# Resource Evaluation of the Dutch Offshore Rotliegend Play

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## Abstract

To revert the declining Dutch gas production and limit the impact of the dismantling of offshore production platforms on exploration activities, it is crucial that recent findings about the Dutch hydrocarbon plays are easily made accessible to all oil and gas operators so that they can continue exploring in the Dutch offshore in a safe and efficient way. EBN aims to create an online Atlas in which all recent knowledge per play will be summarized and compiled into maps and publicly made available. This project is part of that initiative, focusing on the Dutch offshore Rotliegend play. It combines public data into regional common risk segment (CRS) and combined common risk segment (CCRS) maps to quantify the geological risks of the Rotliegend play and subplays on a spatial scale. Additionally, the volumetric potential of the Rotliegend play was assessed using a creaming curve and a statistical missing fields analysis. The study shows that the Rotliegend play still may hold high potential for future discoveries in various regions. The region with the highest probability of success (POS) is the southern K and L blocks. The main limiting play element in terms of risk is reservoir while south of the Zechstein salt pinch-out line the inhibiting play elements are top seal and trap. Resources are primarily present in the traditional Slochteren play fairway. Outside this fairway two recent discoveries have been made, the Cygnus and Ruby fields, confirming that prospectivity in the Rotliegend is not limited to this region. The gas volumes found until today and expected in the future are sensitive to geological, technological and political developments. The regional overview provided by this research can be used as a guideline in future regional risk evaluations of the Rotliegend play.

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# 1. Introduction

With the Groningen gas field closing and the production from small fields rapidly declining, the Dutch gas supply does not meet the local demand for gas in the Netherlands (Gasterra, 2019). Recent developments related to household heating, such as replacing gas boilers with electric boilers, reduce the demand for gas in the Netherlands, but not as fast as the Dutch gas supply decreases. As a result, the use of domestic Dutch gas is swiftly being replaced by imported Russian and Norwegian gas, which is not in the best interest of the Netherlands neither from an environmental nor an economical point of view. For the Netherlands to cover its own demand for gas, the decline in production must be reverted.

The recent gas field (re)discoveries of Cygnus (2014) and Ruby (2017) have shown that the Rotliegend still may hold a high exploration potential despite being the most mature and productive hydrocarbon play of the Netherlands. Interest in the Rotliegend began with the discovery of the Groningen gas field in the 1950's and has resulted in a large amount of literature with different scopes, locations and quality. However, no spatial overview of this data exists. To revert the decline in domestic gas production, there is a need to create scientific material at a regional scale which provides to the oil and gas operators with an overview of the geological risks in this Dutch hydrocarbon play. This research is part of an initiative by EBN to create such overviews for all Dutch hydrocarbon plays and to make the data publicly available via an online Atlas. This research therefore focusses on combining public data on a regional level for the Dutch offshore and thereby gain information about the remaining resource potential of the Rotliegend play. The Dutch offshore was divided into three play segments based on different regional geology: The Feather Edge area, the Northern Offshore and the Eastern Offshore (figure 1.1).

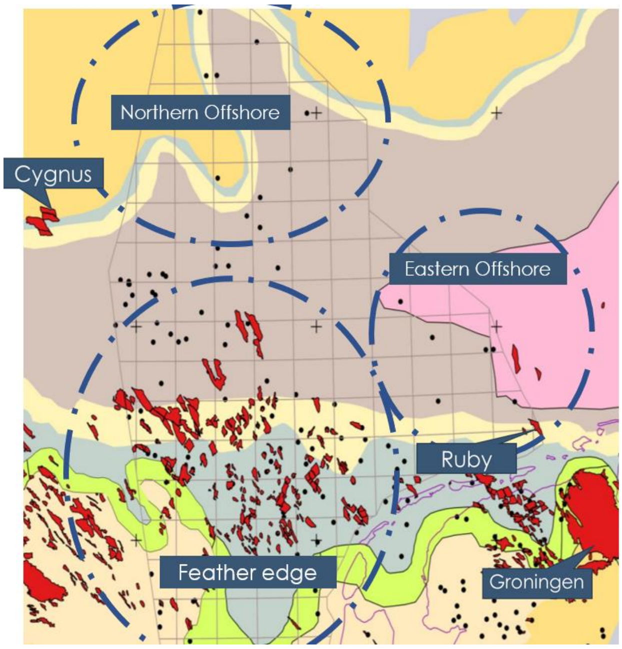



*Figure 1.1. The Rotliegend play in the Dutch offshore. Rotliegend fields are shown in red. The area is divided into three regions, the Feather Edge, the Eastern Offshore and the Northern Offshore. Modified from Jongerius (2018).*

To gain insight into the remaining resource potential five questions are assessed.

1. In which regions lies the highest potential for new discoveries?
2. What is the critical factor in derisking the play?
3. What is the relationship between the different geological features and the spread and quantity of the resources and reserves?
4. What yet-to-find volume estimation applies best to the play and how is the yet-to-find volume influenced?
5. What can we learn from the history of the play for the future?

To identify the areas with the highest potential for new discoveries and to gain insight in what is needed for further derisking, the risk must be assessed on a spatial scale. A hydrocarbon play can be separated into different regional play elements such as reservoir, seal and charge. By subdividing each play element into areas with low, medium or high risk, corresponding to the colours green, yellow and red, common risk segments (CRS) maps can be made (figure 1.2). By multiplying individual CRS maps of the play, the total risk of the entire play can be assessed in a combined common risk segment (CCRS) map. This map is a powerful tool in assessing the spatial quantitative risks and possibilities in a play.

With respect to the volumes, an analysis of the existing volumetric data is made. To gain insight into future scenarios and the attractiveness of the Rotliegend play, a study is conducted by creating and evaluating a creaming curve of the play. The relationship between the geology and the current resources and reserves is investigated with the CCRS map and the spread of resources and reserves. The method used to investigate the influence on the future volumes, the yet-to-find (YTF) volume, is discussed in the methods chapter. The outcome of the analysis is discussed in the discussion chapter.

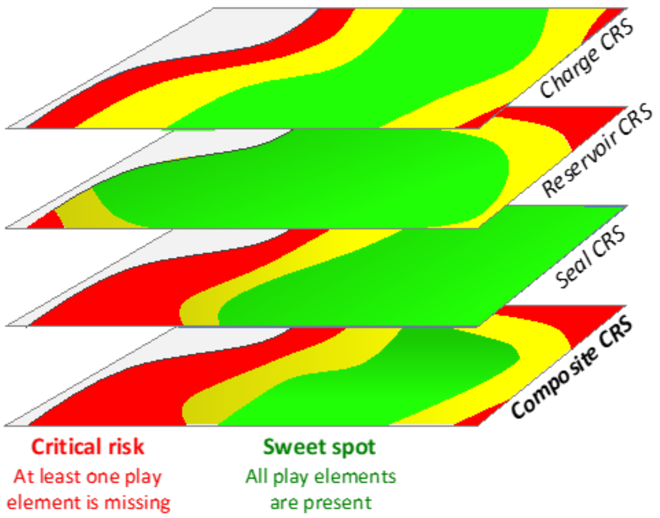



*Fig 1.2: Play element specific maps are multiplied for the composite common risk segment map which shows the risk of the entire play. From de Jager, 2020*

## 2. Geological Background

Sediments of the Rotliegend group, a Permian stratigraphic group, are present in the subsurface of a large part of northwestern Europe such as the UK, the Netherlands, Germany, Norway, Denmark and Poland (Kombrink & Patruno, 2020). These sediments were deposited in the east-west trending Northern and Southern Permian Basin, which were separated by the Ringkøbing-Fyn High and the Mid North Sea High. These basins came into existence when rifting started in the late Carboniferous, caused by the destabilization of the Variscan orogeny (Doornenbal et al., 2010). The Variscan orogeny was a result of the assembly of Pangea, which was fully realized at the end of the Permian (de Jager, 2007). During the late Carboniferous, a combination of wrench-tectonics, intrusive and extrusive magmatism and thermal uplift caused a deep widespread truncation and erosion of older sediments over Europe, known as the Base Permian Unconformity. Thermal subsidence set in after cooling of the region, creating the Southern and Northern Permian basins (Doornenbal et al, 2010)).

The Southern Permian Basin can be subdivided into three smaller sub-basins: the Anglo-Dutch basin, the North German basin and the Polish Through. Each sub-basin has its own history and its own distribution of the Rotliegend sediments which are related to spatial variations in their tectonic and structural evolution. Deposition of the Lower Rotliegend is related to early rift and includes mainly volcanic sediments, while the two Upper Rotliegend units consists of thick syn-rift sedimentary deposits. The Netherlands is located in the Anglo-Dutch basin. This basin primarily consists of Upper Rotliegend sediments, sourced from the Mid North Sea High in the north and the Variscan mountains to the south (Gast et al., 2010). In the northern offshore Lower Rotliegend volcanic and volcanoclastic sediments have been locally preserved.

Due to continued rifting, the Southern and Northern Permian Basin which had already subsided below sea level, got flooded in the Late Permian. The Kupferschiefer, the oldest formation of the Zechstein group, is proof of a catastrophic flooding of the basins (Doornenbal et al., 2010). The Zechstein group which was deposited in the Southern Permian Basin in the late Permian consists of thick salt deposits, which form a perfect seal over the Rotliegend sandstones.

After the Permian, several important tectonic events occurred which are relevant for the Rotliegend play. Many of the main structural elements in the Netherlands originate from the Late Jurassic to Early Cretaceous and formed under an extensional to transtensional tectonic regime (de Jager, 2007). During this time, the Texel-IJsselmeer High, Winterton High and locally the Cleaver Bank High got heavily eroded and lost strata down to the Carboniferous (Pharaoh et al., 2010). During the Alpine orogeny, several Jurassic-Cretaceous basins got inverted such as the West Netherlands Basin, Central Graben and Broad Fourteens basin (figure 2.1).

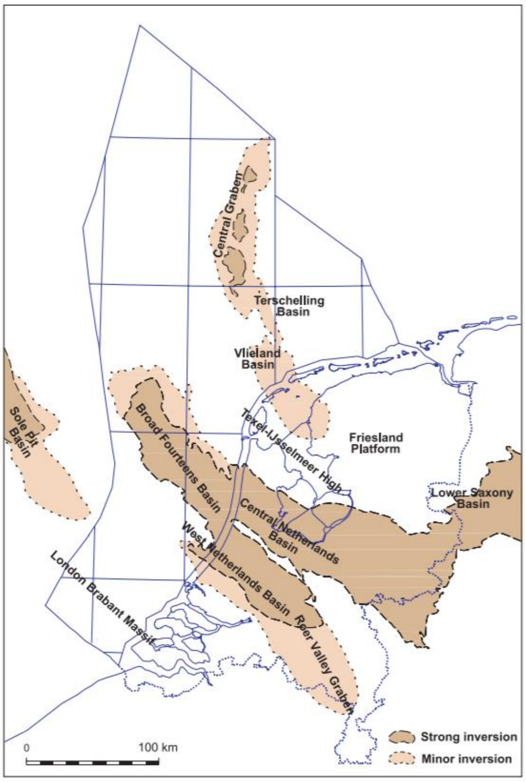



*Figure 2.1. Inverted basins of the Netherlands. The Broad Fourteens Basin has been strongly inverted during the Alpine orogeny. From de Jager, 2007.*

## 2.1 Rotliegend charge in the Dutch offshore

The Rotliegend play is a gas play, whose gas is primarily sourced and charged from the Westphalian coals (Figure 2.2, de Jager & Geluk, 2007). The Westphalian coals are not present on the London-Brabant Massif and in the far Dutch northern offshore. In the northern offshore, organic rich shales and coals from older Carboniferous formations may contribute to the charge of the Rotliegend. Here, coals in the Yoredale, Epen and Scremerstons formation are expected to be present and mature, all of Namurian and Visean age (Arfai & Lutz, 2017; Ter Borgh, 2019a; Hanemaaijer, 2020; Houben et al., 2020).

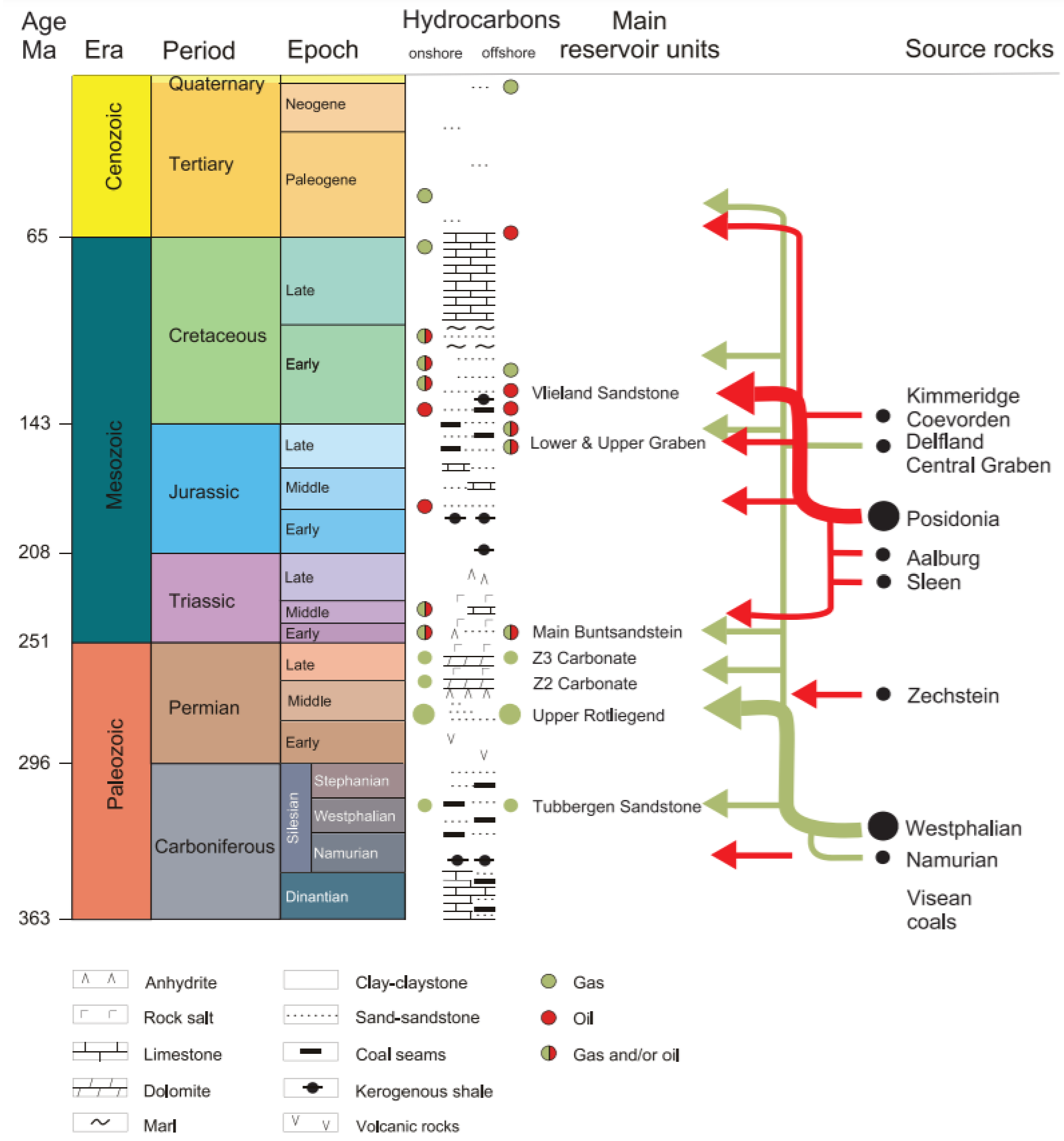



*Figure 2.2. An overview of the petroleum systems in the Netherlands. The Rotliegend is charged by Carboniferous source rocks of the Westphalian, Namurian and Visean (Dinantian) time stages. From de Jager & Geluk (2007).*

## 2.2 Rotliegend reservoir in the Dutch offshore

The oldest reservoir interval of the Dutch Rotliegend group can be found in the Lower Rotliegend in the Dutch northern offshore and eastern onshore, the Basal Rotliegend Clastics member. This member formed in a fluvial setting with extensive volcanism related to the early rifting stages of the Southern Permian Basin (TNO-GDN,2021). Deposited in these west-north-west-trending rift basins, the Basal Rotliegend clastic member contrasts to the Upper Rotliegend, which follows a west-east configuration (Gast et al., 2010). Bruin et al. (2015) provides a detailed well analysis of the distribution of the Basal Rotliegend Clastics member in the northern Dutch offshore. Gas fields in the Lower Rotliegend have been found in Germany (A6/B4 field), but no economic discoveries have been made in this reservoir interval in the Dutch offshore yet.

In the Netherlands, the Slochteren formation and Silverpit formation make up the Upper Rotliegend group. Sediments of the Slochteren formation form the main Rotliegend play reservoirs with deposits ranging from alluvial fan to playa margin environments. Reservoir thickness decreases towards the middle of the basin where the Slochteren members interfingers with finer clastics and evaporites from the Silverpit members. This sedimentary succession in which Silverpit members are succeeded by Slochteren members and in reverse, is caused by alternating wet and dry periods. The cyclic manner of sedimentary succession is primarily depending on the base-level lake-level fluctuations and relates to the 20, 100 and 400 ka frequencies of the astronomically forced climate cycles of Milanković (Gast et al., 2010). The three main members of the Slochteren formation are the Upper Slochteren, the Lower Slochteren and the Basal Rotliegend Sandstones which form the main reservoirs in the Dutch Rotliegend Play (figure 2.3).

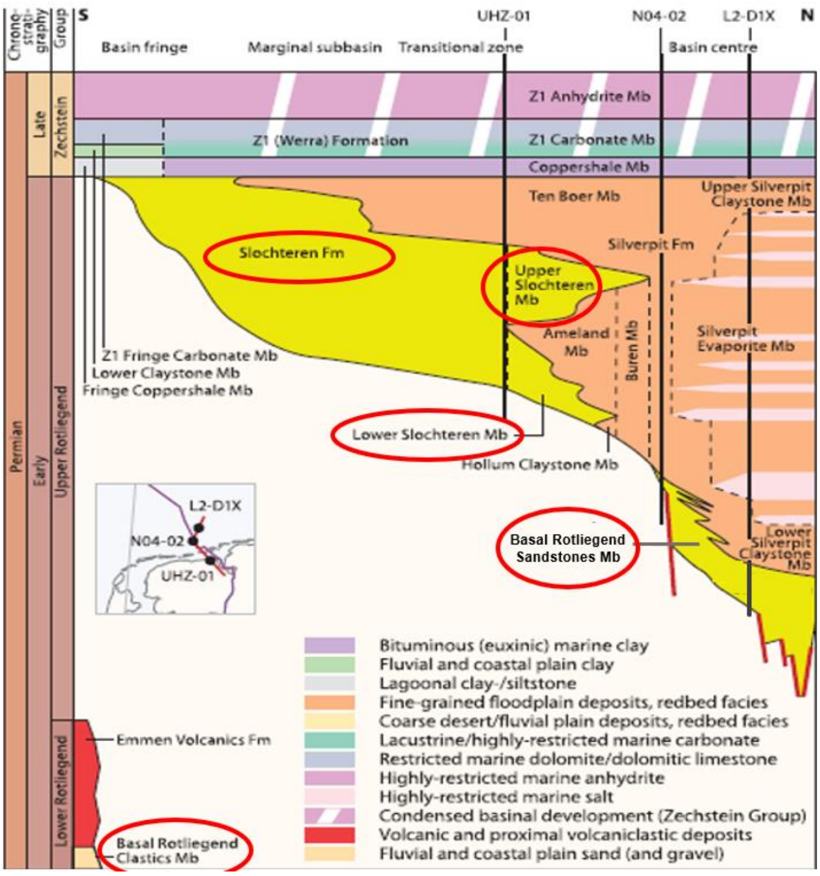



*Figure 2.3. Schematic cross-section of the Rotliegend group in the eastern Dutch offshore with the main reservoir layers and seals. Reservoir are circled in red. Modified from Doornenbal et al., 2020.*

The Basal Rotliegend Sandstones member is present in the eastern Dutch offshore. This member is also known as the Findorf sandstones, Ruby sandstones or Havel sandstones (Corocan et al., 2014). Recently, the member gained more attention by the discovery of the Ruby field, one of the largest Dutch gas finds in the last 25 years (Burgess et al, 2018). The member consists of fluvial, alluvial and aeolian sandstones. Presence and thickness of the member depends on the underlying formations, which are of Carboniferous age or older. Prior to the deposition of the Basal Rotliegend Sandstones member in the Permian, these formations had formed topography. Harder lithologies such as sandstones formed cuestas in areas with softer lithologies such as shales (Mijnlieff & Geluk, 2011). Initially, the Basal Rotliegend Sandstones member did not get deposited on the high cuestas, but in the low-lying areas on the softer lithologies. Due to continued deposition of the Rotliegend sediments, paleotopography became increasingly less visible, leading to thin deposits on top of the harder cuesta forming lithologies. The cuesta model is visualized in figure 2.4.

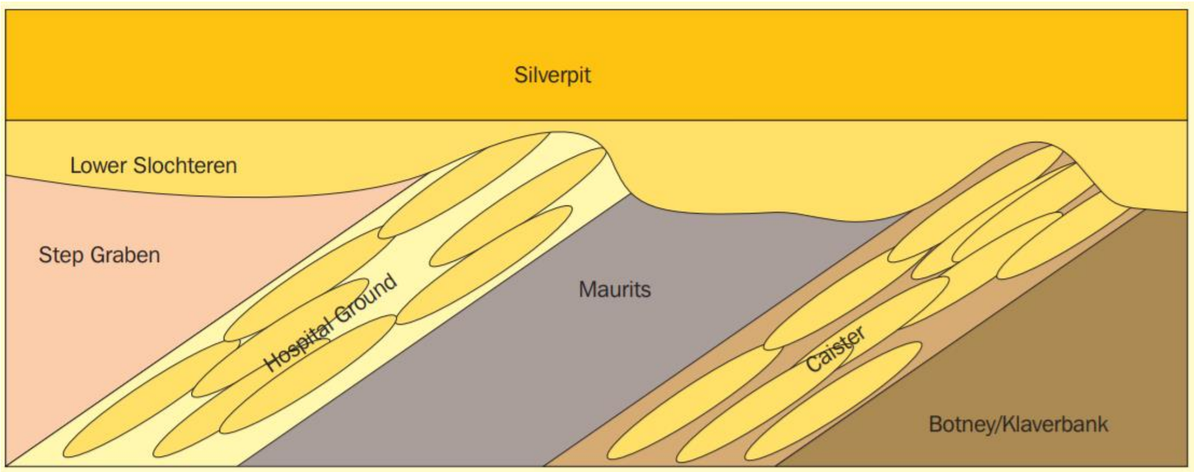



*Figure 2.4. Cuesta model in which the subcropping formations determine the topography and the thickness of the overlying deposits. Caister and Hospital Ground formation have harder lithologies than the Step Graben, Maurits and Klaverbank formations, leading to thinner Lower Slochteren deposits in this figure. Both the thickness of the Lower Slochteren member and the Basal Rotliegend Sandstones member are influenced by this process. Figure from Geluk & Mijnlieff, 2001.*

The Lower Slochteren member is a younger version of the Basal Rotliegend Sandstones member with the same paleotopographic controls, deposited more to the west. Unlike the Basal Rotliegend Sandstones, the Lower Slochteren member is present in a large part of the Dutch offshore. Sediments of the Lower Slochteren member are sourced from the Variscan mountains in south and the south-east. Additionally, the Lower Slochteren member is the only Rotliegend reservoir with a known northern sediment source, which was confirmed by the discovery of the Cygnus field in 2014 (Catto et al., 2017). The Lower Slochteren consists of a mix of fluvial, alluvial and aeolian sandstones with more lacustrine deposits towards the middle of the basin.

The Upper Slochteren member, where present, is separated from the Lower Slochteren member by the Ameland member of the Silverpit formation (figure 2.3). Deposition of the Upper Slochteren member is most likely not significantly controlled by paleotopography and consist of mixed fluvial and aeolian sediments missing the coarser alluvial sediments which are present in the other older members.

## 2.3 Rotliegend seals in the Dutch offshore

Two types of seals in the Rotliegend play prevent leakage of hydrocarbons towards the surface: seals within the Rotliegend group and seals outside the Rotliegend group. As mentioned in the former section about reservoirs in the Upper Rotliegend group, the group consists of two formations: The Slochteren formation and the Silverpit formation (figure 2.3). The Silverpit formation consists of shales and evaporites which acts as a seal for the interfingering reservoirs in the Slochteren formation and the subcropping Westphalian Play (Jager & Geluk, 2007).

The Ameland member of the Silverpit formation interfingers with the Lower and Upper Slochteren member (figure 2.3). When present with sufficient thickness it could prevent gas migration from the Lower to the Upper Slochteren member. Due to the stratigraphic location the member cannot form a seal for the Upper Slochteren member or the Slochteren formation.

Locally, the Ten Boer member (of the Silverpit formation) separates the Upper Slochteren member or the Slochteren formation conformably from the Coppershale member of the Zechstein Werra Formation (TNO-GSN, 2021). The member forms a seal or can be part of a seal for all Rotliegend reservoirs.

Yet the most efficient seal system of the Rotliegend play is the overlaying Zechstein Group. Consisting of alternating evaporites, carbonates and claystones deposited in shallow marine environments the group has a strong cyclic sedimentary succession which can reach over 1200 meters in thickness (TNO-GSN, 2021). These cycles represent progressive evaporation: marine sediments at the base succeeded by increasingly higher salinity sediments at the top (Peryt et al., 2010). Due to basin infill of the Zechstein group, the Southern Permian Basin became increasingly shallow with each cycle. In younger cycles, the group therefore loses its marine sediment to become more continental. Shallowing of the basin also effects the southern limit of the Zechstein deposits, which gradually moves northwards. Towards the southern edge of the Southern Permian Basin, Zechstein evaporites and carbonates gradually get replaced by Zechstein siliciclastic deposits (TNO-GSN, 2021).

Where neither Zechstein seal nor Silverpit seal are present or are thin, basal Triassic claystones can be an effective top-seal (seen in K15-FK and K15-FC fields) (Jager & Geluk, 2007). The Main Claystone Formation of the Lower Buntsandstein Subgroup overlies the Zechstein group and consists of sealing anhydritic claystones.

# 3. Common risk segment mapping

## 3.1 Methods

### 3.1.1 Principles of Play Based Exploration

Play Based Exploration (PBE) is a method used in hydrocarbon exploration to mature resources in a step wise manner from the regional play scale to the more detailed prospect scale (figure 3.1). The method requires the availability of data at the various spatial levels. At a basin scale, the most important plays of the area will be selected. These plays are then further investigated in the play focus, where the regions with the best geological characteristics for hydrocarbon accumulations can be identified. This is done by risk segment mapping, which will be discussed in the next section. Here, already identified prospects and leads can systematically be ranked based on criteria such as their risked volume or value of information. The prospects with the highest (economic) potential can then be further analysed in more detail in the prospect focus. The final step of the prospect focus is drilling the most attractive prospects. The information which is obtained by drilling the new well can be used to update the play maps, which will in turn may influence the ranking of the remaining prospects.

To combine the PBE process into one project, Player, an Arc-GIS extension made by GIS-PAX, was used to create risk maps for the Rotliegend play. Player functions as a spatial database for all play and prospect related data, but also allows the creation of new data and analysis.

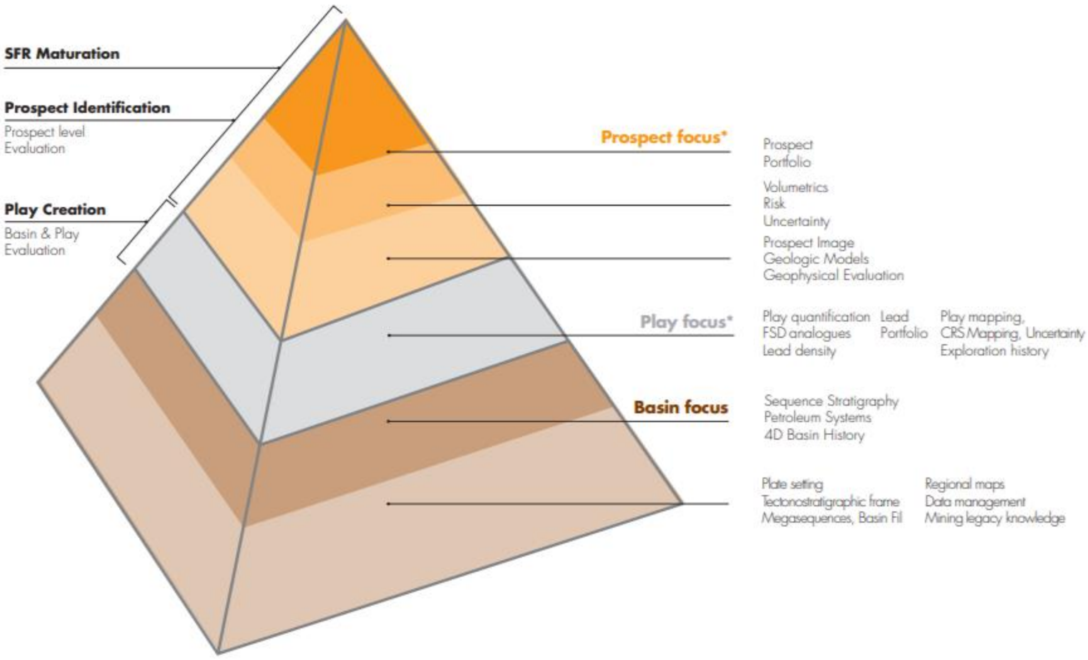



*Fig 3.1. PBE workflow with the different spatial levels and deliverables. The workflow goes from bottom to top. Play focus is the level assessed in this research. From Play Based Exploration Guide, Shell.*

### 3.1.2 Play focus and risk assessment

An important step in the PBE workflow in play focus is creating composite common risk segment (CCRS) maps for a quantitative risk evaluation of the play. As described in the introduction, a play can be subdivided into several regional play elements, here including: reservoir presence, reservoir effectiveness, top seal presence, charge and trap. Each play elements can then be subdivided into regions which have a common risk. Common risk areas are based on the regional understanding of the basin geology. A map in which these areas of common risks are displayed is a CRS map. By multiplying these CRS maps, a CCRS map is created which provides a summary of the risks in the entire play.

Risk can be translated into probability of success (POS):

$$Probability\ of\ success = 100 - risk$$

Each CRS map may consist of a multitude of common risk areas with different POSses, which each represents a different geological feature and/or a different data quality. Borders between these polygons represent geological changes or are related to change in data quality and density. When systematically translating geological characteristics and data quality into a POS, using a split risking approach allows quantitative analysis. Additionally, it provides an overview of the de-risking methods and enables prospect dependencies. Analysing the prospect dependencies is outside the scope of this thesis. In split risking, the risking of a play segment is divided into two components: a play POS and a repeatability POS:

$$Total\ POS = Play\ POS\ \times Repeatability\ POS$$

The play POS is play related (hence its name) and valid for the whole play. For example, a similar geological feature is deposited somewhere else in the play is expected to have the same chance of success of encountering a play element and will therefore share the same POS. The play POS of a specific polygon is also determined by the drilling history inside this polygon. When a play element is demonstrated to be present in a well, the chance that it is present somewhere in the polygon is 100% because it has been proven to be present at least one location inside that polygon.

The repeatability POS of the polygon is determined from geology-dependent parameters inside that polygon. Knowledge of and confidence in some geological elements is strongly affected by data quality and availability (no seismic data vs 2D/3D seismic data, vintage vs reprocessed data, well log data availability etc.). If the play POS is lower relative to the repeatability POS, drilling a well will have more influence on raising the total POS than updating the data which would increase the repeatability POS. However, drilling a well will not influence the geology or the imaging quality. Therefore, the repeatability POS will not change. The repeatability POS can only be altered by improving the imaging quality, which in turn can change the understanding of the geology.

The Rotliegend is a mature play: the play POS is often a 100% due to the large number of wells. The total POS is therefore mostly influenced by the repeatability POS. Determining the repeatability POS can be complicated as it is influenced by many parameters. Imaging quality has a low influence on the repeatability POS when a deposit inside a basin is one kilometer-thick and laterally homogeneous at a regional scale: reservoir will always be present and is easy to identify independent on the imaging quality. However, when the reservoir is only locally deposited in small, discontinuous and sparse structures (for example channels or fans), the imaging quality becomes more important in the estimation of the repeatability POS. The repeatability POS was determined using a similar figure as figure 3.2 as a guideline. Ideally, the total POS of a polygon should be similar to that of a prospect located in that polygon. The prospects element specific POS can therefore be used as a guideline for CRS mapping.

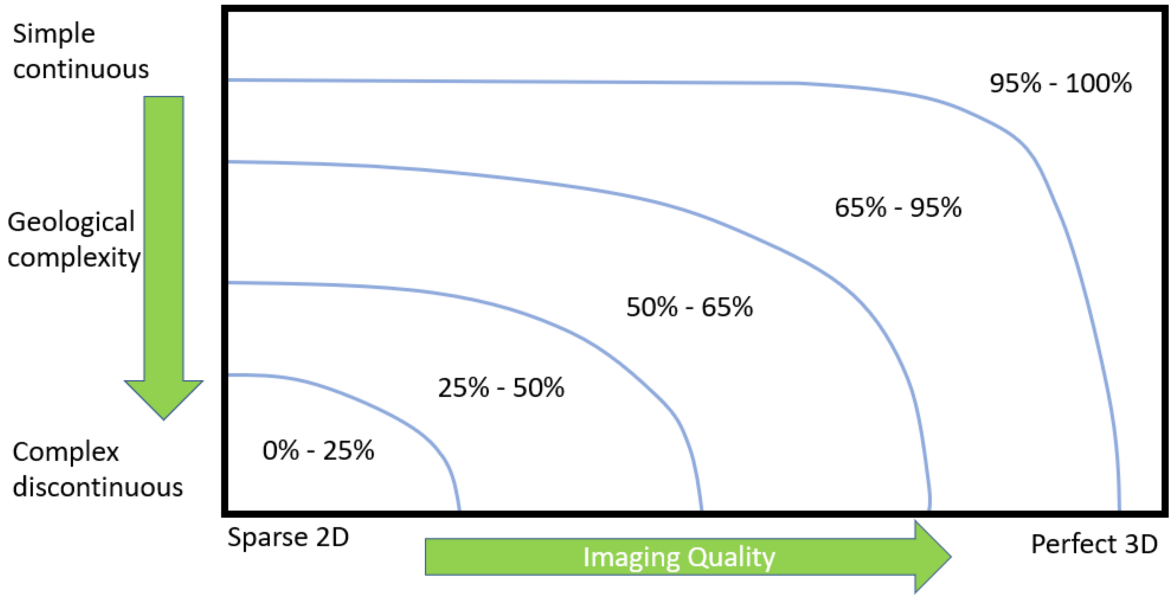



*Fig 3.2: The repeatability POS depends on the imaging quality and the geology inside the polygon. When the repeatability POS plots low in the diagram, improving the imaging de-risks the polygon. When the repeatability POS plots near the top of the diagram, improving the imaging quality has much less impact on the POS.*

## 3.2 Results

In this chapter the results of a quantitative spatial analysis of the geological risks in the Rotliegend play are presented. In this research, the Rotliegend play has been separated into three subplays: the Basal Rotliegend Sandstones subplay, the Lower Slochteren subplay and the Upper Slochteren subplay (which includes the undefined Slochteren as well). For each subplay, CRS maps have been created per play element to assess the geological risks of the subplay. CRS maps were created for the following play elements: reservoir presence, reservoir effectiveness, top seal presence and charge. Additionally, a CRS map for the regional trap was made for the Upper Slochteren subplay since trap form a regional risk in this subplay. The maps provide a POS per common risk polygon per play element which are then multiplied to create a CCRS maps. This chapter is arranged per play element, finishing with the CCRS maps for each subplay and the Rotliegend play. A detailed synthesis of these maps can be found in appendix 1.

### 3.2.1 Reservoir Presence

For each subplay a reservoir presence CRS map was made. The reservoir presence CRS map of the Basal Rotliegend sandstones (figure 3.5) is based the reservoir depositional facies map from ONE-Dyas (figure 3.3), presented at the EBN Exploration Day in 2018. The reservoir presence CRS maps of the Lower and Upper Slochteren subplays (figure 3.6,3.7) are based on the outline of the reservoir property maps made by TNO in 2017 (figure 3.4) and thickness maps of the DGM-deep models (TNO, 2011; 2019). These reservoir property maps are based on the DGM-deep models (2D and 3D seismic data) and well data from TNO, EBN and Panterra.

For the Lower Slochteren subplay, additional literature was incorporated. The thickness of the Lower Slochteren member depends on the paleo topography as discussed in the geological background in chapter 2 (Mijnlieff & Geluk, 2011). Locations with underlying hard lithologies (cuestas) such as sandstones have a lower thickness than areas underlain with soft lithologies (valleys). Formations containing these lithologies have been mapped on the Permian subcrop map (Doornenbal et al., 2010) which was used to determine regions with larger thickness variation. Regions with a high variety in thickness got assigned a lower POS compared to regions without clear paleotopography.

Since both the thickness map and the reservoir property maps did not include sufficient data for the northern Dutch offshore, additional literature was also incorporated to create the CRS map for reservoir presence in this region. The discovery of the Cygnus field proved the existence of the northern fringe sands of the Rotliegend, originating from the Mid North Sea High area (Catto et al, 2017). The Mid North Sea High consists of three smaller highs: the Elbow Spit High, the Dogger High and the Mid North Sea Platform (Houben et al., 2020). In 2018, the lake margin of the Cygnus field was mapped in the offshore UK (Brackenridge et al., 2018). Recently, the lake margin has been continued towards the Dutch offshore E blocks based on 3D seismic and well analysis (Heldreich et al., 2019). The thickness of the Rotliegend group and the regional trends of the Southern Permian Basin suggest an east-west depositional trend, which was connected to the Cygnus lake margin polygon (TNO,2019; Heldreich et al., 2019). The Rotliegend group thickness map shows no deposition on the Elbow Spit High and a very thin Rotliegend in the A12 and B10 blocks (TNO,2019). Around the Elbow Spit High, a sediment bypass is expected (Heldreich et al., 2019). Other common risk polygons in this region are based on structural elements mapped on 2D and 3D seismic data which are used to differentiate between distal deposits in the Dutch Central Graben and proximal deposits in the Step Graben (Ter Borgh et al., 2019b). To the north, the P5-fault, a pre-Permian regional east-west trending normal fault, was used to separate Lower Rotliegend sediments in the A15 block from the Upper Rotliegend deposits south of the fault line (Ter Borgh et al., 2019b, Houben et al., 2020). The reservoir interval of the Lower Rotliegend clastics member is included in the Lower Slochteren CRS map in the Northern offshore.

The Basal Rotliegend sandstones, the Lower and Upper Slochteren members together form the main reservoirs in the Rotliegend play. The reservoir presence CRS map of the Rotliegend play is therefore a combination of the CRS reservoir presence maps of these subplays. The Lower and Upper Slochteren overlap in the Feather Edge area. The Rotliegend play reservoir presence POS in this location should not be lower than the maximum POS of either the Lower or Upper Slochteren reservoir presence POS. A maximum stack, in which the maximum POS per location is taken, was used to make the Rotliegend play reservoir presence CRS map (figure 3.8). The CRS map shows that the POS of finding reservoir is highest in K, L, P and Q offshore blocks: there reservoir should be encountered with a high probability.

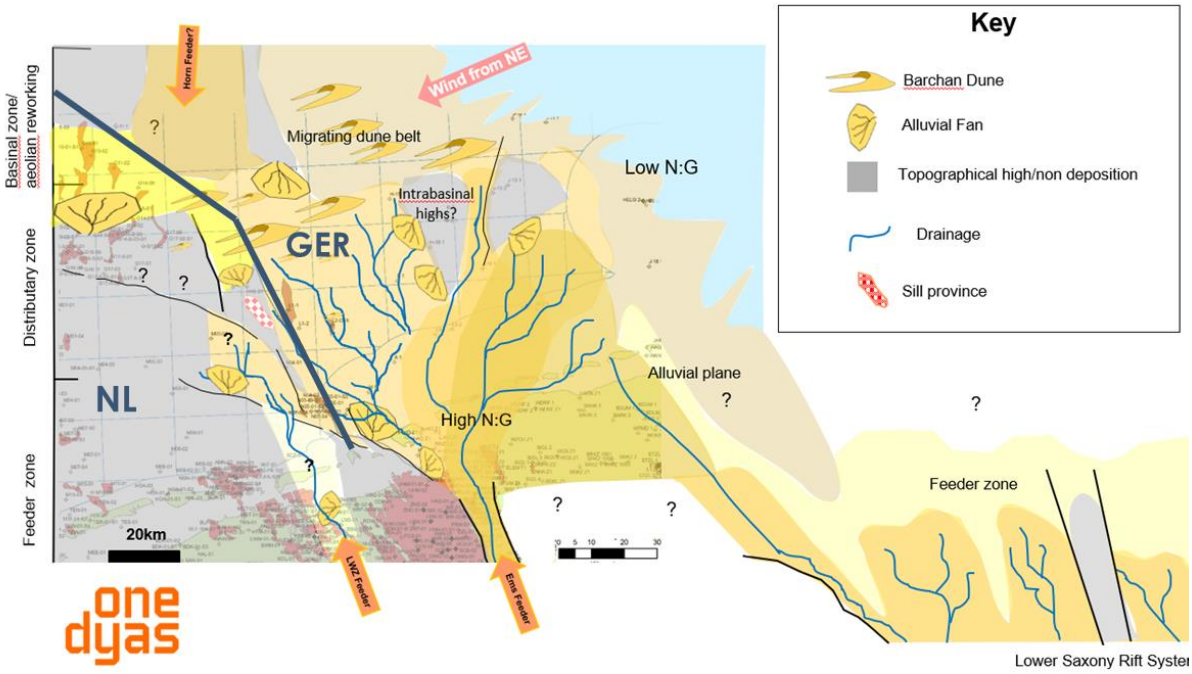
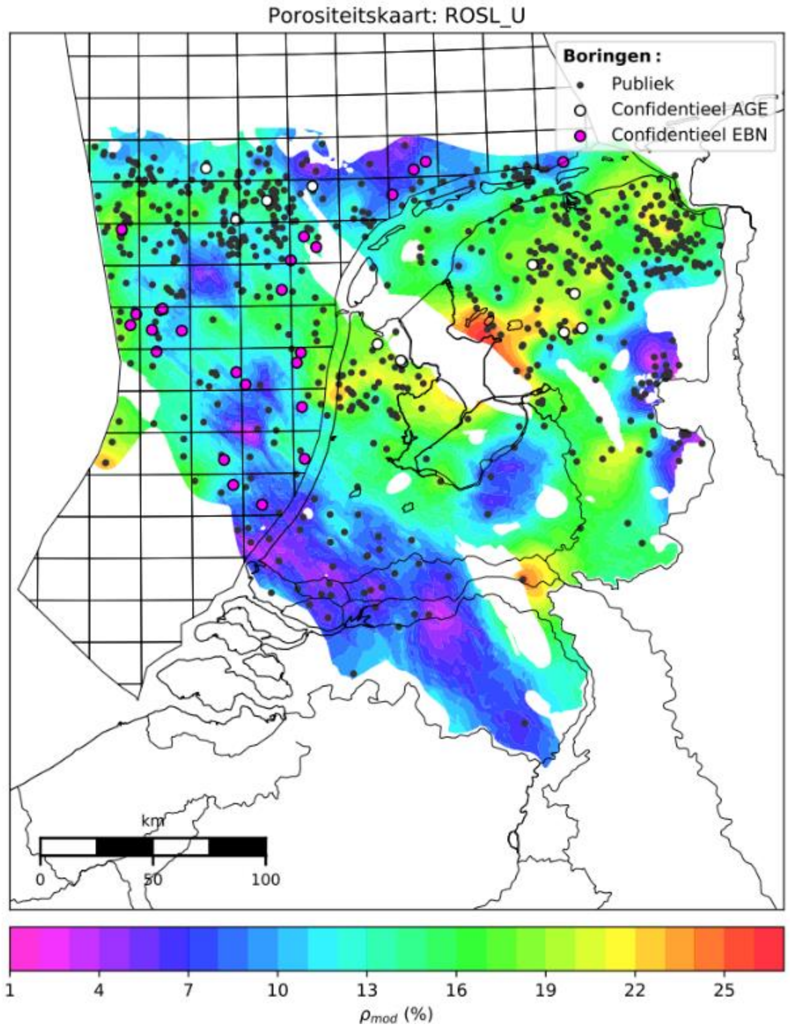



*Figure 3.3. Depositional map of the Basal Rotliegend sandstones in the eastern offshore Netherlands above the Province of Groningen. The Basal Rotliegend Sandstones member in the Netherlands have two southern sediment sources and two northern source areas based on this map. The reservoir consists of a combination of alluvial, fluvial and aeolian deposits. Modified from ONE-DYAS (2018).*



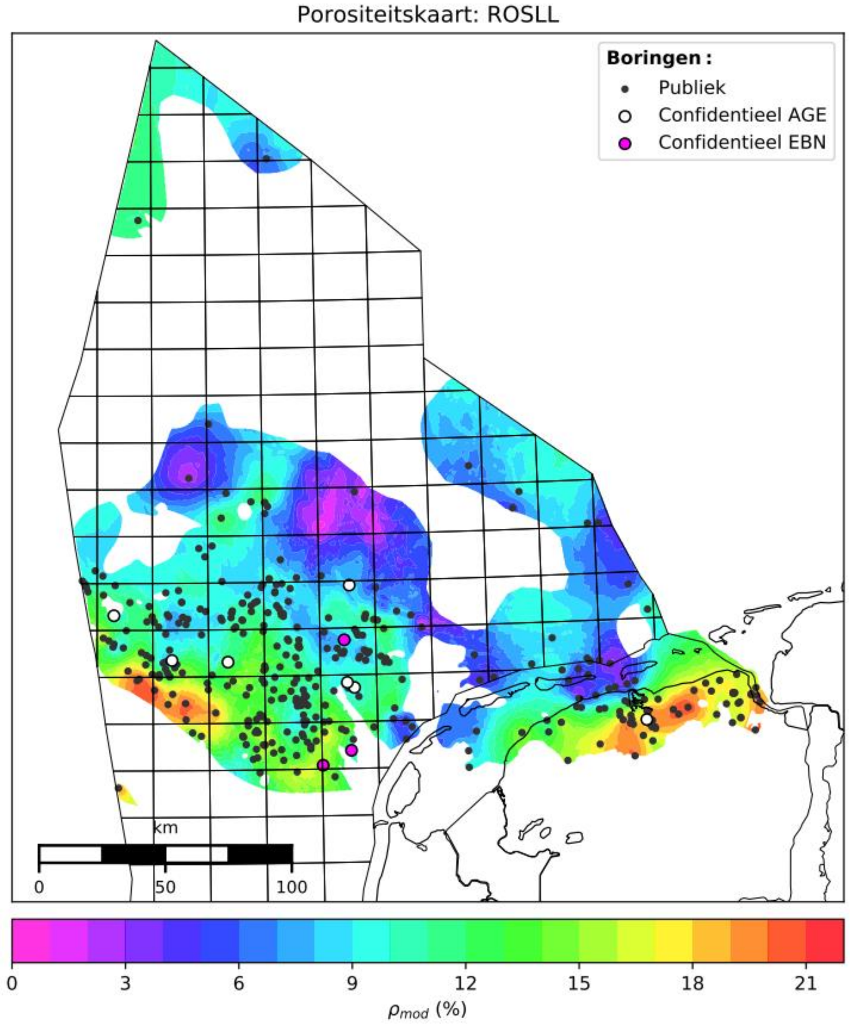




*Figure 3.4a. Porosity map for the Slochteren formation and Upper Slochteren member in the Netherlands. This map is the result of combining well data with depth trends. Low porosity zones in the offshore can be found in the Broad Fourteens Basin, the West Netherlands Basin and*

*Figure 3.4b. Porosity map for the Lower Slochteren member in the Netherlands. This map is the result of combining well data with depth trends. Low porosity zones can be found in the Dutch Central Graben and around E14 (TNO, 2017). Confidentiality status 2017. These maps have at date reached their end date for confidentiality.*

*Vlieland Basin. (TNO, 2017). Confidentiality status 2017. These maps have at date reached their end date for confidentiality.*

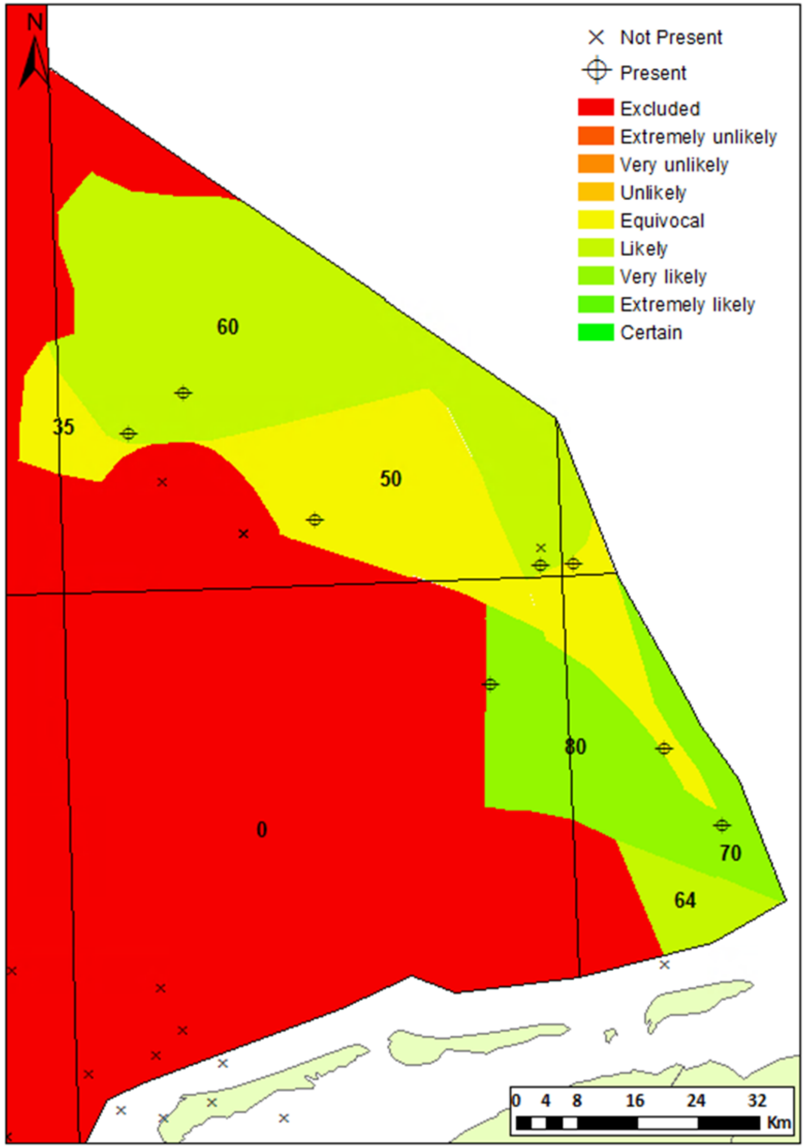



*Figure 3.5. Reservoir presence CRS map for the Basal Rotliegend subplay including public wells from nlog.nl which were classified by thickness (present >5m reservoir). Map is colour coded on the POS, where red represents a low POS and green a high POS.*

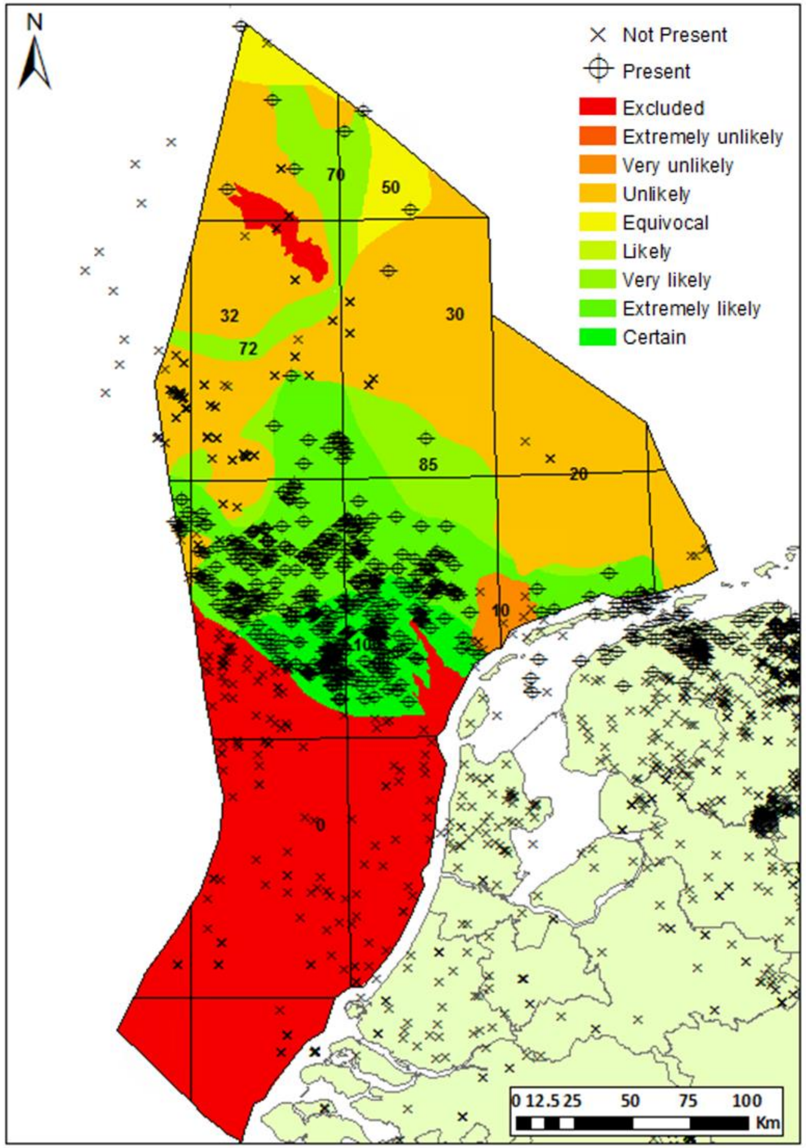



*Figure 3.6. Reservoir presence CRS map for the Lower Slochteren subplay including public wells from nlog.nl which were classified by thickness (present >5m reservoir). Map is colour coded on the POS, where red represents a low POS and green a high POS.*

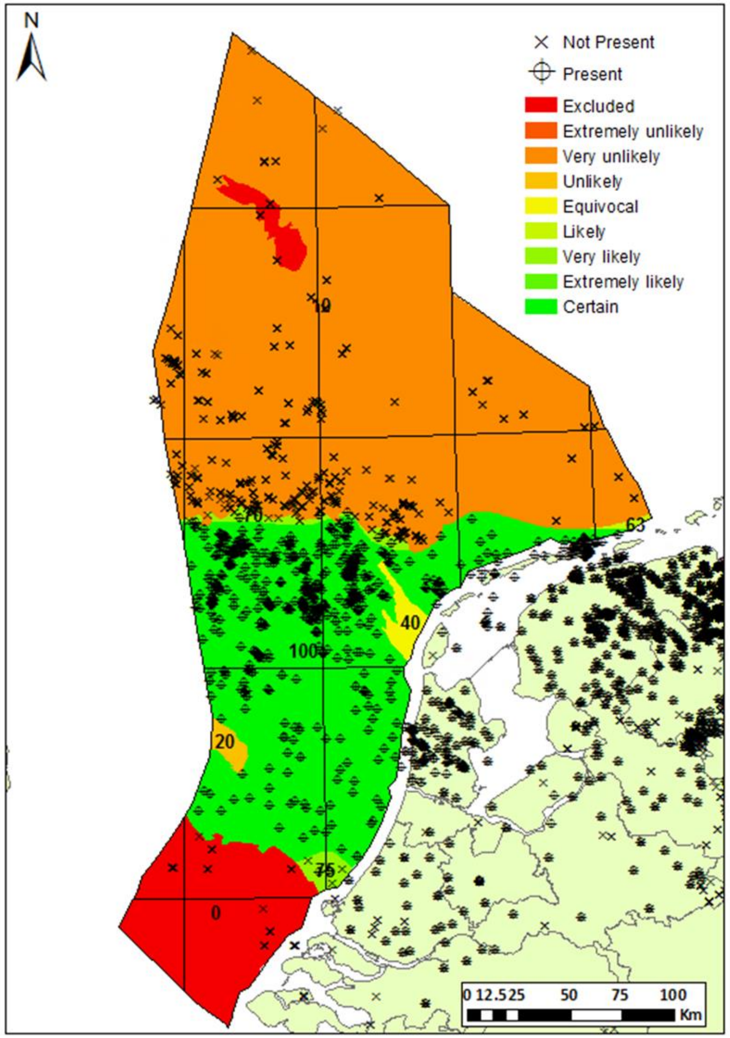



Figure 3.7. Reservoir presence CRS map for the Upper Slochteren member and Slochteren formation subplay including public wells from nlog.nl which were classified by thickness (present >5m Slochteren or Upper Slochteren member). Map is colour coded on the POS, where red represents a low POS and green a high POS.

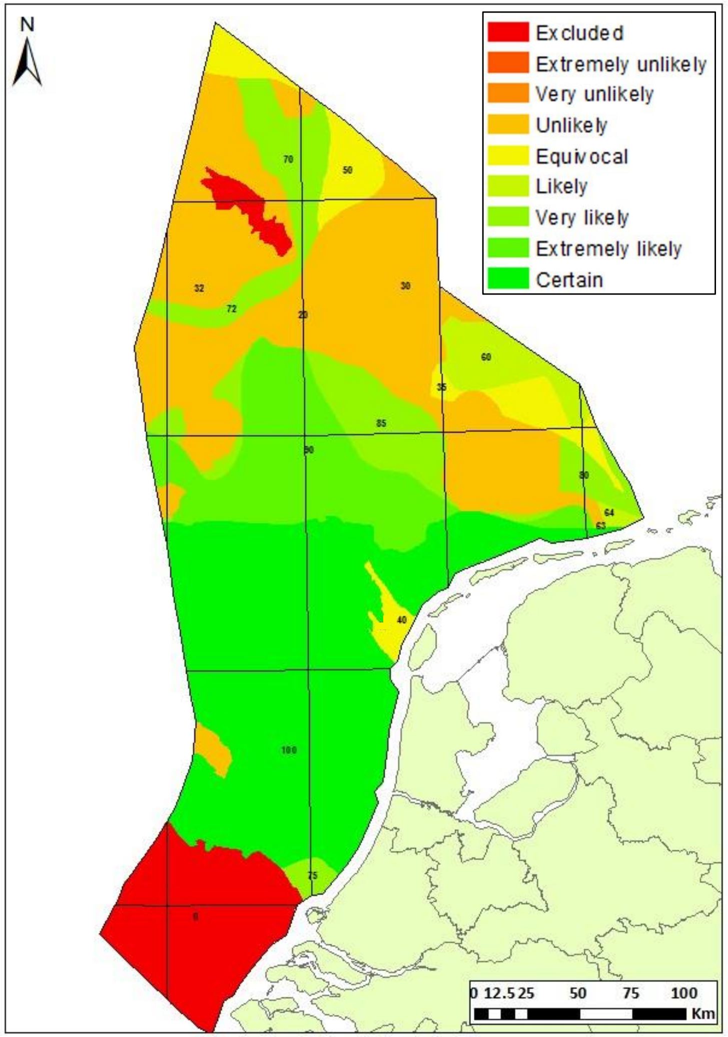



Figure 3.8. Reservoir presence CRS map for the Rotliegend Play. This map shows the highest reservoir presence POS over all Rotliegend subplays, made with a maximum stack of the reservoir presence CRS maps of the Rotliegend subplays.

### 3.2.2 Reservoir Effectiveness

Key parameters which indicate the quality of the reservoir are the porosity and the permeability values. The reservoir property maps of TNO (2017) for permeability and porosity (figure 3.4 for porosity) for the Slochteren members were used to determine the reservoir quality. These maps have at date reached their end date for confidentiality. The porosity maps were subdivided into three classes corresponding to a risk based on the EBN post-drill well analysis classification for clastic gas reservoirs: good (>6% porosity), ambiguous (4%-6% porosity) and poor (<4% porosity). Similarly, the permeability maps were classified: good (>0,1mD), ambiguous (0,001mD – 0,1mD), poor (<0,001mD). To create a reservoir effectiveness CRS map, the POS assigned for both parameters was stacked using a minimum stack, incorporating the lowest assigned POS in the CRS map.

The permeability and porosity values on the TNO reservoir property maps are determined by burial depth, burial anomaly and well data. Yet depositional facies and cements also have an influence on the quality of the reservoir. Cements often depend on the facies. Illite cements which lower the permeability with 1 to 2 orders of magnitude are more common in fluvial reservoirs (Gaupp, 2009; Goldberg et al., 2017). Lacustrine playas and sabkhas are clay rich and contain evaporitic deposits due to climatic wetting and drying cycles. Additionally, post-depositional processes in lacustrine environments can lead to the formation of anhydritic cements, which are a low-grade metamorphic product of gypsum. A mudstone/sandstone (M/S) ratio can be used to determine the presence of dolomitic cements, high M/S ratio (>70%) shows strong carbonate cementation (Busch et al., 2020). Although facies independent, lacustrine environments contain a high M/S ratio which is devastating for the reservoir quality.

To include the depositional facies and cement formation, regional depositional facies maps for the Slochteren members published by Fryberger et al. in 2011 were incorporated into the CRS maps. These maps are the result of the combination of studies performed by NAM and Shell, comprising of literature and well data of the Rotliegend deposits covering the UK and Dutch on- and offshore in the Southern Permian Basin. For the Basal Rotliegend sandstones the depositional map of the member was classified in proximal deposition, higher quality reservoir, and distal deposits, lower quality reservoir (Figure 3.9). Expected reservoir quality was checked with the porosity and permeability values from the EBN Spotfire database and the wells used for the TNO reservoir property maps, which were classified similarly as TNOs reservoir property maps. There were no wells with poor permeability values (<0,001 mD).

Again, the Dutch Northern Offshore was not included in the previous named studies and the POS of the common risk polygons was based on the quality and facies of the Cygnus field reservoir (fluvial alluvial, good quality, Catto et al. 2017), the available well data from the EBN Spotfire database, the well data used for the reservoir property maps from TNO-AGE, EBN and Panterra and the distribution and facies of the deposits researched by Heldreich et al. (2019).

For each subplay a reservoir effectiveness CRS map was made (figures 3.9 – 3.11). A maximum stack of these maps, in which the highest expected POS for reservoir quality was used, is shown in the reservoir effectiveness CRS map for the Rotliegend play (figure 3.12).

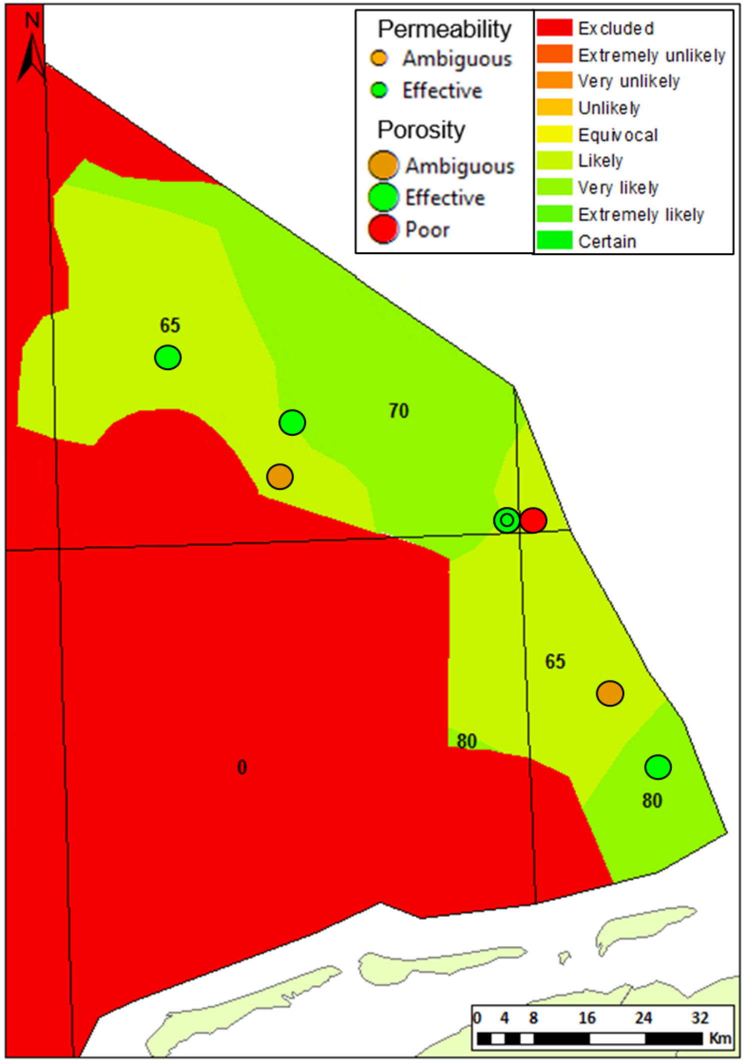



Figure 3.9. Reservoir effectiveness CRS map of the Basal Rotliegend Sandstones subplay in the eastern Dutch offshore. Well data indicates if Rotliegend reservoir has been found in the region and the quality of the reservoir. Well data outside the Eastern Offshore area that includes Rotliegend reservoir was removed from this map.

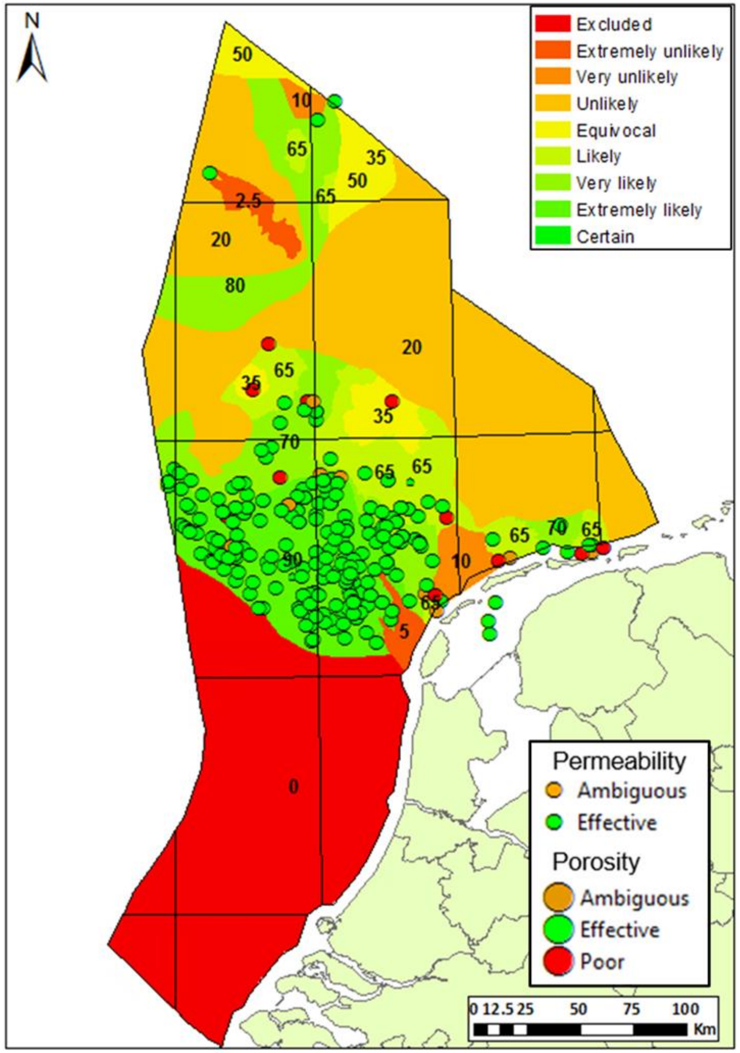



Figure 3.10. Reservoir Effectiveness CRS map of the Lower Slochteren subplay with permeability and porosity well data. Map is colour coded with the total POS, where red represents a low POS and green a high POS.

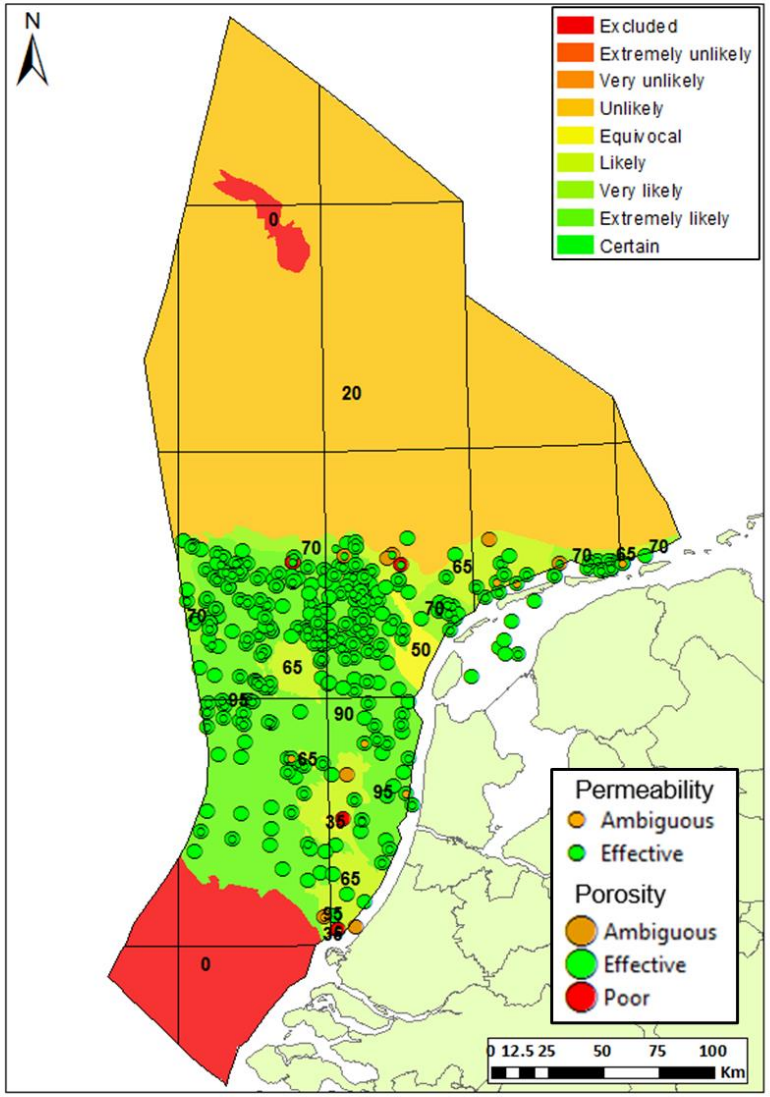



Figure 3.11. Reservoir Effectiveness CRS map of the Upper Slochteren and Slochteren formation with permeability and porosity well data. Map is colour coded with the total POS, where red represents a low POS and green a high POS.

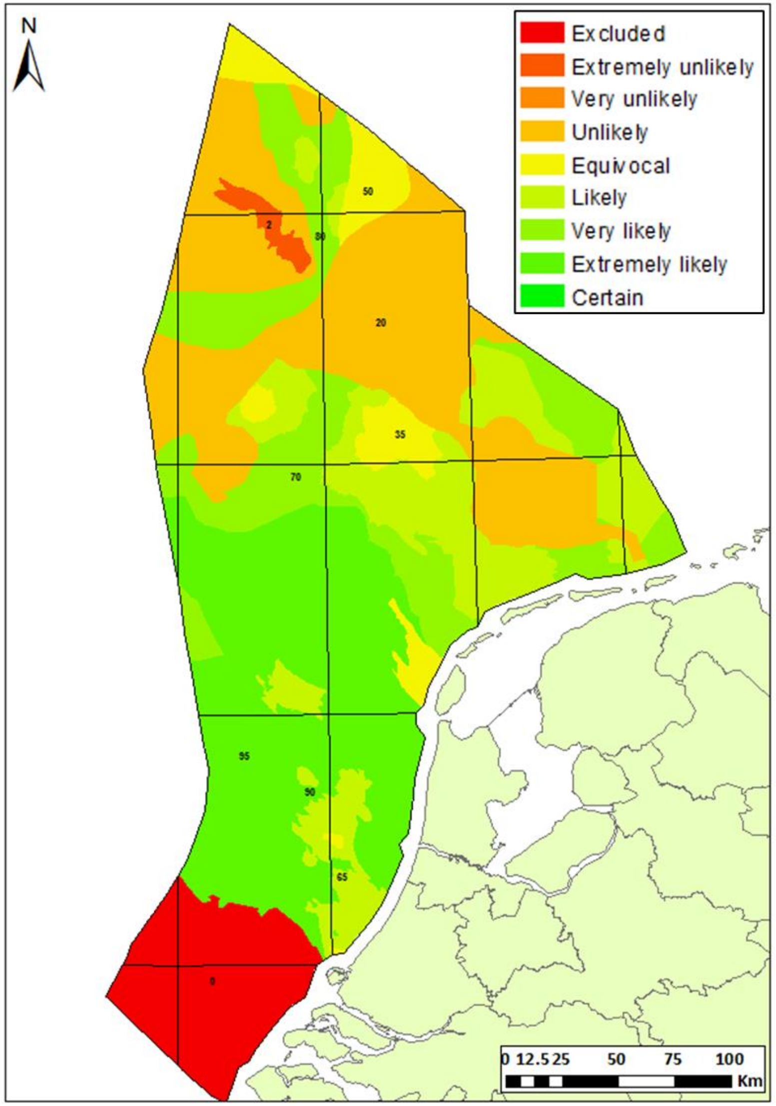



Figure 3.12. Reservoir effectiveness CRS map for the Rotliegend Play. This map shows the highest reservoir effectiveness POS over all Rotliegend subplays. Highest POS is found in the Feather Edge area.

### 3.2.3 Top Seal Presence

Two types of seals in the Rotliegend play prevent leakage of hydrocarbons towards the surface: seals within the Rotliegend group and seals outside the Rotliegend group. The location of the reservoir determines which seal is in place (figure 3.13).

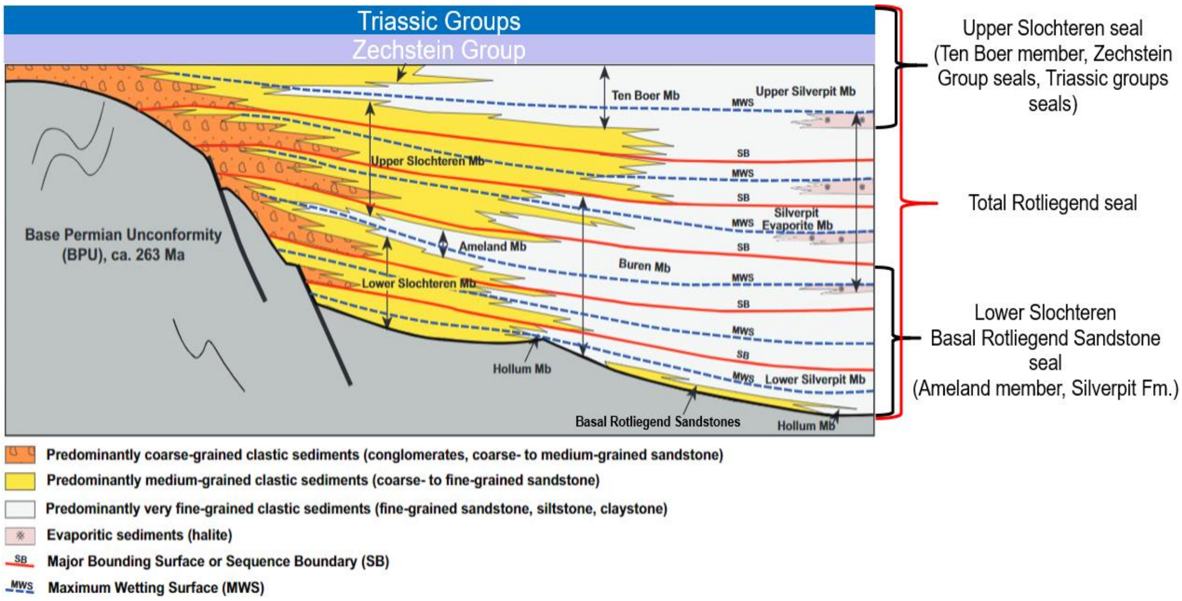



*Figure 3.13. This illustration shows the Rotliegend group in the Dutch subsurface. In light gray and pink lithologies with sealing qualities are displayed, in yellow and orange the reservoir intervals are shown. The location of the reservoir in the Rotliegend group determines the seal. Intra Rotliegend Group seals seal the gas reservoirs in the Basal Rotliegend Sandstones and in the Lower Slochteren member. The Upper Slochteren member is sealed by the Ten Boer member, but also by the seals in the Zechstein group and in the Triassic groups. Modified from Ojik et al., 2011.*

The Basal Rotliegend Sandstones and the Lower Slochteren member are both sealed by the same internal Silverpit formation and the Ameland member from this formation and can therefore be mapped in one CRS map. The thickness of the Ameland member mapped by Mijnlieff & Geluk in 2011 was incorporated in the seal CRS map of the Lower Slochteren and Basal Rotliegend Sandstones subplays at locations where the Upper Slochteren member overlies the Lower Slochteren member (figure 3.14). The thickness of the seal was divided into three risk classes based on the EBN post-drill well analysis classification for clastic gas plays: a seal with a thickness over 50 meters is considered a good seal, a thickness between 10 and 50 meters is ambiguous and a seal with less than 10 meters is poor.

The Upper Slochteren member is sealed by the Ten Boer member, evaporites from the Zechstein group and by the Triassic Main Claystone formation. For each seal, a CRS map was made with the classifications from the EBN post-drill well analysis for clastic gas plays. The CRS map for the Ten Boer member was based on the Ten Boer thickness maps from Reichwein made in 2007 based on well data. The Zechstein seal CRS map was based on the TNO STEM project (Bouroullec et al., 2017), the DGM-deep models (TNO,2019) and the charge map from Hanemaaijer (2020). Where migration paths are present in the Triassic, charge from the Westphalian source rocks has escaped the Rotliegend and so the seal may not be of sufficient thickness or quality. No regional thickness map of the Triassic Main Claystone formation could be found from literature, which is why the presence of this formation is determined by the thickness trends of the Lower Germanic Triassic group (TNO, 2019). Areas within a range of 7.5 km of a well with more than 50 meters of Main Claystone formation are assumed to be of sufficient seal thickness. Remaining areas have been assigned an ambiguous POS. The three seals (Ten Boer, Zechstein and Triassic Main Claystone Formation) were combined using a maximum stack. When using a multiplication stack, the POS would represent the chance of successfully encountering all three seals with a thickness over 50 meters. However, only one good seal (>50 meters) must be present to have enough sealing thickness. Using a maximum stack, if only one seal is present which is thicker than 50 meters, the chance of encountering this seal is not artificially lowered by the other seals. However, if two seals have both 30 meters in one location, the top seal is not considered good but ambiguous in the CRS map. The seal CRS map for the Upper Slochteren subplay is shown in figure 3.15.

The seal of the Rotliegend play should contain both the external and the internal Rotliegend group seals (figure 3.13). The Rotliegend play top seal presence CRS map was therefore a maximum stack of the Upper Slochteren subplay CRS map and the Basal Rotliegend Sandstone subplay / Lower Slochteren subplay CRS map. The Rotliegend play top seal presence CRS map is shown in figure 3.16. The map is almost similar to the top seal CRS map of the Upper Slochteren subplay but differ in the L block near the Texel-IJsselmeer High. The chance of encountering sufficient seal thickness is lower near the London-Brabant Massif, the Elbow Spit High, the Texel-IJsselmeer High and the Winterton High.

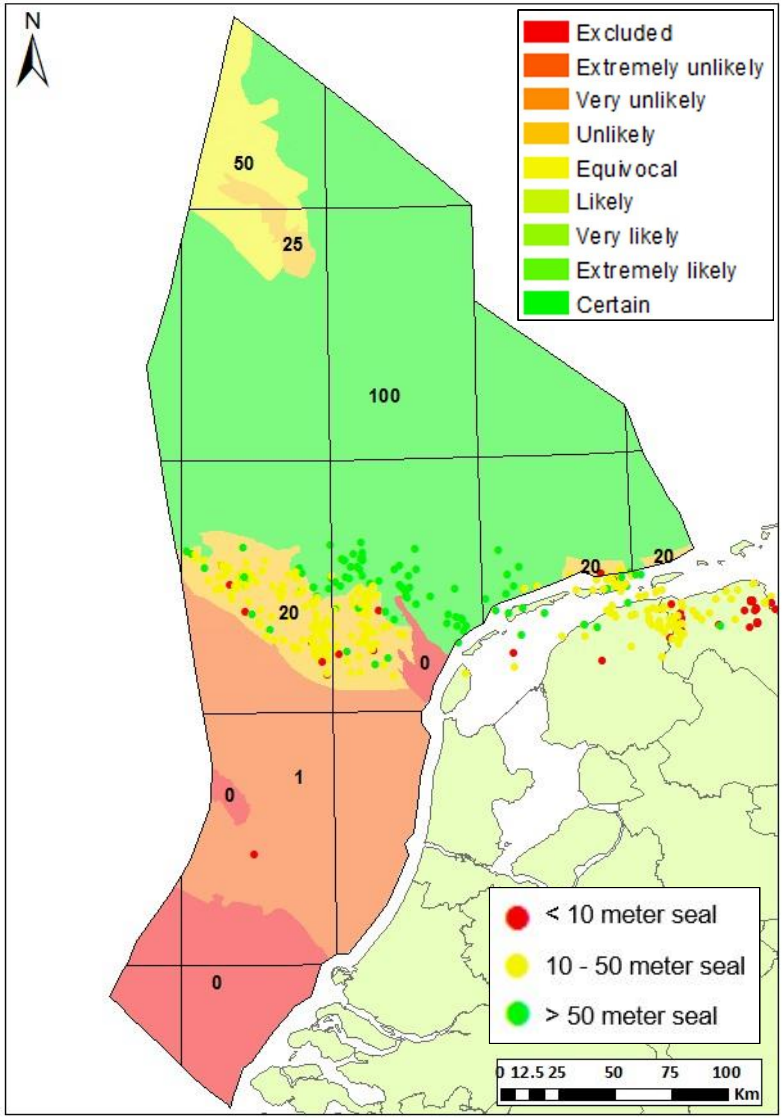



*Figure 3.14. Top seal presence CRS map of the Lower Slochteren subplay and Basal Rotliegend Sandstones subplay. Thickness of the public wells (nlog.nl) on the Ameland member have been included in this map.*

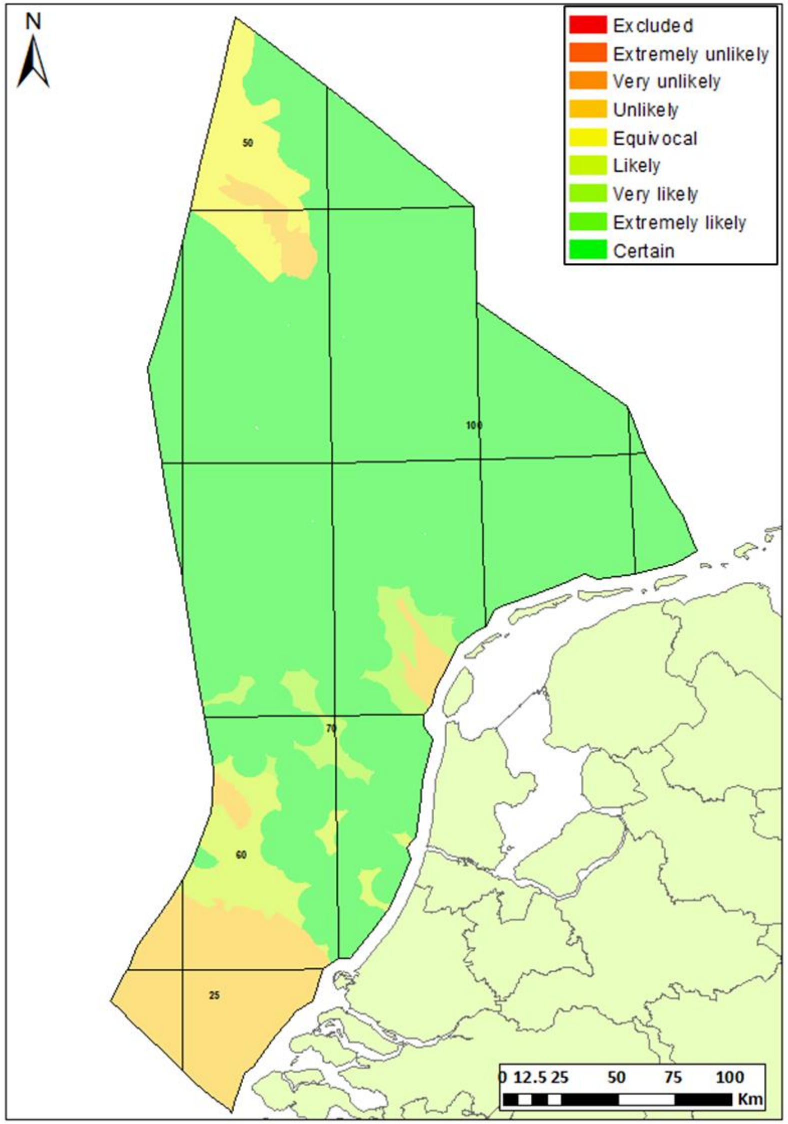



*Figure 3.15. Top seal presence CRS map of the Upper Slochteren member and Slochteren subplay. The seal presence map is a combination of three different seals: the Ten Boer member, the Zechstein evaporites and the Triassic Main Claystone Formation. POS changes from 70% to 60% at the Zechstein salt pinch-out line.*

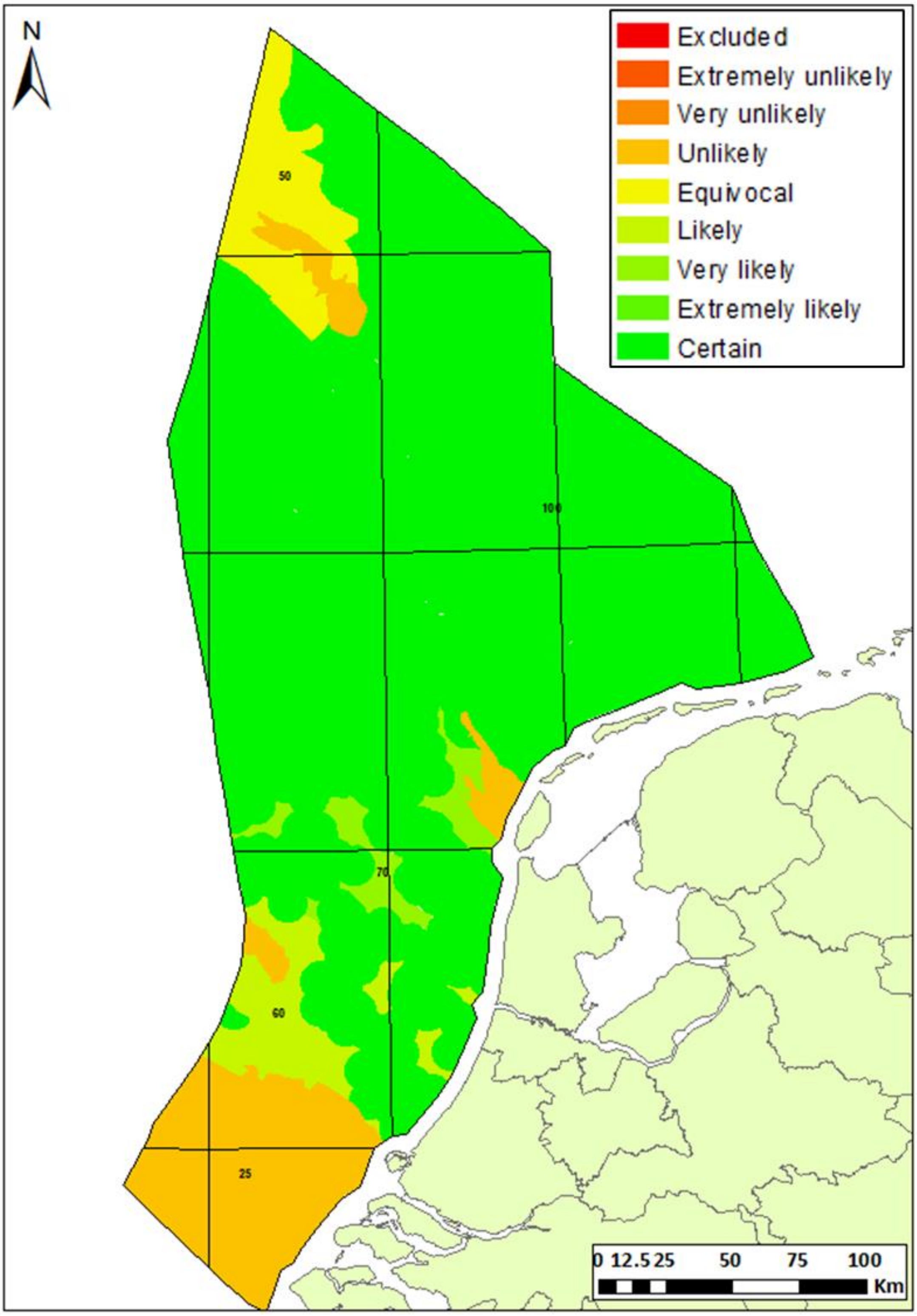



*Figure 3.16. Top seal CRS map for the Rotliegend Play. The map is a maximum stack of the top seal CRS maps of the Rotliegend subplays, shown in the two previous figures.*

### 3.2.4 Trap Presence

The absence of Zechstein evaporites in the OPQ blocks does not result in a lower seal presence risk because of the presence of other younger seals such as the Triassic Main Claystone formation. Yet due to the reservoir potential between the younger seals and the Rotliegend reservoir, the hydrocarbon column must be larger for the Rotliegend reservoir to contain hydrocarbons (figure 3.17). Because the hydrocarbon column risk depends on the absence of Zechstein salts, the risk of the hydrocarbon column not being large enough can be regionally mapped. Therefore, a trap CRS risk map was created in figure 3.18. The Lower Slochteren subplay and the Basal Rotliegend Sandstones subplay primarily sealed by internal Rotliegend group seals, and therefore are not affected. The entire offshore is assigned a trap POS of 100%, except for the OPQ region which lacks Zechstein salt but does contain the Zechstein group. The SR blocks have also been included because of the lack of Zechstein group. The CRS map does not account for other (local) trap risks, such as the presence of trap structures, closing contours and faults.

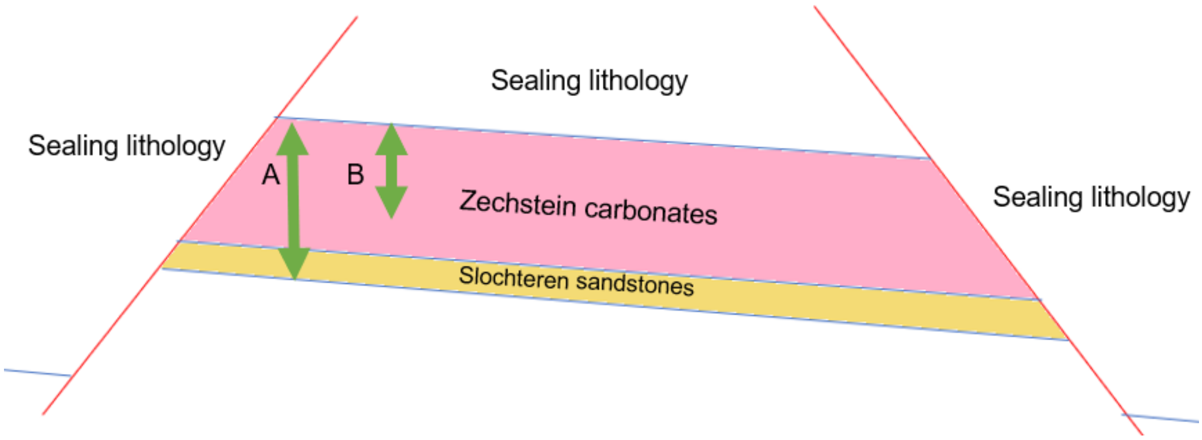



*Figure 3.17. An illustration based on geology of field Q10-A (Tulip Oil, 2019). Field Q10-A has multiple reservoir layers including the Zechstein carbonates and the Slochteren sandstones. Due to lack of seal between the Zechstein carbonates and the Slochteren sandstones, the height of the hydrocarbon column (shown in green) determines the presence of hydrocarbons in the Rotliegend group. Hydrocarbon column A is large enough for charge in the Rotliegend, but hydrocarbon column B is not. This risk of having a smaller hydrocarbon column can be regionally mapped.*

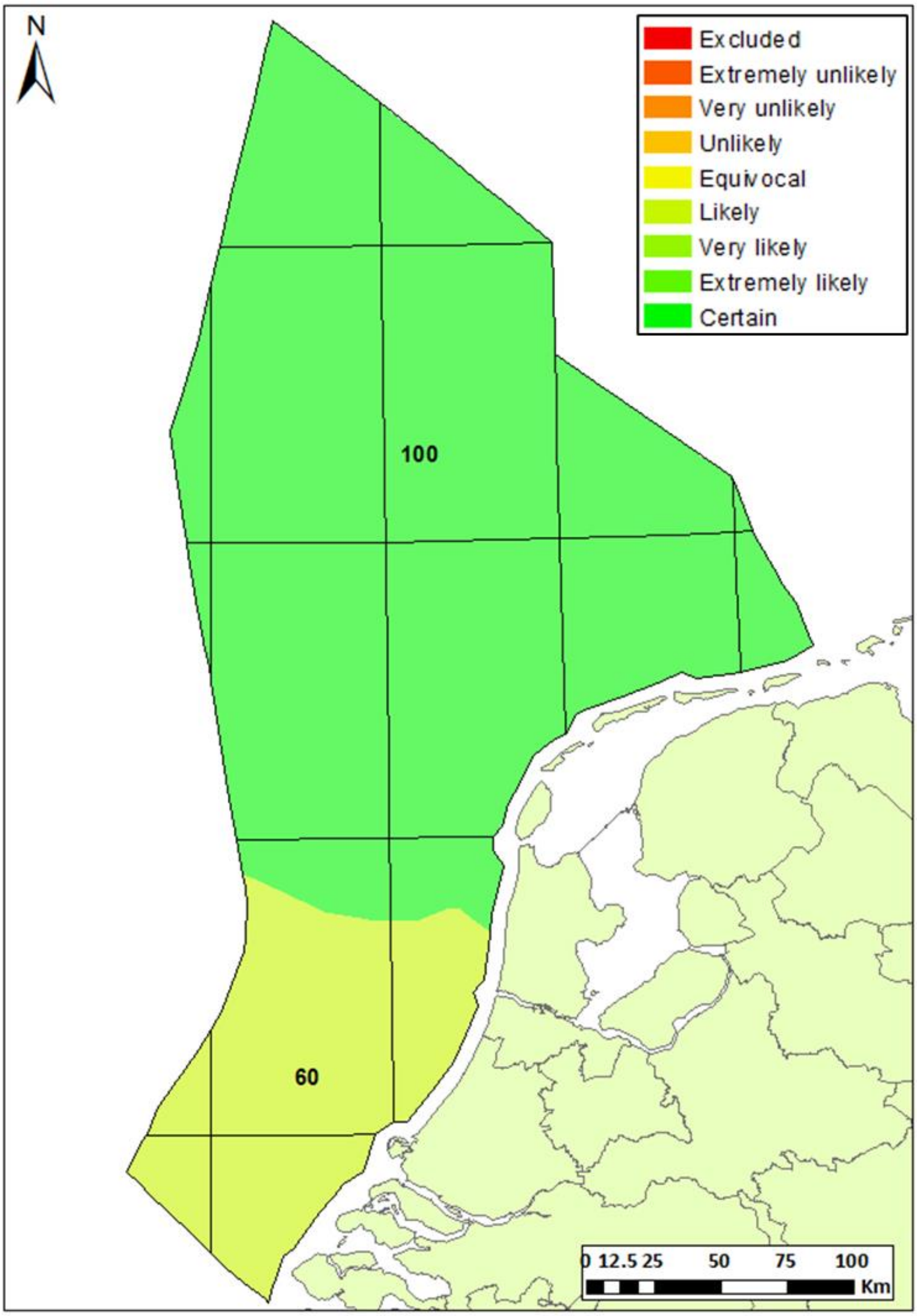



*Figure 3.18. Trap CRS map for the Rotliegend play and the Upper Slochteren and Slochteren formation subplay. The line between green and yellow-green represents the boundary of Zechstein salts (Ten Veen et al., 2012).*

## 3.2.5 Charge Presence

IGI (Integrated Geochemical Interpretations) performed a 3D basin modeling study for the expulsion of the Westphalian coals for different time frames for the entire Dutch offshore (Gardiner et al., 2019). Based on the entire expulsion of the Westphalian coals, a Westphalian charge CRS map was made by EBN (figure 3.19).

In the far northern Dutch offshore, Westphalian source rocks are not present. The EBN hydrocarbon show database does indicate hydrocarbon finds in this area, possibly due to mature Scremerston and Epen source rocks Hanemaaijer (2020). Not much is known of these source rocks and their lateral extent in the Netherlands: their deep burial was considered counter-productive for hydrocarbon generation and oil and gas operators have traditionally considered these two source rocks of lower importance compared to the Westphalian coals and Posidonia shales whose source-rock potential is proven and well-known. Hanemaaijer (2020) compiled a source rock presence and maturity map for the DEFAB-blocks area, including the Scremerston and Epen source rocks (figure 3.20). By combining this map and the CRS map made from the regional expulsion study on the Westphalian, the charge CRS map for the Rotliegend play has been created (figure 3.21).

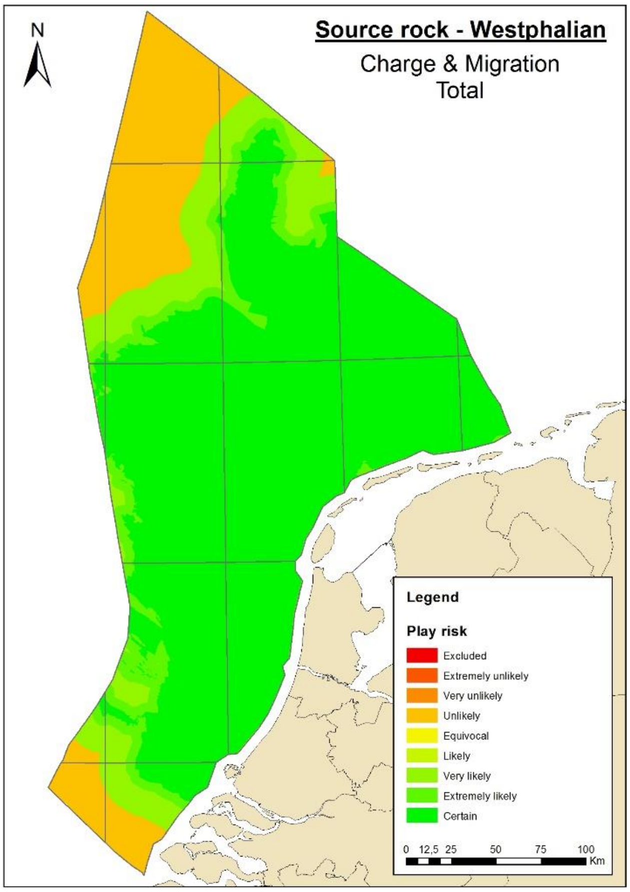



*Fig. 3.19. Charge CRS map for the Westphalian source rocks based on the total expulsion of the Westphalian from Gardiner et al., 2019. (From: EBN)*

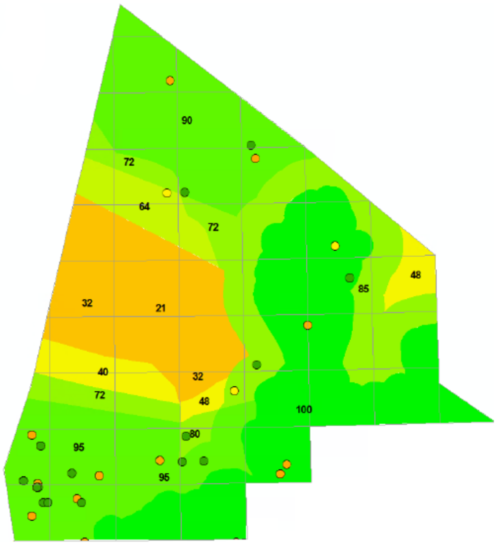



*Fig. 3.20. Charge map for the offshore ABDEF blocks. Westphalian combined with Epen and Scremerston source rocks. Hydrocarbon shows from the EBN hydrocarbon show database over the map which are colour coded based on the quality (poor (orange) – good (green)) of the show. Same colour legend applies as shown in fig. 3.19 (From: Hanemaajier, 2020).*

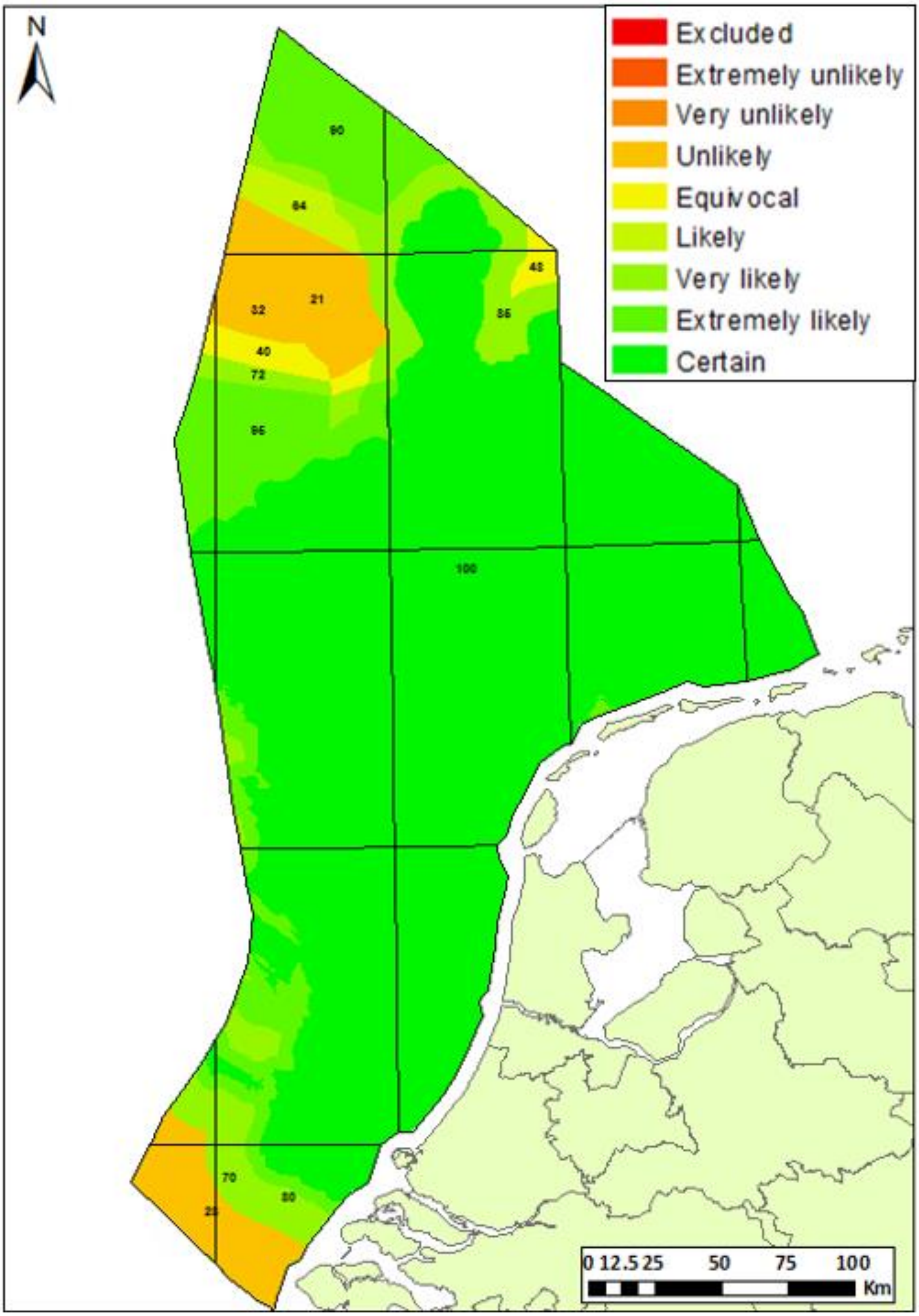



*Figure 3.21. Charge CRS map for the Rotliegend play. Map is colour coded on the total POS, where red represents a low POS and green a high POS. The Dutch Northern Offshore region has a lower POS due to the lack of Westphalian source rocks.*

### 3.2.6 (Sub)play Risk Maps

Combined common risk segment (CCRS) maps show the overall regional geological risk of the play or subplay. This research discusses three subplays based on the reservoir: Basal Rotliegend Sandstones subplay, Lower Slochteren subplay and the Upper Slochteren subplay. These subplays are part of the Rotliegend play, of which the aggregated POS should be similar to the highest POS of the subplays.

The CCRS maps are made with a multiplication stack of the CRS maps seen in the former sections. The Basal Rotliegend Sandstones subplay CCRS map is shown in figure 3.22. The chance of encountering all play elements is highest in the N-block, where the map is light green and the aggregated POS is highest. The limiting play element here is reservoir presence and reservoir effectiveness as shown in figure 3.23.

The Lower Slochteren subplay CCRS map is shown in figure 3.24. The highest aggregated POS of this subplay can be found in the L block, where the POS is 90% of encountering all play elements. The limiting play element here is reservoir effectiveness (figure 3.25)

Upper Slochteren subplay CCRS map in figure 3.26 has the highest chance of encountering all play elements in the bright green area in the K, L, P and Q blocks which is partially divided by a yellow lower POS zone in the middle. The limiting play factors are reservoir effectiveness, top seal and charge (figure 3.27).

The Rotliegend play CCRS map is a multiplication stack of the Rotliegend play CRS maps presented in the former sections. The highest chance of encountering all play elements is in the same area as the highest POS in the Upper Slochteren subplay (figure 3.28). Similarly, the limiting factors are the reservoir, the top seal and the charge (figure 3.29). The Rotliegend play map will be further discussed in the risk mapping discussion section (chapter 3.3) and in the general discussion (chapter 5) to answer the question of the locations with the highest potential. Additionally, this map will be used to compare the resources and the reserves to the expected potential in section 4.2.

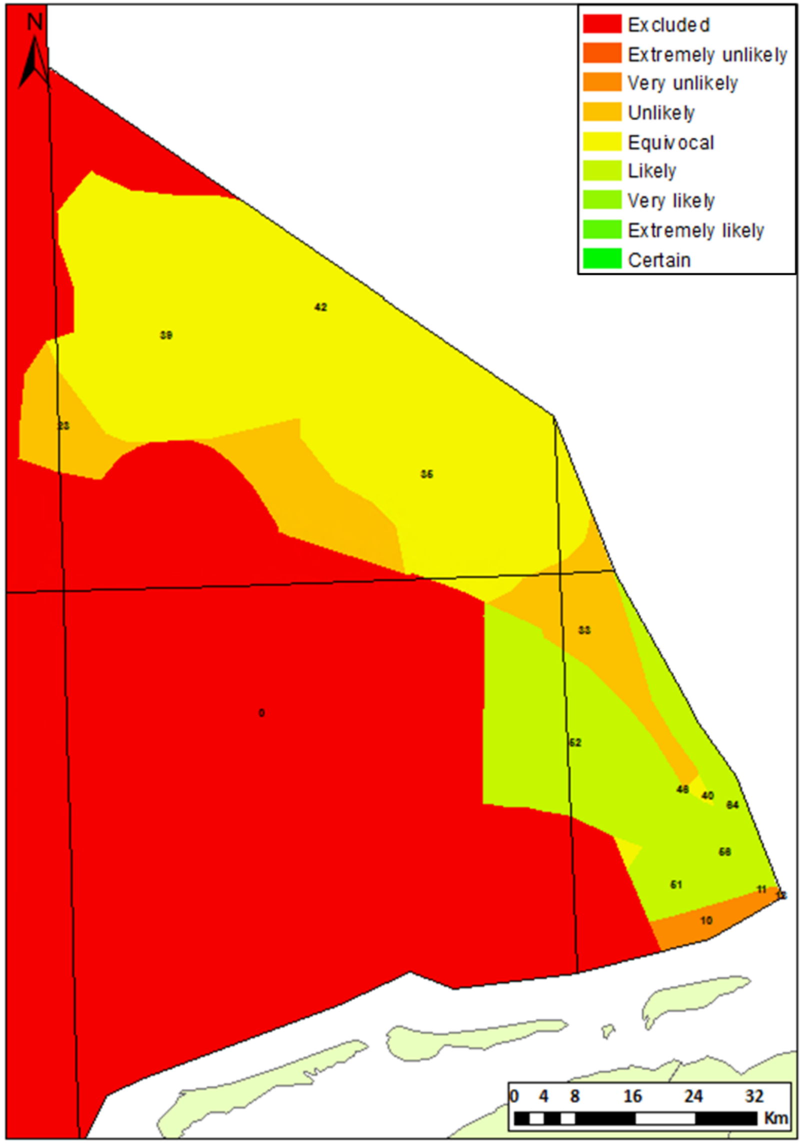



*Figure 3.22. CCRS map for the Basal Rotliegend Sandstones subplay. This map visualizes the total POS of the subplay on a spatial scale and describes an estimate of the average prospect POS per polygon.*

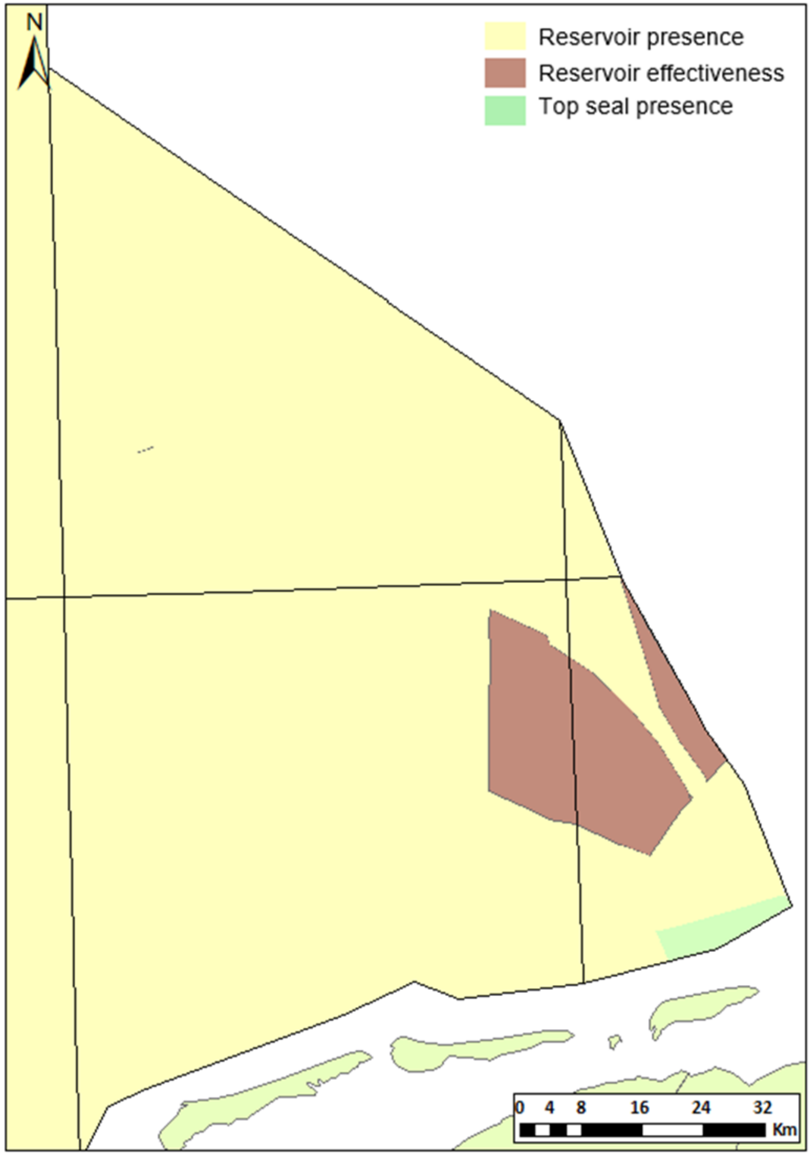



*Figure 3.23. Weakest element map of the Basal Rotliegend Sandstones subplay. This map shows that reservoir is the biggest risk for this subplay, followed by a seal risk in southwestern part of the N-block.*

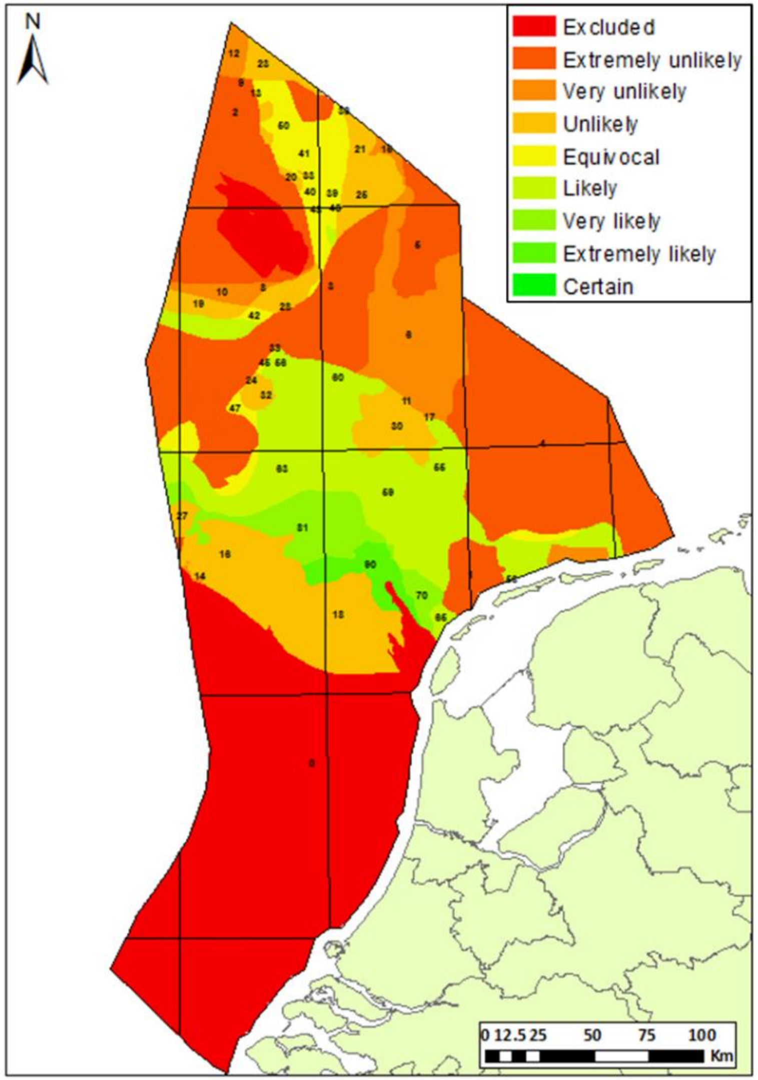



*Figure 3.24. CCRS map for the Lower Slochteren subplay. This map visualizes the total POS of the subplay on a spatial scale and describes an estimate of the average prospect POS per polygon.*

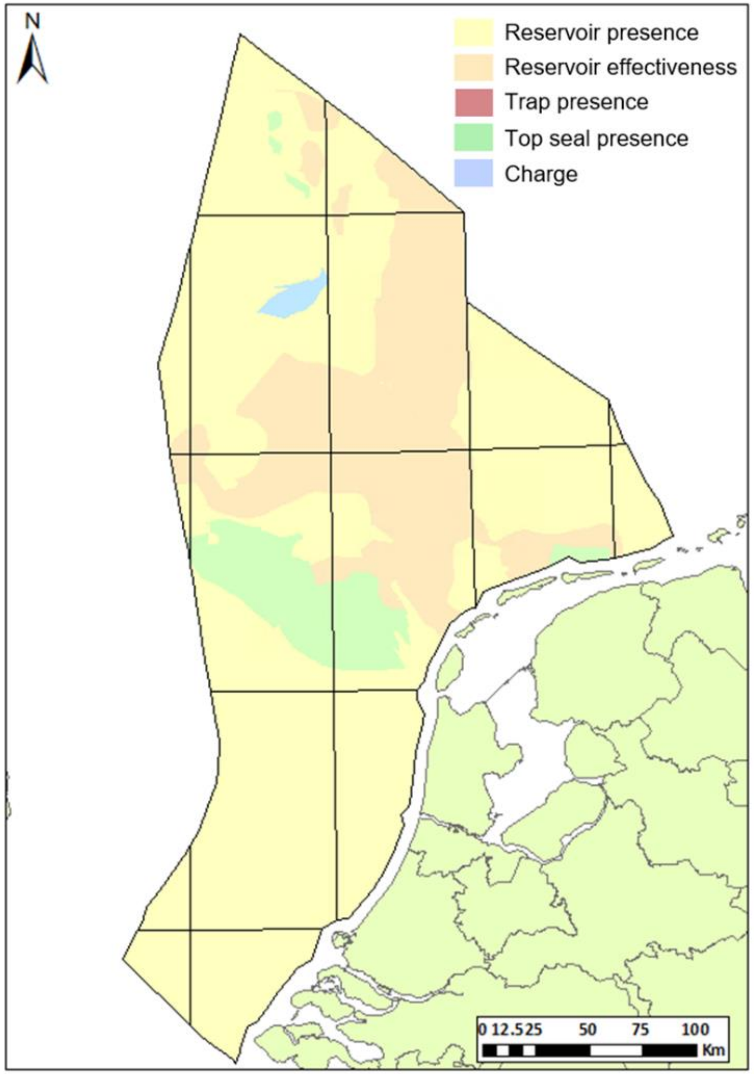
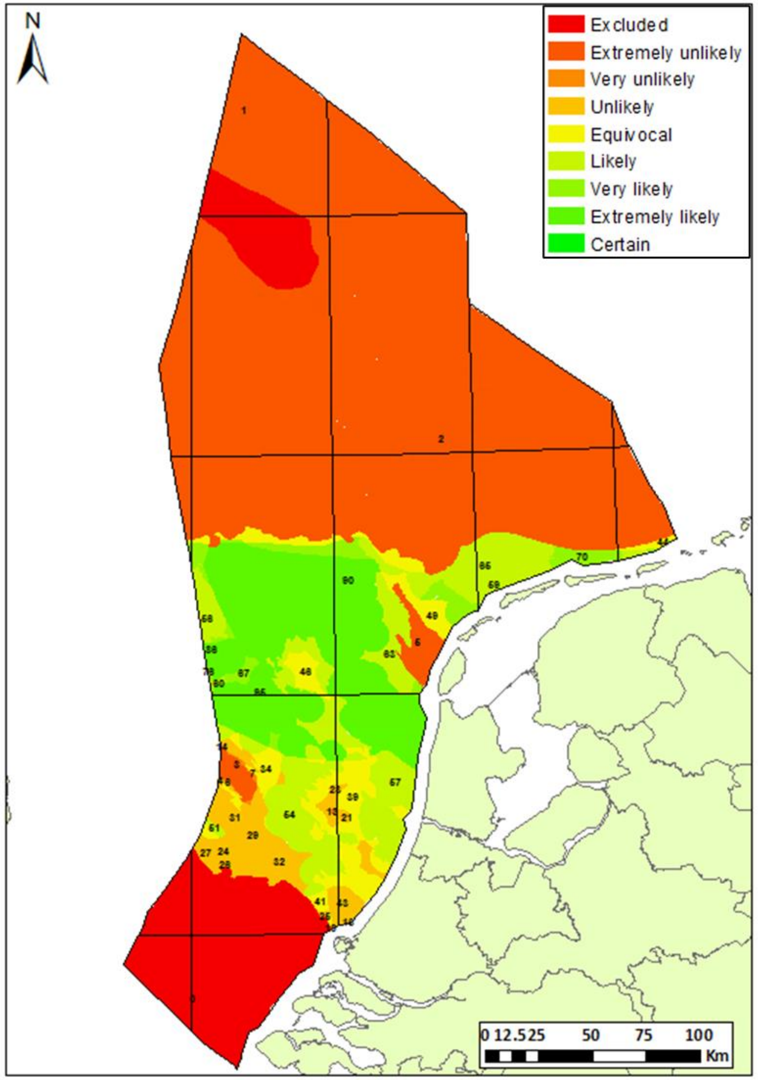



*Figure 3.25. Weakest element map of the Lower Slochteren subplay. This map shows that reservoir is the biggest risk for this subplay, followed by seal and charge. Trap risk was not incorporated in this subplay.*



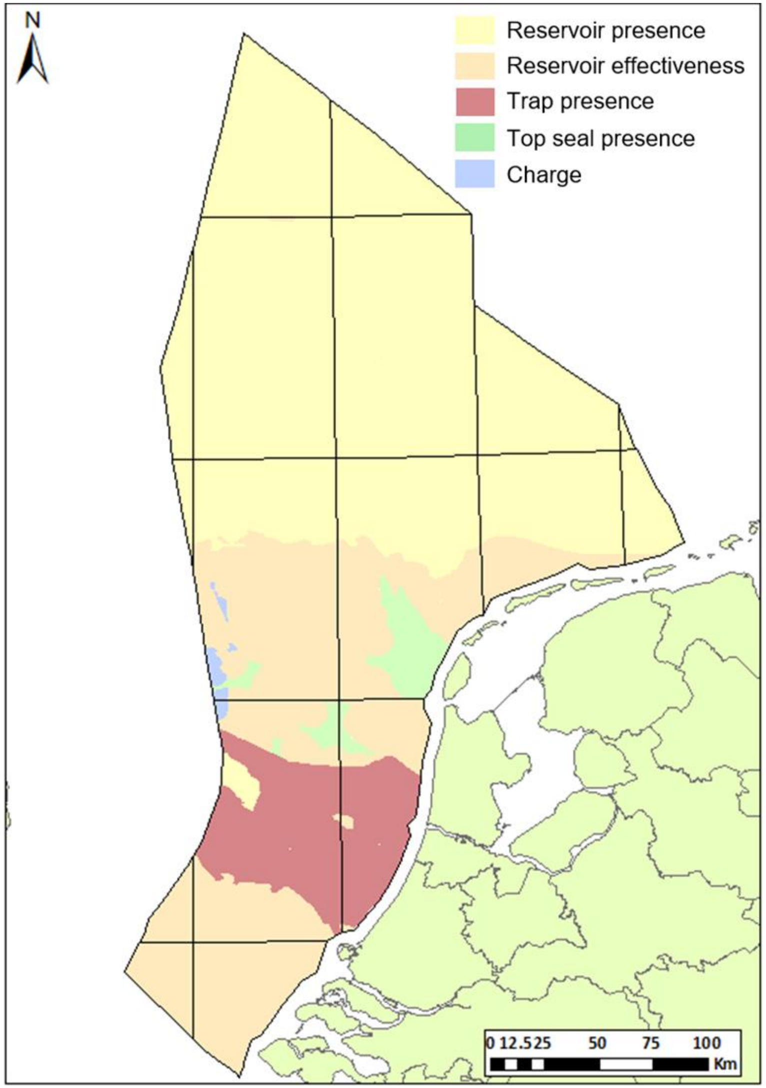




*Figure 3.26. CCRS map for the Upper Slochteren member and Slochteren formation subplay. This map visualized the total POS of the subplay on a spatial scale and describes an estimate of the average prospect POS per polygon.*

*Figure 3.27. Weakest element map of the Upper Slochteren member and Slochteren formation subplay. All play elements can form the inhibiting play element.*

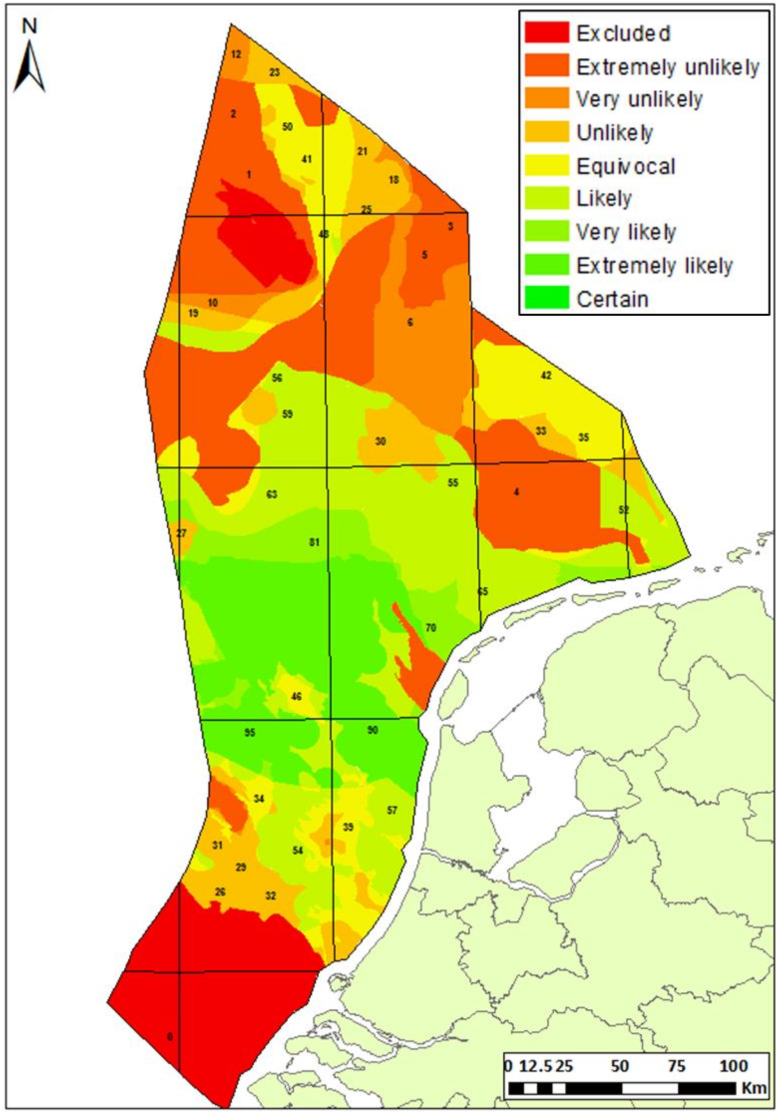



*Figure 3.28. CCRS map for the Rotliegend play. This map visualized the POS of the play on a spatial scale and describes an estimate of the average prospect POS per polygon.*

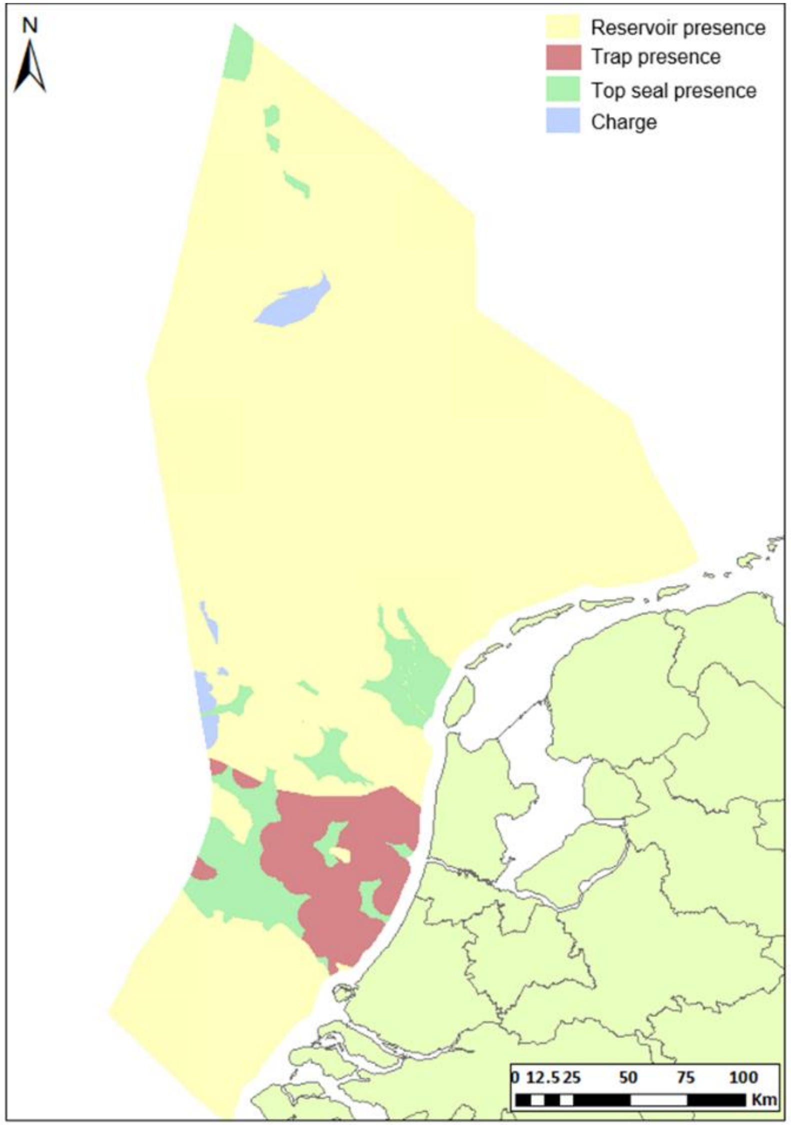



*Figure 3.29. Weakest element map of the CCRS map of the Rotliegend play. This map shows that reservoir is the biggest risk for most of the play, followed by trap, seal and charge risk.*

## 3.3 Discussion

The Rotliegend (sub)play CRS and CCRS maps have been created at a regional scale to combine and summarize the geological risks of the Rotliegend play based on the current available public data and literature. For the subplay CCRS maps, subplay CRS maps have been aggregated and multiplied. CCRS maps therefore inherit the uncertainties of the underlying individual CRS maps. The play element maps and the uncertainties related to these maps will be discussed in this section. The potential of the Rotliegend play will be discussed in the general discussion (chapter 5).

Some visualization problems and uncertainties are universal for all CRS maps discussed. All boundaries of the polygons on the CRS maps are abrupt, while the underlying geology transitions smoothly from one facies to another making borders less sharp than mapped on these maps. The borders on these maps can therefore only be considered as approximation of the geological transitions and should not be considered as hard boundaries at a smaller scale. Since these maps are regional, local risks have not been studied and are not incorporated into these maps.

The play and subplay maps are based on public data. Yet there are some areas for which no public literature was available. This is the case for the reservoir property maps (TNO, 2017) and the detailed Zechstein Thickness map (Boullourrec et al, 2017) which are not available in the public domain yet. While the reservoir property maps are clearly visible in the resulting maps, the Zechstein thickness map is less obvious in the seal CRS map, since the seal CRS map is based on more than one sealing formation.

### 3.3.1 Reservoir Presence

Reservoir presence has a large influence on the POSes of all the (sub)play CCRS maps. The certainty of reservoir being present is bigger in the more mature Feather-Edge area, where the data density is high and the geology is better understood than in the less mature areas in the Eastern and Northern Offshore which results in different POS values assigned. Reservoir gets thinner to the north and the south of the Feather-Edge area. In the south the reservoir gradually gets thinner where it disappears towards the London-Brabant Massif (TNO, 2011; 2019). North of the Feather-Edge area, the reservoir interfingers with the Silverpit formation and progressively gets thinner. The exact pinch-out line of the reservoir is uncertain due to the reservoir thickness falling under the vertical seismic resolution. Moving the pinch-out line of the Slochteren reservoirs has a large influence on the POSes in the CRS and CCRS maps in this region, which is why the pinch-out line was locally mapped closer to wells with Slochteren reservoir than the reservoir property maps of TNO suggested.

The presence of Rotliegend reservoir in the Dutch Northern Offshore region is confirmed by a limited number of Dutch wells and varying quality of seismic data (Jongerius, 2018). The reservoir presence CRS map is based on well data from nlog.nl and a combination of regional studies. Priority was given to the most recent data when selecting the inputs for the various maps. The reservoir presence CRS map for the Northern Offshore area contradicts parts of the findings of Bruin et al. (2015). Bruin et al. concluded that the most prospective regions of this area based on reservoir and charge are in the F01, F02, F04, F05, A15 and B13 blocks, while according to the Rotliegend reservoir presence CRS map F04 and F05 have a low POS for reservoir presence (20% and 30% respectively, figure 3.8 page 17). The disagreement between these two studies is caused newly available information and a different mapping approach: the conclusion on the most prospective blocks by Bruin et al. is based on a net sand map, constructed from an interpolation of well data, which does not contain any regional geological data. Bruin et al. state that the relationship between the Elbow Spit High and the Rotliegend could not be resolved at the time of their publication and that further fault analysis work could increase the understanding in the area. Since 2015, research has been conducted on both topics: on the Elbow Spit High by Heldreich et al. (2019) and on structural elements and faulting by Ter Borgh et al. (2019b) and Houben et al. (2020), which changed the geological understanding of this area. These studies have therefore been used to update the map on the Northern Offshore.

North and east of the Elbow Spit High the presence of reservoir is not well understood. The region lies in a transition zone between the Southern and Northern Permian basin and differs in this from the rest of the Dutch offshore (Kombink & Patruno, 2020). To the north, a large fault zone was recently identified (Houben et al., 2020). Although the fault was active during the pre-Permian, it was used as a boundary on the reservoir presence CRS map to capture the difference between the Lower Rotliegend reservoir north of the fault and Upper Rotliegend reservoir south of the fault. Yet the actual cause of this contrast remains unknown. East of the Elbow Spit High a difference in POS is made based on the distance to the Elbow Spit High. Reservoir near the Elbow Spit High is expected to be sourced from the Elbow Spit High or Mid North Sea High while reservoir further away to the east may also be sourced from highs across the border, such as the Ringkøbing–Fyn High. While a sedimentary transition from one source to the other one exists, it cannot be easily mapped due to the lack of available well data. A Cretaceous fault near the Dutch Central Graben has therefore been selected to represent this. The actual reservoir transition may occur somewhere else. Yet, if sediment is sourced from several highs in the region, it may be debatable if a clear sedimentary transition among the different facies exists at all. Data from Germany could provide additional insights on this issue.

Poor imaging in the Dutch Central Graben and limited well control leads to uncertainty and speculation on the reservoir presence. Historically, little attention has been paid to understand the presence of possible Rotliegend sediments in the Dutch Central Graben. Due to the increasing interest in the Northern Offshore in view of the Cygnus development more research has been carried out, leading to the identification of leads and prospects at Rotliegend level. Additionally, with Lower Rotliegend volcanic strata present in the graben (Heeremans et al., 2004), another explanation could be that lower Rotliegend clastic deposits are expected. These speculations have not been translated into the CRS maps yet, but the lack of data has been considered as positive evidence that reservoir could be present, resulting into a higher POS for this play element. It could be argued that the POS for reservoir presence should be higher than the proposed 30% and closer to 50%. However, reservoir presence is not the highest risk in this area; reservoir effectiveness is the inhibiting play element. Deep burial of the reservoir formation decreases porosity and permeability values, resulting in a lower POS for the reservoir effectiveness and therefore also in a lower POS in the CCRS map. An increase by 10% or 20% of the reservoir presence POS has a minor influence on the aggregated POS (+2%, +4% respectively).

Although stratigraphically incorrect, the Basal Rotliegend Sandstones and Lower Slochteren member could have been stacked into one reservoir CRS map, creating one subplay. This would decrease the uncertainty on the boundary between the Lower Slochteren and Basal Rotliegend sandstones, which is now based on a regional Rotliegend group trend and is relatively uncertain. It can be argued that this boundary is not needed anyway, since both members can be present in one well. However, wells in this region contain only one of the reservoir layers. These wells were assigned to the Basal Rotliegend Sandstones member based on the location on the map made by ONE-Dyas in 2018 (figure 3.3, page 14). A better way to assign these wells would be to date the reservoir layers. Yet, the Rotliegend formation is notorious for being hard to date due to the lack of organic material (Gast et al., 2010). If this problem could be resolved by cyclostratigraphic dating, correlating the sedimentary succession of the Rotliegend to the astronomical forced climate cycles of Milanković, it remains questionable if it will provide additional information on the spread of Rotliegend reservoir.

### 3.3.2 Reservoir Effectiveness

The Rotliegend reservoir effectiveness CRS map (figure 3.12, page 20) yields some unexpected results. POS variations on this map are caused by depth, tectonic inversion, changing reservoir facies or non-deposition of all the subplays. The inversion of the Broad Fourteens Basin caused a lower reservoir quality in the Upper Slochteren reservoir but not in the Lower Slochteren reservoir, resulting in only a partly lower aggregated POS in the Rotliegend play reservoir effectiveness CRS map. A higher quality in the Lower Slochteren reservoir at the same location as the lower quality Upper Slochteren reservoir is unexpected because the Lower Slochteren is buried deeper than the Upper Slochteren. Yet, the quality is confirmed by the Lower Slochteren well data and both the Lower Slochteren reservoir effectiveness CRS map and the Rotliegend Play CRS map are therefore an accurate representation of the reservoir quality data.

### 3.3.3 Top Seal

The Rotliegend seal CRS map (figure 3.16, page 24) does not show any unexpected results. The seal POS is rather high compared to the other CRS maps, which is the result of stacking several seals together. But also because the location and thicknesses of these seals are well known which results in a high POS. Seal effectiveness was not considered making this map.

There are three main uncertainties related to the seal. The most obvious uncertainty is related to location of the Zechstein salt pinch-out line. This problem is similar to the reservoir pinch-out of the Upper and Lower Slochteren. The Zechstein pinch-out line was based on Ten Veen et al. (2012), but a lateral displacement of this pinch-out has a high influence on the POS.

The second problem is related to the presence or absence of the three seals considered. Absence of all three is expected in the Texel IJsselmeer High, Elbow Spit High, Winterton High and London Brabant Massif. Presence of younger seals were not considered for this research but could be present at these locations, which is why a POS of 25% was acknowledged (50% play POS, 50% repeatability POS). This POS could be increased by risking the other seals. However, an increase of seal POS for these areas has a very low influence on the Rotliegend CCRS map, since the Rotliegend reservoir is also not expected on these highs.

In the absence of the main two seals, the Zechstein and Silverpit formation, the Main Claystone Formation was considered. No thickness map of the Main Claystone Formation exists, which is why the presence of the formation was based on 7.5km radius around 50-meter thick Main Claystone Formation in wells. This map could be improved by applying knowledge of the regional geology of the Main Claystone Formation.

### 3.3.4 Charge

The charge CRS map does not show any unexpected features, since it is a mere combination of the Westphalian expulsion map and the Charge CRS map made by Hanemaaijer (2020). The weakest play element map of the Rotliegend CCRS map shows that the charge forms a limiting factor in the K and E blocks. In the E-blocks charge has a low POS due to the lack of source rocks so the limiting factor is the CCRS map is expected. In the K blocks finding charge is still very likely, so the inhibiting play element risk is much lower.

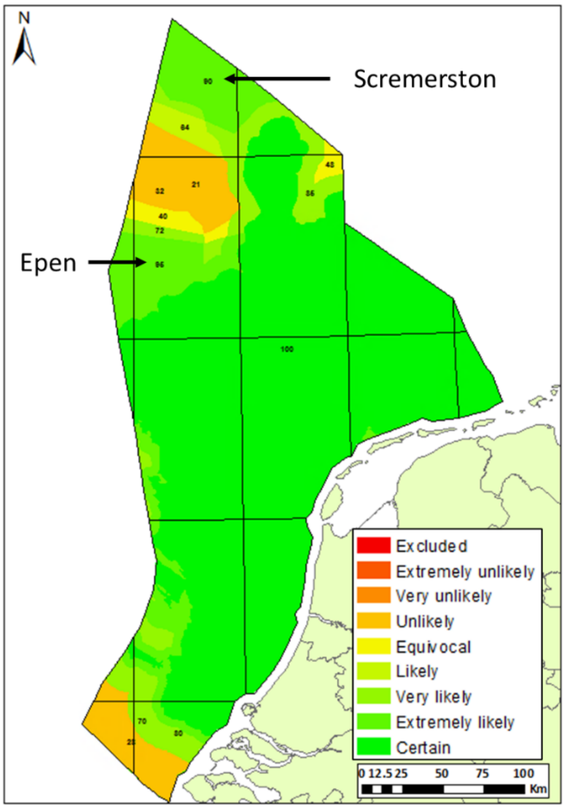


*Figure 3.30. Charge CRS map of the Rotliegend Play with the Scremerston and Epen polygons highlighted in the Northern Offshore region.*

Timing and maturity of the Epen and Scremerston source rocks has not been considered in the creation of the charge CRS map, the polygons based on these formations in the Northern Offshore area being not entirely consistent with the Westphalian CRS map (Hanemaaijer, 2020). Additionally, Hanemaaijer (2020) artificially increased the POS on his charge CRS map to counter the low POS of vertical migration through the Zechstein, but this does not result in a large discrepancy in the POS between the polygons based on the Westphalian in the Westphalian CRS made by EBN and Hanemaaijers charge CRS map. The largest influence of the increased POS will therefore be seen at the Epen and Scremerston polygons (figure 3.30). It could therefore be argued that the POS assigned to these polygons should be lowered to counter for the low level of knowledge. However, expulsion from the strata in the polygons discussed is proven by wells incorporated in the EBN hydrocarbon database (Hanemaaijer, 2020). The relative high POS of the Scremerston formation in the polygons is more reasonable when the cross-border features are considered. Scremerston formation is proven by several UK and German wells with considerable thickness and is regarded as one of the most promising source rocks of the Carboniferous next to the more widely studied Westphalian source rocks (Houben et al., 2020). The polygon which should be mostly influenced by charge from the Epen formation may also be in range of lateral migration from the Westphalian source rocks. Aside from the Epen and Westphalian source rocks other source rocks in the Yoredale formation are present and can form a source for charge. The relatively high POS for the charge was therefore not changed. Yet the Rotliegend CCRS map is sensitive to a change in POS for these polygons. A change of 10% charge POS results in a decrease in CCRS POS of 5%. A change of 20% charge POS results in a decrease of CCRS POS of 10%.

# 4. Volumes of the Rotliegend play

## 4.1 Methods

### 4.1.1 Creaming curve

The volumes of a hydrocarbon play can be evaluated with a creaming curve. A creaming curve is a diagram which shows the cumulative resource volumes from a play over the number of wells. A pseudo creaming curve shows the same data, but over time. The main principle of a creaming curve analysis is that big discoveries are typically made early in the history of a play and that the number of large discoveries and the size of the discoveries tends to decrease over time. The creaming curve provides therefore information about the discovery stage of the play. When the curve flattens the play is in its creaming phase. In this phase, discoveries are still made but the volumes are small. The curve can then be extrapolated to get an idea of the Yet-To-Find (YTF) volume. Based on the principle that discovery size decreases over time, late large finds cannot be predicted. Another complicating factor in predicting the YTF using a creaming curve extrapolation is that large plays, such as the Rotliegend play, often have several plateaus, which can correspond to new geological ideas (Snedden et al., 2003). While evaluating volumes of the past is useful to understand the controls of the attractiveness of the play, the extrapolation of the creaming curve for the Rotliegend play will have limited value and is therefore not included in this research.

### 4.1.2 Yet-to-find

Sections 4.1 to 4.3 have been blanked in the public version in view of confidentiality.

# 5. General discussion

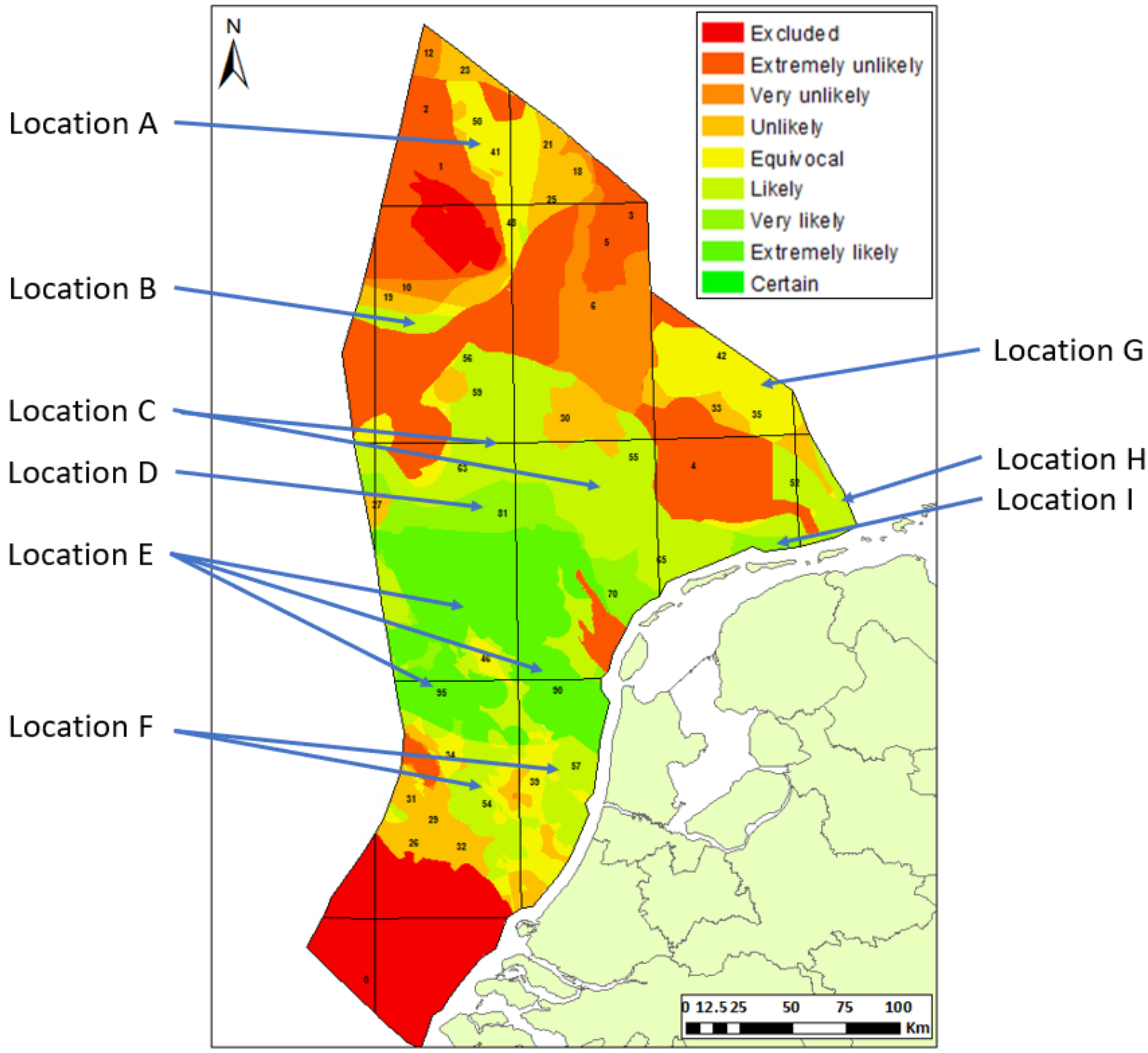



*Figure 5.1. Rotliegend CCRS map in which several locations are highlighted by arrows and discussed in this section. Location E has the highest potential of finding hydrocarbons.*

Figure 5.1 shows the Rotliegend play CCRS map, which describes the geological risk of the entire play. Areas with a high POS are marked in green and have a high probability of encountering all play elements. The area with the highest POS is location E, followed by location I and D, all located in the Feather Edge area.

## 5.1 Feather Edge

The Feather Edge area is the traditional Rotliegend play region. The area with the highest potential of finding hydrocarbons in the Rotliegend is in location E, located in the southern K and L offshore blocks. The southern border of location E is dependent on the pinching out of the Zechstein salts. The northern border depends on the extend of the Upper Slochteren member northwards and the depositional facies. The POS transition to the west is determined by the charge CRS map. Towards the east seal presence forms a limiting factor. This area partly located in the Broad Fourteens Basin, which has a high reservoir effectiveness risk. The attractiveness of this region is confirmed by a large presence of resources and reserves (figure 4.3;4.4 page 42)

Another successful region according to the CCRS map is the south-eastern polygon in the M block, location I. Location I is located just north of the Ameland field, a large Rotliegend field on Ameland, but the attractiveness of this offshore region is not confirmed by the resources and reserves from the EBN database. The lack of reserves and resources in this region cannot be explained by the CCRS map. This could either be the result of local geological variations not considered by this play map that should come up when assessing prospect focus or by non-geological factors such as legislative and political aspects.

Location D also shows a high density of resources and reserves but is limited by the reservoir POS. Paleotopography influences the POS of the Lower Slochteren reservoir while the quality of the Upper Slochteren reservoir is influenced by thinner lacustrine deposits. It could be argued that the combined reservoir would result in a thick, high quality reservoir. With the majority being fluvial and a small part being lacustrine deposits. The total POS for reservoir would increase and result in a higher CCRS POS for the Rotliegend play. Although the Rotliegend CCRS map does include risk for both Lower and Upper Slochteren, such a combination of the two reservoirs cannot be made in Player. A complicating factor would be the intraformational Ameland seal. In a part of this area the Ameland seal is considered leaky, because it is below the required 50 meters thickness. This does not influence the Rotliegend CCRS map because of the methodology used for the map stacking but can influence the quality of the Rotliegend reservoir if both the Lower and Upper Slochteren members are added up as one reservoir. The POS of 81% on the CCRS map is therefore reasonable.

The biggest influence on location C is the decrease of reservoir quality by gradual facies change towards the north. While this involves a gradual change over a large area, a similar change over a small space cannot be visualized, which leads to a high POS neighbouring a low POS, such as at the northern border of location C. Towards the Dutch Central Graben depth increases quickly, which has a great effect on the POS because of the influence on reservoir quality.

Location F has a similar POS as location C but is controlled by seal and trap risks. Reservoir is thick and the area is cut in two by a lower reservoir quality zone in the Broad Fourteens Basin. To the north this location neighbours a location E by the southern Zechstein salt limit. Due to lack of Zechstein salts and possible reservoir potential of the Zechstein located above, the chance of finding a suitable trap is lower or it requires a larger hydrocarbon column. The exact POS for trap needs to be assessed on prospect level.

## 5.2 Eastern and Northern offshore

The highest POS for the Eastern Offshore is located at the N-blocks, where the Ruby field was recently discovered. In context of the entire Rotliegend play, the presence of hydrocarbons is likely here. Distribution of the Basal Rotliegend Sandstones depends on paleotopography. A local structural high runs from the H-blocks towards middle of the N-blocks, resulting in a thinner reservoir on the high but thicker reservoir on the neighbouring local lows. This has a large influence on the CCRS POS. Whether this local high continues towards the G-blocks in location G is unknown.

Location G does not contain any reserves but does see an increase in resources. The POS of the area is mainly determined by the lack of data, resulting in an equivocal POS. Because all play elements are proven, an increase of data quality would benefit this area. Not only better-quality data, but also data from Germany could provide more regional information to this region.

Interest has increased in the Northern Offshore since the discovery of the Cygnus field. Yet this area is still susceptible to rapidly changing geological understanding of this area. The highest POS in the Northern Offshore region can be found in location B. Reservoir forms the main risk at this location. The location is bounded by low charge POS in the north east and low reservoir POS in the north and the south. Location B represents the Cygnus lake margin extrapolated towards the Dutch offshore (Heldreich et al., 2019). The same geology as location B is expected at location A, but the data quality on location B is better. The play POS of location A is not a 100%, meaning that the polygon could benefit from a well. The play POS of polygon B is 100%, meaning that an increase of data quality could aid the area.

# 6. Conclusions

This research aimed to identify the remaining resource potential of the Rotliegend play. Based on a quantitative spatial analysis of the regional geological risks, it can be concluded that the Rotliegend play still holds high potential for future discoveries in various regions. The Feather Edge area has the highest POS and holds the largest volume in resources and reserves. Yet other regions should be considered as well. These areas are annotated on the Rotliegend Play CCRS map in figure 5.1. The main inhibiting play element for the Rotliegend play is the reservoir, south of the Zechstein salt pinch-out line, seal and trap are the main risks.

Reserves are present in the traditional Rotliegend play fairway, with the Upper and Lower Slochteren members as reservoir and Zechstein as a seal. The only exception from this rule is the Ruby field, where the Basal Rotliegend Sandstone member acts as a reservoir. Next to the traditional fairway, the distribution and quantity of the resources shows an increase in volumes for the Basal Rotliegend Sandstones member in the N and G blocks. The similarly recently confirmed northern fringe sands do not show the same increase. Next to new reservoir concepts, the distribution of resources also shows an increase in the P and Q blocks, possibly relating to non-traditional trap seal configurations.

Based on available data and the scope of this project, the missing fields methodology is the best way to analyze the YTF volumes. The statistical analysis shows that the YTF volume is very sensitive to the increase of minimum field sizes, which is in turn influenced by the geological, political and technological developments. This has been confirmed on historical data through creaming curve analysis.

# 7. Recommendations

This research provides a combination of the current available public literature and data on a regional scale for the Rotliegend play to assess the geological risks in a simple and concise manner. To finish the PBE workflow, the prospective regions identified by this research could be further investigated. Also, when new information becomes available, updating Player project should be considered to keep the project relevant.

In the upcoming years, some pipe-line infrastructure will close in the Dutch offshore which will have a spatially varying impact on the minimum field size and thus on the YTF volumes. To better understand this spatial relationship, the Player database of this project could be extended with post drill well analysis and trap data to visualize the YTF volumes on a spatial scale. Comparing the spatial YTF volumes with closing infrastructure can provide valuable information about where the loss of YTF will be the greatest.

For future CRS and CCRS mapping, a clear generalized workflow for the split risking should be considered. The great advantage of this would be to have the ability to compare different plays to each other, which is currently not possible.

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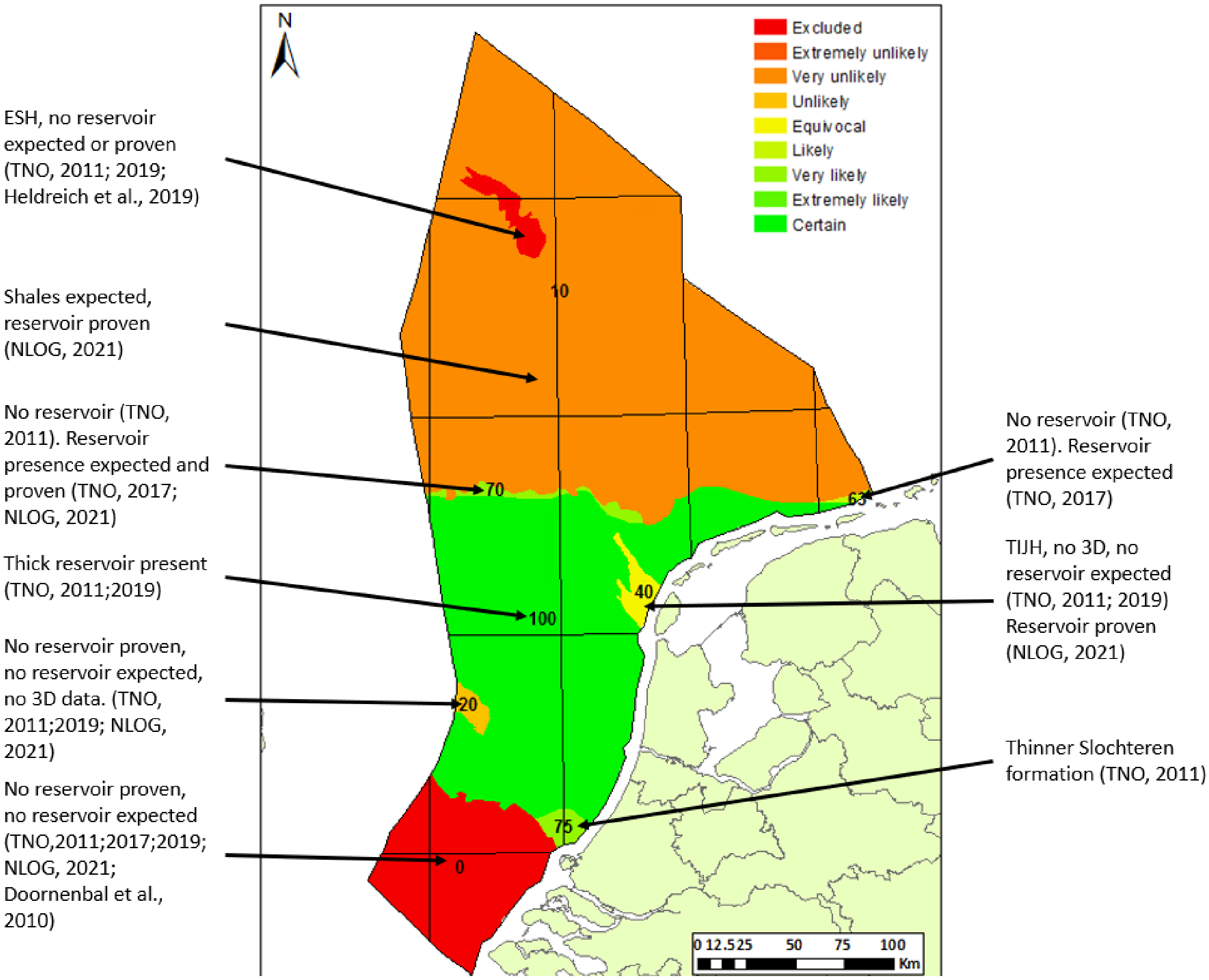
# 10. Appendices

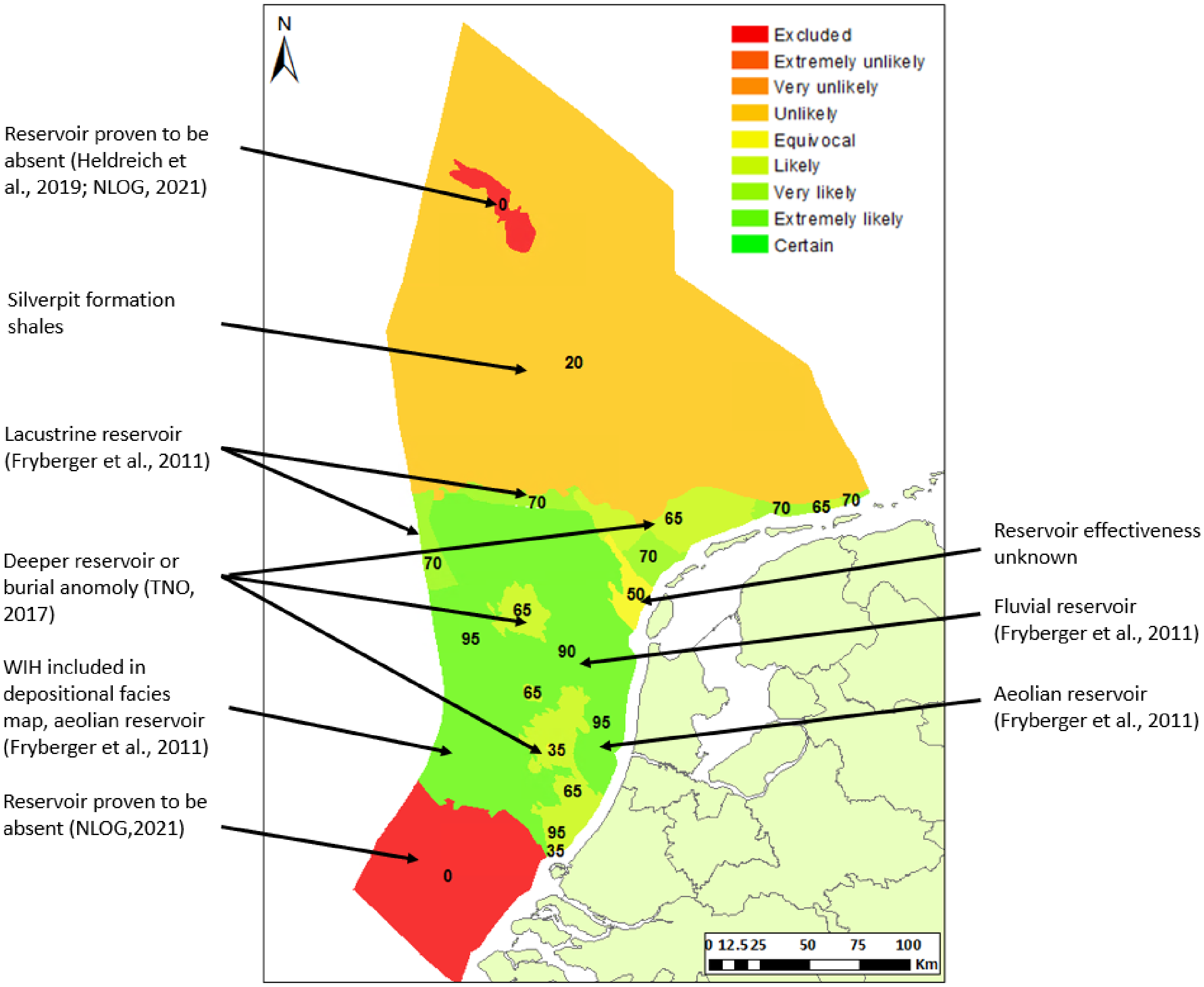
## 10.1 Appendix 1 - Synthesis of the (C)CRS maps

### Upper Slochteren subplay

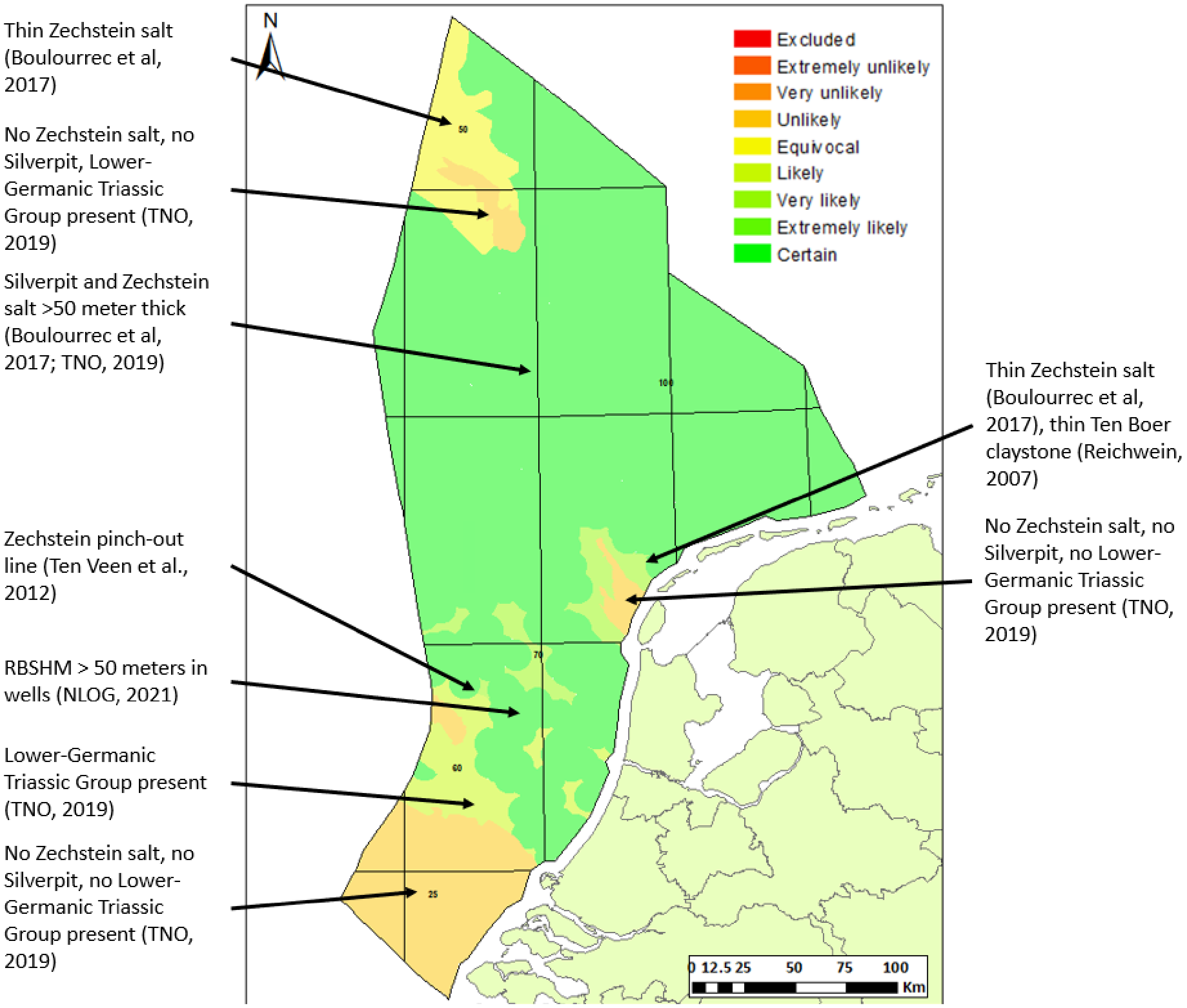
*Upper Slochteren subplay reservoir presence CRS*



*Upper Slochteren Reservoir effectiveness CRS*

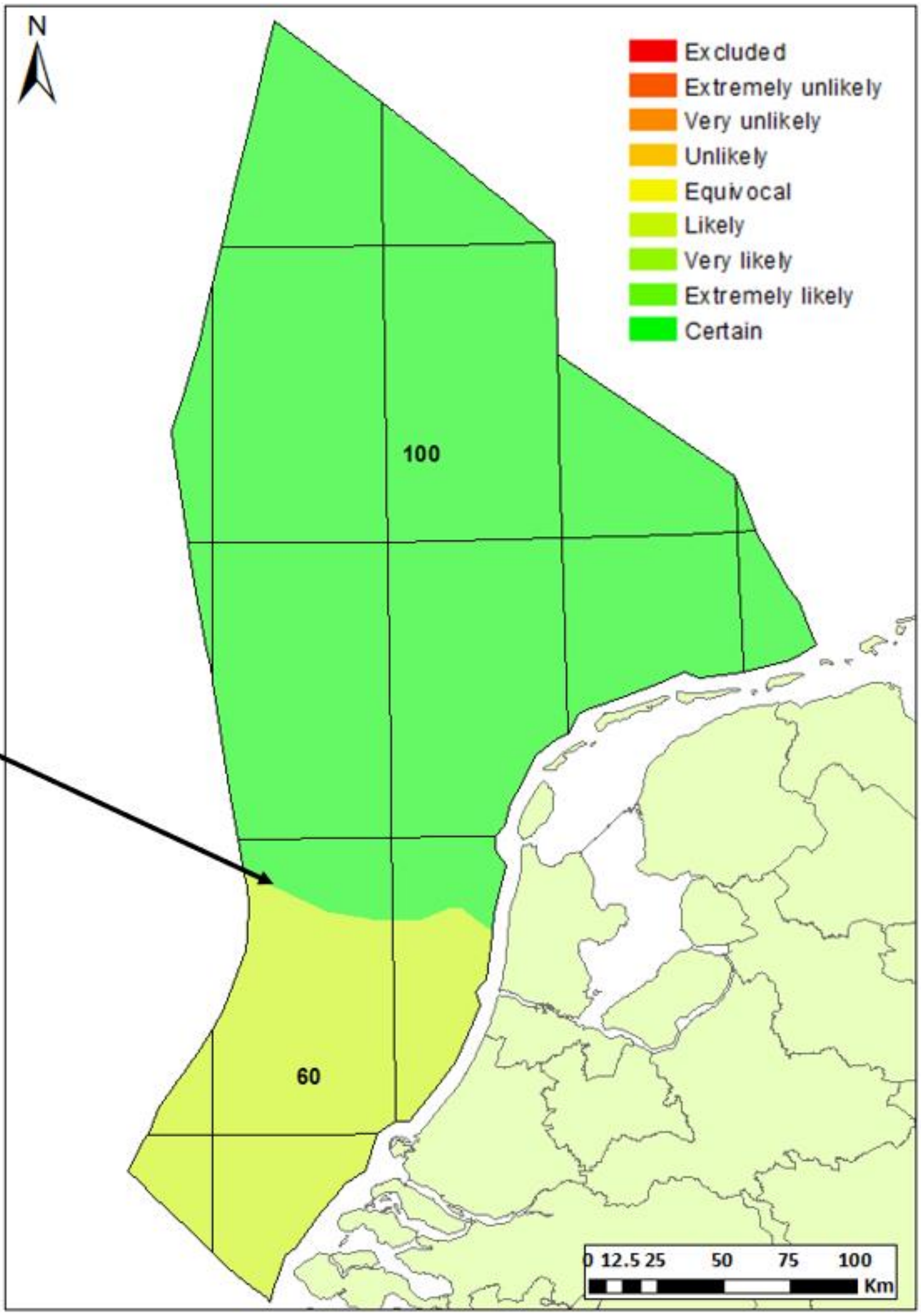


*Upper Slochteren Top Seal Presence*

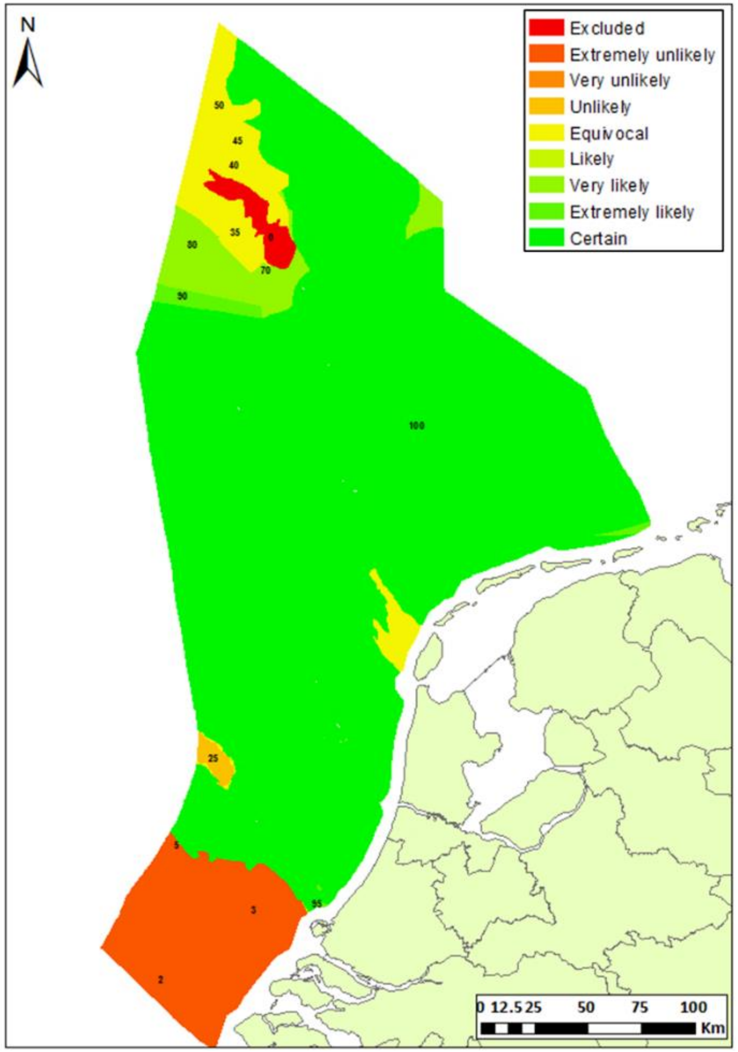


*Upper Slochteren Trap CRS*

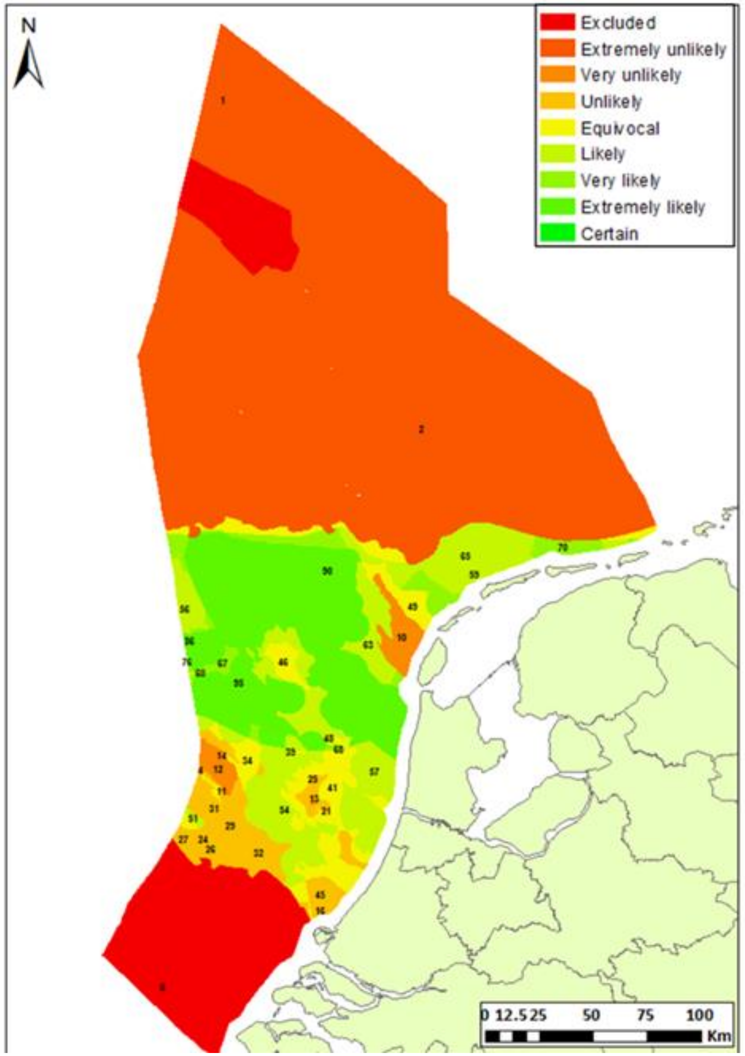
Zechstein pinch-out line (Ten Veen et al., 2012)



*Upper Slochteren Subplay CCRS maps*



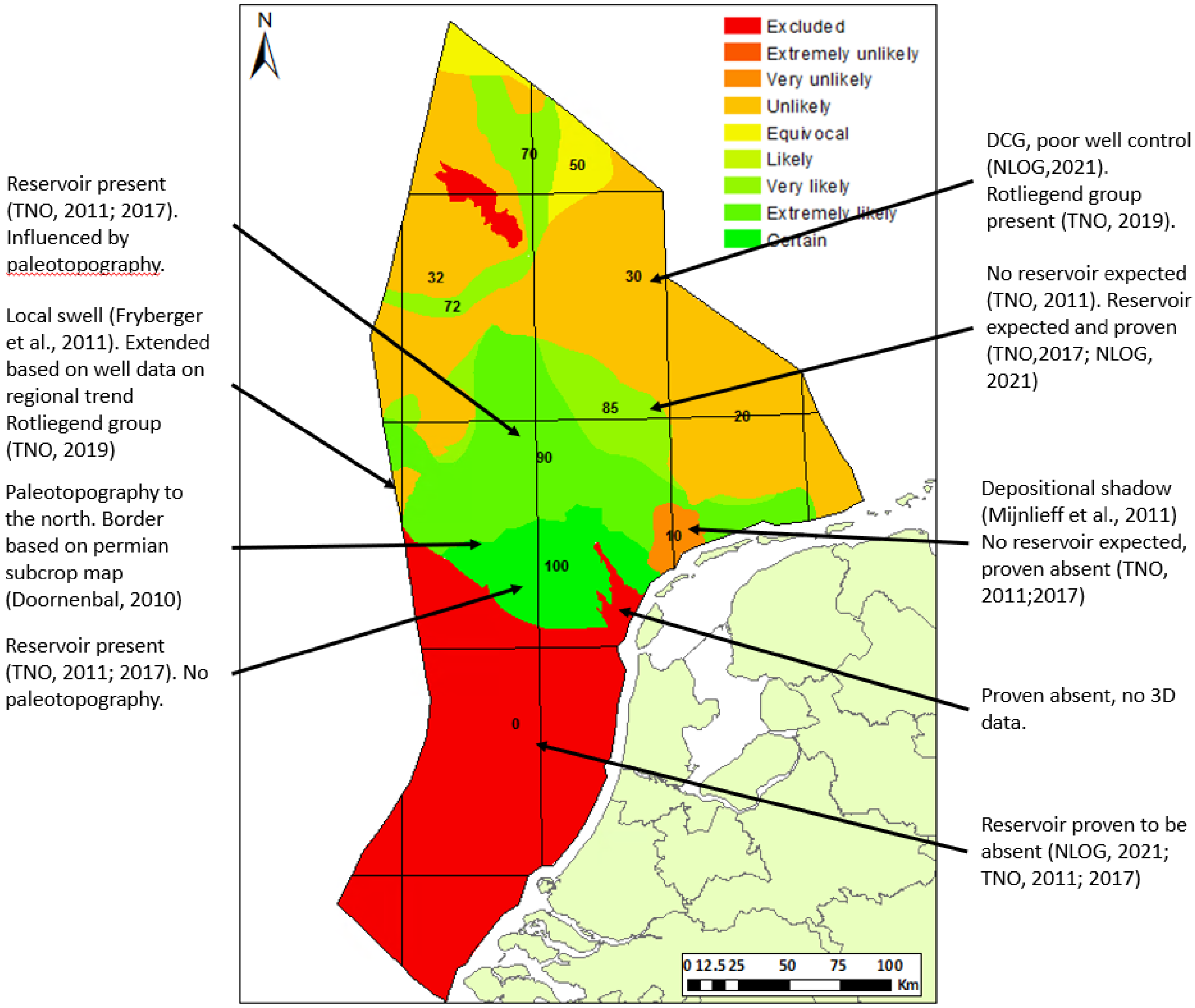

*Play POS CCRS map of the Upper Slochteren subplay. Play POS is 100% when all play elements are proven.*



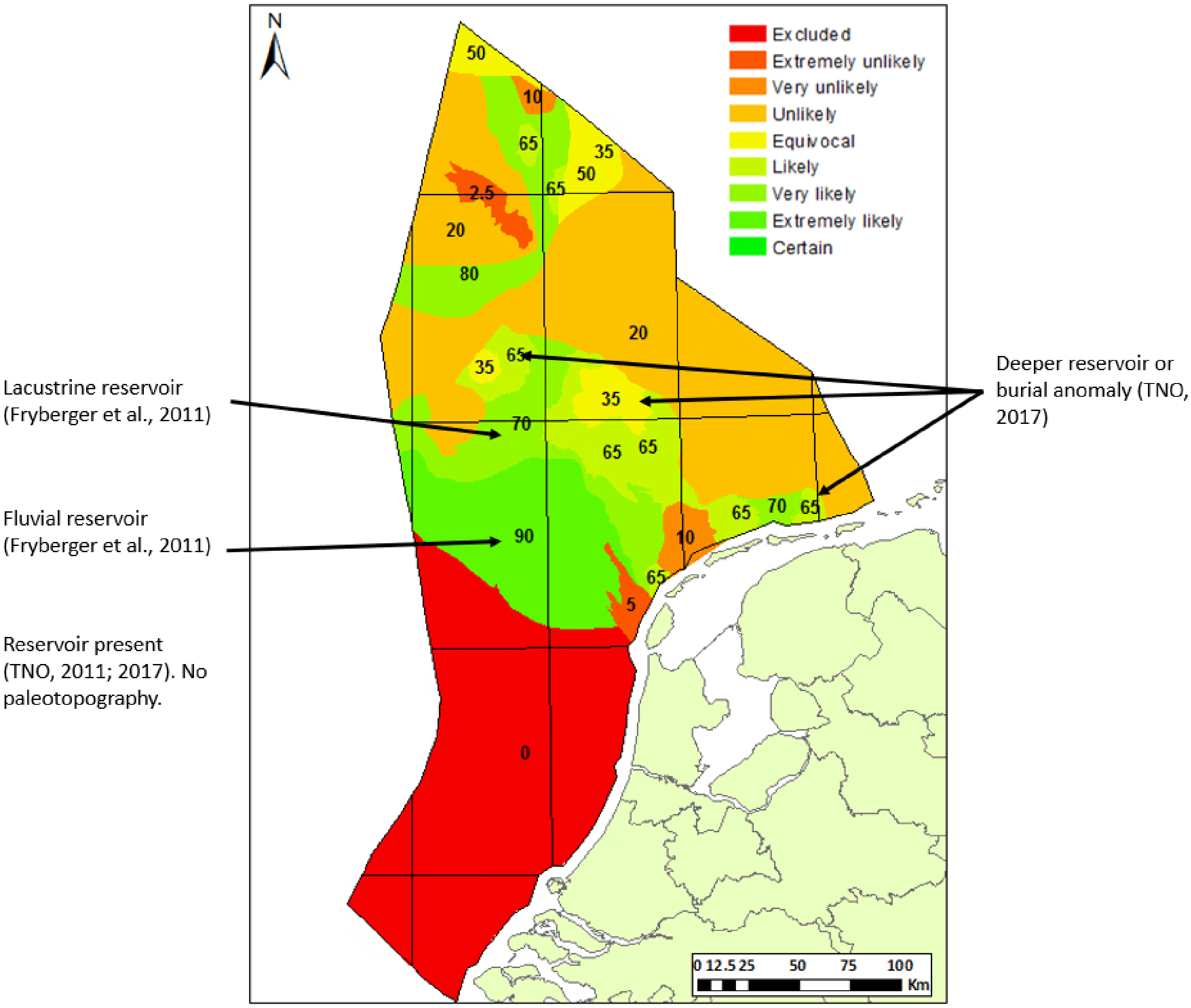

*Repeatability POS CCRS map of the Upper Slochteren subplay. Repeatability POS is 100% when either the geology is simple, or the data quality is high.*

## Lower Slochteren subplay

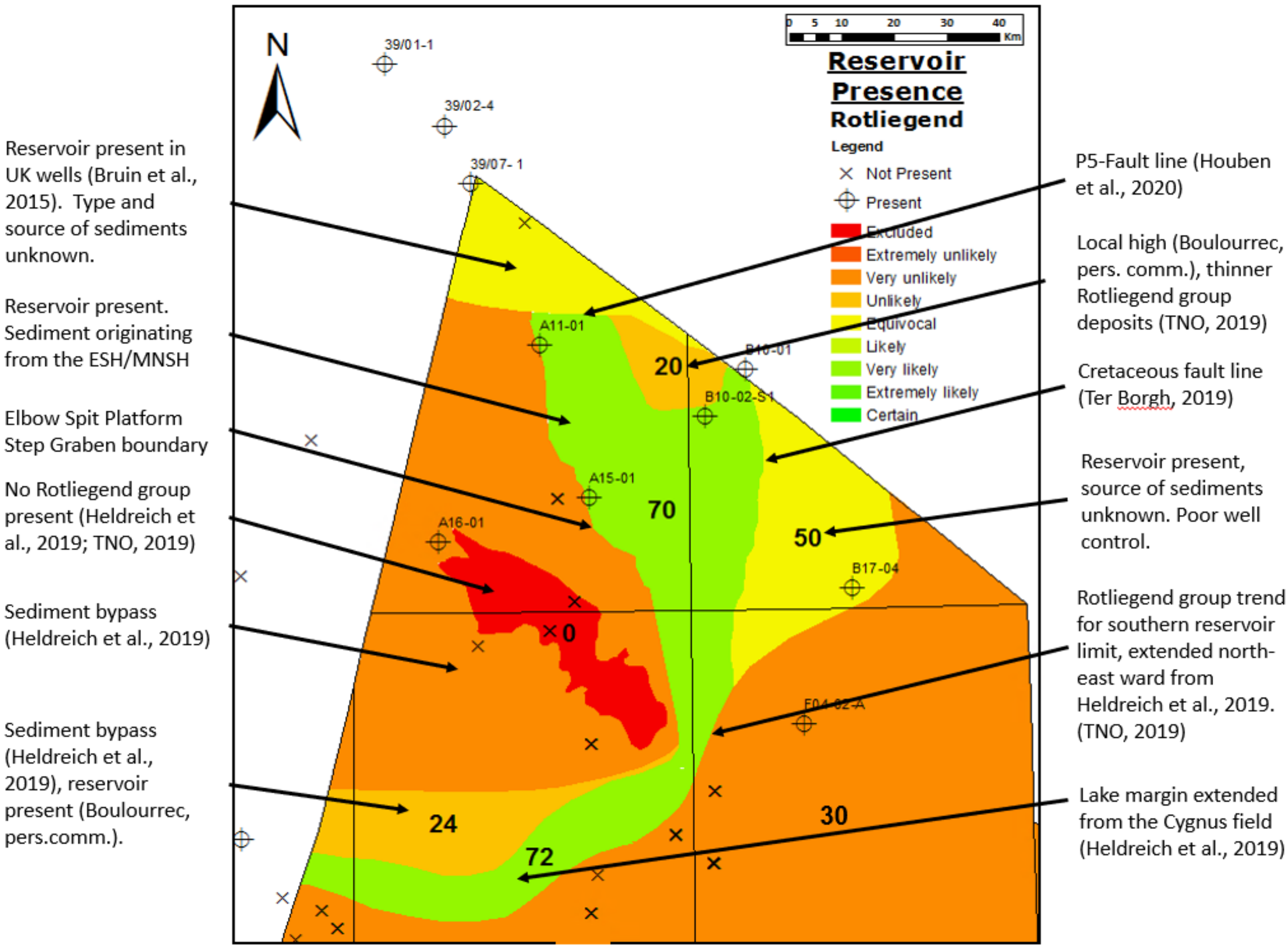
*Lower Slochteren Reservoir Presence CRS – Feather Edge*



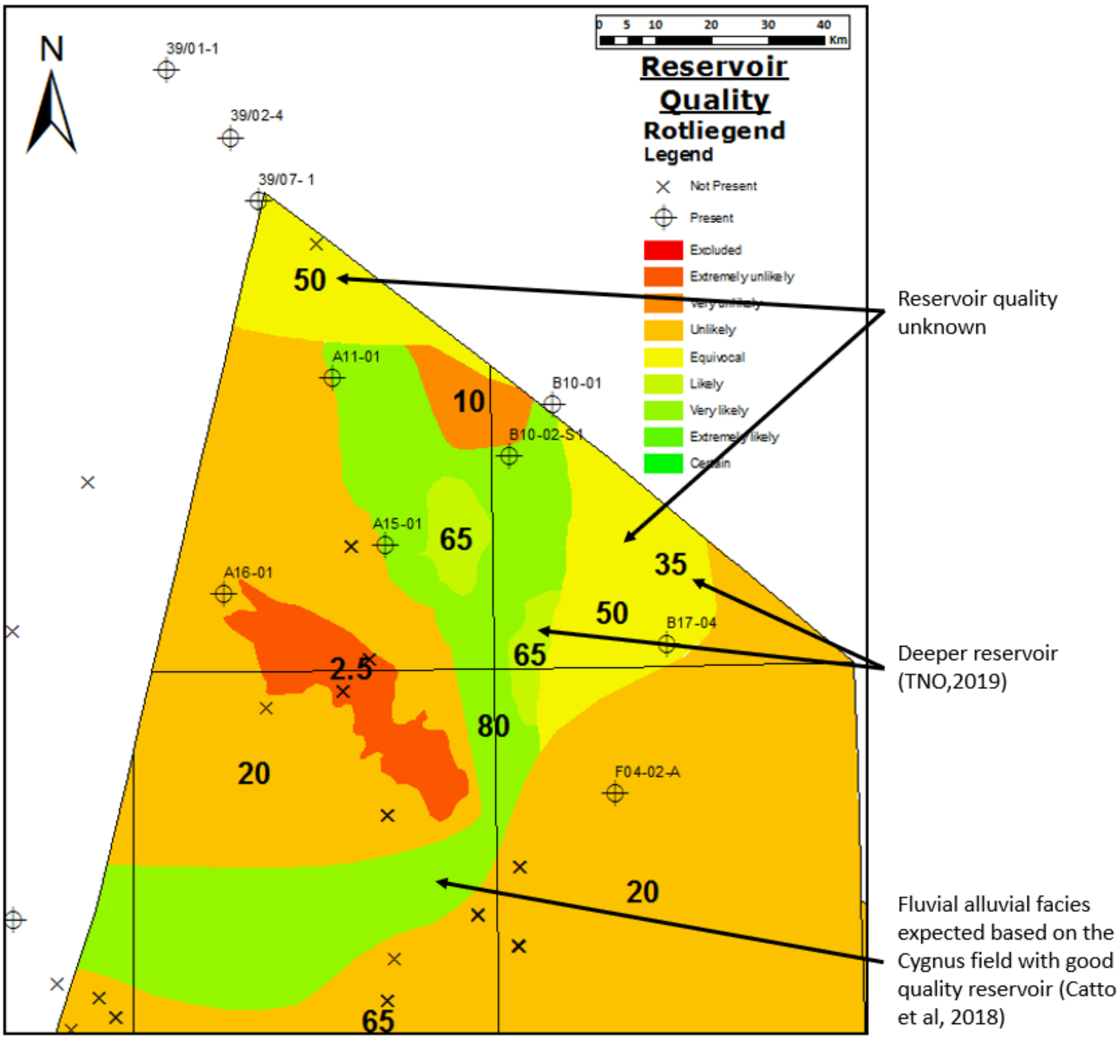
*Lower Slochteren Reservoir Effectiveness CRS – Feather Edge*



*Lower Slochteren Reservoir Presence CRS – Northern Offshore*



*Lower Slochteren Reservoir Effectiveness CRS – Northern Offshore*

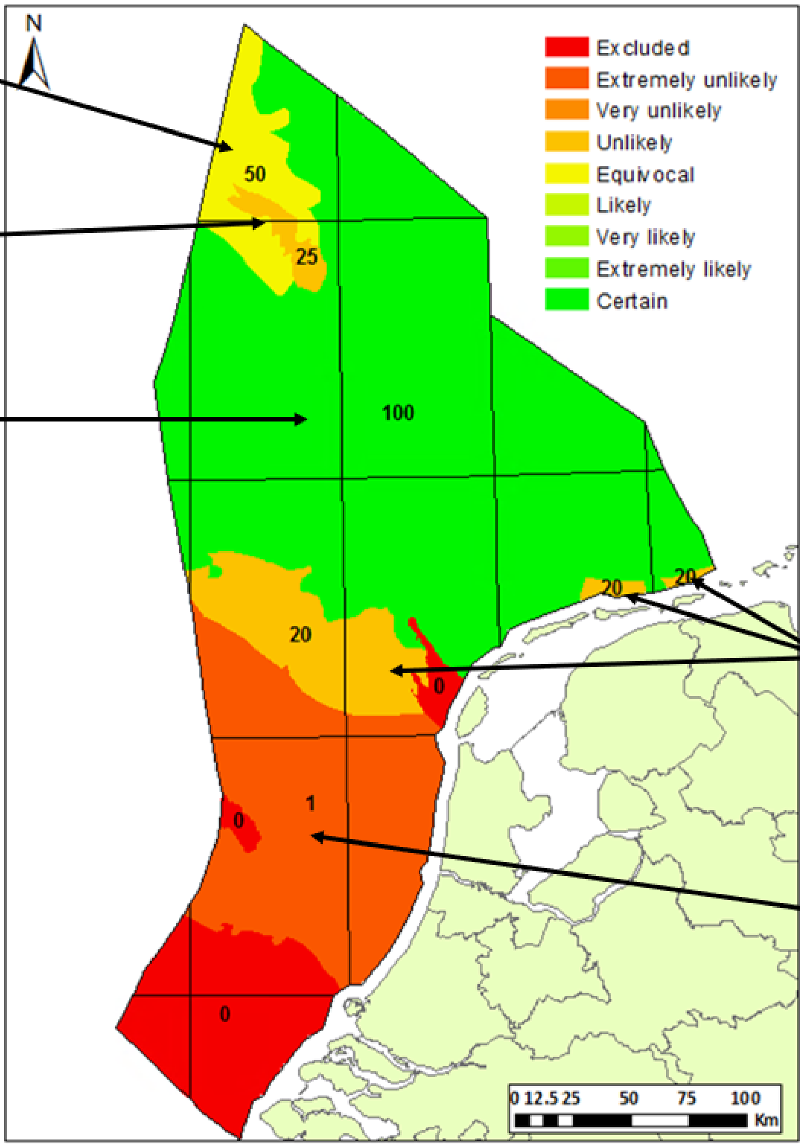


*Lower Slochteren Top Seal CRS*

Thin Zechstein salt, thin Silverpit formation (Boulourrec et al, 2017)

No Zechstein salt, no Silverpit, Lower-Germanic Triassic Group present (TNO, 2019)

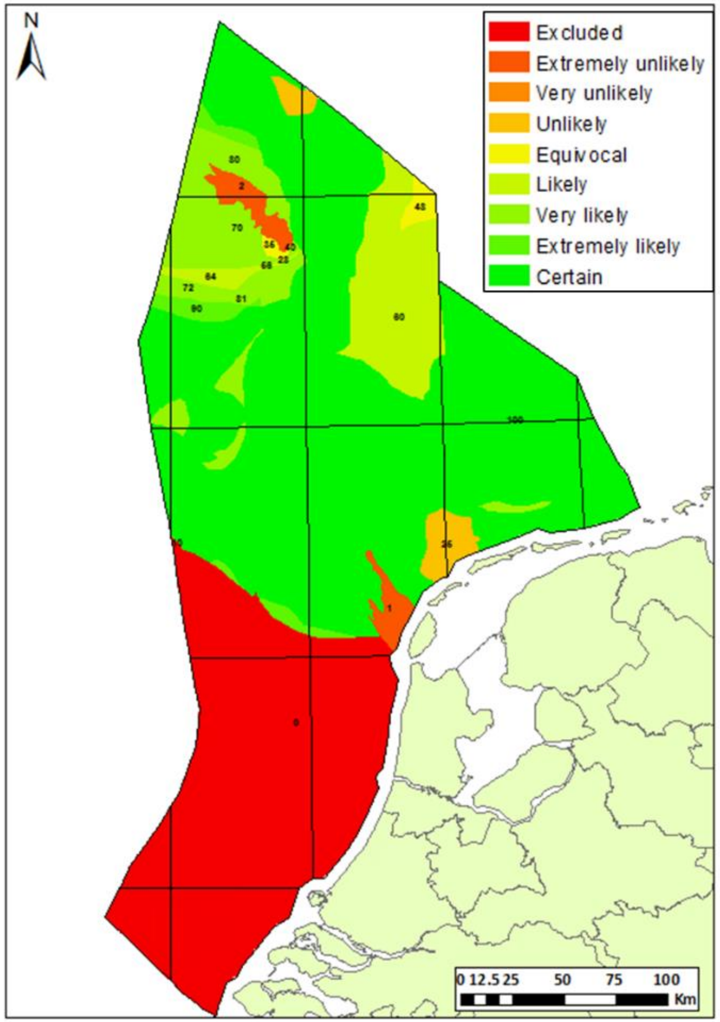
Thick Silverpit formation, no Upper Slochteren (TNO, 2017; 2019)



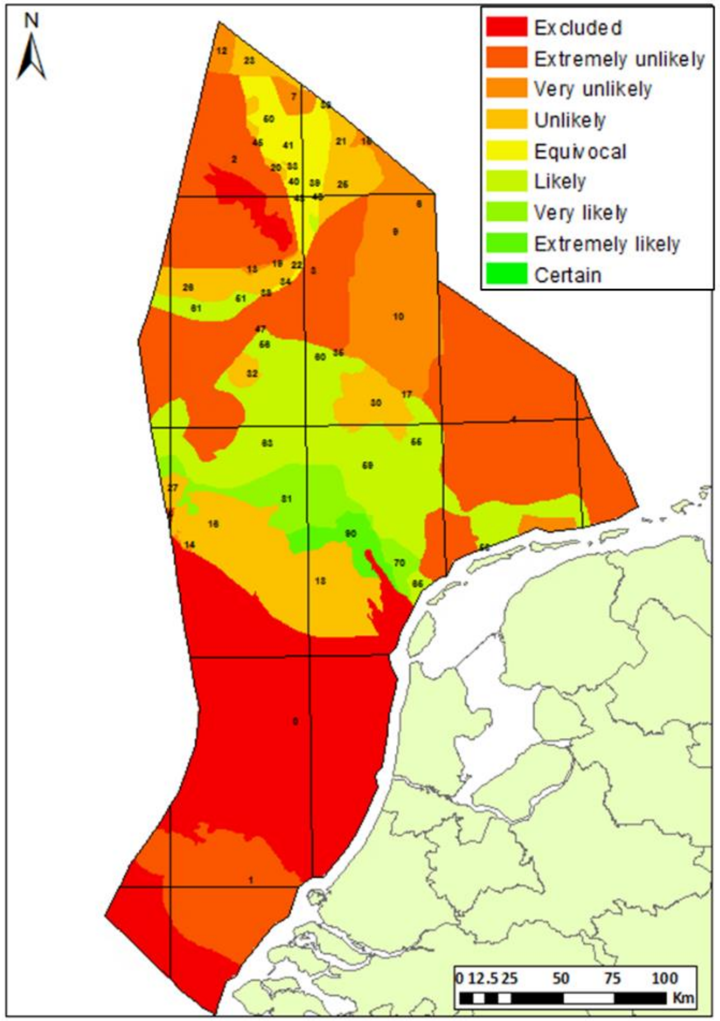

Thinner Ameland seal (<50 meters) (Mijnlieff et al., 2011)

Ameland seal proven by one well, but thin and not expected (NLOG, 2021)

*Lower Slochteren subplay CCRS maps*



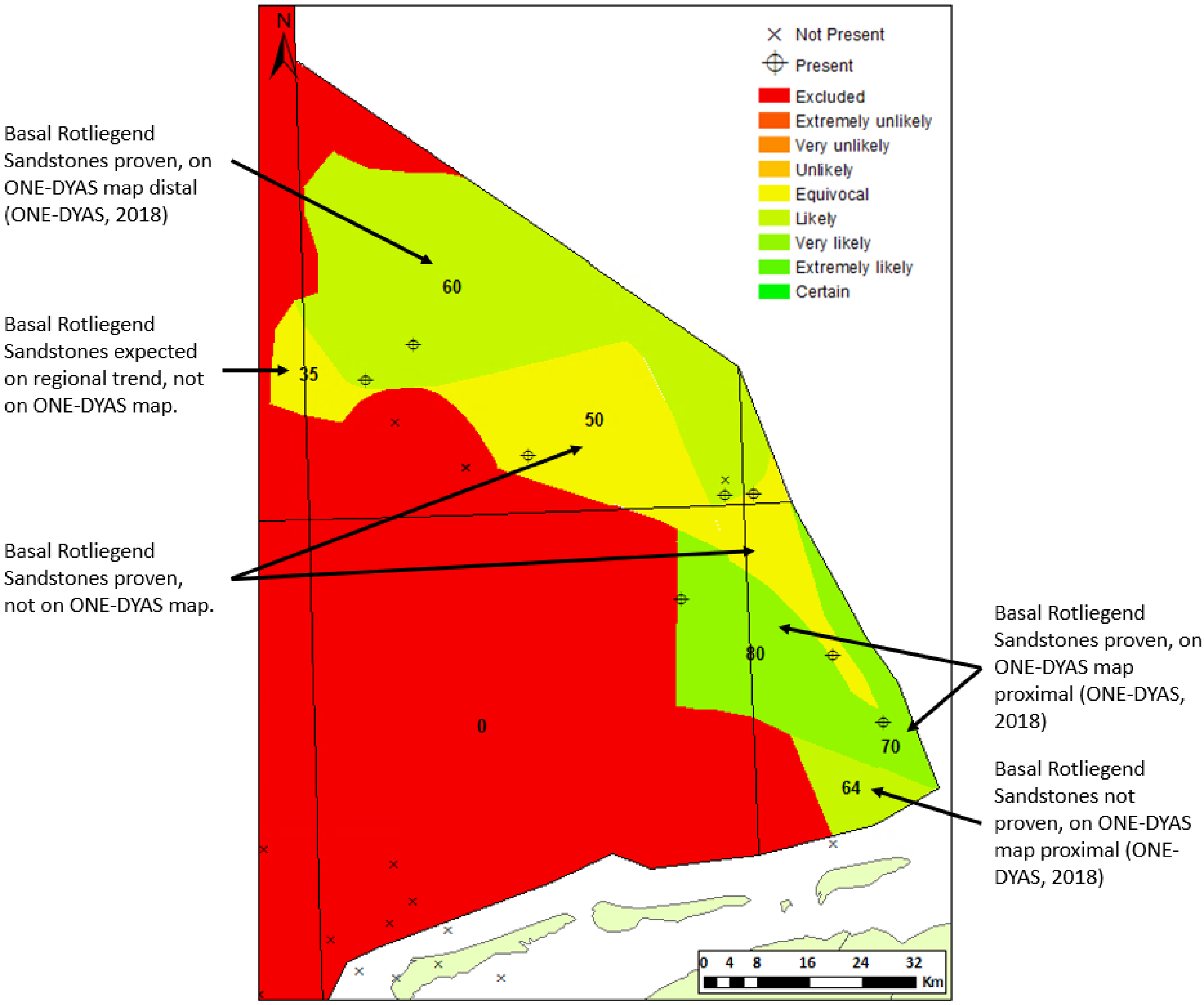

*Play POS CCRS map of the Lower Slochteren subplay. Play POS is 100% when all play elements are proven.*



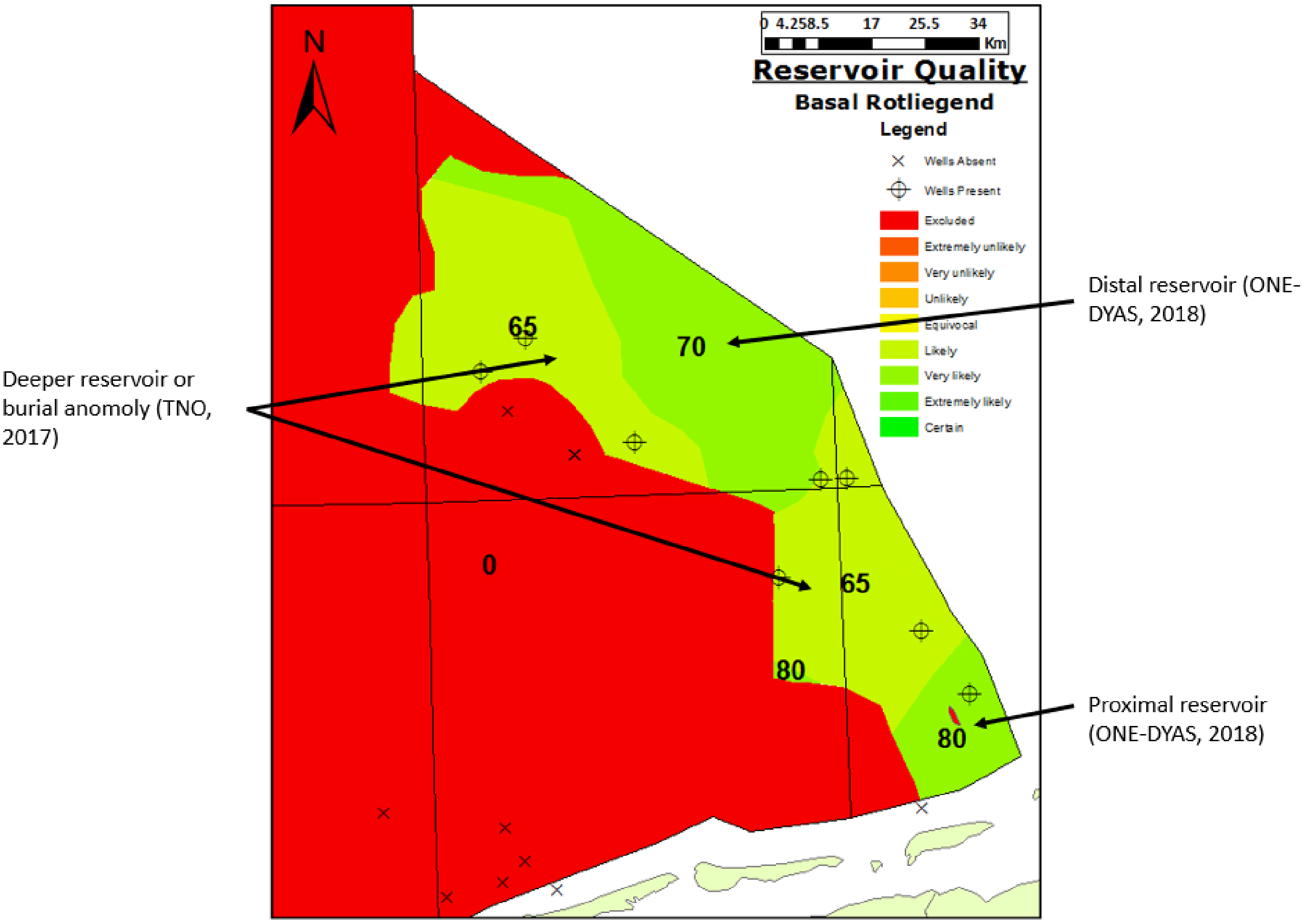

*Repeatability POS CCRS map of the Lower Slochteren subplay. Repeatability POS is 100% when either the geology is simple, or the data quality is high.*

## Basal Rotliegend Sandstones

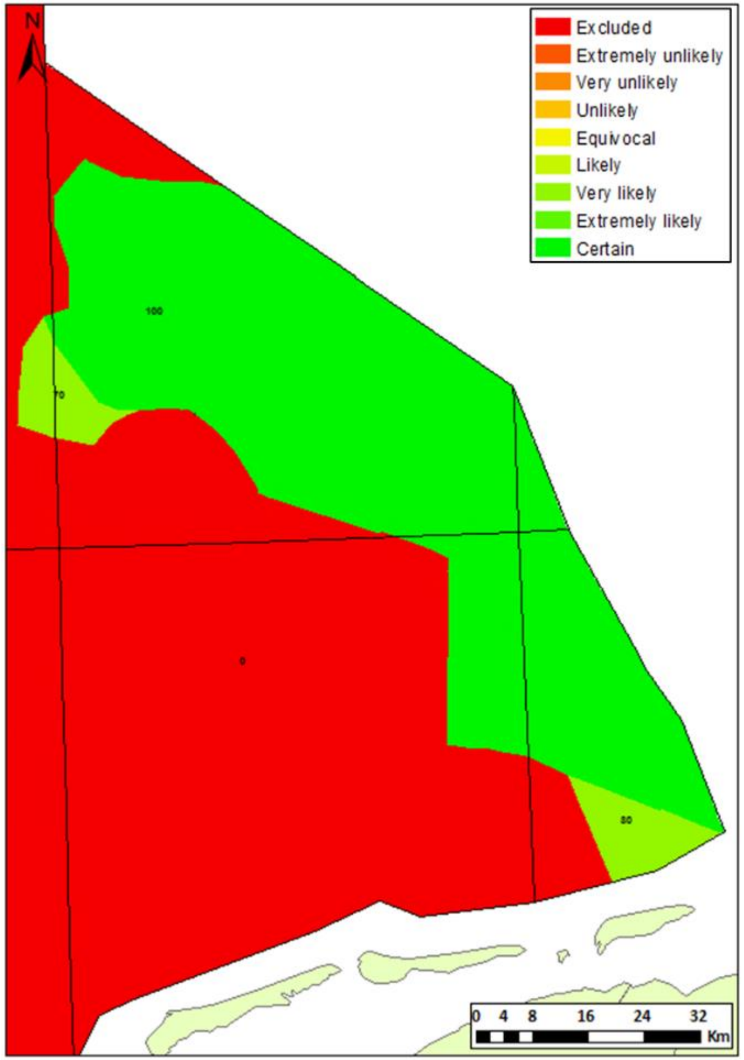
*Basal Rotliegend Sandstones Subplay Reservoir Presence CRS*



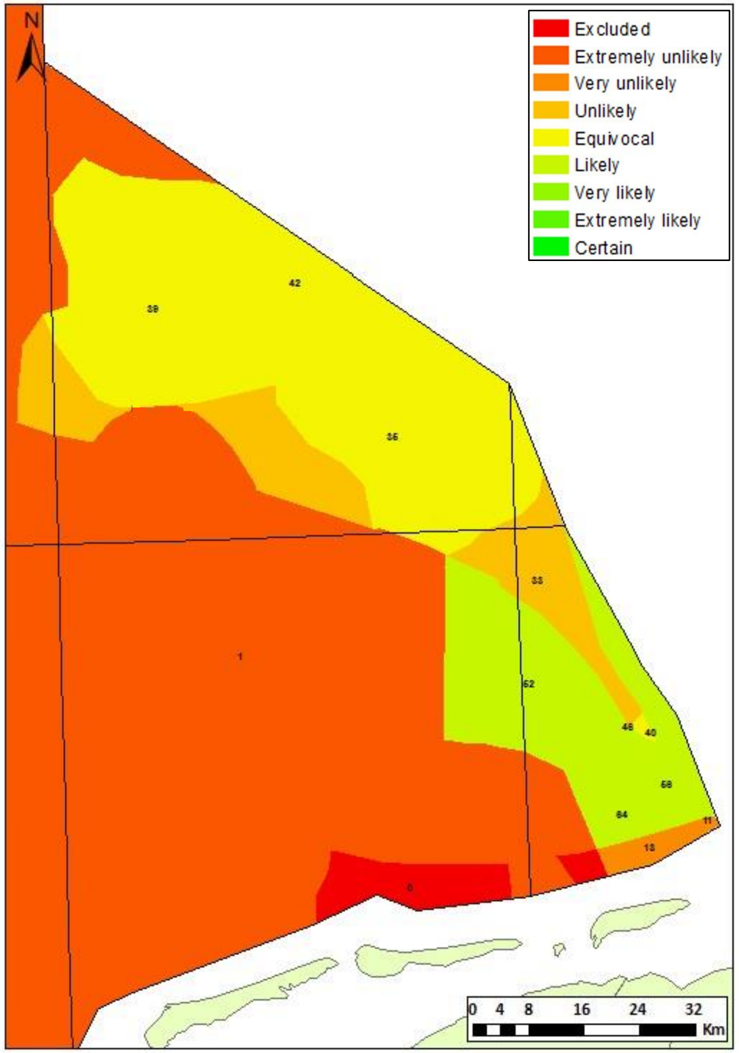
*Basal Rotliegend Sandstones Subplay Reservoir Effectiveness CRS*



*Basal Rotliegend Sandstones Subplay CCRS maps*




*Play POS CCRS map of the Basal Rotliegend Sandstones subplay. Play POS is 100% when all play elements are proven.*




*Repeatability POS CCRS map of the Basal Rotliegend Sandstones subplay. Repeatability POS is 100% when either the geology is simple, or the data quality is perfect.*

Appendix 10.2 has been blanked in the public version in view of confidentiality.