Geological evaluation for the seismic acquisition programme for SCAN area C (Nijmegen – Haarlem)

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Geological evaluation for the seismic acquisition programme for SCAN area C (Nijmegen – Haarlem)

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Inleiding en duiding

Voor u ligt één van de geologische evaluaties van het SCAN programma, zoals deze in september 2018 is vastgelegd. Deze inleiding en duiding is later toegevoegd om de actualiteit te kunnen toevoegen en duiding te geven aan het rapport.

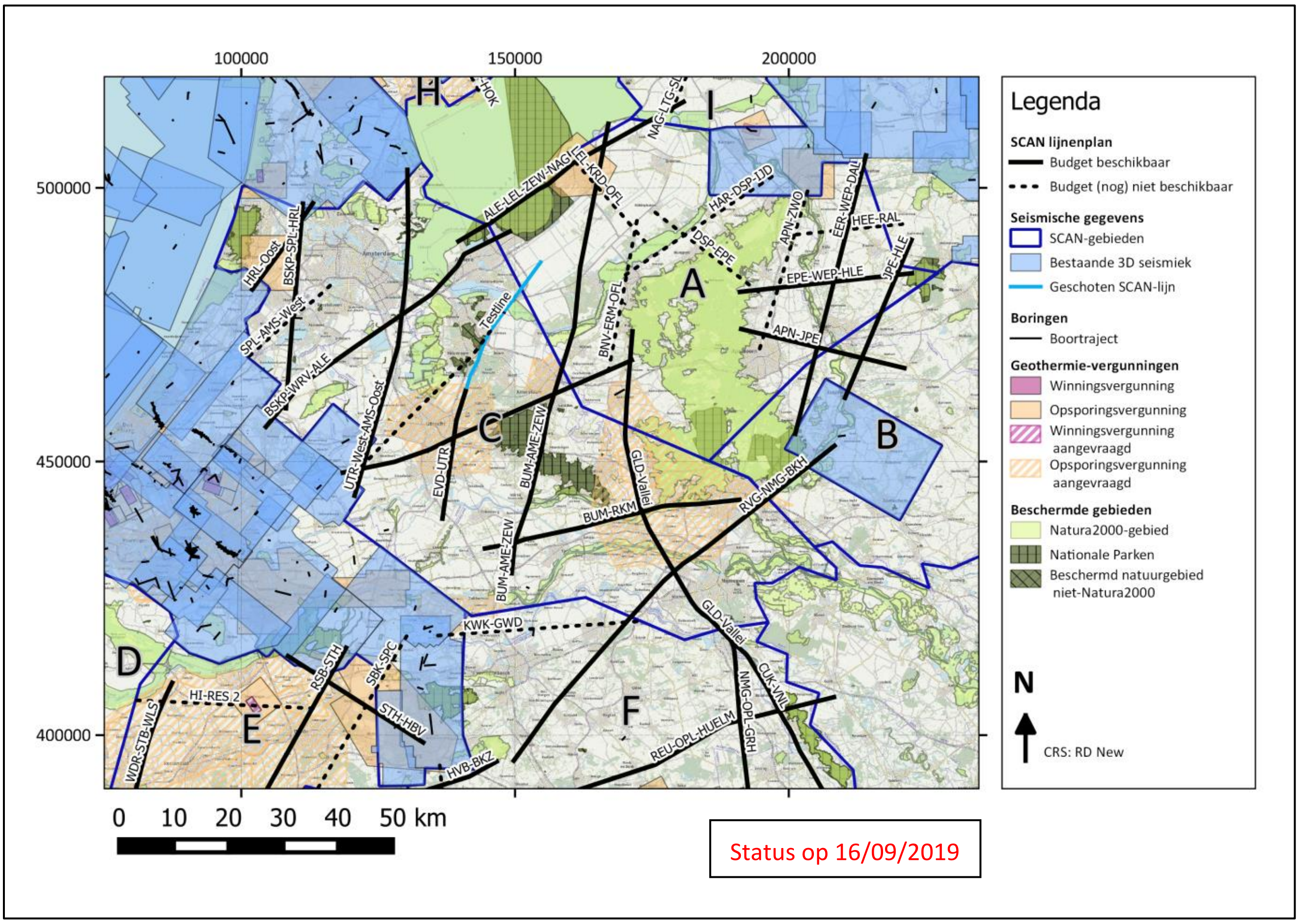
Om het acquisitieplan voor de SCAN 2D seismische lijnen te kunnen bepalen zijn door geologen en geofysici ondergrondevaluaties gemaakt van de verschillende SCAN-gebieden. Hierbij is gelet op welke delen van de ondergrond de beste kansen bieden voor geothermische projecten en welke informatie nog ontbreekt 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 C is het resultaat zoals dat op 05-09-2018 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 C 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 SCAN-gebied C 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 and area C, which comprises major urban centers such as Haarlem, Amsterdam, Almere, Utrecht, Wageningen, Nijmegen and Arnhem was identified as the area with the highest priority.

This document outlines the geological objectives and design criteria for the seismic acquisition ("Acquisitieplan" in the tentative planning, EBN, TNO-AGE, 2017, appendix 6). The reprocessing of existing seismic lines through area C, the reprocessing strategy and the parameters used for reprocessing are documented in a separate document that has already been reviewed.

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.

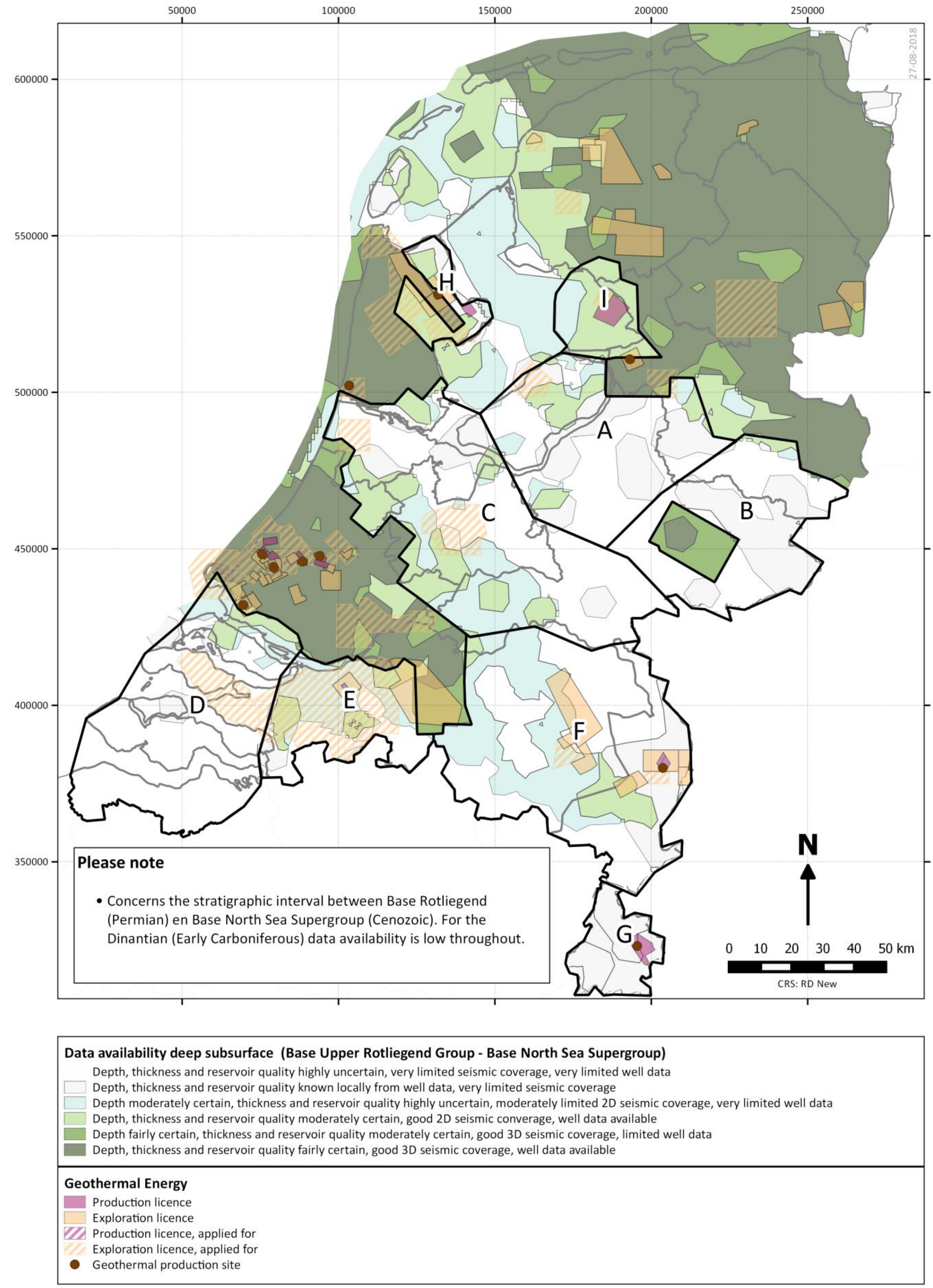


Figure 1 – SCAN areas, geothermal licences and producing geothermal installations (after EBN -TNO-AGE 2017).

2. Geological overview of SCAN area C

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 200 m below mean sea level (Van Adrichem Boogaert& Kouwe, 1993–1997). The primary targets for geothermal projects in the area are Lower Carboniferous carbonates and Permian (Rotliegend) sandstones (Figure 2). Cenozoic sands may prove a primary target for low temperature geothermal systems and/or high temperature storage applications. Secondary targets include Zechstein carbonates, Triassic sandstones, Upper Jurassic/Lower Cretaceous sandstones and possibly Upper Cretaceous Chalk and Upper Carboniferous sandstones (Figure 2).

Within area C the following structural elements can be distinguished for the Mesozoic–Cenozoic tectonostratigraphic evolution of the area (Figure 3a):

- Northern part of the West-Netherlands Basin (WNB);
- Zandvoort Ridge (ZVR), which in turn is on a structural trend to the SE with the Maasbommel High (MBH);
- Central Netherlands Basin (CNB) (extending offshore into the Broad Fourteens Basin (BFB)).

The Paleozoic structuration of the area is not well constrained and is discussed in section 2.2.

The area was subjected to multiple phases of subsidence, inversion and erosion. These events did not affect all parts of the area in the same way, meaning that each part of the area was subjected to its own distinctive sequence of events. This resulted in a complex subsurface architecture: numerous angular unconformities and correlative disconformities are present, and the region is cross-cut by normal, reverse and strike-slip faults (De Jager, 2007; Figure 4). From old to young the stratigraphy relevant for geothermal projects in area C is expected to consist of:

- Lower Carboniferous (Dinantian) carbonates and shales. Deposition of carbonates during this period, in either platform and / or basinal setting was related to a regional extension phase. Syn-sedimentary faults with offsets of hundreds of metres to kilometres may be present. The presently available data do not image the depths at which the Dinantian is expected.
- An Upper Carboniferous siliciclastic sequence (sandstones, claystones and coal) (Figure 4; units marked with 'DC'). The top of the Upper Carboniferous sequence was eroded along the Base Permian Unconformity (BPU) during the Late Carboniferous to Permian, following uplift related to the Variscan Orogeny. Locally the Base Cretaceous/Rijnland unconformity cuts down into the Upper Carboniferous.

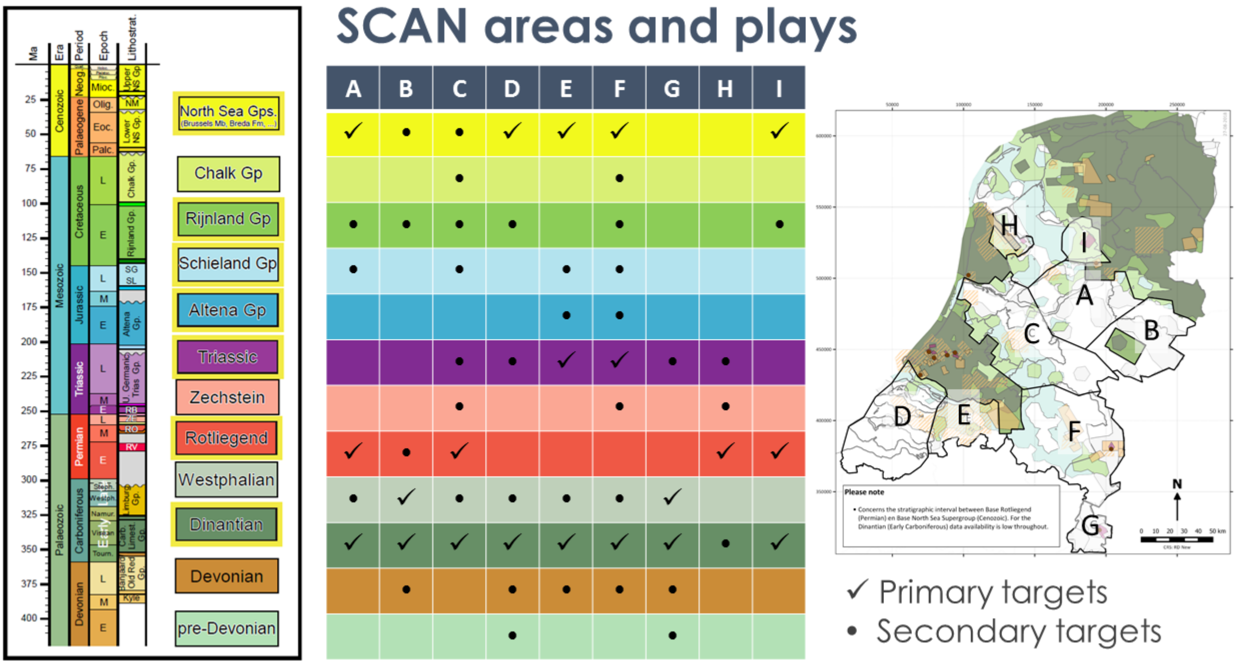


Figure 2 – Overview of the primary and secondary targets in the SCAN areas.

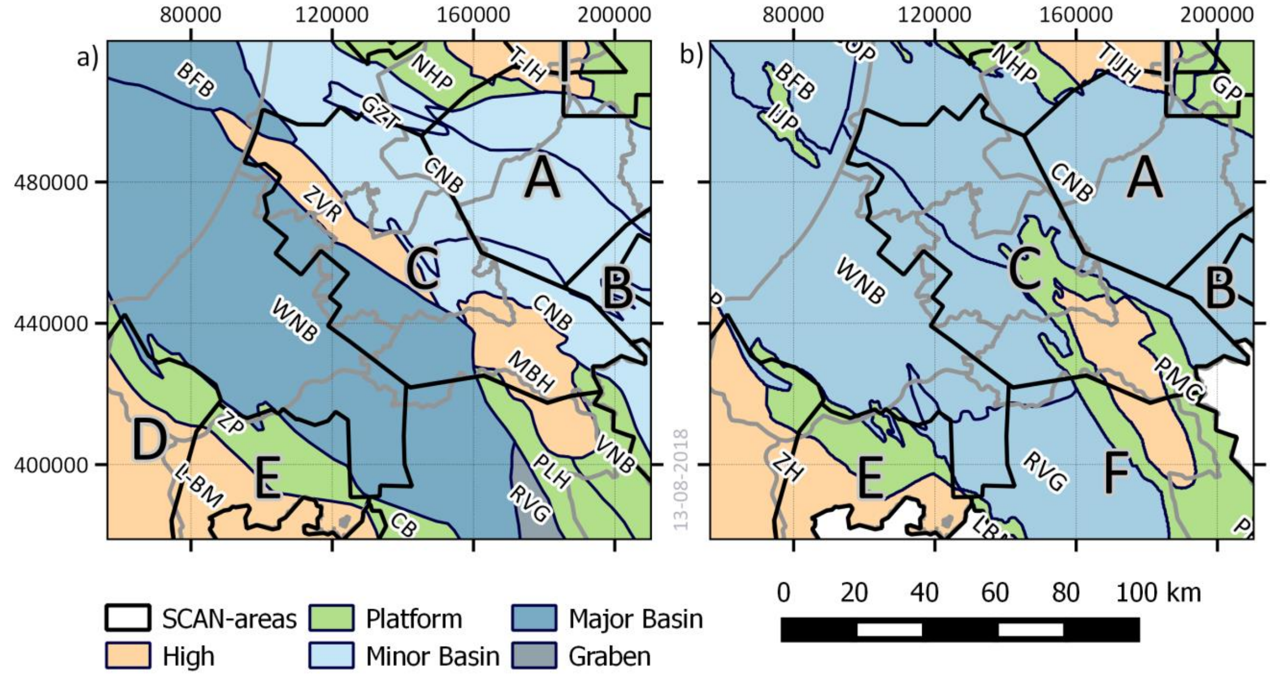


Figure 3 – Late Jurassic – Early Cretaceous structural elements in and around SCAN area C. a) after Doornenbal & Stevenson (2010), Early Cretaceous b) after Kombrink et al. (2012), Late Jurassic – Early Cretaceous. BFB – Broad Fourteens Basin, CB – Campine Basin, GZT – Gouwzee Trough, CNB – Central Netherlands Basin, COP – Central Offshore Platform, GP – Groningen Platform, IJP – IJsselmeer Platform, LBM – London–Brabant Massif, MBH – Maasbommel High, NHP – Noord-Holland Platform, PLH – Peel Block, PMC – Peel–Maasbommel Complex, RVG – Roer-Valley Graben, TIJH, Texel – IJsselmeer High, VNB – Venlo Block, WNB – West Netherlands Basin, ZH – Zeeland High, ZP – Zeeland Platform, ZVR – Zandvoort Ridge.

- The Permian Rotliegend Slochteren Sandstone interval (Figure 4; RO) overlies the BPU. Its primary thickness in the area varies from about 150 m in the northwest to 0 m in the southeast.
- The Permian Zechstein interval (Figure 4; ZE) is relatively thin in area C (compared to the Friesland – Groningen area). Main lithologies are carbonates, anhydrites and claystones with possibly minor amounts of rock salt in the north and east of area C.
- The Lower Germanic Trias Group (Figure 4; RB) comprises the Lower Buntsandstein Formation including the Main Claystone Member (Geluk, 2007). This Group comprises interbedded claystones and sandstones. The Main Claystone Member is a laterally continuous and homogeneous stratigraphic interval. Seismic stacking velocities or log data from this unit can be used to estimate the maximum burial of Triassic and older units; in part of the area maximum burial is possibly higher than present-day burial, causing lateral velocity variations (Japsen, 2000; *Figure 5*).
- The Upper Germanic Trias Group (Figure 4; RN) comprises sandstones, claystones, carbonates and evaporites (predominantly anhydrites and some rock salt).
- The claystones of the Lower Jurassic Altena Group (Figure 4; AT) are only preserved in areas where they were sheltered from erosion by Late Jurassic to Early Cretaceous erosive events.
- The Lower Cretaceous Rijnland Group (Figure 4; KN) consists predominantly of claystones with commonly a basal sandstone sequence. At some locations in area C, sand and claystones of the Schieland Group (S) are present below the Rijnland Group. The Rijnland Group overlies a major unconformity. The presumed thickness of the removed section varies over area C; the deposits below the unconformity may by as young as the Upper Jurassic–Lower Cretaceous Schieland Group (if it was deposited) and as old as the Upper Carboniferous Limburg Group.
- The Upper Cretaceous Chalk Group (Figure 4; CK) consists, as the name suggests, almost exclusively of Chalk. It has a variable thickness caused by intraformational erosive events but predominantly the base North Sea Supergroup Unconformity. The internal seismic velocity of this Chalk interval may vary considerably, both vertically and laterally.

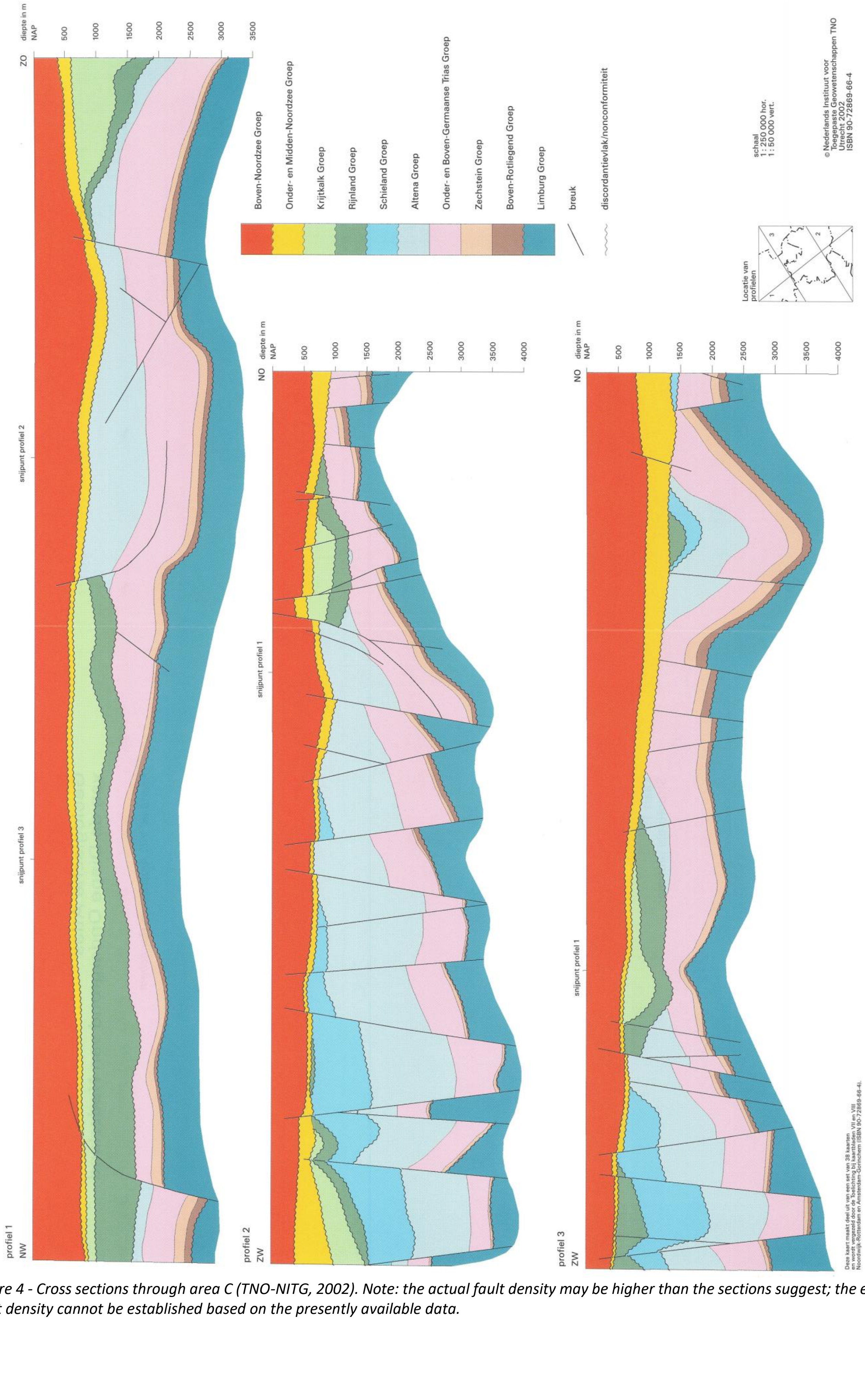


Figure 4 - Cross sections through area C (TNO-NITG, 2002). Note: the actual fault density may be higher than the sections suggest; the exact fault density cannot be established based on the presently available data.

- The uppermost lithostratigraphic group, the North Sea Supergroup (Figure 4; NL, NM, NU) consists primarily of unconsolidated sandstones and claystones. Its base is a major unconformity which progressively cuts down into the Triassic and results from a major tectonic inversion event and subsequent erosion.
- The youngest sediments, part of the Upper North Sea Group, were deposited during the Quaternary period and constitute the near surface and soil profile, comprising sands, clays, peat and glacial deposits. The distribution of these sediments is well mapped and can be viewed on https://www.dinoloket.nl/en/subsurface-models-betaversion using the model GEOTOP or DGM v2.2.

2.1 Structure

The sequence of tectonic events, also applicable to area C, 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 in 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 intermediate platforms and/or highs (possibly the Zandvoort Ridge / IJmuiden platform, Figure 3). 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 C, 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. Constraints are needed at least down to the top of the Dinantian, which is expected at a depth of 4 to 7,5 km in area C.

The structural configuration of area C is uncertain at present. This can be illustrated by comparing structural elements maps from different sources. Figure 3a, based on the Southern Permian Basin Atlas, (Doornenbal & Stevenson 2007 shows the Zandvoort Ridge as a prominent structural high. This in contrast to the structural elements map in the "Tectono-stratigraphic Charts of the Netherlands Continental Shelf (Kombrink et al., 2012), where the Zandvoort Ridge is not present (Figure 3b). This difference in structural configuration stems, primarily, from poor imaging of the subsurface.

Additionally, from regional maps it appears that the structural architecture of area C is fairly simple, with long NW-SE trending faults bounding a horst structure (Figure 4; *Figure 5*). However, maps from the areas to the northwest and south of area C, where 3D seismic data is available, show a complex fault pattern with a spacing between major faults of a few hundred metres to a few kilometres. A single 2D line that traverses the area (Figure 4) suggests the structural framework of area C is similar to these areas and consists of an amalgamation of WNW-ESE and NNW-SSE trending faults. In the West Netherlands Basin, south of area C, this structural style is thought to be related to flower structures formed above reactivated deep seated basement faults (De Jager 2007).

From the limited amount of 2D data that is available in area C it can be inferred that:

1) The area is crosscut by WNW-ESE to NNW-SSE trending faults, with a spacing between faults of hundreds of metres to kilometres (*Figure 6*).
2) Strike-slip deformation occurred, as indicated by the presence of flower structures (*Figure 6*; *Figure 8*)
3) Thrusting or oblique slip occurred at the southern boundary fault of the Zandvoort High to Peel Platform.
4) The Zandvoort Ridge is presently at maximum burial depth (Engelen, 2016).

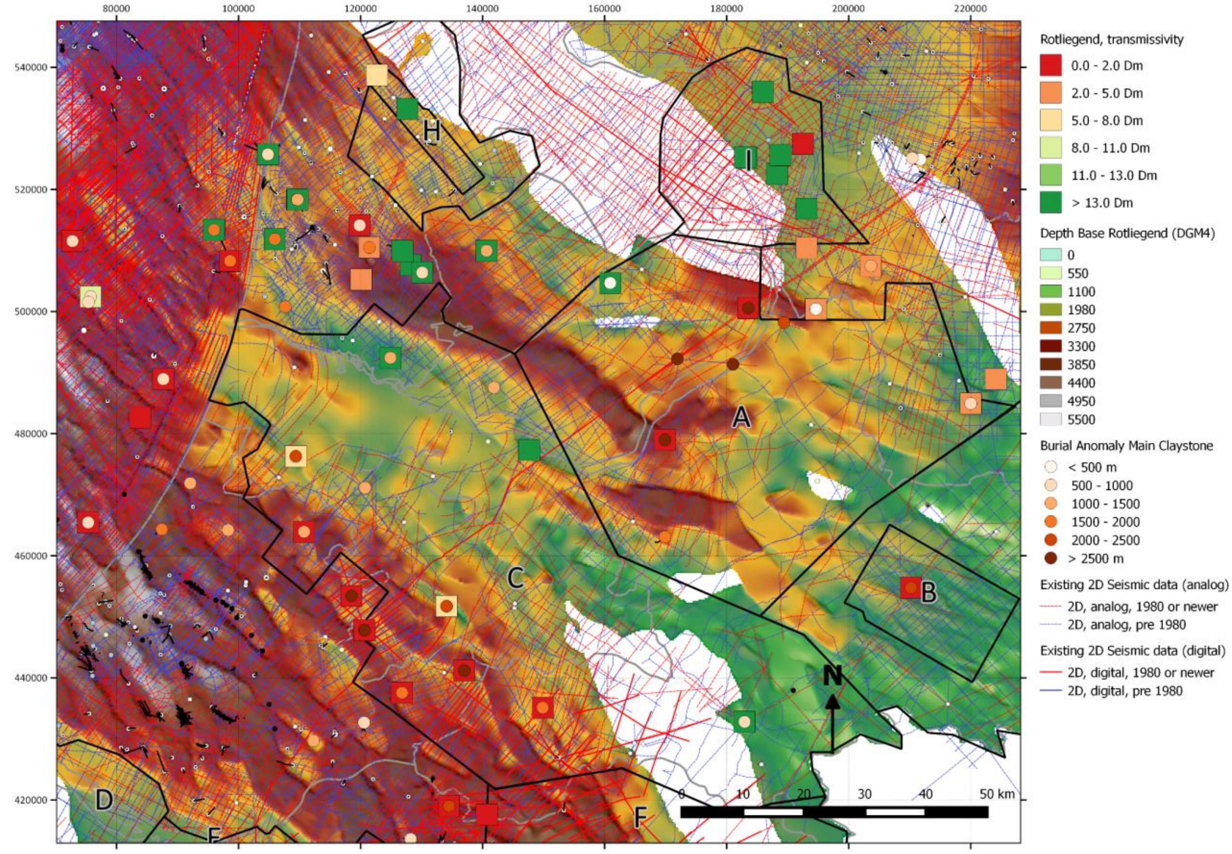


Figure 5 –The depth to Base Rotliegend gives an indication of the structure of the area. In areas where data is scarce the structuration appears to be relatively simple. It is plausible that the actual structure is more complex. Burial anomalies derived from the Triassic Main Claystone Member are high in the southern (West Netherlands Basin) part of area C

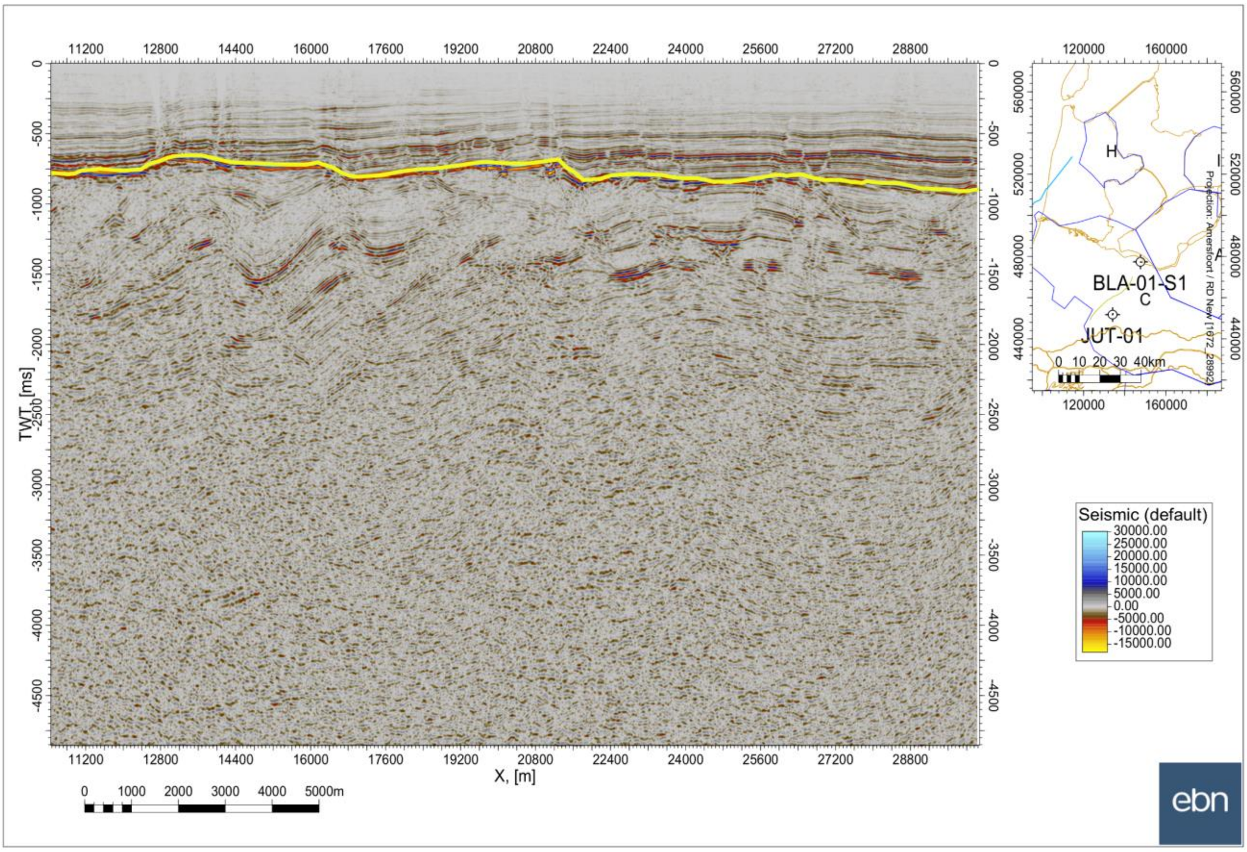


Figure 6 – Seismic Line NAM DEEP; the only seismic line crosscutting area C in NE-SW direction with decent imaging at depth. The subsurface is imaged down to about 2,5 s TWTT. The top of the Dinantian is expected at 3 – 3,5 s TWTT (DGM). Units below the North Sea Supergroup (base indicated with yellow line) are affected by strike-slip faulting

2.2 Primary targets

2.2.1 Rotliegend sandstones

An overview of the aquifer potential in terms of transmissivity of the Rotliegend is given in *Figure 7*. In the northern part of the area three wells with sufficient data (LSM-01, ALE-01 and BLA-01-S1) are available and these wells suggest fair geothermal potential. In the central part of the area, which encompasses major residential centres such as Haarlem, Amsterdam, Almere, Utrecht and Nijmegen, no well data is available and as a result it is currently not possible to give an accurate estimate of the geothermal potential of this area. In the southwestern part of area C well data is available, which consistently shows very poor reservoir characteristics.

The main uncertainties for the Rotliegend in this area are:

- Reservoir quality. The wells in the southernmost part of area C show poor reservoir quality as a result of deep maximum burial. The present day depth is not excessive, but the reservoir has been buried deep prior to inversion, causing the reservoir to have a very poor transmissivity (< 2 Dm). Hence, it is essential to assess which areas were affected by inversion, and by how much.
- Thickness. On a regional scale the Rotliegend Group has an onlap configuration onto the London-Brabant-massif in the south. Its thickness is of the order of hundreds of metres in the north of the Netherlands, and zero in the south of the Netherlands. Local thickness variations may occur that are related to the topography at the time of deposition, which in turn resulted from Variscan faulting and folding, and from differential erosion of the Westphalian. Relatively shale prone intervals of the Westphalian subcrop are eroded more intensely at the BPU and consequently more accommodation space is created and thicker Rotliegend is expected (e.g., Mijnlieff & Geluk, 2008). In the central part of area C two wells are present where the Rotliegend is exceptionally thin (<10 m) compared to the regional thickness of around 100 m: WRV-01 and WSP-01. These wells are currently used in the DGM-deep thickness estimates. Two hypotheses can be defined to explain the thin Rotliegend. What interpretation is used has a large impact on the assessment of the geothermal potential of the region:
    1. The wells do not capture the actual regional thickness of the Rotliegend because primary (depositional) thickness is reduced by fault cut-out. This would imply that these data points should not be used to estimate the regional thickness of the Rotliegend.
    2. The thickness observed in the wells is low because the reservoir was not deposited, or eroded during the Permian. The central part of area C was a regional high, and the Rotliegend thickens north and south of this high. This would imply that these data points should be used to estimate the regional thickness of the Rotliegend.

  The first hypothesis is deemed most likely as existing seismic lines and well data show indications for fault cut-out: well WRV-01 is drilled into a flower structure (*Figure 8*), and core descriptions from WSP-01 mention the presence of slickensides in the Rotliegend.

In the eastern part of area C the Rotliegend has a different character. Only few wells are available, but well NVG-01, near Nijmegen, shows a very high (~28%) porosity. Compared to the previously described area the thickness in this well is limited (18 m) and present day burial is low (around 1100 m). Despite the low thickness the transmissivity of the aquifer may still allow for economic projects, because of the high porosities and hence, probably, permeabilities. In this area it is required to establish the thickness and presence of the Rotliegend, and it needs to be confirmed that the aquifer is presently close to its maximum burial depth.

Other issues affecting reservoir properties in the Rotliegend in area C include (Figure 11):

- Early diagenesis and local depositional phenomena, which may adversely affect reservoir quality locally and are hard to predict.
- The top part of the Rotliegend is commonly adversely affected by "Weissliegend" diagenesis. The thickness of this zone may be predicted, but uncertainties remain.
- Cementation close to the boundary between the Rotliegend and Carboniferous occurs as well and also affects aquifer quality negatively.

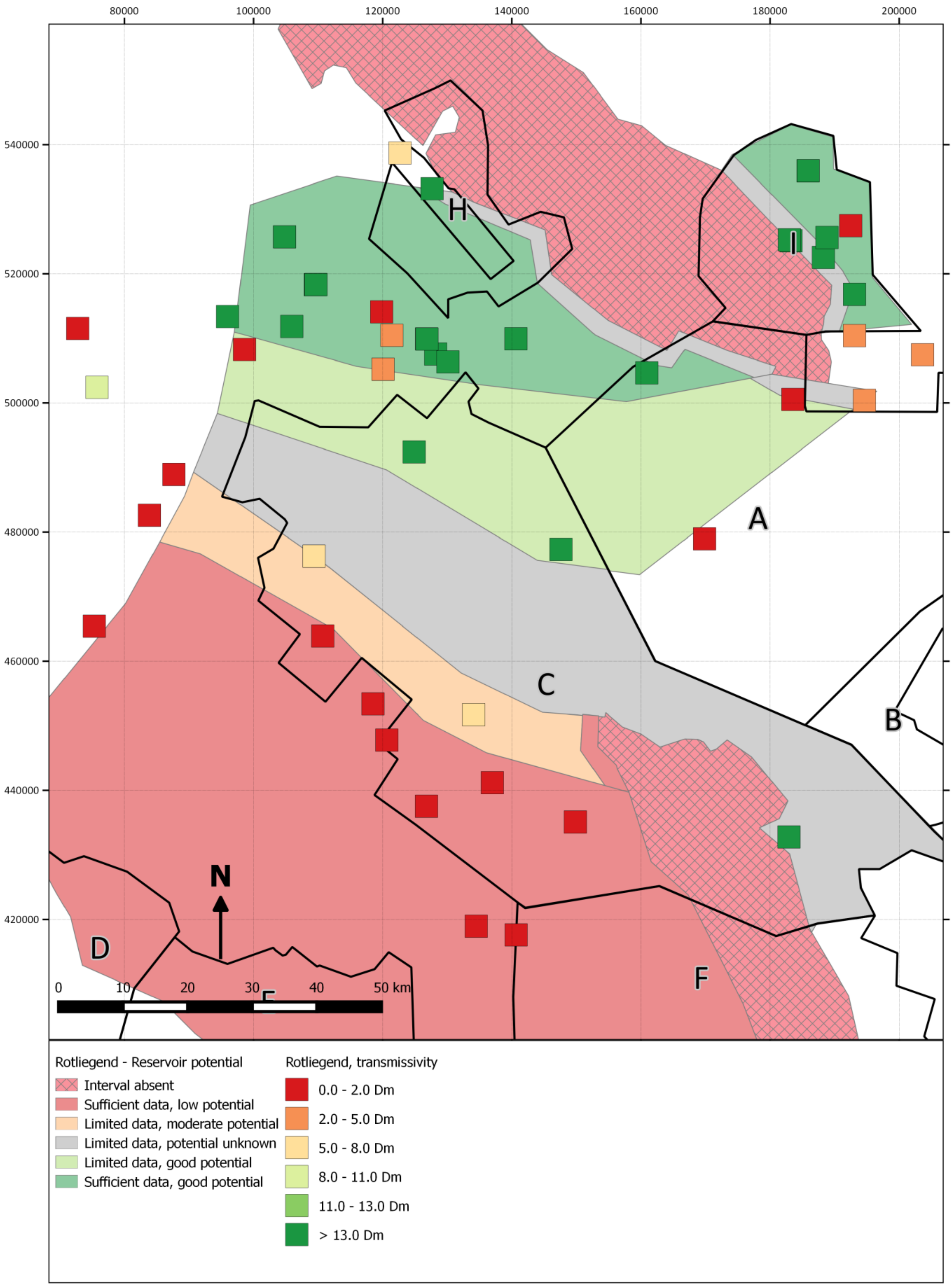


Figure 7 – Aquifer potential of the Rotliegend in area C

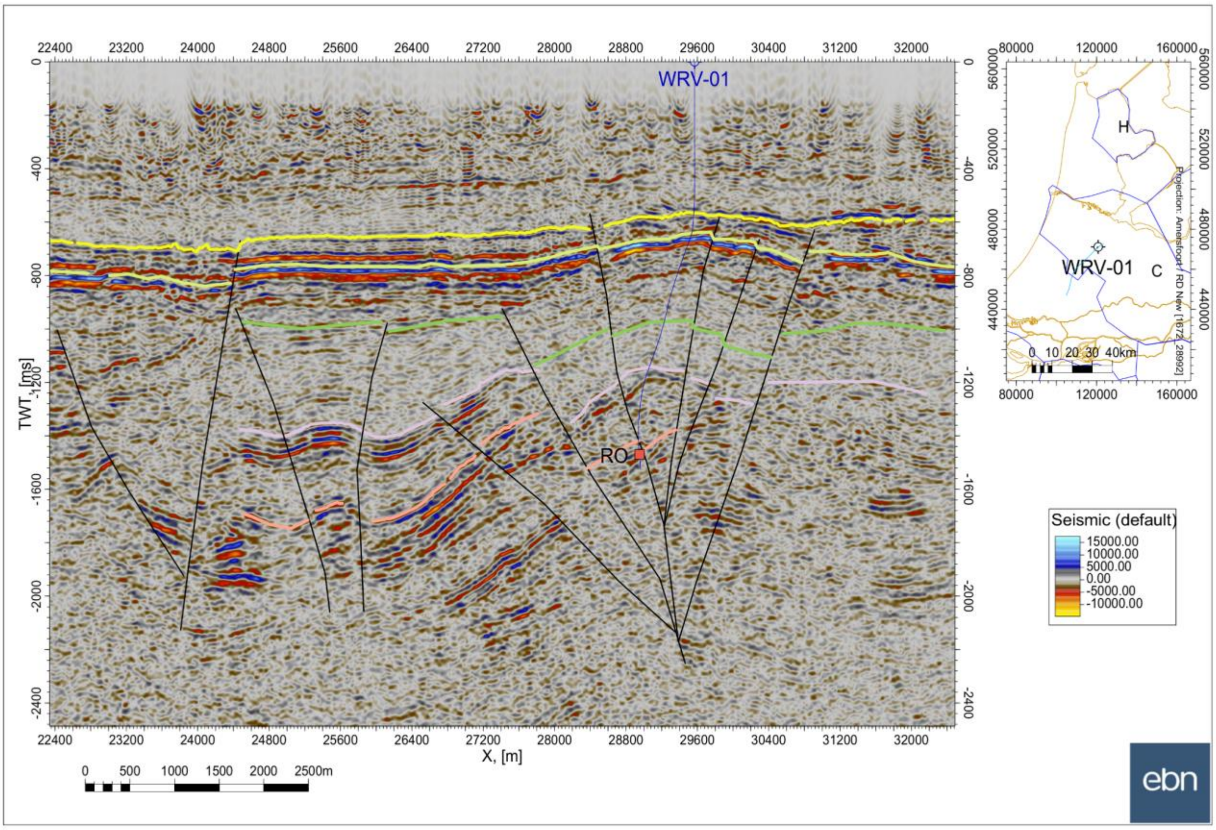


Figure 8 – Interpreted seismic line XYZ with well trajectory of well WRV-01. The well is drilled into a flower structure, supporting the hypothesis that the limited Rotliegend thickness (RO: Top Rotliegend) is due to fault cutout.

2.2.2 Lower Carboniferous (Dinantian) carbonates

The presence of Lower Carboniferous (Dinantian) carbonates has not yet been proven in area C. Their presence is inferred (*Figure 9*) from the fact that the central part of the area was a high from Westphalian (Late Carboniferous) to Cenozoic times. Based on the assumption that highs are generally long-lived, a fault-bounded high with a carbonate build-up on top is inferred, which would have been surrounded by deeper water (Pagnier et al., 2002; Geluk et al., 2007; Van Hulten& Poty, 2008; Boxem et al., 2016). The presence of an Early Carboniferous fault-bounded high and thus carbonate platforms is estimated based on the sucrop pattern at BPU-level; regions where relatively old Westphalian (A or B) subcrops the Base Permian Unconformity are taken to indicate the presence of a Dinantian carbonate build-up; the surrounding basinal deposits are expected to compact more easily, allowing for the preservation of a thicker section of Westphalian (Van Hulten& Poty, 2008). This assumes that Variscan inversion was of secondary importance for the subcrop pattern (e.g., Pagnier et al., 2012), an assumption that can be challenged (e.g., Kombrink, 2008). The outline in *Figure 9* is based on the present-day preservation of the Late Cretaceous Chalk Group, based on the assumption that the underlying Lower Carboniferous carbonate platform prevented inversion here during the Cenozoic, preserving the Chalk.

To test these hypotheses subsurface data is required. The presently available seismic data does not image depths (4–7,5 km) at which the Dinantian is expected and no wells are drilled in this area to these depths.

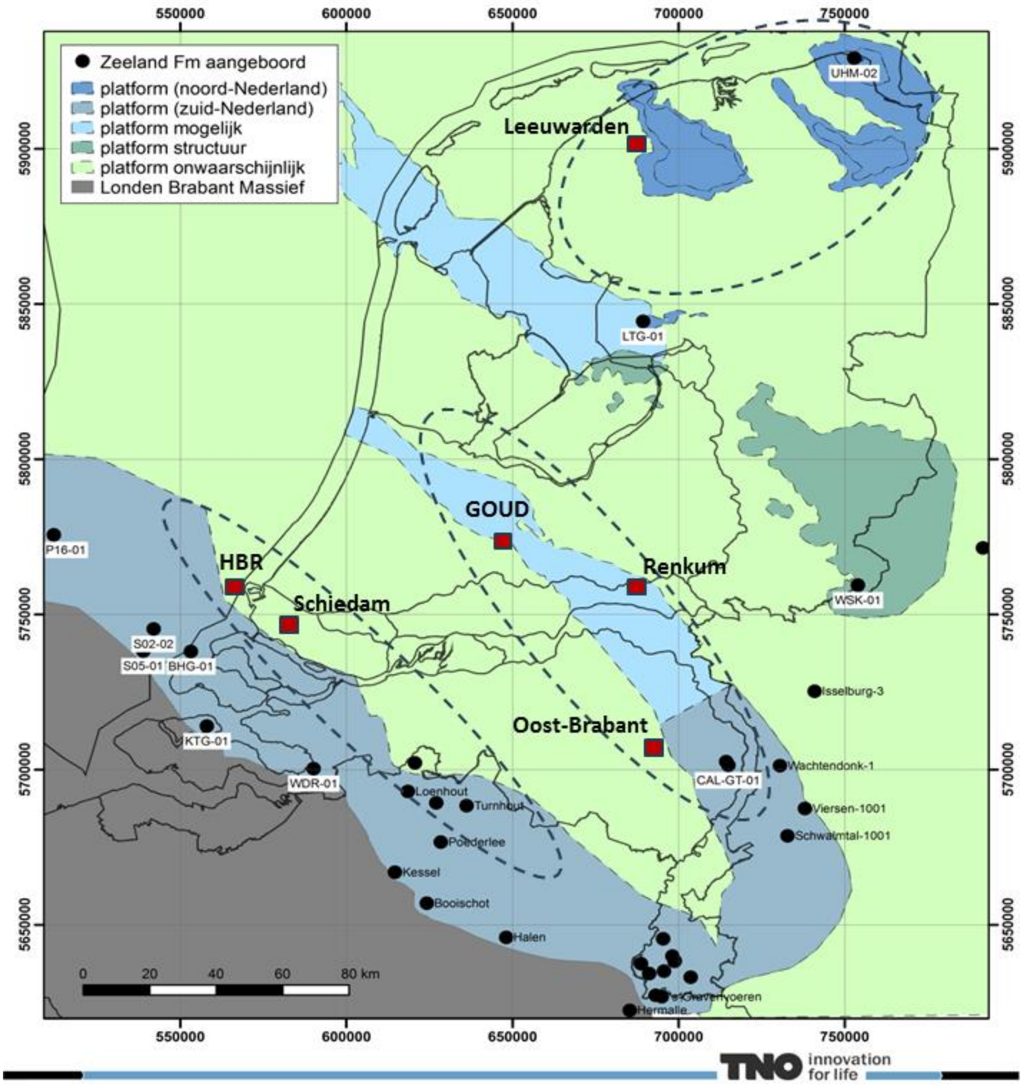


Figure 9 – Facies map of the Dinantian (Early Carboniferous) from Boxem et al. (2016). "Platform mogelijk": platform possible, "Platform structuur": platform structure, "Platform onwaarschijnlijk": platform unlikely, "Zeeland Formatie aangeboord": Zeeland Fm encountered in well. NB: This map may be outdated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

2.3 Secondary targets

Secondary geothermal targets in area C are Zechstein Carbonates, Triassic sandstones, Upper Jurassic / Lower Cretaceous sandstones and Cenozoic sands.

2.3.1 Zechstein Carbonates

Locally, Zechstein carbonates are proven gas reservoirs. It appears that the permeable intervals are either facies related, or result from fracturing, or leaching. Permeable facies include slope and platform facies including collapse breccias. From regional mapping (Geluk, 2007) it may be concluded that the Zechstein -1 and -3 carbonate sequences may have some potential in area C. Large scale leaching may have occurred around the Maasbommel High, below the Kimmerian Unconformity and potentially in the area of Amsterdam below the Kimmerian and Laramide Unconformities.

2.3.2 Triassic Sandstones

Where present Triassic sandstones may provide a geothermal reservoir. However, in the western northern and eastern parts of area C only the Volpriehausen sandstones is present, but rapidly thinning to the north-east. To the south they increase in thickness and there the Röt interval is present in a fringe sandstone facies as well. Similar to the Rotliegend the Triassic reservoirs have been uplifted during inversion and suffer from poor reservoir quality as a result (see also 2.2.1 - Rotliegend Sandstones). As for the Zechstein the Triassic sandstones may have been locally leached below the Kimmerian and Laramide Unconformities, for this sub-play especially the Volpriehausen of the north-western part of area C is of interest. Next to the Maasbommel High well NVG-01 shows good reservoir quality (leached?) sandstones (Nederweert Fm.) in the Lower Buntsandstein interval.

2.3.3 Vlieland Sandstone

Within the larger surroundings of area C the Upper Jurassic / Lower Cretaceous strata, amongst which the Vlieland Sandstone Formation, proves to be a prolific reservoir for both hydrocarbons and geothermal resources. There is a very general rule of thumb stating that a relation exists between the total thickness of the Vlieland Subgroup (KNN) and the presence of a basal sandstone interval. Within area C a Rijnland Group thickness trend is mapped, which may indicate a Vlieland Sandstone reservoir in the NW of area C, but no wells are available in the area to demonstrate the presence or absence of these sandstones. Just north of Area C in well ZWK-01 a reservoir quality section of Vlieland Sandstone was found, this reservoir may extend into the northernmost tip of area C near Volendam. The Schieland Group has been mapped in the West Netherlands Basin on the western boundary of area C, containing sandstone as e.g. in well ARV-01. Also in other locations the Schieland Group sandstones can be of interest, e.g. in well WSP-01 a potential “Wealden” interval was found.

2.3.4 Cenozoic sands

Constraints on the geothermal potential of the Cenozoic below 200 m are few and far between, even though all oil and gas wells drilled through this interval. This results from the fact that data acquisition (logging) in this interval was limited to the bare minimum. Additionally, the well density in area C is very low. The first prerequisite for assessing the geothermal potential or the potential for heat storage/buffering, is a reliable reservoir delineation of the main sand packages such as the Brussels Sand Member. Focus should be on the seismic recognition of these intervals and the identification of intra-Cenozoic truncation surfaces under which the potential reservoir zone may not be present due to erosion. In area C, as it is positioned on the Kijkduin High, a large part of the Middle and Lower North Sea interval has been eroded. Chances of encountering reservoir sands are better at the flanks of the Kijkduin High to the northeast (e.g. ALE-01) and to the southeast in the Nijmegen area.

2.3.5 Other secondary targets

The possible secondary targets Chalk and Westphalian (Upper Carboniferous) are present in area C but matrix porosity and permeability of these potential reservoir units is generally expected to be very low. Only in specific circumstances (areas with severe fracturing) they may have geothermal potential. The Upper Carboniferous may have potential in the western part of the area, in case sand-rich intervals of Westphalian-C age are present, secondary porosity has been generated and maximum burial was limited. Near the city of Utrecht, the Chalk interval has been offset by several large faults, this may have created a zone with increased permeability. In the Nijmegen area the Chalk and Rijnland Gps. are changing in a Greensand facies, which may have sufficient reservoir quality.

3. Seismic survey design

Figure 10 summarizes the main geologic complexities. These are the starting point for defining the goals for the new seismic survey. Additionally, next to the geological objectives (3.1) the new seismic survey design should meet a number of essential technical criteria (3.2).

3.1 Geological objectives of the seismic survey

The geological objective of the seismic survey acquisition is to be able to:

- Constrain the structural architecture of the area.
- Establish presence, location and displacement of faults in relation to stratigraphy.
- Establish presence, and if present, depth, thickness and internal configuration of a Dinantian carbonate build-up.
- Establish presence, depth and thickness of the Rotliegend.
- A qualitative assessment of reservoir quality of Rotliegend and Triassic units based on the maximum burial depth, derived from seismic stacking velocities in the Triassic Main Claystone.
- A better definition of the boundaries between stratigraphic groups and formations.
- Map (angular) unconformities; in particular the Base Permian Unconformity, the Base and Intra-Delfland and Base Cretaceous Unconformities.

3.2 Criteria for design of the seismic survey

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 stratigraphic levels deeper than the Lower Cretaceous, preferably by choosing the line trajectory over / nearby an existing well location.
- Tie to 3D seismic data on both ends of the 2D line.
- Minimalize complications from near-surface geology: push moraines, swamps, 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.

3.3 Survey design

Figure 11 shows the proposed line locations covering area C which do conform to the above listed geological objectives and design criteria. The geological goals for each of the lines is given in *Table 2*. 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 C was estimated at 396 km, of which 132 were considered conditional. The current design amounts to 597 km, 88 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 will be developed to assess how well they meet the design criteria.

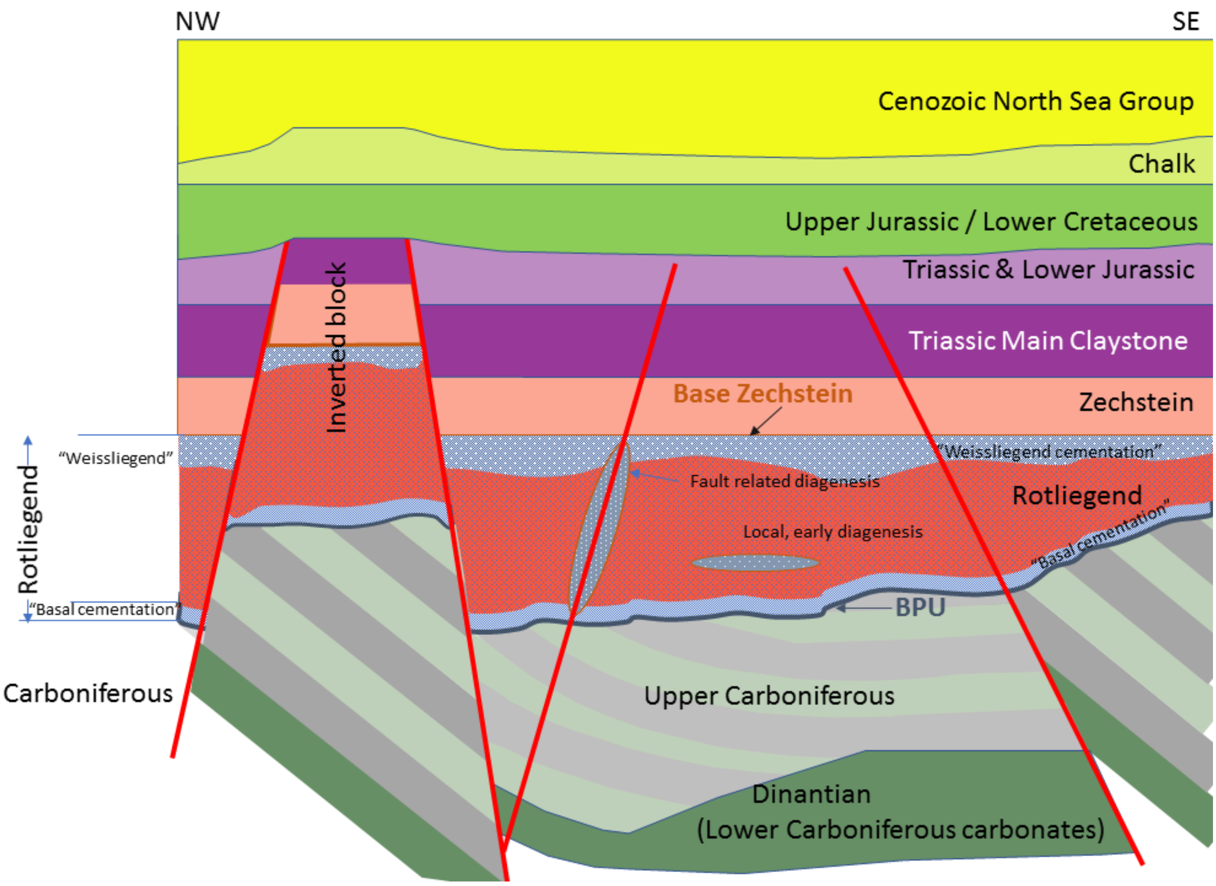


Figure 10 – Cartoon illustrating uncertainties affecting the assessment of the geothermal potential of the Rotliegend: thickness, dia-genesis, and inversion.

Line	Goals
AMS-Oost	Image Rotliegend, Dinantian. De-risk Rotliegend depth, thickness and reservoir quality, Dinantian presence, facies and depth, west of Utrecht, east of Amsterdam and area in between.
BSKP-WRV-ALE	Image Rotliegend Dinantian. De-risk Rotliegend depth, thickness and reservoir quality, Dinantian presence, facies and depth, Amsterdam Southeast, Uithoorn, Almere and area in between. Connection to SCAN area A.
BUM-AME-FLV	Image Rotliegend, Dinantian, De-risk Rotliegend reservoir quality, depth, thickness. Continuity of Dinantian build-up, Focus on area Amersfoort. Connection to SCAN area A.
BUM-RKM-BKH	Image Dinantian, (Rotliegend). De-risk presence, depth and facies of Dinantian. Focus on UDG project RKM, Wageningen, Arnhem. Connection to SCAN area B, Bronkhorst 3D.
EVD-UTR-BLA	Image Rotliegend, Dinantian. De-risk Rotliegend reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on UDG project GOUD (De Uithof), LEAN, area southeast and east of Utrecht, Soest, Hilversum, Blaricum, Huizen, Baarn, Eemnes and areas in between. Connect lines JUT-AME, NAM-DEEP.
GLD-Vallei	Image Rotliegend, Dinantian. De-risk Rotliegend reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on area Barneveld, Wageningen, Veenendaal, Ede, Nijmegen and areas in between. Connect lines BUM-RKM-BKH, RVG-NMG-BKH and JUT-AME. Connection to SCAN area A.
HRL-Oost	Image Rotliegend, Dinantian. De-risk Rotliegend thickness and reservoir quality, Dinantian presence, facies and depth. Focus on Haarlem, Hoofddorp, Westpoort and vicinity.
JUT-AME	Image Rotliegend, Dinantian. Derisk Rotliegend reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on UDG project GOUD (De Uithof), LEAN, area South of Utrecht (Nieuwegein), southeast Utrecht, south Amersoort and areas in between. Connection to SCAN area A.
RVG-NMG-BKH	Image Dinantian, Rotliegend. De-risk continuity of Dinantian across Roer Valley Graben, presence of thin, shallow high-porosity Rotliegend in Nijmegen area. Connection to SCAN area F, B, Bronkhorst 3D.
SPL-AMS-West	Image Rotliegend, de-risk thickness, depth and reservoir quality in the area Schiphol, Amstelveen, Amsterdam, Westpoort and Hoofddorp. Possible extension towards Amsterdam-Noord, Zaandam. Requires access to Schiphol.
BSKP-SPL-HRL (conditional)	*Image Rotliegend, Dinantian. De-risk Rotliegend depth, thickness and reservoir quality, Dinantian presence, facies and depth,. Focus on Alphen a/d Rijn, Schiphol, Hoofddorp, Haarlem, Amsterdam-Westpoort and Zaandam. Connect lines HRL-Oost, SPL-AMS-West, BSKP-WRV-ALE and tie 3D seismic.*
UTR-West (conditional)	*Image Rotliegend, Dinantian. De-risk Rotliegend reservoir quality, depth and thickness, Dinantian presence, facies and depth. Focus on LEAN, area west of Utrecht, Almere, Hilversum, Bussum, Huizen, Eemnes, Blaricum and areas in between.*

Table 2 – Geological goals for the proposed lines

Line	Total Length (km)	Comment
AMS-Oost	60.8	Includes section through IJmeer
BSKP-WRV-ALE	57.8	
BUM-AME-FLV	52.2	
BUM-RKM-BKH	65.0	
EVD-UTR-BLA	58.5	
GLD-Vallei	51.8	
HRL-Oost	19.3	
JUT-AME	54.5	
RVG-NMG-BKH	68.6	
SPL-AMS-West	20.3	Challenging, requires access to Schiphol. Extension AMS not included currently
BSKP-SPL-HRL	*37.5*	***Conditional**, depending on reprocessing of Mobil surveys*
UTR-West	*50.5*	***Conditional**, depending on reprocessing of NAM-DEEP line*
Total length	596.7	

Status of 05/09/2018

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

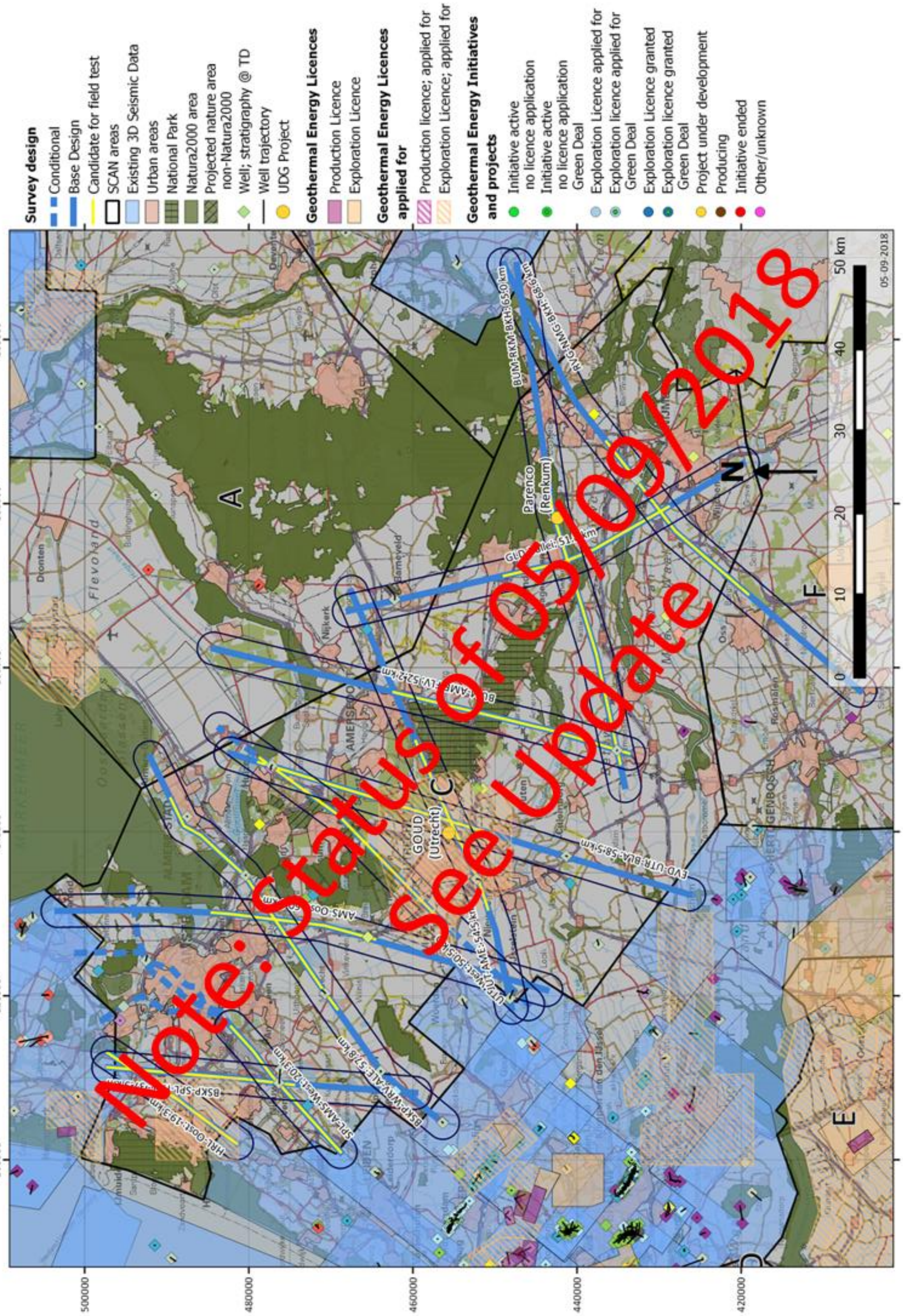


Figure 11 – Seismic survey design for SCAN area C. The outlines show the area where full-fold coverage is required. Note: the actual acquisition of these lines is subject to ranking and budget appropriation. **Please note that this figure displays the status of 05/09/2018, an updated map can be found on page 6 of this report**

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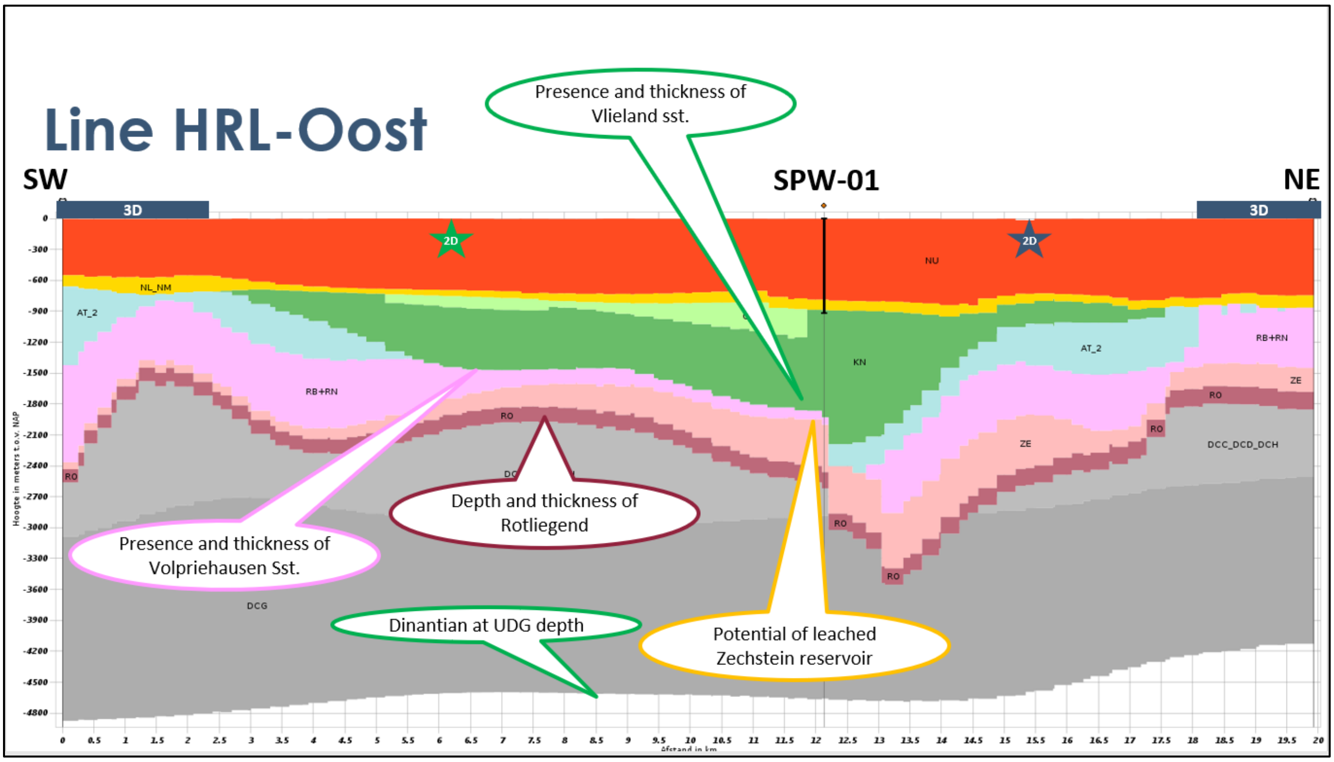
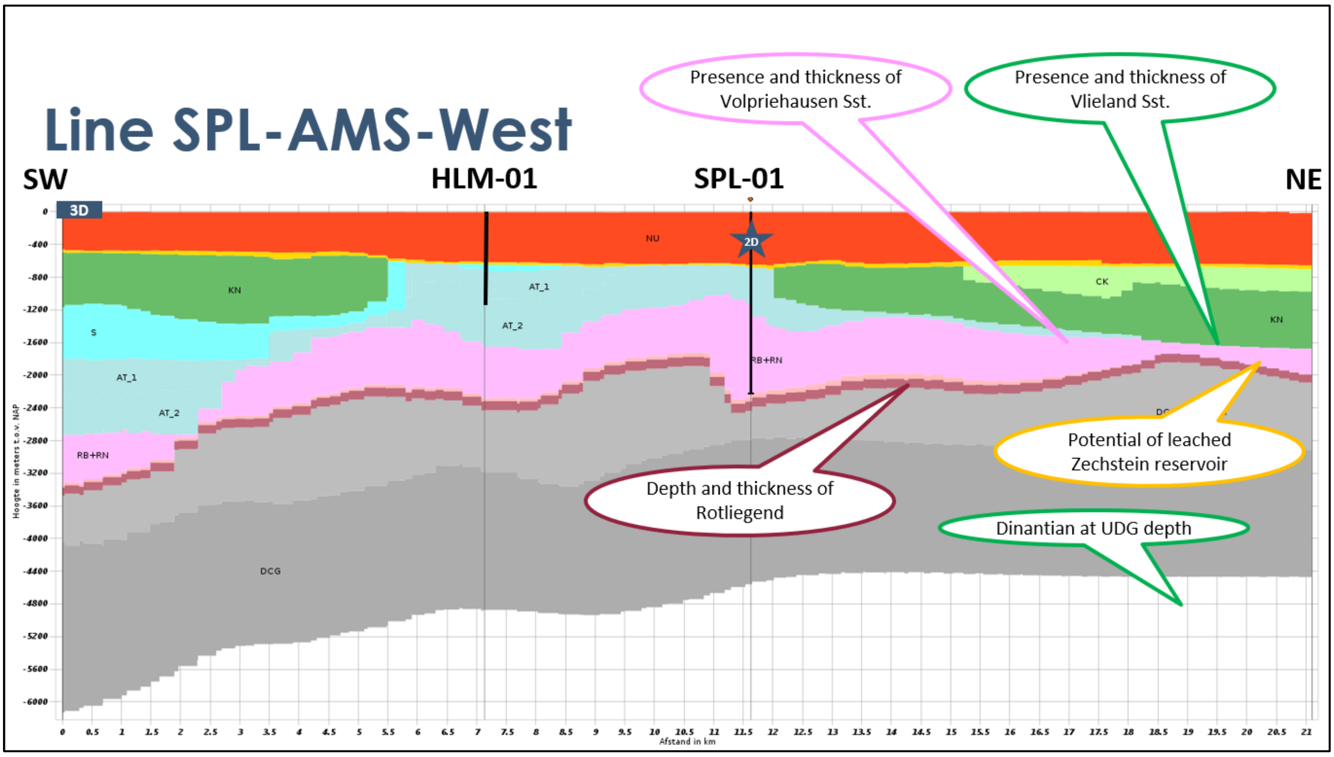
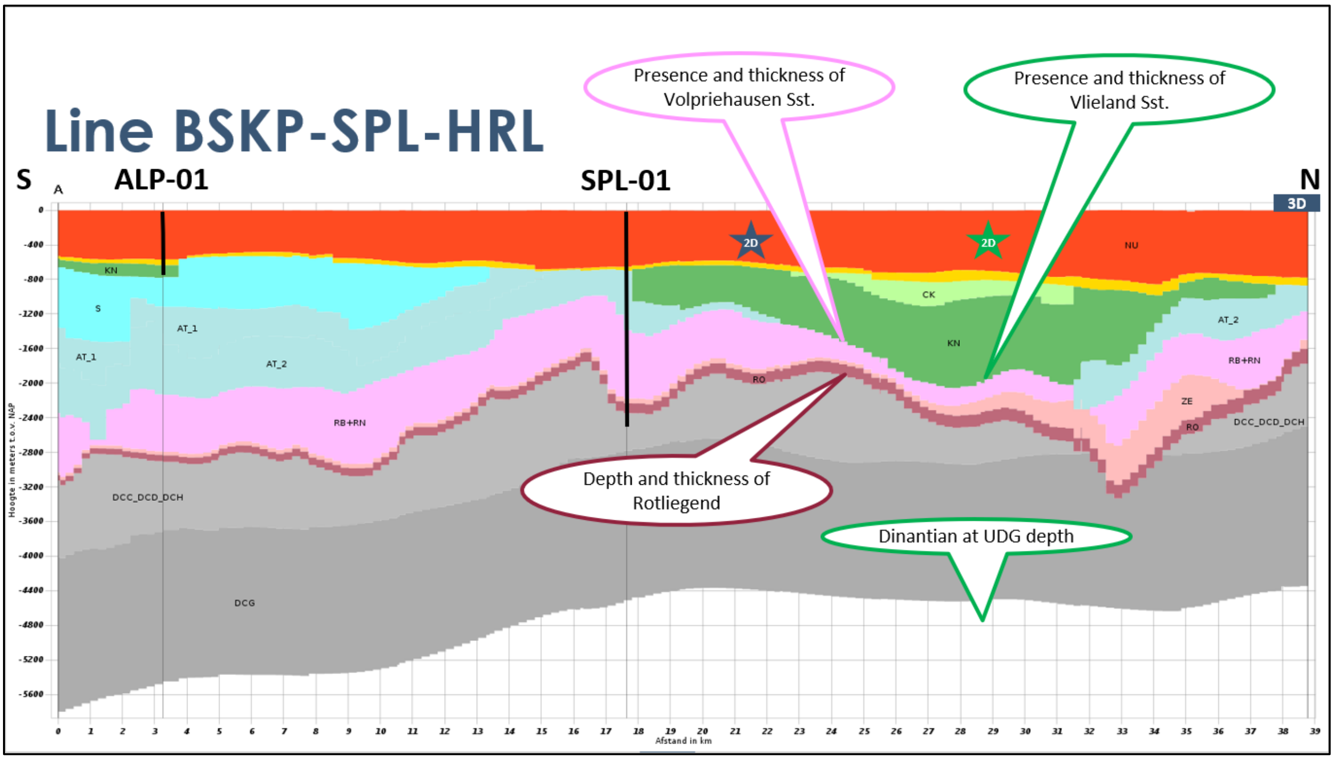
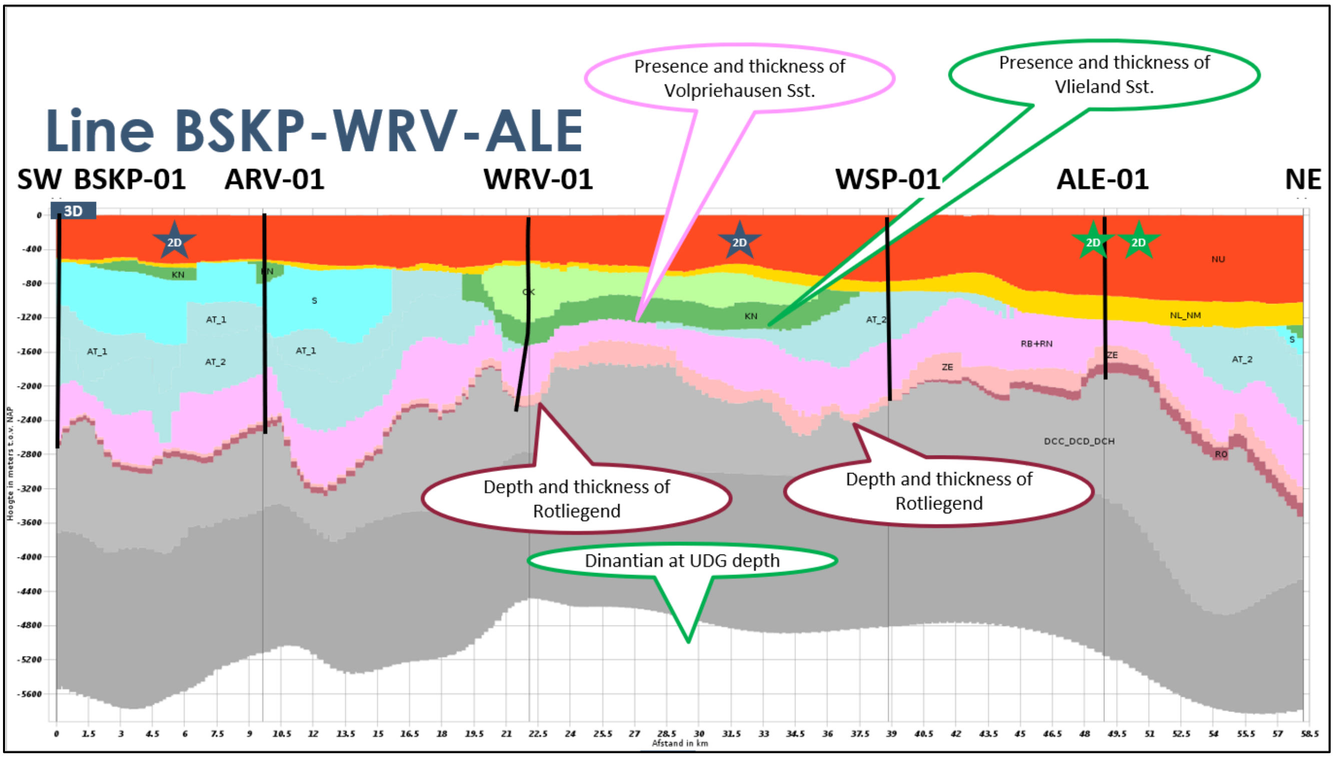
5. Appendices

5.1 Depth sections from DGMdiep v4.0 in Dinoloket over proposed seismic sections area C






Line BSKP-SPL-HRL
S
ALP-01
SPL-01
N
3D
Presence and thickness of Volpriehausen Sst.
Presence and thickness of Vlieland Sst.
Depth and thickness of Rotliegend
Dinantian at UDG depth
Afstand in km
Hoogte in meters t.o.v. NAP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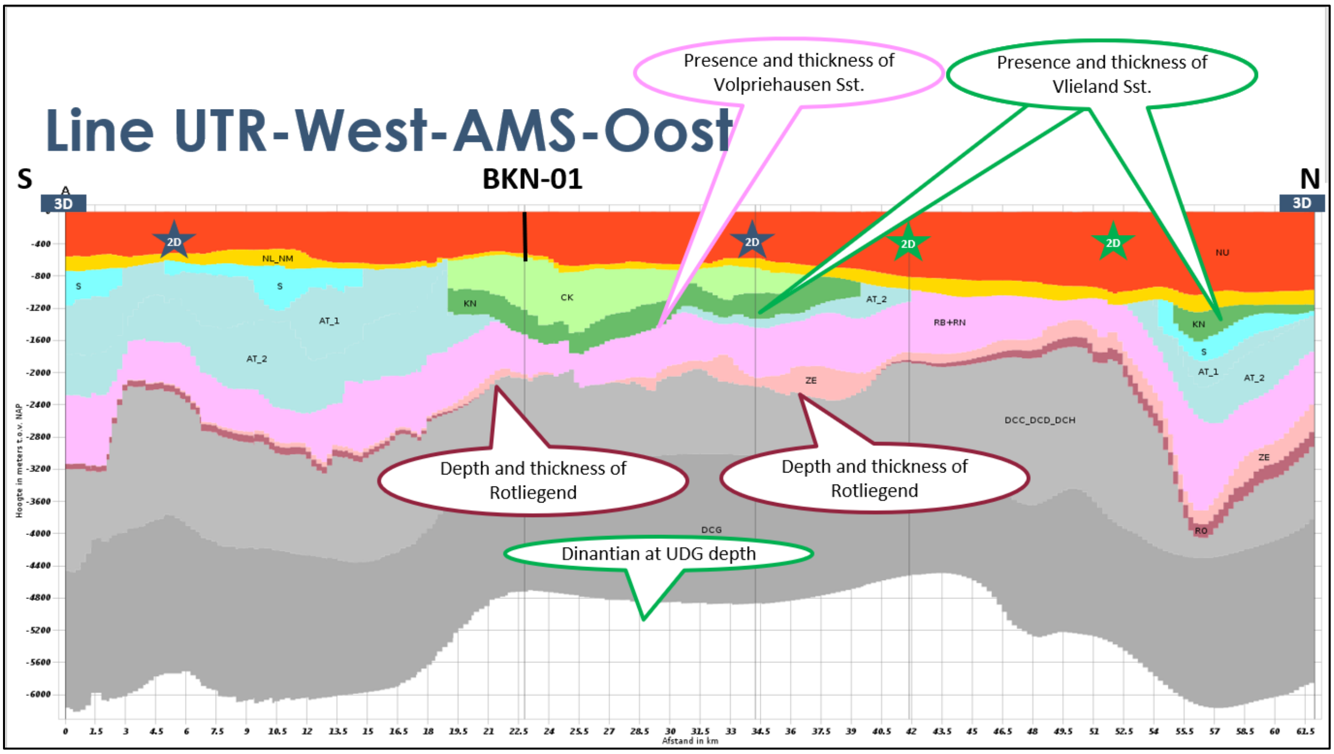
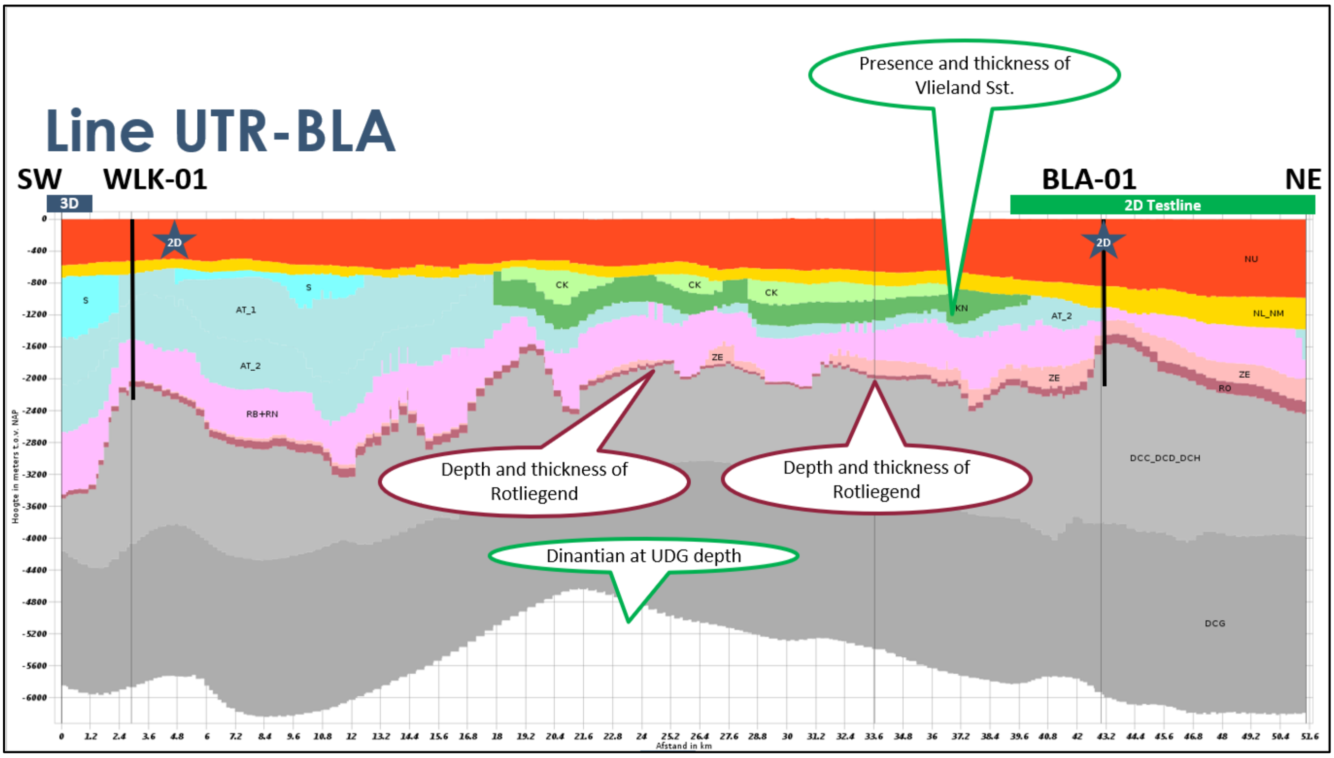
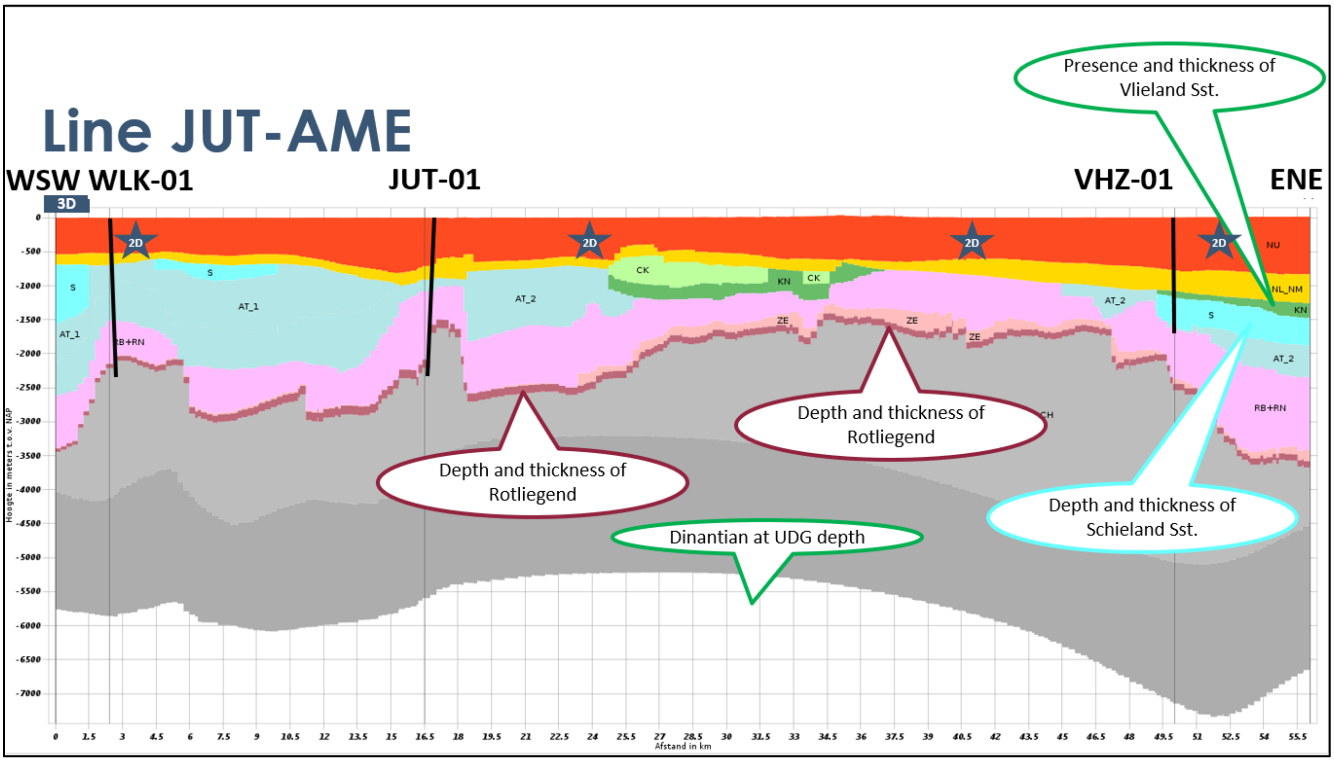
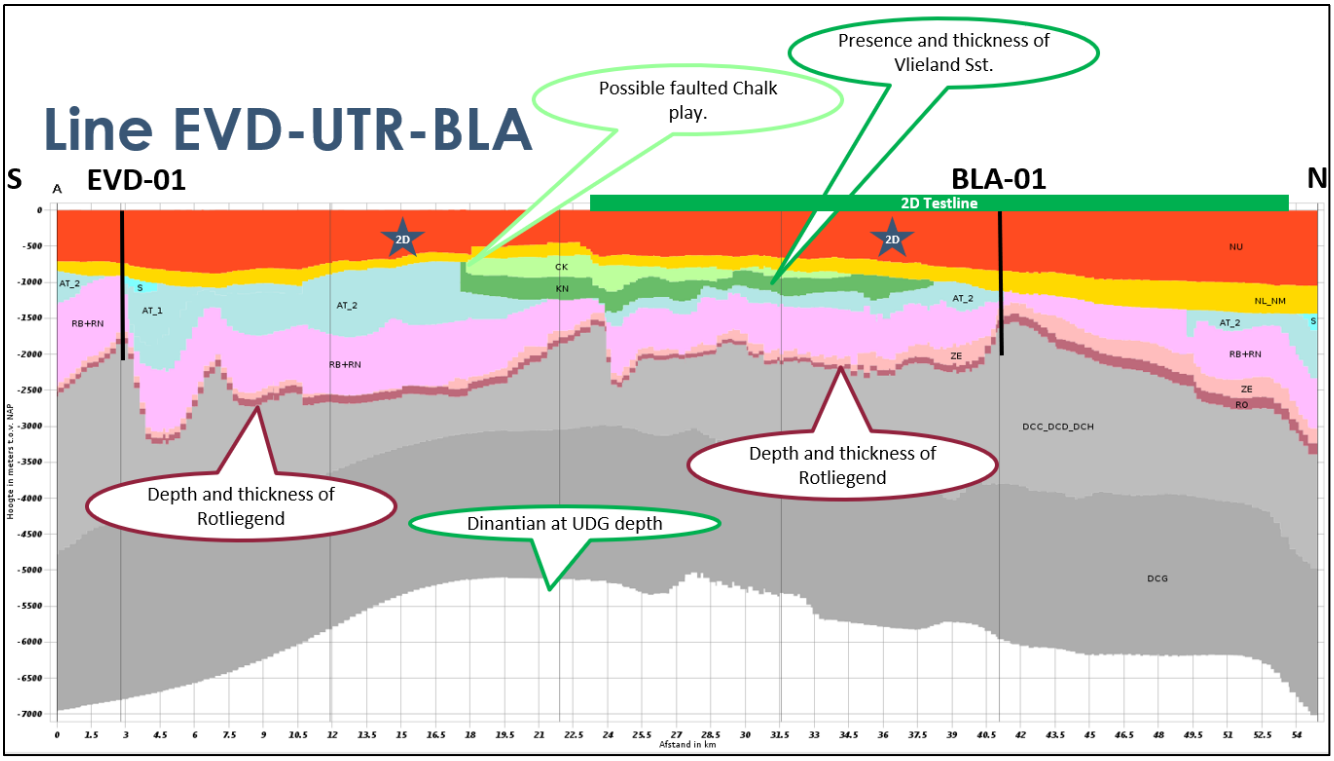
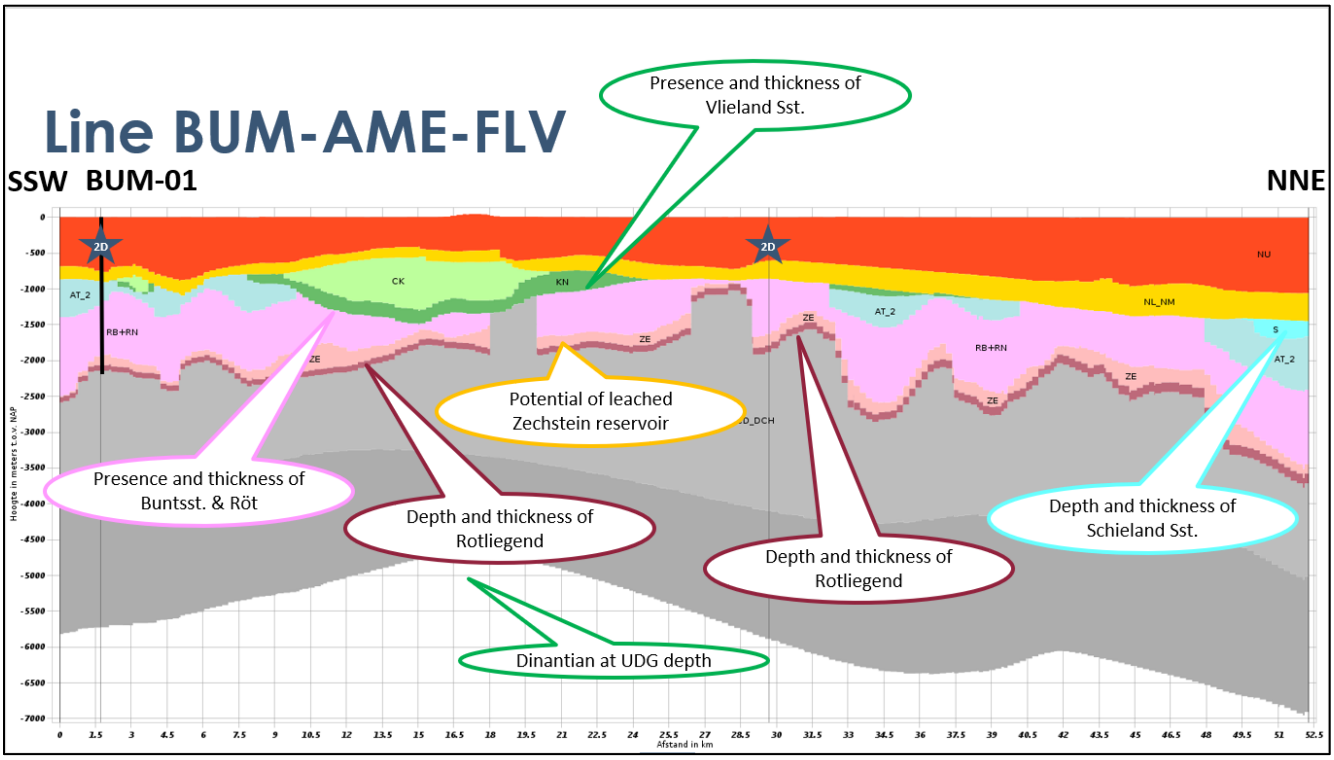
SW
BSKP-01
ARV-01
WRV-01
WSP-01
ALE-01
NE
3D
Presence and thickness of Volpriehausen Sst.
Presence and thickness of Vlieland Sst.
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
Dinantian at UDG depth
Afstand in km
Hoogte in meters t.o.v. NAP

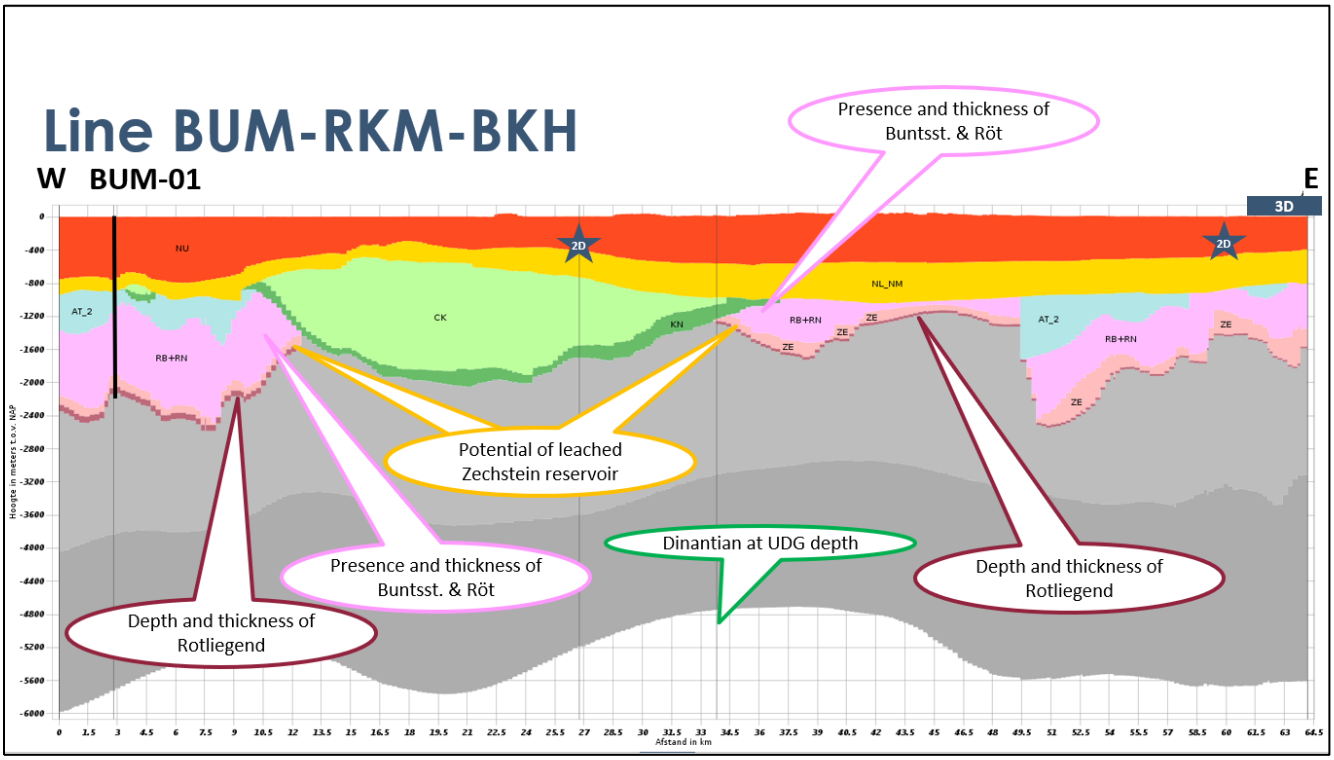

Line UTR-West-AMS-Oost
S
BKN-01
N
3D
3D
Presence and thickness of Volpriehausen Sst.
Presence and thickness of Vlieland Sst.
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
Dinantian at UDG depth
NL_NM
S
AT_1
AT_2
KN
CK
AT_2
RB+RN
ZE
DCC_DCD_DCH
DCG
NU
RO
Afstand in km

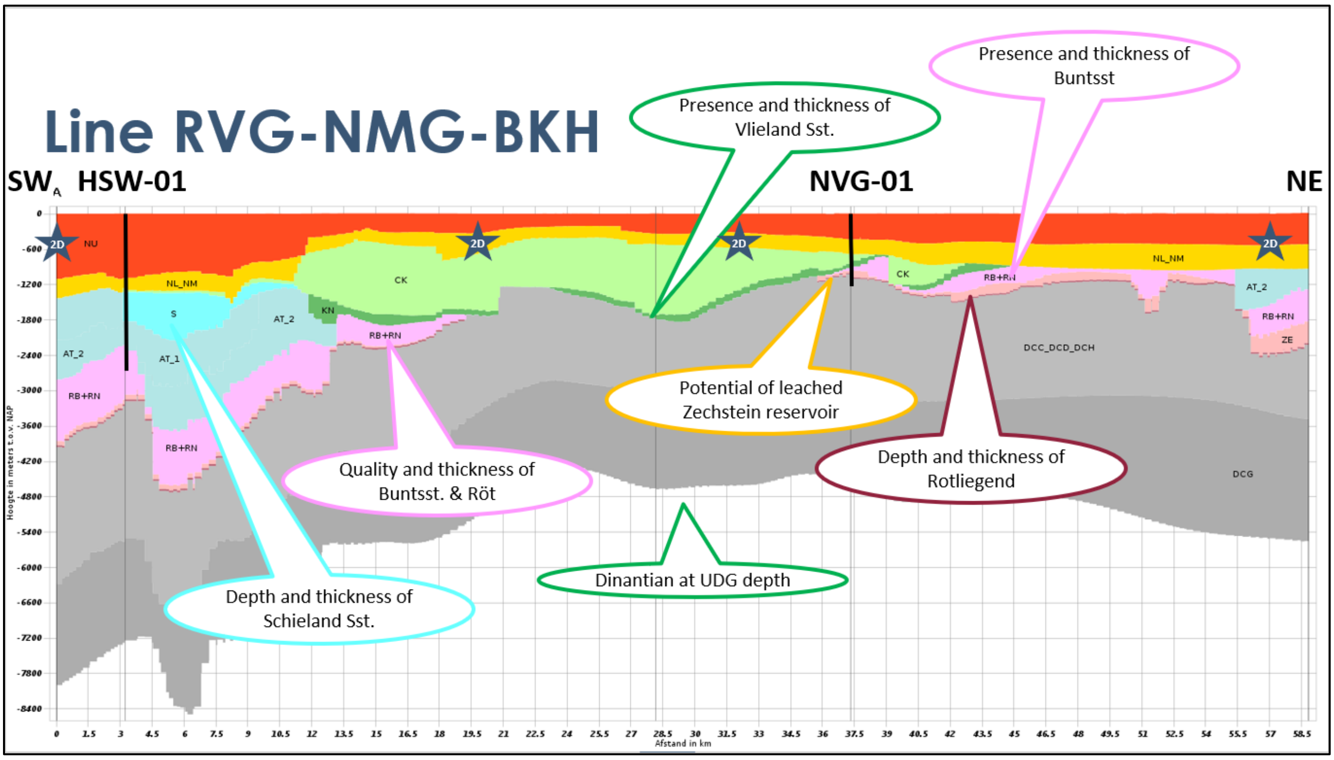

Line UTR-BLA
SW
WLK-01
BLA-01
NE
3D
2D Testline
Presence and thickness of Vlieland Sst.
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
Dinantian at UDG depth
S
AT_1
AT_2
RB+RN
CK
KN
ZE
NU
NL_NM
RO
DCC_DCD_DCH
DCG
Afstand in km

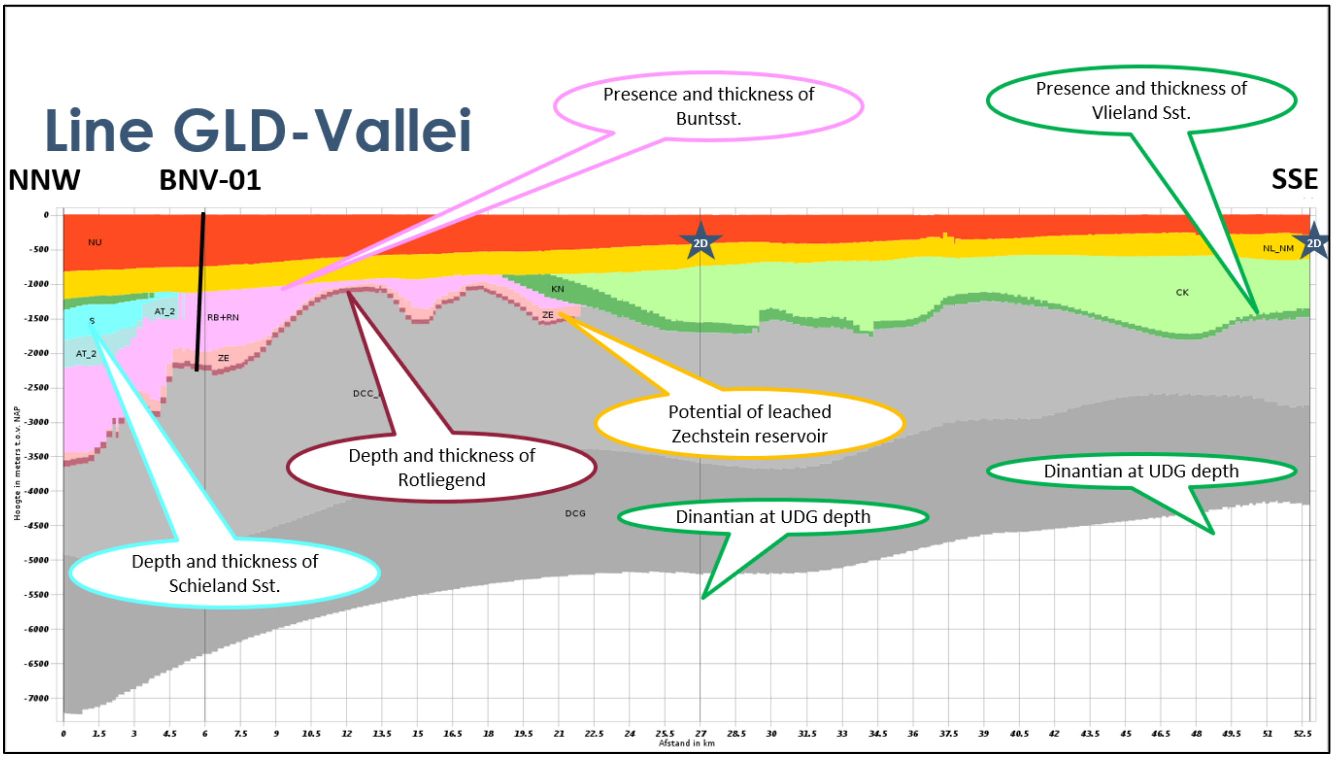

Line JUT-AME
WSW WLK-01
JUT-01
VHZ-01
ENE
3D
2D
Presence and thickness of Vlieland Sst.
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
Dinantian at UDG depth
Depth and thickness of Schieland Sst.
NU
NL_NM
KN
CK
S
AT_1
AT_2
RB+RN
ZE
Afstand in km


Line EVD-UTR-BLA
S
EVD-01
BLA-01
N
2D Testline
2D
Possible faulted Chalk play.
Presence and thickness of Vlieland Sst.
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
Dinantian at UDG depth
NU
NL_NM
CK
KN
AT_1
AT_2
RB+RN
ZE
RO
DCC_DCD_DCH
DCG
Afstand in km

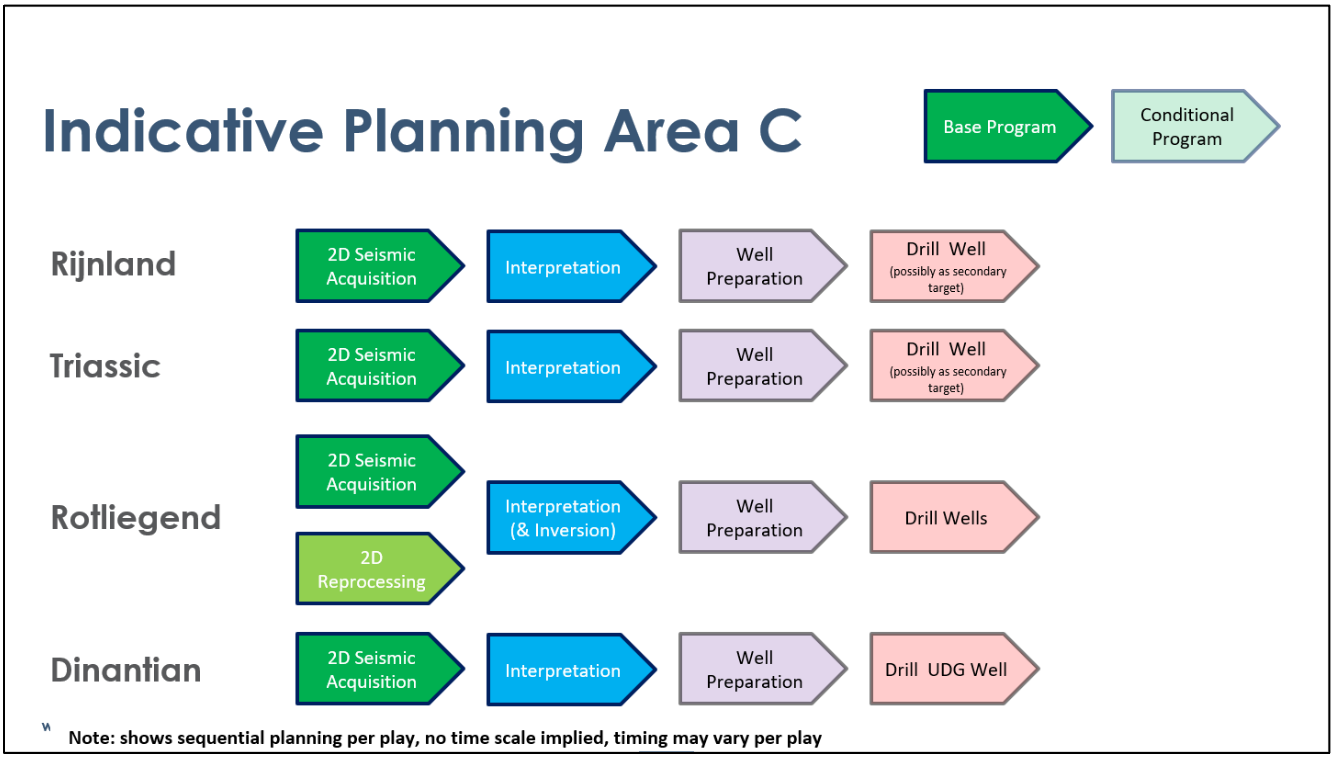

Line BUM-AME-FLV
SSW BUM-01
NNE
Presence and thickness of Vlieland Sst.
Potential of leached Zechstein reservoir
Presence and thickness of Buntsst. & Röt
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
Depth and thickness of Schieland Sst.
Dinantian at UDG depth
2D
2D
NU
NL_NM
CK
KN
AT_2
RB+RN
ZE
Hoogte in meters t.o.v. NAP
Afstand in km


Line BUM-RKM-BKH
W BUM-01
E
3D
Presence and thickness of Buntsst. & Röt
Potential of leached Zechstein reservoir
Dinantian at UDG depth
Presence and thickness of Buntsst. & Röt
Depth and thickness of Rotliegend
Depth and thickness of Rotliegend
2D
2D
NU
NL_NM
CK
KN
AT_2
RB+RN
ZE
Hoogte in meters t.o.v. NAP
Afstand in km


Line RVG-NMG-BKH
SW
HSW-01
NVG-01
NE
Presence and thickness of Buntsst
Presence and thickness of Vlieland Sst.
Potential of leached Zechstein reservoir
Depth and thickness of Rotliegend
Quality and thickness of Buntsst. & Röt
Dinantian at UDG depth
Depth and thickness of Schieland Sst.
Afstand in km


Line GLD-Vallei
NNW
BNV-01
SSE
Presence and thickness of Buntsst.
Presence and thickness of Vlieland Sst.
Potential of leached Zechstein reservoir
Depth and thickness of Rotliegend
Dinantian at UDG depth
Dinantian at UDG depth
Depth and thickness of Schieland Sst.
Afstand in km

5.2 Indicative planning area C



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