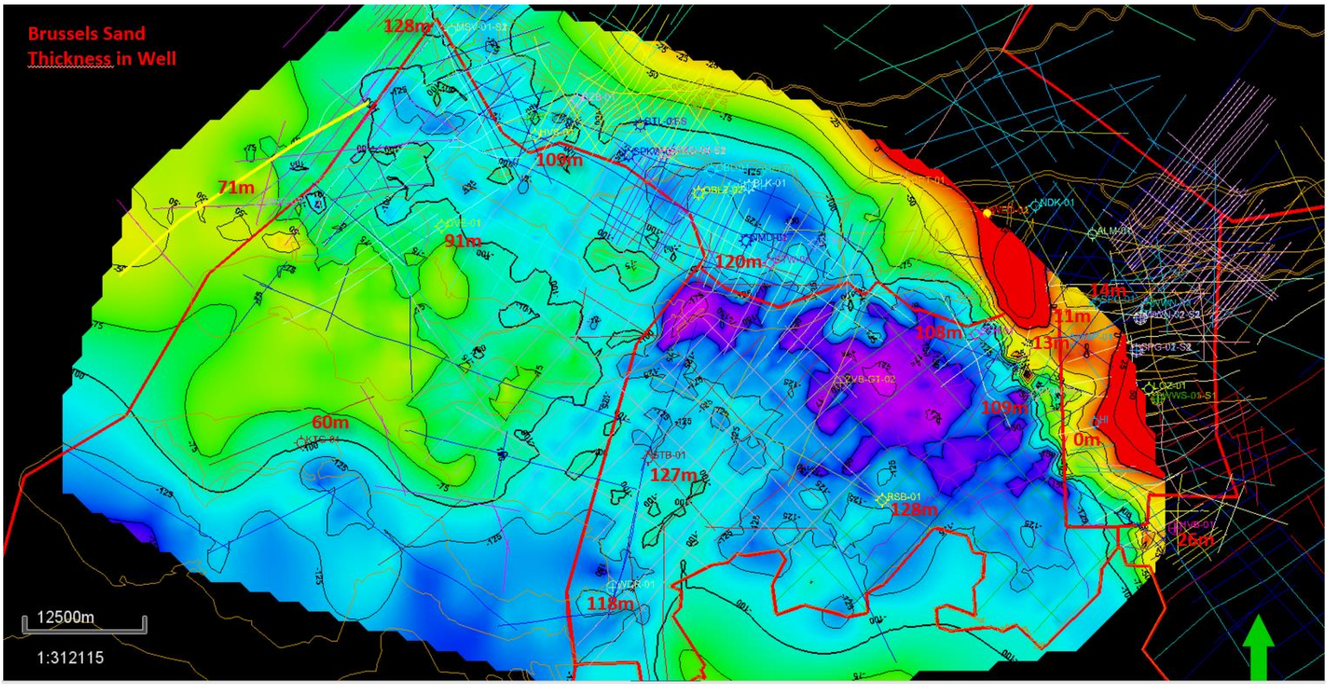


Figure 7 – Isochron map Brussels Sands Mbr. of area D&E with formation thicknesses in m. indicated at well locations

2.3.2 Triassic sandstones

Triassic sandstones of good reservoir quality have been found in well STH-01 and in wells just north of area D&E. In well STH-01, north of Breda, a 104m gross interval of Röt Sandstone is present. This interval has a high N/G ratio and good reservoir properties: core porosity 20-30%, permeability 100-2000mD. According to the Brabant Breed report (*Figure 8*, IF Technology 2012) the transmissivity of the Röt reservoir is 48Dm. The Main Buntsandstein interval has a gross thickness of 129m and good reservoir properties as well. In the Brabant Breed report (*Figure 9*) an average effective porosity of 23.3% is given for the main Buntsandstein of well STH-01 and a derived average permeability of 971mD. The transmissivity of the reservoir is calculated to be 113Dm. In well STH-01 the Lower Buntsandstein (213m gross thickness) also has sandstone intervals of which some may have reservoir quality. It should be noted that concerns have been raised on the quality of the Brabant Breed report in our SCAN evaluation report of area F&G, however, for well STH-01 the results are in line with all available data and thus used for our evaluation.
Wells STW-01 and MSV-01 as well show good reservoir quality in the Triassic just north of area D&E. Whereas near Brielle a geothermal project (Vierpolders) has been producing since early 2016 from a Triassic reservoir.

There is considerable lateral variation of Triassic reservoir properties in the D&E area; the Waalwijk Field area just east of area E has much poorer reservoir with permeabilities typically around 1mD, whereas well HBV-01 between STH-01 and Waalwijk still seems to have good reservoir properties. One of the aspects which could determine the distribution of the reservoir quality is later leaching, when the reservoir was exposed to fresh water influx during phases of uplift and erosion. Distance to the basin or erosion edge and hydrodynamic position could thus be an important factor. However, since more hypotheses are possible more work is needed to test the various ideas.

For a geothermal project in the Triassic sandstones in area D&E the main uncertainty is reservoir quality. In order to reduce this risk, the following work program could be proposed:

- A feasibility study to test seismic inversion, to seismically determine areas of good porosity. This will include a comprehensive petrophysical evaluation of the Triassic reservoirs, building on existing work and a sedimentological and diagenetic study of the Triassic cores
- Reprocessing of the existing 2D seismic data (if field data available)
- Acquisition of 3 new seismic lines intersecting STH-01 and HBV-01, if the inversion feasibility study is successful
- Use the new seismic data (and the reprocessed data) for seismic inversion to predict reservoir quality trends

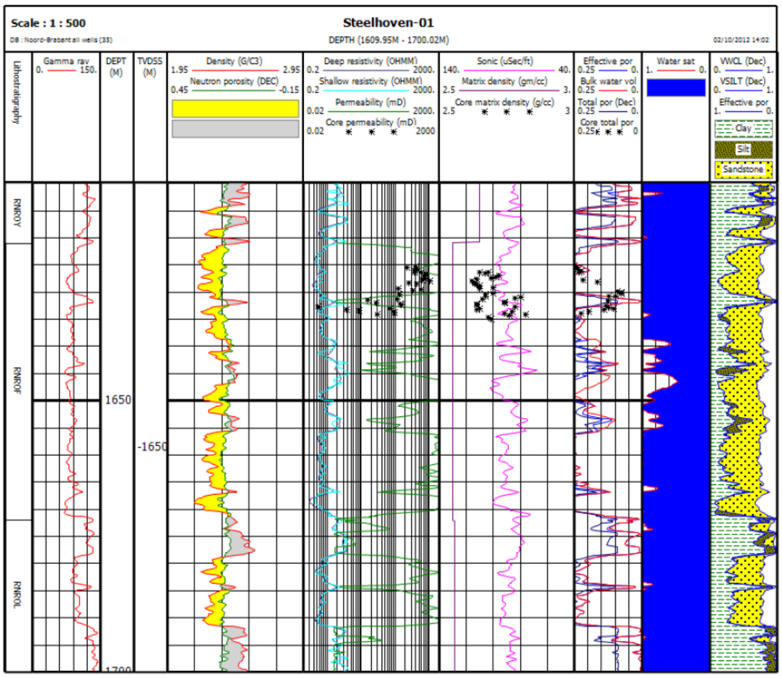


Figure 8 – Petrophysical evaluation Röt Formation STH-01 (IF Technology 2012). Courtesy: HydrecoGeomec/IF Technology, 2012

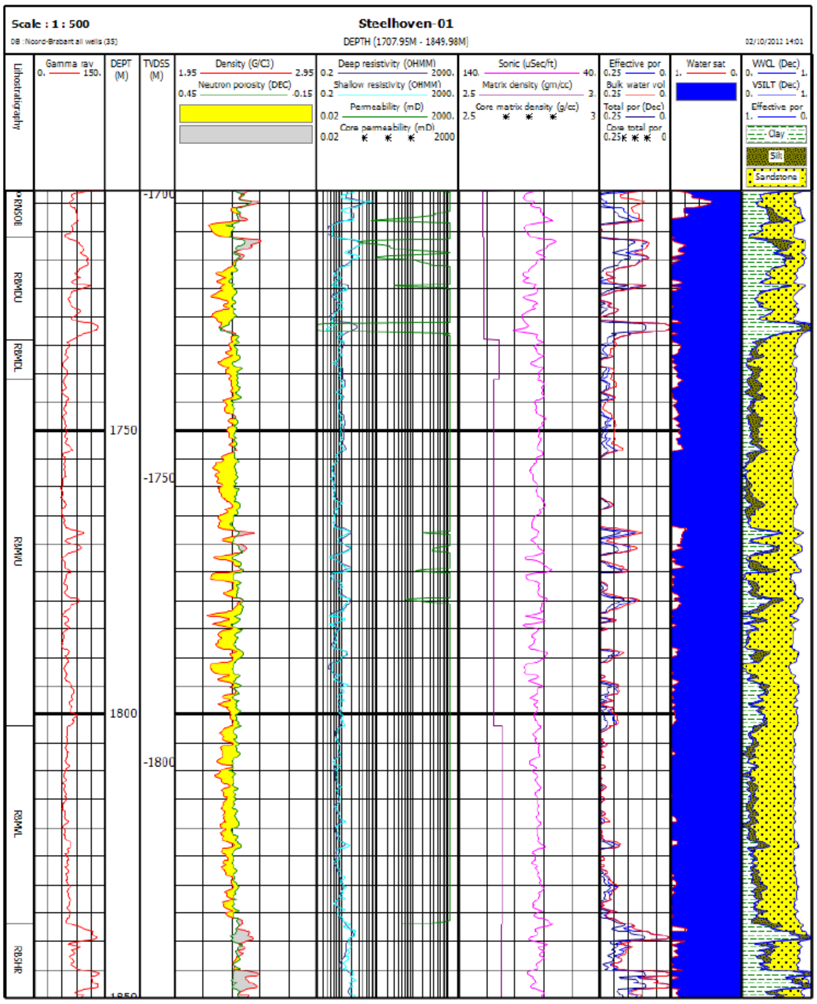


Figure 9 – Petrophysical evaluation Main Buntsandstein Subgroup STH-01 (IF Technology 2012). Courtesy: HydrecoGeomec/IF Technology, 2012

2.3.3 Lower Carboniferous (Dinantian) carbonates

Area D&E is one of the few areas in The Netherlands were the presence and thickness of the Lower Carboniferous (Dinantian) carbonates is relatively well constrained (Figure 11). Wells KTG-01, BHG-01 and WDR-01 have drilled and cored this interval and offshore in blocks S02, S05 and O18 more well penetrations are available. Also, Belgian wells to the south of area D&E add to the knowledge of these formations. Reijmer et al 2017 provide a good overview of the available data and reservoir facies interpretations. The top and base of the formation can be mapped with some confidence on seismic data over area D&E, only in the Breda area the seismic data quality is insufficient. Reijmer et al 2017 provide TWT maps of the top and base of the formation together with an isochron map of the Dinantian (*Figure 10*).

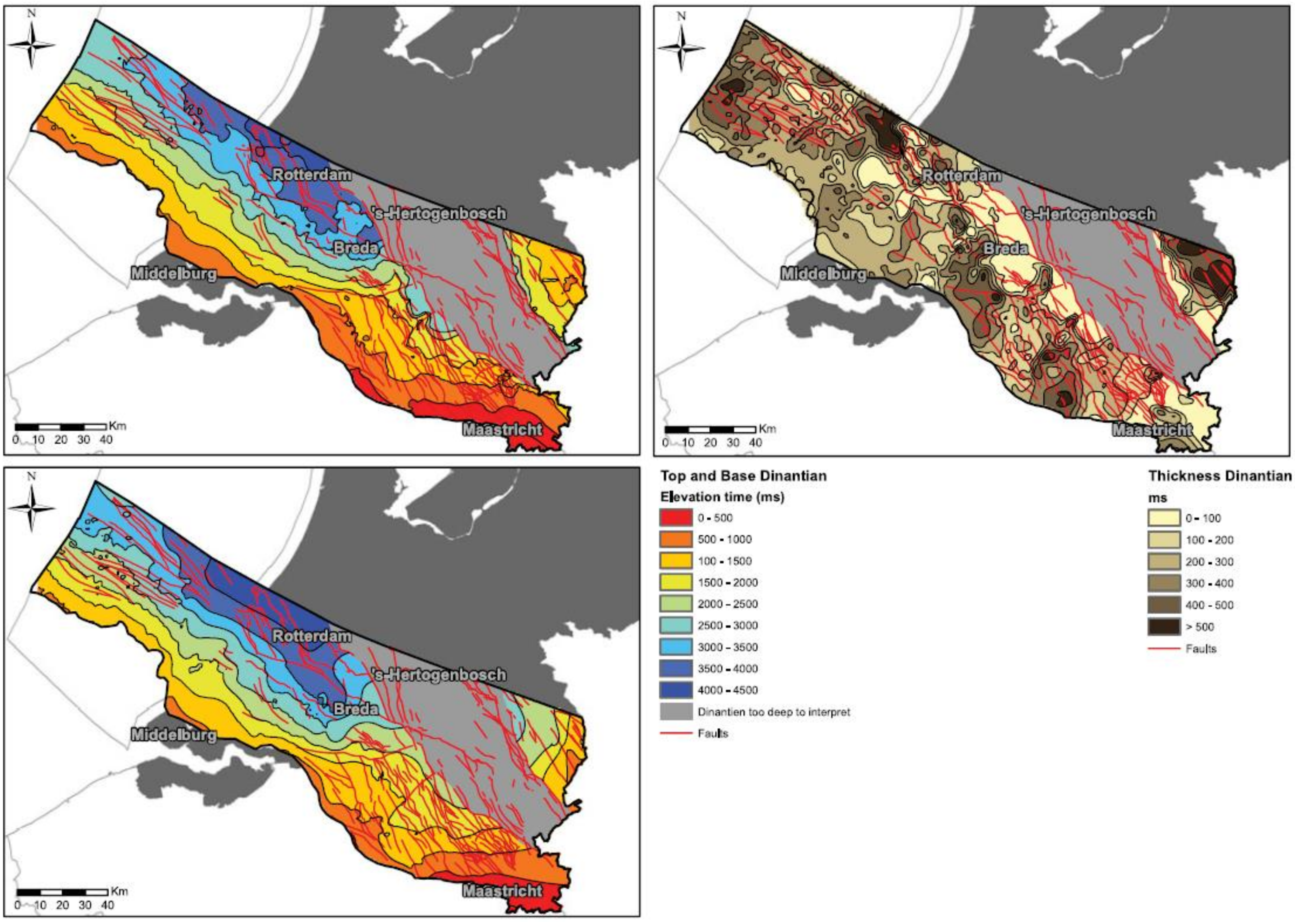


Figure 10 – Maps showing the elevation time of the interpreted top and base Dinantian horizons (top and bottom left, respectively) and the isochore thickness, both in ms. Note that in the center of the Roer Valley Graben the top and base of the Dinantian cannot be interpreted in seismic data and are left blank. Fault lines (in red) represent those faults present that penetrate the top of the Dinantian; these include deep-seated syn-sedimentary faults as well as much younger ones. (from Reijmer et al 2017)

A depth map of Top Dinantian is available from Dinoloket. Some concerns can be raised with respect to the depth conversion to this layer. Well RSB-01 has TD-ed in Namurian shales above the Dinantian carbonates, however the TNO depth map of Base Limburg (TNO 2014) is 378m above the TD of the well. This TNO Base Limburg depth map shows a regional high in the area from Biesbosch to Breda, which is much less obvious on the TWT maps of Reijmer et al 2017 and on the available seismic sections.

The depth to top Dinantian in area D&E ranges from 1km near KTG-01 in the south to 6km north of Breda and near Rotterdam. So, the play varies from an UDG project in deeper areas to a conventional to even low temperature project in the south. A special situation may be present where the Dinantian carbonates subcrop against sediments overlying the Base Cretaceous Unconformity. Here the carbonates may have been more extensively leached and a karstified fracture network may exist. Well KTG-01 was in fact drilled in such a position. In this well the reservoir was cored and tested and evidence for karstification was seen. In the Belgian Loenhout gas storage porosity and permeability in the Dinantian carbonate reservoir are provided by karstification processes during the Dinantian and Namurian. In the Californië Dinantian geothermal project faults and fractures seem to an important mechanism to create the reservoir permeability. Since the normal matrix permeability of Dinantian carbonates is very low, geothermal plays in this reservoir will depend on secondary permeability, as indicated by the aforementioned subplays.

To reduce the risk of geothermal projects in the Dinantian of area D&E the following activities can be proposed:

- A detailed seismic interpretation and depth mapping of the Dinantian (in progress)
- A reservoir study of the Dinantian (in progress)
- Reprocessing of existing seismic data (if field data available) to improve the seismic mapping
- Acquisition of a seismic section just offshore the west coast, from the expected subcrop line of the Dinantian reservoir, tie-ing to well S05-01 to the Maasvlakte, where an UDG project is being evaluated
- Acquisition of one seismic line over KTG-01 to evaluate the Dinantian subcrop play and one south of WDR-01 to test the same.
- Acquisition of 3 new seismic sections between RSB-01 and a poor data area near Breda and the possible high in the Breda area

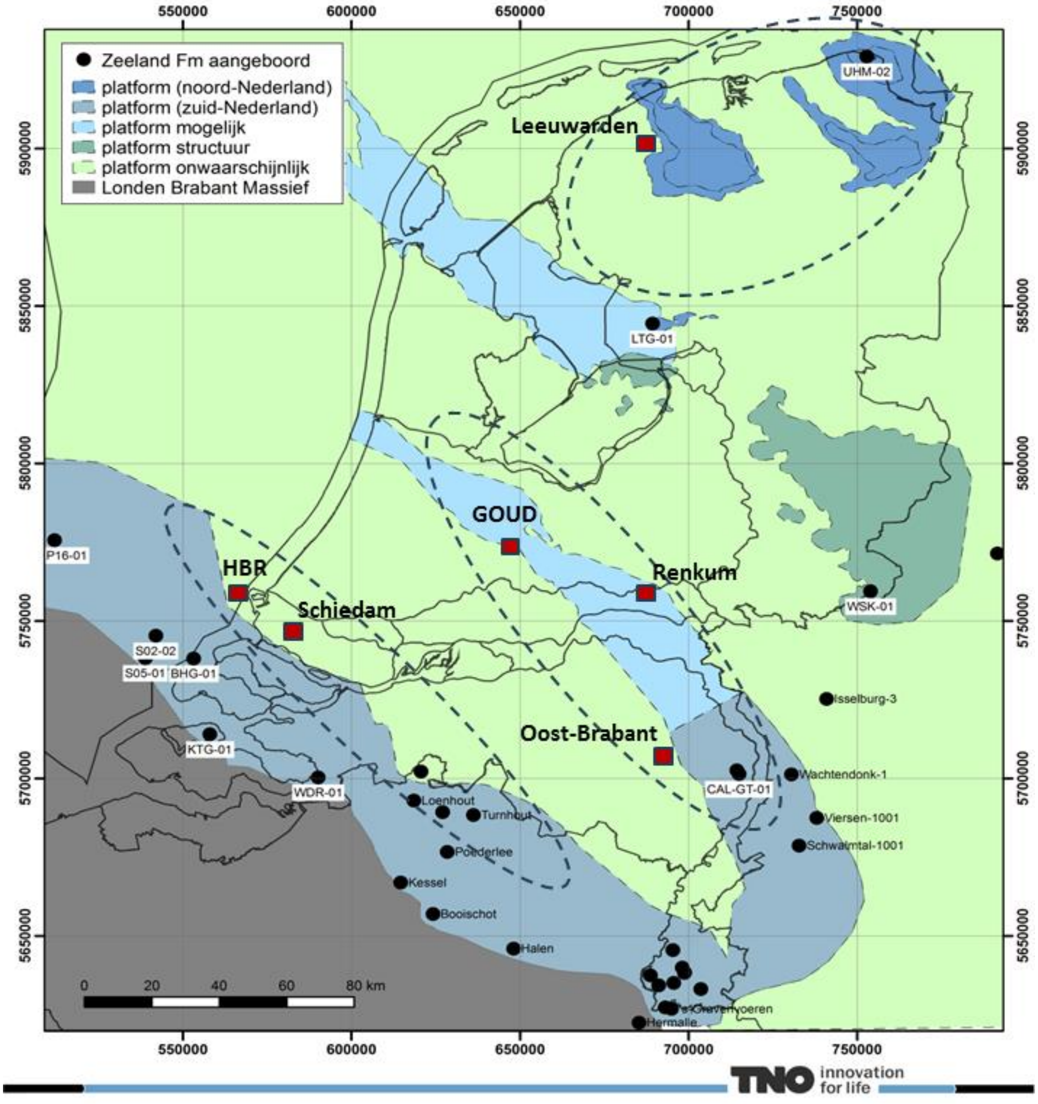


Figure 11 – Facies map of the Dinantian (Early Carboniferous) from Boxem et al. (2016). "Platform mogelijk": platform possible, "Platform structuur": platform structure, "Platform onwaarschijnlijk": platform unlikely, "Zeeland Formatie aangeboord": Zeeland Fm encountered in well. NB: This map may be outdated as it does not reflect the ongoing SCAN Dinantian work.

2.4 Secondary targets

2.4.1 Upper Jurassic sandstones

The Upper Jurassic interval found in the Roer Valley Graben can serve as an prospective geothermal reservoir. The Schieland Group consists of fluvial sandstones interbedded with floodplain claystones. The N/G ratio is typically around 50%, which, for this type of facies, would mean the sandstone bodies are 3D spatially interconnected. The sandstones are found to have good reservoir properties in the cores of wells DON-01, WAP-01 and OIW-01. The core plug porosity varies between 27-34% and the core permeability typically varies between 200-5000mD. Since the play is located in only a small corner of area D&E not much work can be performed here.

The flowing work could be proposed for the Upper Jurassic play in area D&E:

- The proposed seismic acquisition for the Triassic and Dinantian plays near Breda could also connect the Upper Jurassic key wells DON-01, WAP-01, SPC-01 and HBV-01 resulting in a better correlation between the reservoir intervals
- 3D seismic data could assist in a better evaluation of the connectivity of the reservoir sandstones
- Comprehensive petrophysical evaluation

2.4.2 Pre-Dinantian interval

In the area D&E some information is available on the Pre-Dinantian intervals. In well KTG-01 a thick sandstone interval is found at the TD of the well. These sandstones are either of Silurian age, as indicated in the Dinoloket tops, or of Devonian age as suggested in the RGD core report. These tight lithic sandstones will subcrop south of well KTG-01 below the Base Cretaceous Unconformity. At the location of the subcrop they maybe more leached or fractured improving the reservoir quality. Further south in Zeeuws Vlaanderen even older rocks may subcrop, probably of Silurian or Ordovician age, also the reservoir quality of these formations may have benefited from their position below the unconformity. Also fracture zones may be a target if it can be ascertained that these are not tectonically stressed.

Lastly, if the crystalline basement play were to be tested in The Netherlands then Zeeuws Vlaanderen would be the best location, since the crystalline basement of the Brabant Massif here is expected to be at it shallowest depth in The Netherlands. However, this is out of drilling reach since the thickness Cambro-Silurian interval is expected to be more than 13km. It should be noted that in Zeeland no wells have drilled the top of the Paleozoic south of KTG-01, making any predictions on this interval in this area highly speculative. In Belgium some wells just across the border of Zeeuws Vlaanderen have reached the Paleozoic. The depth of top Paleozoic in Zeeuws Vlaanderen, Zuid Beveland and Walcheren ranges between -400 and -800m depth

The following work could be proposed for the Pre-Dinantian plays in area D&E:

- Continue the line over KTG-01 south over Zuid-Beveland and Walcheren to image a possible subcrop play of the Silurian/Devonian sandstone of KTG-01
- Use Belgian well data to make a better prediction of the subcrop expected in Zeeuws Vlaanderen
- Use gravimetry and magnetic data to predict the stratigraphy and structural configuration in Zeeland and depth to crystalline basement
- Drill a well into the Paleozoic of Zeeuws Vlaanderen, conditional on favourable study results, 2D seismic data to drilling this well is needed

2.4.3 Other secondary targets

Both the sandstones of the Westphalian and the Lower Cretaceous can locally act as secondary reservoir. The Lower Cretaceous sandstones are generally of very good quality in the West Netherlands Basin. In area D&E nearly no Lower Cretaceous Rijnland strata are present except in the Voorne-Putten area of the West Netherlands Basin near well HVS-01. Here this reservoir may offer an attractive secondary target next to the Triassic reservoirs.

The Upper Carboniferous may have some potential in the northern part of the area, where sand-rich intervals of Westphalian-C or -D age are present. However, the Triassic sandstones of this area are probably more attractive.

3. Seismic survey design

In the previous chapter proposals were made for the further geological and geophysical evaluation of area D&E. 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 12* 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).

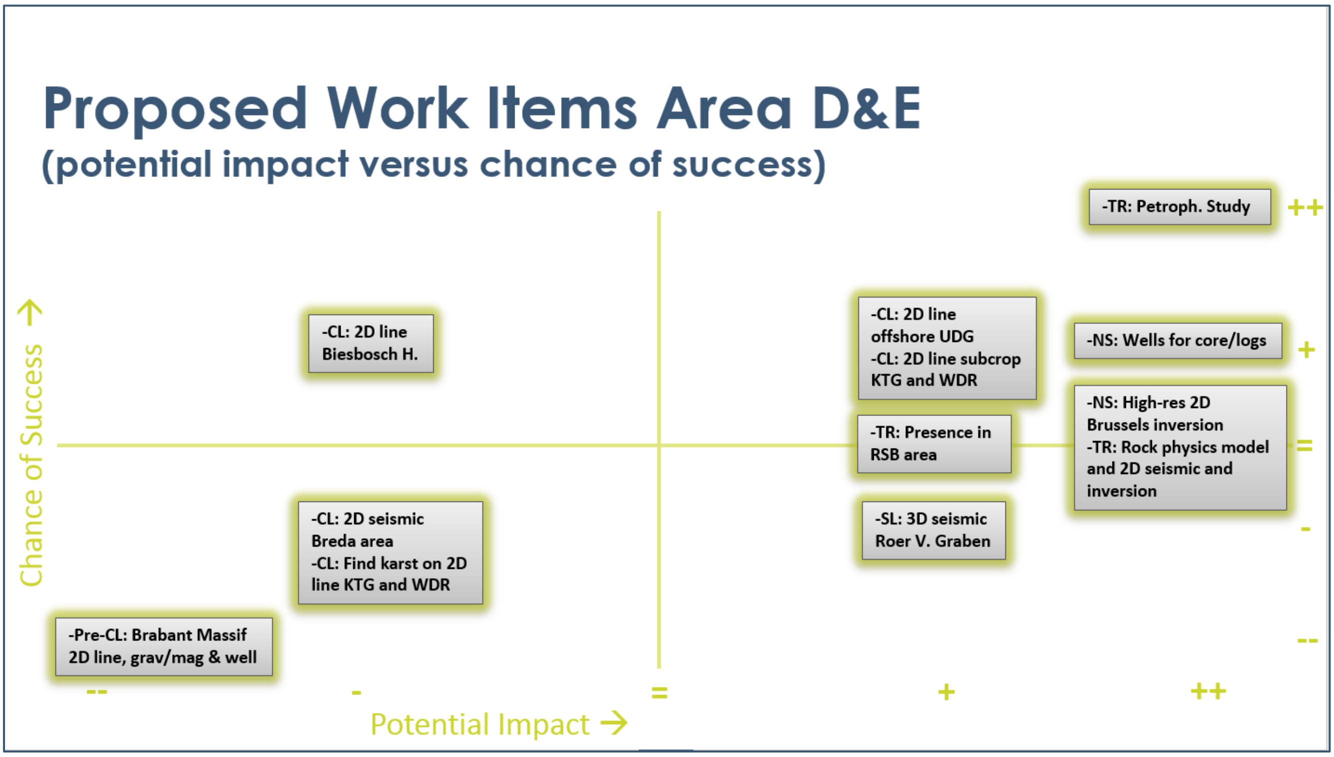


Figure 12 – Cartoon showing the main proposed work items for further evaluation of area D&E ranked according to potential impact of the play and estimated chance of success

3.1 Geological objectives of the seismic survey

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

- For the Brussels play high resolution 2D seismic data may help to better constrain reservoir properties, especially if seismic inversion is successful. However, at this moment it is seen more important to obtain core and log data of this reservoir. Any decision on obtaining specific seismic data for the Brussels can better be postponed till after obtaining core, log and well test data. Some of the seismic lines planned here for a deeper target could still be helpful for the Brussels play evaluation.
- Provide new high-quality seismic data to perform an inversion study on the Triassic near well STH-01 to seismically predict the presence of good quality (leached?) reservoir. The 2D seismic lines tie to the wells STH-01 and HBV-01 with good reservoir quality and well SPC-01 with a poorer reservoir quality. Rock physics modelling will be performed before acquisition to test if seismic inversion can be successful and if so what the acquisition parameters are needed for this seismic inversion.
- Offshore seismic line showing the Dinantian development from well S05-01 to the north to the UDG area Maasvlakte and to the south to the subcrop of the Dinantian (and Devonian) below the Base Cretaceous Unconformity. Well S05-01 was selected as tie point over BHG-01, which is located in too shallow water for regular seismic streamers. Also, the well log dataset of well S05-01 is deemed better than well S02-02. Which resulted in the preference for well S05-01, even while the top of the Dinantian limestone has been eroded below the Base

Cretaceous unconformity. In the tendering phase of this line as alternative to this single line an offer will be requested for two lines: one from S05-01 to S02-02 and one from S02-02 to the Maasvlakte.

- A seismic line over well KTG-01 and a seismic line near WDR-01 to position the subcrop of the Dinantian since that area may be prone to enhanced porosity and permeability due to karstification and/or leaching. The chance to be able to determine the karstification itself on the seismic data is seen as low. South of KTG-01 and WDR-01 the Devonian sandstone seen in KTG-01 is expected to subcrop. The exact location may be visible on new seismic data.
- North of well RSB-01 an area of thin (good-quality) Triassic is present on the TNO maps. A new seismic line from RSB-01 to STH-01 may resolve the question if this interpretation is correct
- In a small corner of the area D&E the Schieland could provide an interesting reservoir. A 3D survey may be helpful for the correlation of reservoir intervals from well penetrations. However, since nearby in the Waalwijk area sufficient 3D data is available to test this play in a comparable setting, no 3D acquisition is proposed here. The 2D line crossing well SPC-01 will also cross wells WAP-01 and DON-01 which have an important Schieland section.
- The TNO Base Limburg map shows an important high to the north of Breda (Biesbosch High). The presence or absence of this potential UDG target could be verified on new seismic lines. The location of these are in the same area as the lines for the Triassic inversion study, so no additional seismic acquisition in needed.
- In the Breda area the seismic data is poor with respect to the imaging of the Dinantian. New seismic data may help to highlight if an UDG target is possible in this area. Seismic should tie with well RSB-01, which TD-ed just above the Dinantian. The acquisition of seismic data for the Dinantian in the Breda area can be combined with lines for Triassic objectives.
- If a well is planned into the Lower Paleozoic in Zeeuws Vlaanderen 2D seismic data is needed to better position this well to avoid any hazard or, if this is seen as advantageous, to drill into a fracture zone.

3.2 Criteria for design of the seismic survey

The position and orientation of the lines of the survey were planned 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.
- Straight, long (>20 km) lines.
- Well ties for wells penetrating stratigraphic levels deeper than Base Cretaceous, preferably by choosing the line trajectory over / nearby an existing well location.
- Tie the 2D line to 3D seismic data.
- Minimalize 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
- 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 13 shows the proposed line locations covering area D&E 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 D&E was estimated at 250 km, of which 132 were considered conditional. The current design amounts to 303 km, 64km of which are conditional (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
S05-01-MVL-KDZ	Image Dinantian. De-risk Dinantian depth, thickness and facies near UDG Haven Rotterdam. Position of Dinantian and Devonian subcrop location. Alternative option two lines. Line 1: S05-01 to S02-02, line 2: S02-02-MVL-KDZ
VLS-KTG-ZNM	Image Dinantian. De-risk Dinantian depth, thickness and facies. Find evidence for karstification. Determine subcrop Devonian south of KTG. Explore for leached or fractured Devonian
WDR-STB	Image Dinantian. De-risk Dinantian depth, thickness and facies. Find evidence for karstification south of WDR-01. Explore for leached or fractured Devonian
RSB-STH	Image Triassic, Dinantian. De-risk Triassic reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on improved reservoir quality near STH, provide data for seismic inversion project in Triassic. Seismic quality of Dinantian is poor on current seismic data, de-risk Biesbosch high. Line will also cover Brussels sand target area
SBK-SPC	Image Triassic, Dinantian. De-risk Triassic reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on improved reservoir quality near STH, provide data for seismic inversion project in Triassic. Tie to well SPC with poorer Triassic reservoir quality. Seismic quality of Dinantian is poor on current seismic data, de-risk Biesbosch high. Line will also cover Brussels sand target area (tie well DON-01) and the Schieland wells DON-01 and WAP-01
STH-HBV	Image Triassic, Dinantian. De-risk Triassic reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on improved reservoir quality near STH, provide data for seismic inversion project in Triassic. Line will also cover Brussels sand target area and the Schieland of well HBV. Connect lines RSB-STH and SBK-SPC
OSN-STEK (conditional)	*Determine Top of Brabant Massif. Explore for permeable fracture zones. Tie to Stekene well in Belgium*
HI-RES 1 & 2 (conditional)	*Image Brussels sand. Determine depth thickness and facies trends (via inversion) in the Brussels Sand. Tie to new cored well in Brussels. Tie to ZVB project and STB-01 (or another legacy well). Tie to deep target SCAN lines.*

Table 2 – Geological goals for the proposed lines

Line	Total Length (km)	Comment
S05-01-MVL-KDZ	70.9	Offshore acquisition. Alternative of two-line acquisition in tender phase
VLS-KTG-ZNM	40.2	Oosterschelde crossing
WDR-STB	28.0	
RSB-STH	38.4	Acquisition after inversion feasibility study
SBK-SPC	32.1	Acquisition after inversion feasibility study
STH-HBV	29.3	Acquisition after inversion feasibility study
OSN-STEK	*20.1*	*Conditional, depending on results Grav/mag project*
HI-RES 1	*18.8*	*Conditional on drilling of Brussels well*
HI-RES 2	*31.1*	*Conditional on drilling of Brussels well*
Total length	310.9	

Status of 20/03/2019

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

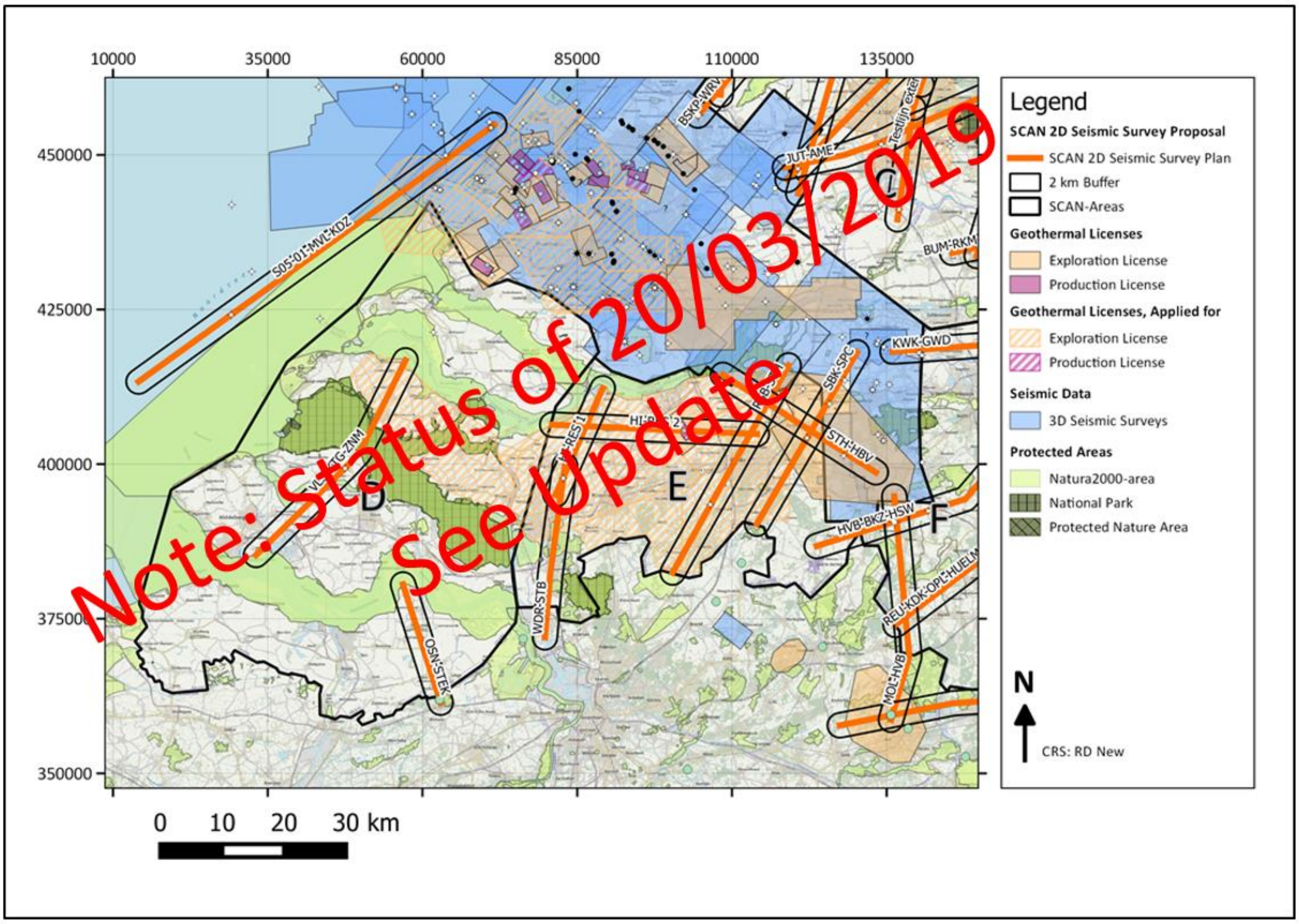


Figure 13 – Seismic survey design for SCAN area D&E. The outlines show the area where full-fold coverage is required. Note: the actual acquisition of these lines is subject to ranking and budget appropriation. **Please note that this figure displays the status of 20/03/2019, an updated map can be found on page 6 of this report**

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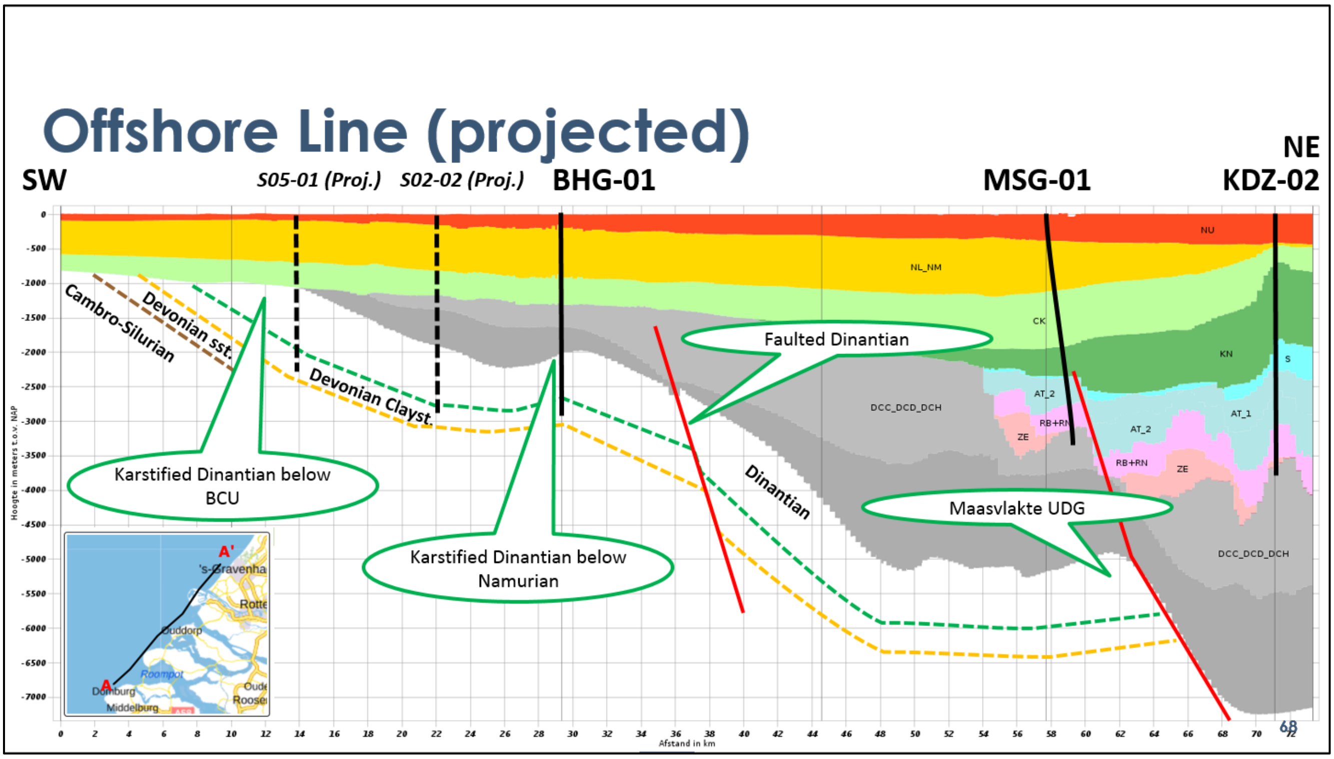
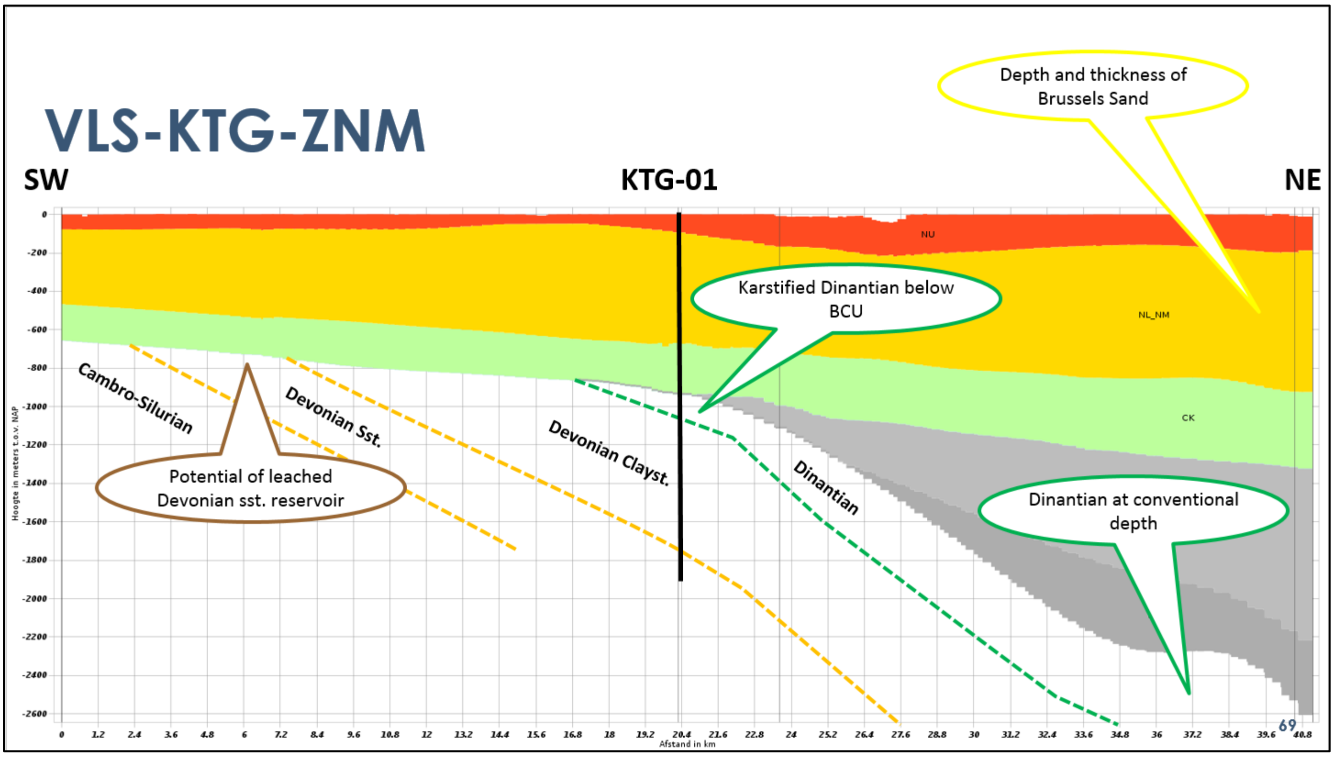
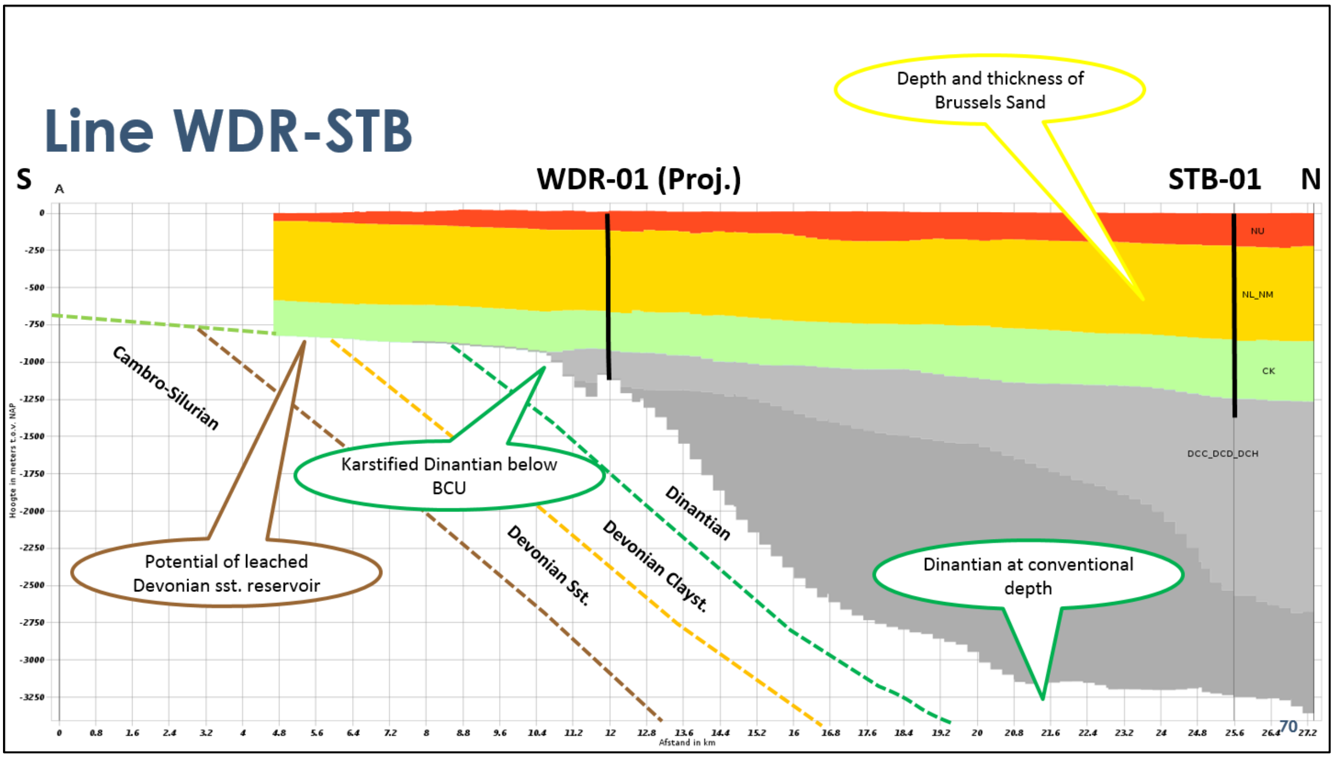
5. Appendices

5.1 Depth sections from DGMdiep v4.0 in Dinoloket over proposed seismic sections area D&E

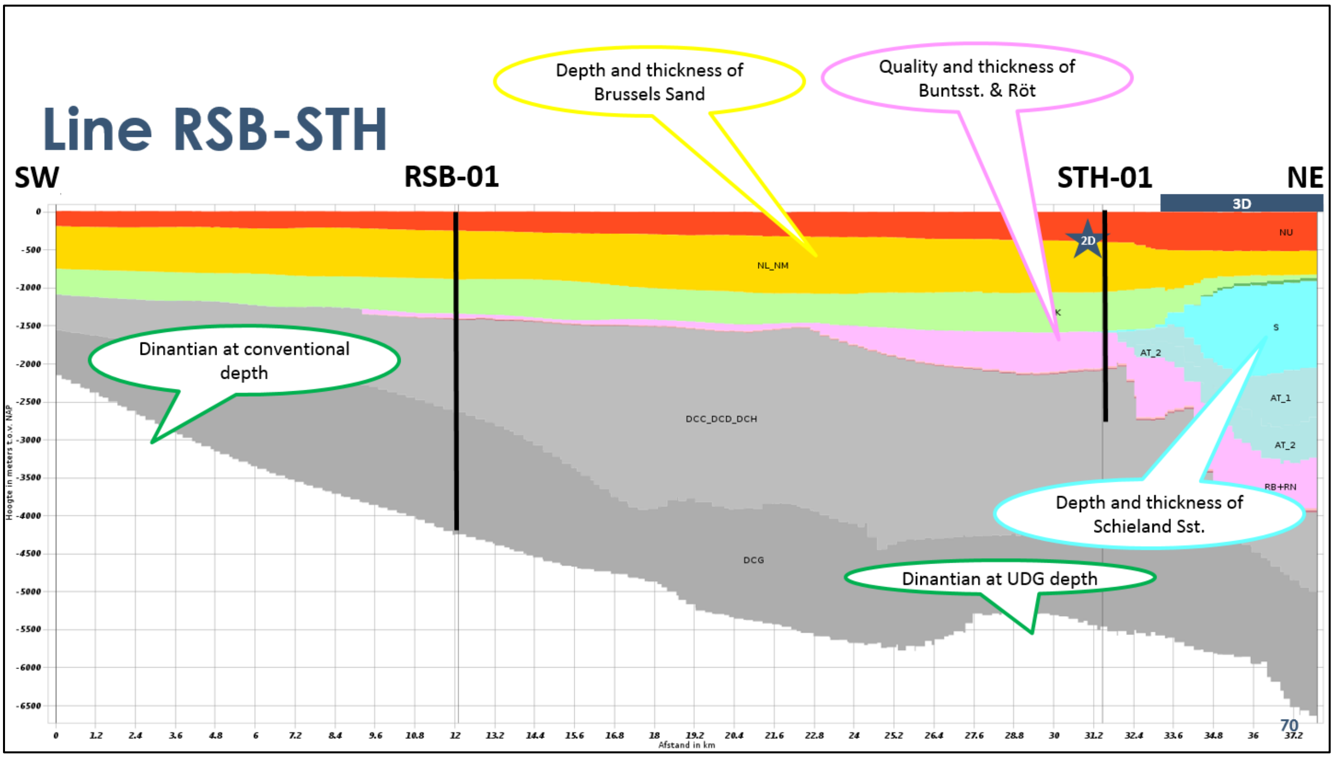


Note: This section is not positioned on the actual acquisition location of the line. It has been projected more inshore to be located within the DGMdiep v4.0. However, the geology at this level of detail is quite comparable.

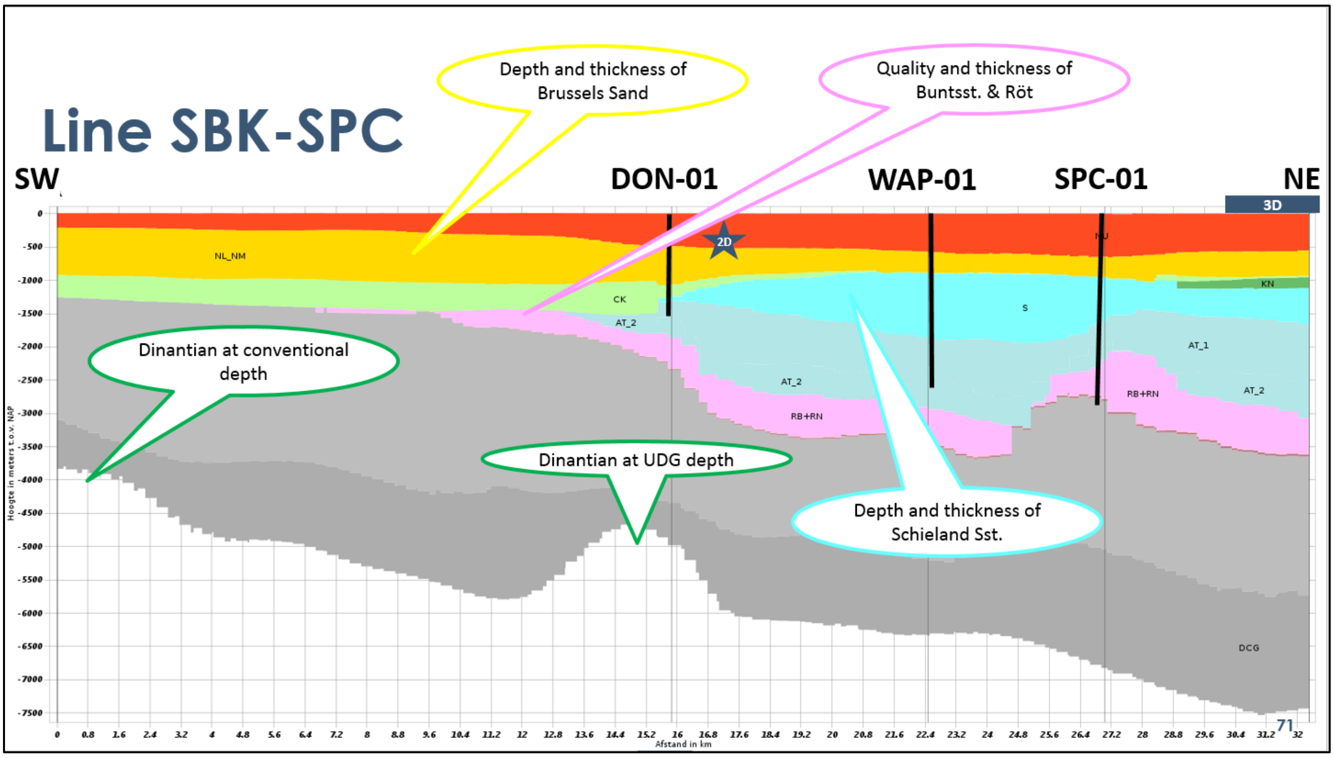


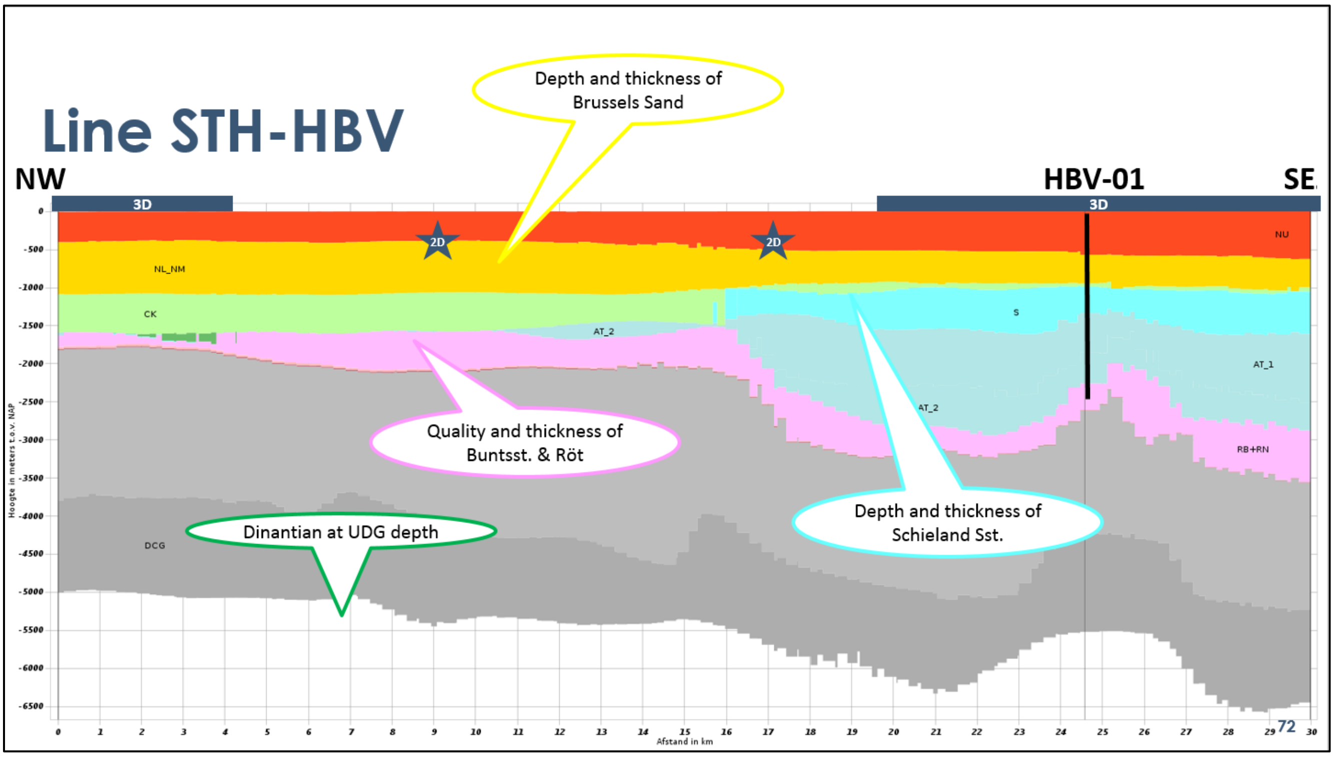


Line WDR-STB
S
A
WDR-01 (Proj.)
STB-01
N
Depth and thickness of Brussels Sand
NU
NL_NM
CK
DCC_DCD_DCH
Cambro-Silurian
Karstified Dinantian below BCU
Dinantian
Devonian Sst.
Devonian Clayst.
Potential of leached Devonian sst. reservoir
Dinantian at conventional depth
Hoogte in meters t.o.v. NAP
Afstand in km
70

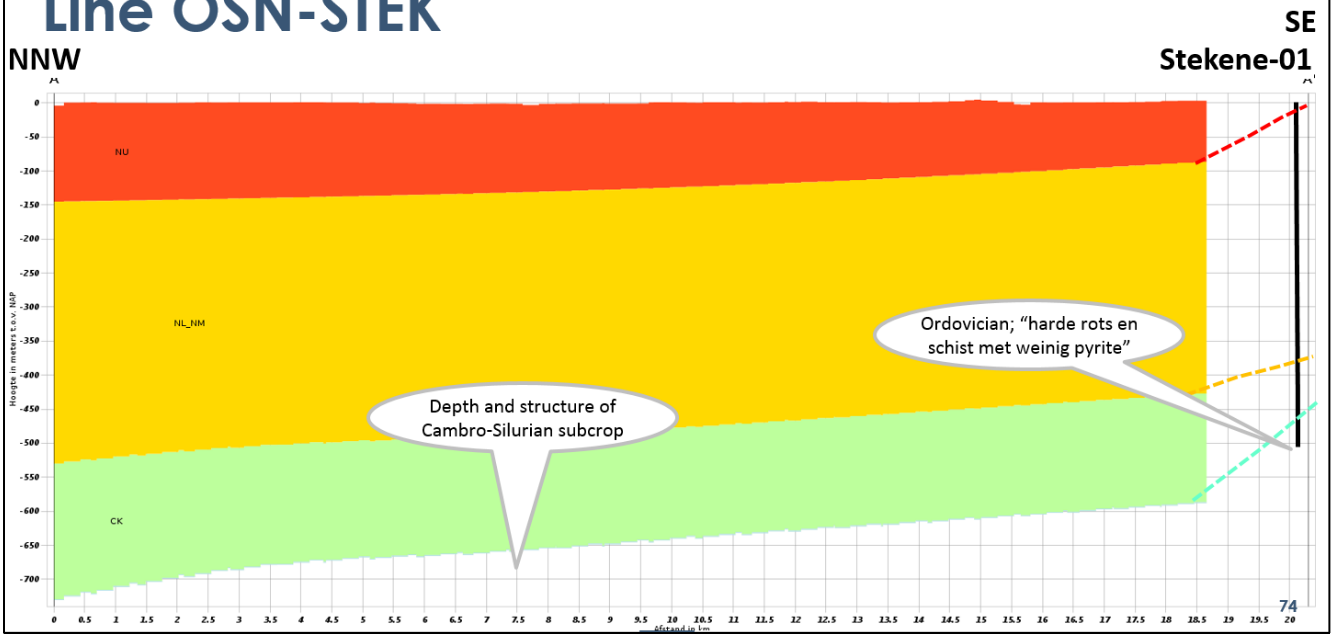


Line RSB-STH
SW
RSB-01
STH-01
NE
3D
2D
Depth and thickness of Brussels Sand
Quality and thickness of Buntsst. & Röt
NU
NL_NM
K
S
AT_2
AT_1
RB+RN
DCC_DCD_DCH
DCG
Dinantian at conventional depth
Depth and thickness of Schieland Sst.
Dinantian at UDG depth
Hoogte in meters t.o.v. NAP
Afstand in km
70

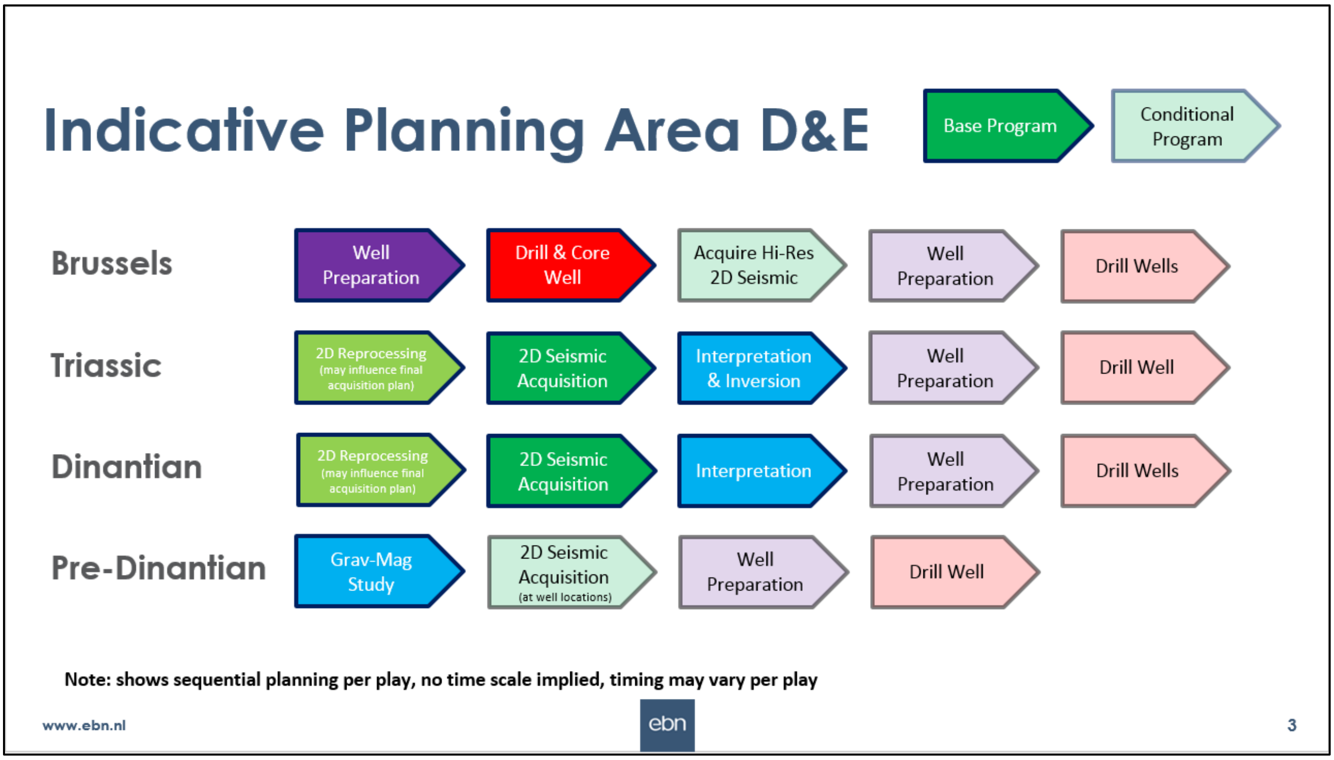

Line SBK-SPC
SW
DON-01
WAP-01
SPC-01
NE
3D
Depth and thickness of Brussels Sand
Quality and thickness of Buntsst. & Röt
Dinantian at conventional depth
Dinantian at UDG depth
Depth and thickness of Schieland Sst.
NL_NM
CK
AT_2
S
KN
AT_1
RB+RN
DCG
Hoogte in meters t.o.v. NAP
Afstand in km
71


Line STH-HBV
NW
HBV-01
SE
3D
3D
Depth and thickness of Brussels Sand
Quality and thickness of Buntsst. & Röt
Dinantian at UDG depth
Depth and thickness of Schieland Sst.
NL_NM
CK
AT_2
S
AT_1
RB+RN
NU
DCG
Hoogte in meters t.o.v. NAP
Afstand in km
72

Line OSN-STEK



5.2 Indicative planning area D&E



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