Zechstein Fringe Sandstone

Well correlation and reservoir quality of the Zechstein fringe sandstones in the Southern Dutch offshore

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Contents

Abstract

Keywords: Zechstein, Fringe sandstones, Well correlation, Reservoir quality, Petrel

Understanding the presence and quality of subsurface reservoirs is critical for Carbon capture and storage (CCUS), geothermal energy and the gas transition. In the Southern Dutch Offshore, the Zechstein Fringe Sandstone represents a potential reservoir. However, its distribution, stratigraphic correlation, and reservoir properties remain poorly understood. This study aims to define the occurrence, characteristics, and reservoir potential of the Zechstein Fringe Sandstone in the Netherlands, examine its relationship with the Hewett Sandstone in the UK sector, and identify areas with high reservoir quality, particularly in and around Blocks P10, P11, and P18.

To achieve this, well logs, core porosity-permeability data, and 2D/3D seismic datasets from both the Dutch and UK offshore were integrated. Using Petrel, well correlation panels and thickness maps were created to delineate the distribution of the sands and identify potential "sweet spots." The study provides an improved stratigraphic framework, subdividing the Zechstein Fringe Sandstone into multiple reservoir units and clarifying their lateral and vertical relationships.

Results reveal significant variability in thickness, facies, and reservoir quality across the study area. The correlation with the Hewett Sandstone suggests a broader depositional continuity than previously assumed. Several zones of favorable reservoir properties were identified, with implications for ongoing and future CCUS and energy transition projects. A key conclusion of this study is that the current well-top correlations between the UK and NL sectors are inconsistent and require revision, with proposed updates to be communicated to TNO. Notably, the Nederweert Sandstone in the P10/P11 area correlates with the ZEZ4S unit, which also shows strong correlation with the Hewett Sandstone in the Hewett Field. Several "sweet spots" with favorable reservoir properties were identified in the P10–P11 area. The reservoir quality of the Zechstein Fringe Sandstone is influenced by burial depth, presence of anhydrite cement, and proximity to the sediment source. Verification of seismic interpretations using non-confidential data proved challenging, highlighting the need for high-resolution 3D seismic data in the P10/P11 blocks to support further exploration.

This research will lead to insights into the thickness and distribution of the Zechstein fringe sandstones in the UK and NL offshore region, thereby contributing to reservoir evaluation for EBN and partners.

1. Introduction

The understanding of the presence and quality of reservoir sandstones is important for carbon capture and storage (CCUS) as well as the heat- and gas transition. The best-known sandstone reservoirs in the Netherlands (NL) are the Permian Rotliegend and the Triassic Bunter sandstones. The interval between the Upper Permian Rotliegend and the Lower Triassic lower Bunter, the Zechstein, contains mostly claystone and evaporites in NL.

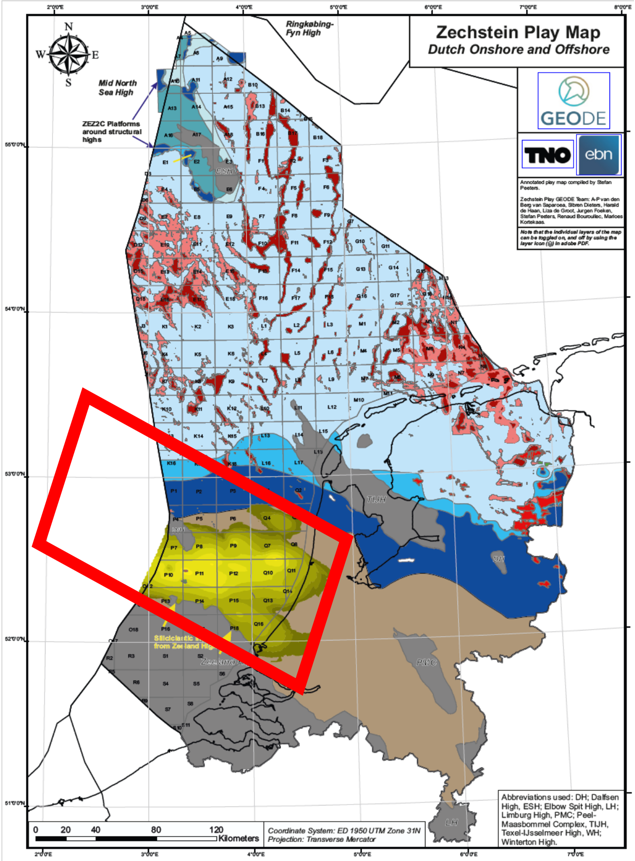

Figure 1 Zechstein Play Map of the Dutch Onshore and Offshore (Kortekaas et al., 2024) showing the Zechstein Fringe Sandstones . Study area indicated in red.

The EBN-TNO Geode project provides an atlas of the subsurface resources in NL. In doing this they have confirmed that one area of the Dutch offshore does not comply with the claystone and evaporite findings, namely quadrants P and Q.

In this area the Zechstein is found to be a sandy reservoir facies (Figure 1). Gas field Q10-A already produces from this reservoir and in blocks P10-P11 there are plans for further exploration of these facies. This sandstone interval is divided into various '' Zechstein Fringe Sandstone'' members ZEZ1S, ZEZ2S, ZEZ3S and ZEZ4S (Bourellec & Geel, 2025). However, their correlation remains uncertain.

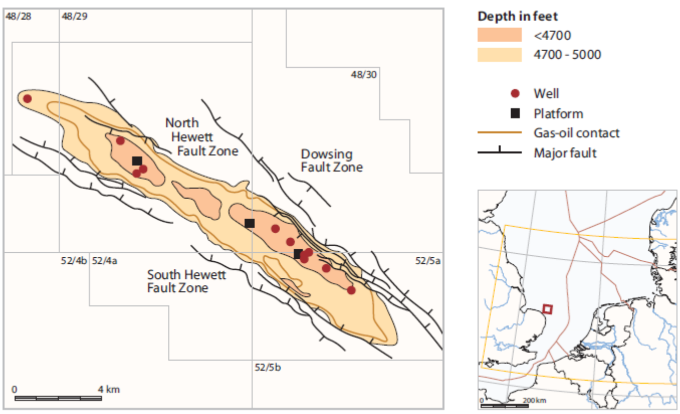

Figure 2 Depth to the Top of the Hewett Zechsteinkalk in the Hewett field (after Southwood & Hill, 1995) (Peryt, 2010).

Adjacent to the Zechstein Clastics of the Dutch offshore lies the Hewett Sandstone of the British offshore. This facies is placed at the base of the Triassic. However, it is suspected to correlate to ZEZ4S (Geluk, 2005) The Hewett sandstone is an important reservoir as it composes the main reservoir in the Hewett Gas field (average porosity 23%), from where over 57 bcm gas has been produced (Figure 2). The total gas volume of the Hewett sandstone accumulation of both the bunter and Hewett sandstone is 74 bcm, with over 96% recovery factor (Peryt, 2010), of which 57 bcm comes from the Hewett sandstone. The overlying Bunter reservoirs, comprising the Lower and Upper Bunter sands of the Bacton Group, are also a well-known high-quality reservoir unit. Both formations possess many of the characteristics required for CO2 storage, including extensive traps, high porosity and permeability and a thick laterally extensive seal above in the Haisborough group (Kingsnorth, 2011).

Since the 1990s few regional studies have been performed at this interval, while a lot of new information has become available.

1.1 Aim of the Study

This project aims to define the **occurrence, characteristics, and reservoir potential** of the **Zechstein Fringe Sandstone** in the Netherlands, while exploring its relationship with the **Hewett Sandstone** in the UK and identifying new areas of good reservoir quality. To achieve this aim, multiple research questions will be answered in this study:

1) The occurrence of the Zechstein Fringe Sandstone in NL will be better defined, both horizontally (on a map) as well as vertically (divided into reservoir units).

2) The relation between the Zechstein Fringe Sandstone in NL and the Hewett Sandstone in the UK will be explained.

3) The thickness, facies and reservoir quality of the different units are determined.

4) ''Sweet" spots of good reservoir quality in the Zechstein fringe Sandstone are better identified.

This is done with the use of well logs, porosity-permeability core data and 2D and 3D seismics of both the NL and UK offshore. Using Petrel software, this data is used to create well correlation panels, thickness maps, find areas of good reservoir quality and to verify these findings on seismic data.

Knowledge of the presence of good reservoirs is important for CCUS, Geothermal and Gas. This study could influence the plans for exploration in blocks P10 and P11 and help understand the reservoirs surrounding the CCUS Porthos project (Block P18). Therefore, lots of new seismics are being acquired and exploration wells are drilled to fill the remaining knowledge gaps in the subsurface. Thus, it is important re-correlate this interval, in both the Netherlands and the adjacent part of the British offshore.

This research will lead to insights into the thickness and distribution of the Zechstein Fringe sandstone in the UK and NL offshore region, thereby contributing to reservoir evaluation for EBN and partners. Moreover, it will enhance our understanding of the occurrence and distribution of the Hewett and Fringe sands in the UK and NL.

Furthermore, this study will provide insight into the geological history of the Zechstein Fringe sands and surrounding regions.

1.2 Study Area

A study area of ~35.000 km^2 was defined. The area of interest was determined by multiple factors. It had to include all Dutch wells that found Zechstein Fringe Sandstone, contain the Hewett field, surround the Hewett sandstone, and had to go along the strike of the faults and basins in the area. The study area mostly covers NL offshore quadrants P and Q, and quadrant 49, 52, 53 and 54 of the UK offshore.

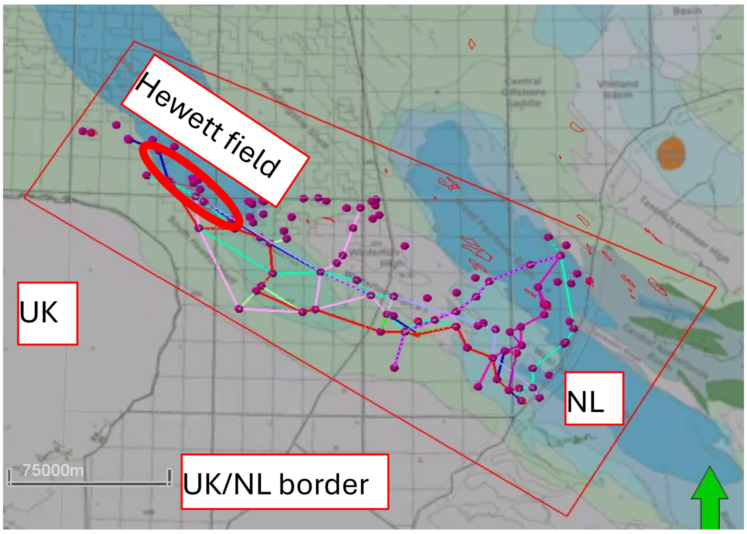

Figure 3 Study area is indicated by the big red quadrangle. The purple dots indicate the used wells that contains ZE fringe sandstones, and all further lines indicate used well panels. The red ellipse indicates the region of the Hewett field. The background is formed by a Structural elements map of the Netherlands showing the Early Permian basins, highs, and platforms (de Jager, 2007).

The Hewett Gas field, offshore UK extends across blocks 48/28 48/29 48/30 52/4 and 52/5 (Figure 3). The reservoir rocks in the gas field are the Triassic Bunter sandstone, the Hewett Sandstone and the Zechstein Kalk. In the UK, the Hewett sandstone and overlying Bunter shale are considered a part of the Triassic Bacton group, whereas in the NL this is recognized as part of the Zechstein group (Peryt et al., 2010). For this study the latter is assumed. The Hewett sandstone is limited in extent and is the erosional product of the London-Brabant massifs uplift. The reservoir pinches out to the North. Claystone barriers can be correlated across the sandstone, delineating different reservoir zones within the Hewett Field. In the Dutch offshore, Field P11b de Ruyter/van Nes is found in block P11. The reservoir rocks in this oil field are comprised of the Triassic Volpriehausen formation and the Z4 Fringe sandstone member.

2. Geological setting

2.1 Zechstein Stratigraphy

Zechstein stratigraphy has been extensively studied (Geluk, 2005; Peryt et al., 2010; Geluk, 2016; Bourellec & Geel, 2025). However, the detailed relationship of the Zechstein fringe sandstone has not been studied in depth.

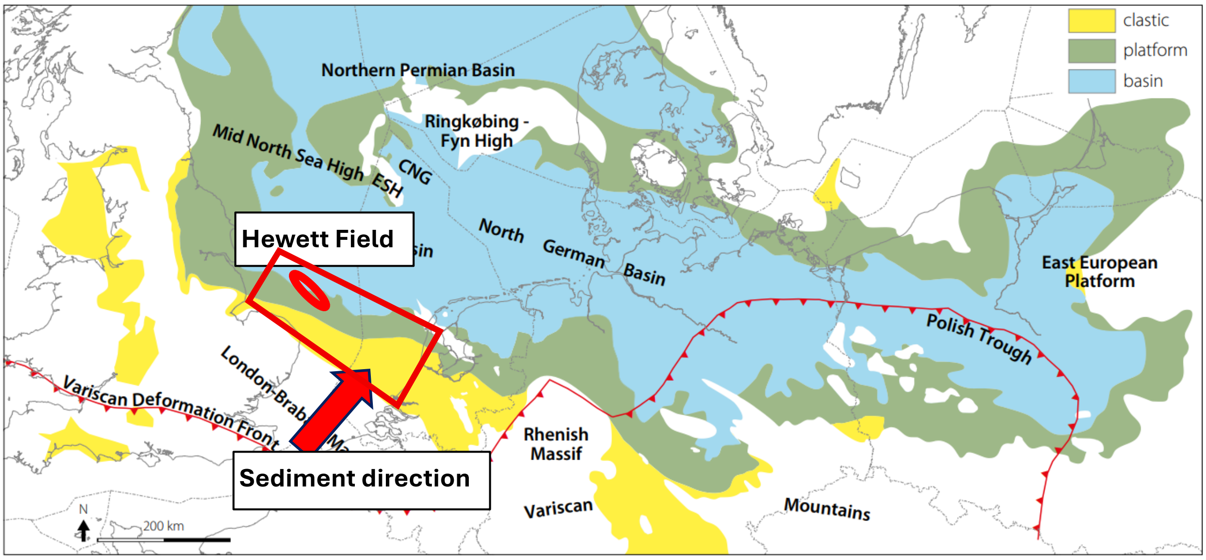

Figure 4 Present day distribution and depositional environment of the Z2 carbonate of the Zechstein Group (Late Permian) in the Southern Permian Basin. CNG=Central North Sea Graben; ESH: elbow spit high. Geology of the Netherland (Bouroullec & Geel, 2025). Study area is indicated with a red polygon..

The Zechstein was deposited during the late Permian (age between ~259 and ~251 million years ago) in an epicontinental basin that extended from the UK to Poland, also known as the Southern Permian Basin. This report focusses on the Zechstein fringe sandstone, which has only been preserved in the Southern part of the basin, between the London-Brabant massif and the deeper evaporite rich areas to the north, as shown by the yellow clastics in Figure 4.

Traditionally, the Zechstein strata shows four evaporitic cycles. These are known as Z1-Werra, Z2-Stassfurt, Z3-Leine and Z4-Aller Series after Richter-Bernburg (1955). Younger Z5-Ohre, Z6-Friesland and Z7-Fulda cycles are also recognized, although less commonly used as they are of different magnitudes. Meaning the salt deposition during these cycles is driven by short-term variations in the climate (Geluk, 1996). These cycles are traditionally divided to reflect progressive evaporation. They start with a normal marine sediment followed by evaporites showing increasing salinity.

Across the Southern Permian Basin (SPB), the different Zechstein cycles are defined by a transgressive surface marked by an indicative clay. At the base of Z1 this is the Kupferschiefer, whilst for the base of Z3 this is the Grey Salt Clay and at the base of Z4 lies the Red Salt clay. These are used to define the base of the cycles (Peryt et al, 2010).

Furthermore, the overall stratigraphic cyclicity is characterized by a basal clay layer, overlain sequentially by dolomitic carbonates, anhydrite, and halite. The cyclicity is attributed to periodic glaciations that controlled the marine incursions, combined with high evaporation rates (Ziegler, 1990).

However, in the Dutch part of the Southern North Sea continental clastic sediments are present within the Zechstein along the basin margin. Mudflats and sabkhas are developed around the London-Brabant Massif (LBM), whereas sands were deposited under fluvial and estuarine conditions. Towards the southern basin edge, the platform graded into a complex of mudflats, sabkhas and fluvial sandstones, whilst carbonates dominated in the southern Netherlands. An overview of the Zechstein formations that are found in the study is provided in Table 1.

Table 1 overview of abbreviations of the formation of the study area as provided by (NLOG ,2025).

Abbreviation	***Formation:***
ZEUC:	Zechstein Boven-Kleisteen Formatie
ZEZ4S:	Z4 Randzandsteen Laagpakket
ZEZ4M	Z4 middle claystone
ZEZ4R:	Rode Zoutklei Laagpakket
ZEZ3S:	Z3 Randzandsteen Laagpakket
ZEZ3U:	Z3 Randkleisteen Laagpakket
ZEZ3C:	Z3 Carbonaat Laagpakket
ZEZ3G:	Grijze Zoutklei Laagpakket
ZEZ2S:	Z2 Randzandsteen Laagpakket
ZEZ2M:	Z2 Midden-Kleisteen Laagpakket
ZEZ2C:	Z2 Carbonaat Laagpakket
ZEZ2R:	Roodbruine Zoutklei Laagpakket
ZEZ1S:	Z1 Randzandsteen Laagpakket
ZEZ1M:	Z1 Midden-Kleisteen Laagpakket
ZEZ1F/ZEZ1C:	Z1 Randcarbonaat Laagpakket
ZEZ1G:	Z1 Onder-Kleisteen Laagpakket
ZEZ1E/ZEZ1K:	Randkoperschalie Laagpakket

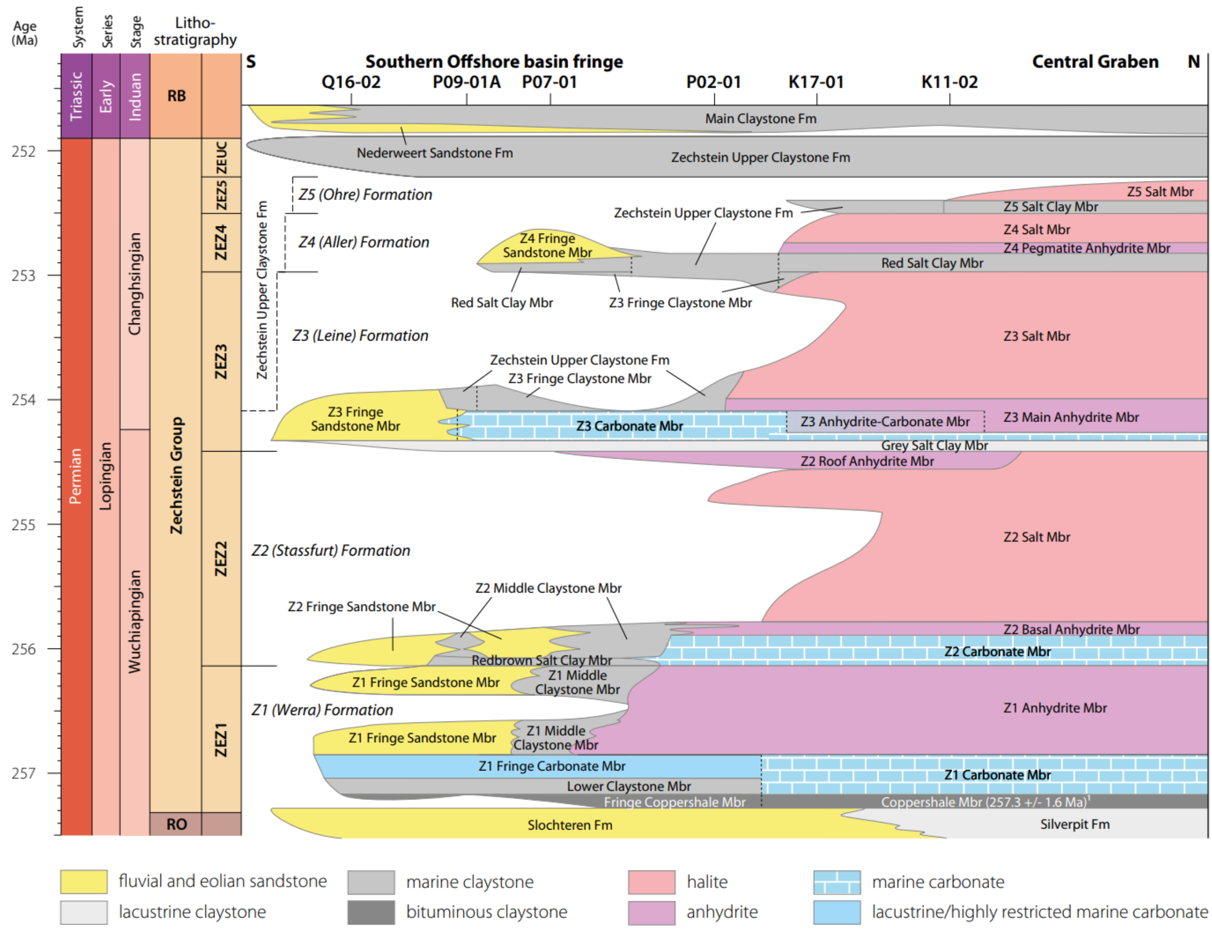

Figure 5 Tectonostratigraphic chart of the Zechstein Group. Geology of the Netherlands (Bouroullec and Geel, 2025)

Figure 5 displays the tectonostratigraphic chart of the Zechstein group as commonly seen in the Netherlands. The region that this study focusses on is best represented by the chart below wells Q16-02, P09-01A and P07-01. Here, the stratigraphy of the first Zechstein cycle starts with a thin layer of Kupferschiefer followed by a claystone and overlain by either a fringe carbonate a fringe sandstone or both. The next cycle starts with red-brown salt clay that is followed by a middle claystone and/or a fringe sandstone. The carbonate of the second cycle is not present in the studied region. The third Zechstein cycle can be recognized by the grey salt clay, led by either carbonate, a sandstone or both. The last Zechstein cycle is characterized by a red salt clay overlain by a thick sandstone. At the Top of the Zechstein Sequence the Zechstein upper claystone formation lies on top of the sands. This differs from the UK Stratigraphic cross section as this does not depict the presence of sands in the Zechstein (Figure 6), whereas a schematic cross section of the Netherlands does indicate a sandy facies across both UK and NL wells (Figure 7). An overview of formal formations and abbreviations in the study area is provided in Table 1.

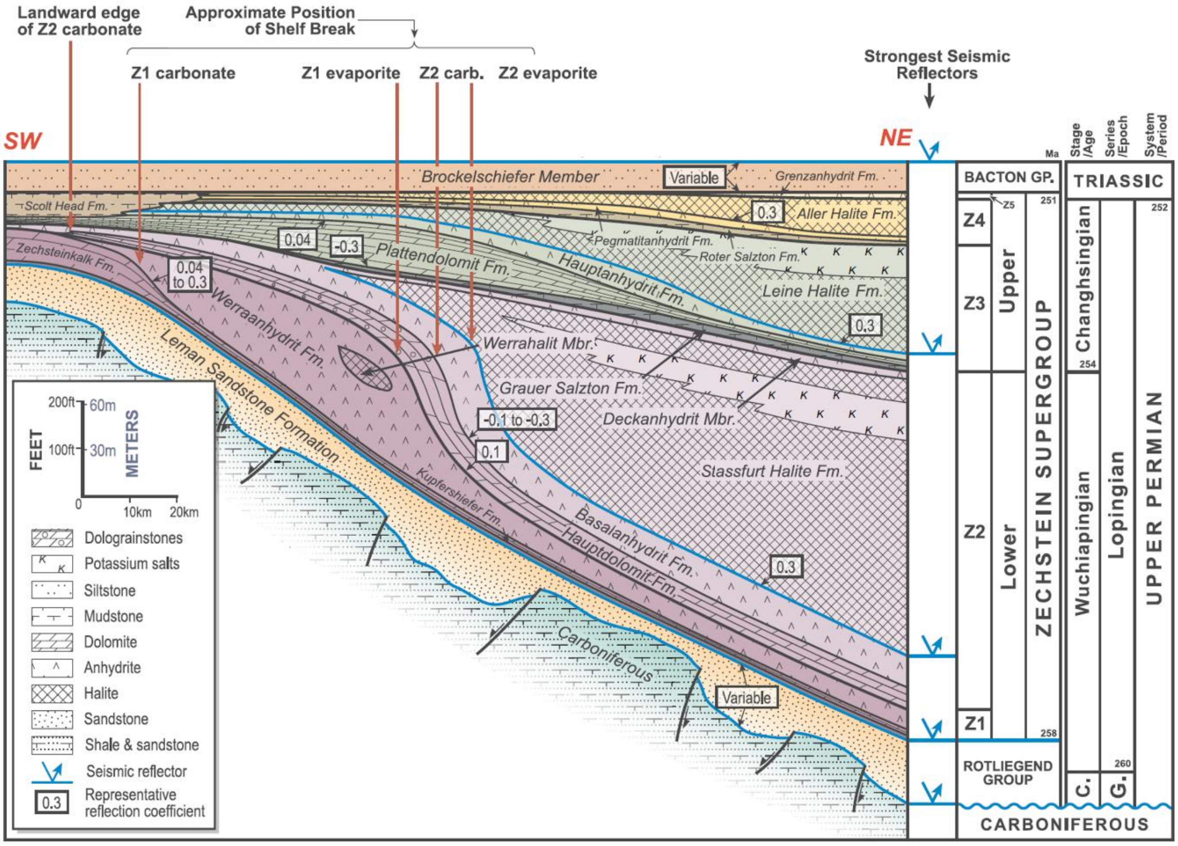

Figure 6 NE-SW striking stratigraphic schematic cross section depicting the elements of the Zechstein Supergroup in the UK Southern North Sea. It shows the shelf break or ramp inflection position for the main carbonate cycles relative to the location of the Juliet and Amethyst fields (Grant et al., 2019).

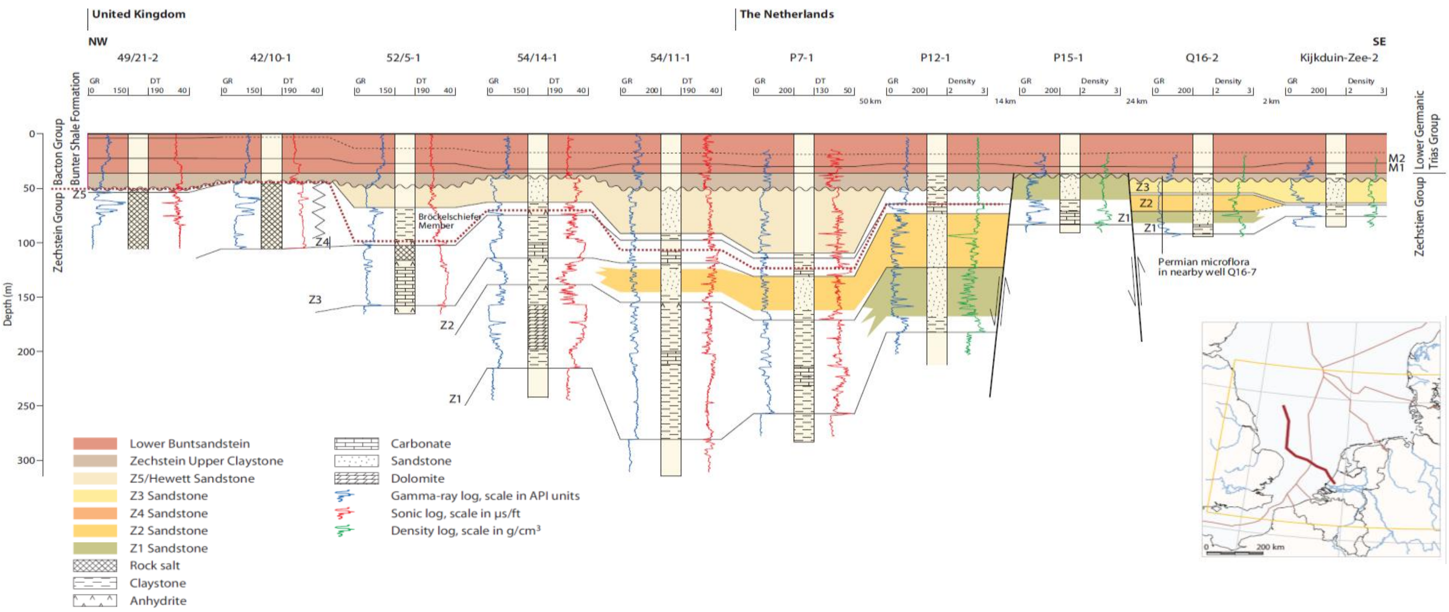

Figure 7 Stratigraphic well-correlation diagram of the uppermost Zechstein and lowermost Triassic in the Southern North Sea area, using gamma ray and sonic logs. The onlap of the basal Zechstein strata onto the platform, as well as a disconformable contact between the ZEUC and underlying deposits. Hewett field well 52/5-1 is included in the correlation. The Red dotted line marks the Zechstein/Bacton Group boundary. Southern Permian Basin Atlas (Peryt et al., 2010)

2.2 Paleogeography

The paleogeography of the Zechstein group within the Southern Permian Basin is comprised of a complex interplay of depositional environment and tectonic influences. As this study examines the characteristics of the fringe sandstone and its reservoir potential, it is important to know the spatial and temporal variations in different Zechstein facies.

Facies maps

Figure 8 displays the facies maps of Zechstein cycle 1-4. The Z1 (Werra) formation shows the initial Zechstein deposition, characterized by a clastic influx of sediments. The main sediment input coming from the SSW. During the overlying Z2 (Strassfurt) formation, the clastic influx became less widespread and onlap caused the edge of the formation to be pushed back. Subsequently, the Z3 (Leine) formation represents a phase of marine transgression where the carbonate platforms expanded into the basin margins. This decreased the amount of clastic influx to the basin. Finally, the Z4 (Aller) formation displays a thick sandstone layer from the South, whilst the rest of the region is formed by mostly sabkha and mudflat facies. The latter displays the terminal phase of the increased restriction and the basin further shallowing northwards (Bouroullec & Geel, 2025).

Tectonic Setting

The entirety of the Permian deposits in the Southern Permian Basin postdate the Variscan Orogeny. Minor tectonic pulses during the late Permian are thought to be one of the first to the breakup of Pangea (Vai, 2003). The Tubantian I and II pulses occurred during the Zechstein. During Tubantian I a connection between the SPB and the Barents Sea was created, while the Tubantian II pulse is believed to be compressional and marks the last junction of Pangea (Bouroullec & Geel, 2025).

These Tubantian I tectonic pulses caused faulting during deposition of Z1 (Werra) formation but was concentrated on anhydrite platforms at the basin margins. Tubantian II movements were syn-depositional and identifiable as an unconformable contact between Zechstein upper claystone (ZEUC) and older deposits. These mildly compressional movements resulted in the uplift and erosion of areas South of the basin, possibly depositing sands in the Western southern offshore area (Z4/Hewett sandstone) (Bouroullec & Geel, 2010). Figure 8 shows areas of deposition during faulting, area of potential clastic reservoir rocks.

According to Kingsnorth (2011) minor uplift of the London Brabant Massif and subsequent erosion led to the local development of the Hewett sandstone. During the Early Triassic, the deposition of these sands came to a halt due to further tectonic uplift., which caused the abrupt onset of deposition of Bunter Sandstone to occur, which consists of fluvial channels and sheetflood deposits (Kingsnorth, 2011a).

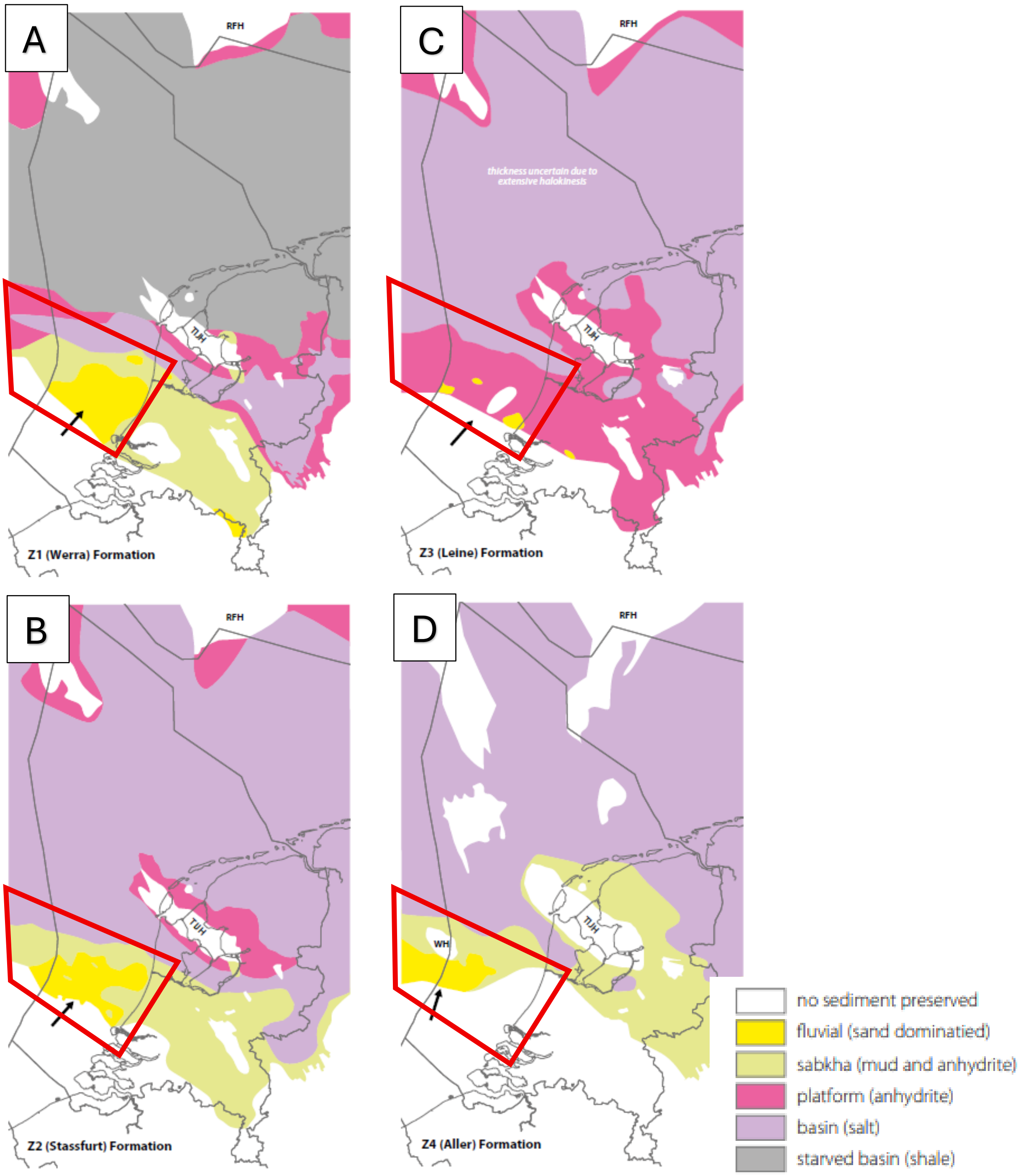

Figure 8 Facies maps of the Zechstein Group. Dutch part of the study area is indicated with the red polygon.

A) The Z1 (Werra) Formation shows sand input into the basin from the western offshore margin (indicated by arrow), while the central basin records a condensed succession of carbonates and evaporites.
B) The Z2 (Stassfurt) Formation is dominated by the deposition of a thick rock salt sequence, particularly within the central Southern Permian Basin (SPB).
C) The Z3 (Leine) Formation reflects a phase of widespread marine transgression, marked by the expansion of carbonate platforms toward basin margins.
D) The Z4 (Aller) Formation is characterized by thin sabkha and mudflat deposits, indicating increased restriction and shallowing. Abbreviations: ESH – Elbow Spit High; MNSH – Mid North Sea High; RFH – Ringkøbing-Fyn High; TIJH – Texel-IJsselmeer High; WH – Winterton High. Modified from Geluk (2007), TNO-GDN (2022), Van Ojik et al. (2021) and Bouroullec et al. (2022). (Bouroullec & Geel (2025))

Depositional environment

During the early Permian, desert conditions dominated, leading to the formation of eolian (dune) and fluvial (wadi) sandstones. This phase of desert conditions ended abruptly when the Rotliegend basin was flooded by the Zechstein Sea, resulting in the deposition of the Kupferschiefer formation. The subsequent marine restriction, coupled with glaciation-driven cyclicity, gave rise to the development of the well-documented Zechstein Cycles. The end of the Zechstein sequence is marked by a transition from marine carbonate and evaporate conditions to a continental environment during the Early Triassic (Grant et al, 2019).

The Hewett Sandstone formation, in the UK referred to as part of the Lower Bunter, comprised of complex of fluvial playa lake and distal floodplain deposits with minor evaporites prograding Northeast towards the SNSB from the LBM (Kingsnorth, 2011Aa). Most of the UK part of the study area lies withing the Indefatigable Platform (IP), which encircles the Winterton High, corresponds to a similarly named structural feature located in UK offshore waters. It is primarily composed of Triassic and Cretaceous sedimentary sequences overlying Permian strata. The platform is extensively dissected by a network of NW–SE trending faults. To the north and east, the IP is bounded by major fault zones that define the margins of the Broad Fourteens and West Netherlands Basins. Along its southern boundary, the Zeeland High marks a zone where both Early Cretaceous and Triassic deposits are absent, indicating a history of uplift and/or non-deposition.

Regional Seismic line

Figure 9 shows a SW-NE regional seismic line through the P and Q blocks. This line shows a basinward progression towards the North. On this line some unconformities can be determined. The first is the Base Permian unconformity (BPU). This represents a hiatus covering 35-80 Ma and was caused by a period of erosion and uplift during late Variscan Shortening. The BPU often shows Upper Rotliegend unconformably overlying Carboniferous deposits. However, it also presents itself as Zechstein deposits on top of the Carboniferous (Bouroullec & Geel, 2025). Permian, Triassic, and Jurassic are truncated below the Base Cretaceous unconformity (BCU).
On the London-Brabant Massif, the proximal part of the Zechstein has been eroded, so the original Zechstein paleogeography remains unknown here.

During the Cretaceous there was not only onlap onto London-Brabant Massif as can be seen in Figure 9. Further North there was also an area of uplift called Winterton High. The Winterton high indicates an area of erosion where the Zechstein is very thin to absent. It is fault-bounded structural high characterized by the presence of Cretaceous deposits directly overlying Carboniferous basement rocks. Significant uplift occurred during the Late Jurassic and Early Cretaceous, resulting in the erosion and subsequent removal of the overlying Triassic and Permian strata (Van Adrichem Boogaert & Kouwe, 1993). Seismic data from adjacent UK offshore areas suggest that the Winterton High may have originated as early as Early Carboniferous, as evidenced by the interpretation of a carbonate platform structure in that region (Total E&P UK, 2007).

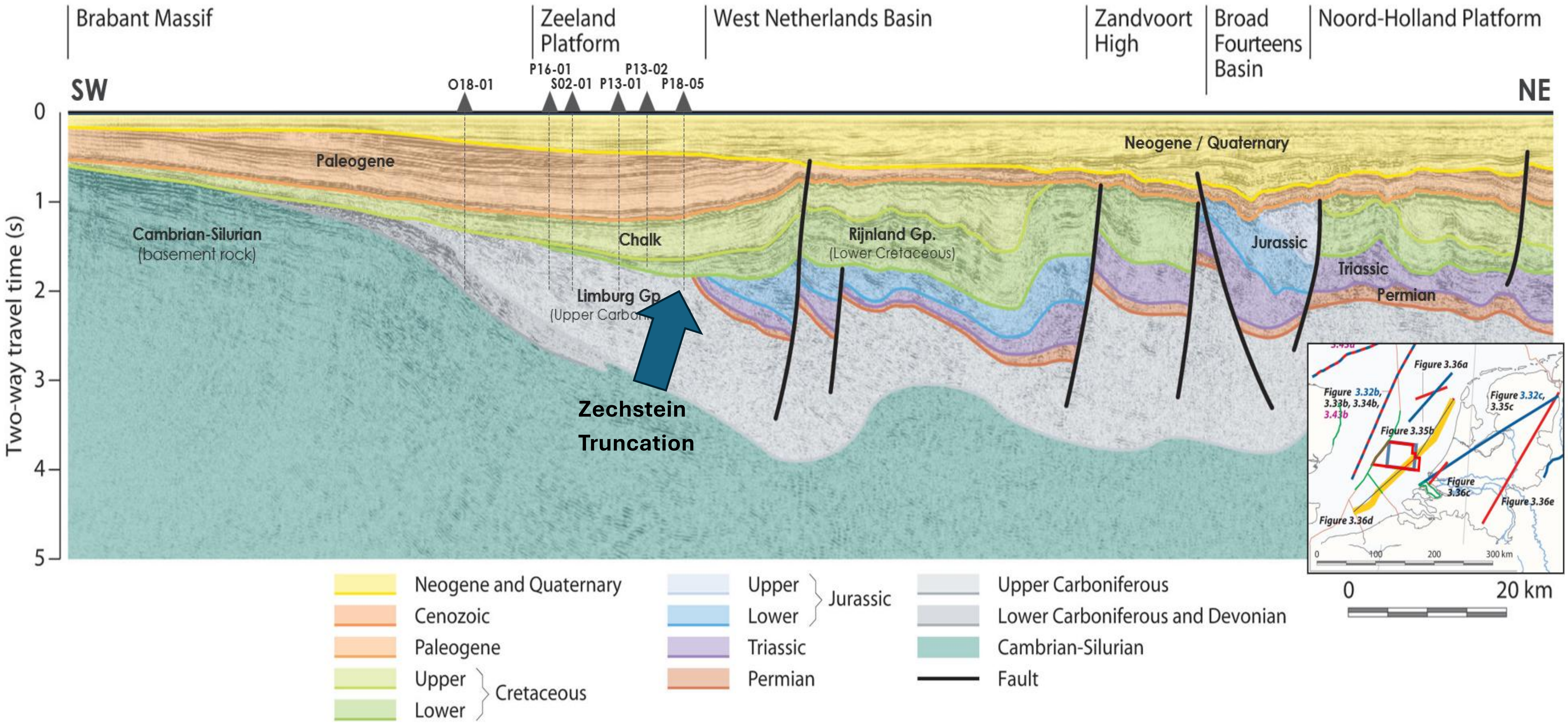

Figure 9 SW-NE regional seismic cross-section with a Vertical exaggeration ~10 to 20x. Modified from Peryt et al. (2010). The Blue arrow indicates the location of the truncation of the Permian.

3. Methods and methodology

3.1 Workflow

This section provides an overview of the data and methods used to accomplish a workflow. A visual representation of the project timeline is provided in Figure 10. Illustrating what was done at each stage of the project.

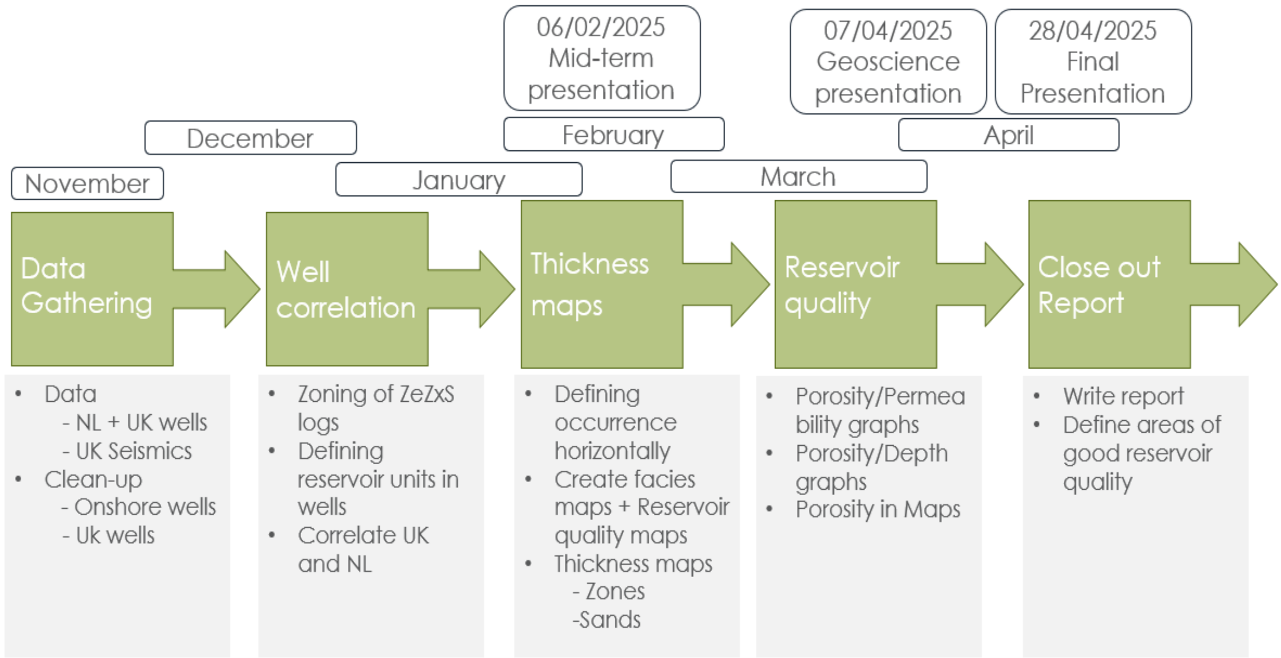

Figure 10 Workflow showing stages of the project

3.2 Available data

Current knowledge on the presence and distribution of Zechstein clastics was gathered from GEODE Zechstein, in particular its playmap (Figure 1) (Kortekaas et al,. 2024).

The Zechstein fringe sandstones were correlated and interpreted using Petrel software version 2024.6.0 (Schlumberger) using a license obtained by EBN. Horizons were interpreted by using the existing data from the TNO DGM-deep V5 dataset.

Well data was collected from the EBN database. For each well the data that was used consisted of Gamma ray (GR), Neutron (NEUT), Density (DEN), True vertical depth (TVD) and Measured depth (MD) data. Composite logs were collected from either NLOG for the NL wells or NDR for the UK wells.

3.3 Data collection

Literature review on the present knowledge about the Zechstein fringe sands in NL, the Hewett field in the UK. A multitude of sources and documents are used, including well reports, composite logs, and seismic data.

Selection of wells

Within the study area, 121 Boreholes that contain information on Zechstein fringe sandstones are available (Figure 51/52).

Clean-up

Unequal spread of well location due to former focus on areas of hydrocarbon potential.

1. Wells that do not contain a ZE sandstone are excluded.
2. Well that contain a fault within the Zechstein are excluded.
3. There needs to be a gamma ray input available for Petrel.

Limitations of wells

To improve correlation, occasionally a 1.1x multiplication was applied to the Gamma ray to provide a more accurate interpretation. Where this was necessary it may be caused by a casing.

Seismic surveys

Multiple 3D surveys and 2D lines were conducted in the Dutch part of the study area (Figure 36). These surveys were made available through the EBN database and are all provided in TWT. The UK seismic surveys were imported from the mega survey by NDR, provided by University Utrecht.

3.4 Well correlation

Zoning of ZeZxS logs

Interpretation of the top and bottom of the Zechstein interval were based on characteristics of the Rotliegend, Zechstein and lower Bunter formations.

The Top of the Zechstein was determined as either the characteristic low gamma ray of the overlying Lower Bunter claystone or by the predetermined top as found in the composite log of the well. The bottom of the Zechstein was determined by either the characteristic maximum flooding surface indicated by the Kupferschiefer or by the predetermined bottom as found in the composite log of the well.

Within the Zechstein interval, six different zones were determined, these were marked by a transgressive/maximum flooding surface at the top. For all well panels the well was flattened on top Zechstein to simulate the filling of a basin during correlation.

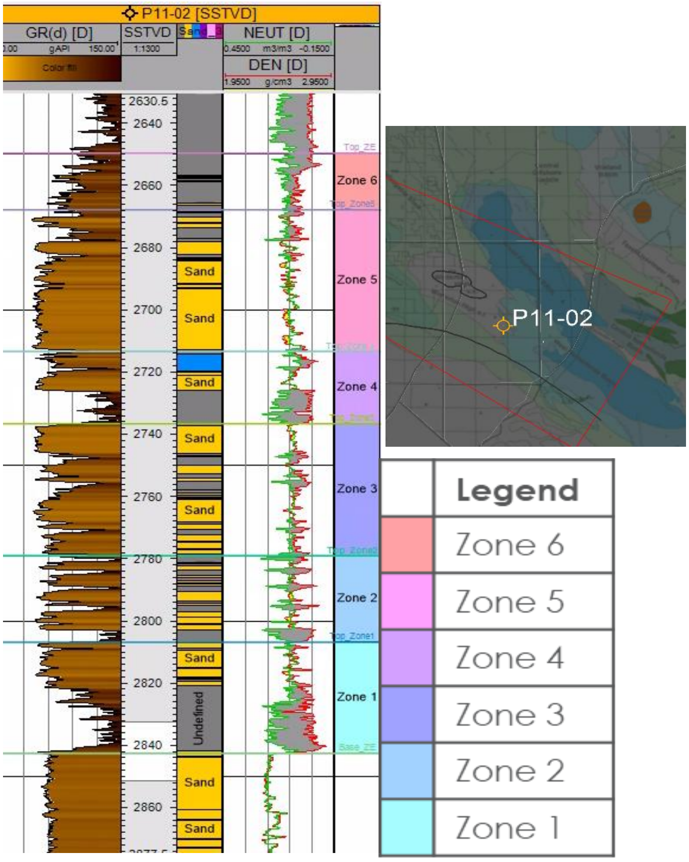

Figure 11 Well P11-02

Table 2 provides an overview of the lithologies present within the six zones in both the UK and NL wells. While figure 11 gives an indication of the zones within a well log.

All wells containing ZeZxS or an equivalent were considered.

Table 2 Overview of the lithologies present within the 6 zones of the Uk and NL wells.

Zone	UK	NL
6	Thin clay rich beds.	Thin clay rich beds, occasionally thin sandstone.
5	Varying thickness of sandstone beds.	Varying thickness of Sandstone, sometimes heterolithic with clay.
4	Thick evaporitic sequence from dolomite to halite.	Varying thickness of carbonate rocks, top sometimes a thin anhydrite layer present. Sandstone Facies is also found here.
3	Thick evaporitic sequence from dolomite to halite.	Thicker clay and sandstone beds.
2	Thick dolomitic beds.	Thin clay and sandstone beds.
1	Thicker accumulation, carbonate, and dolomite rocks.	Thinner accumulation, Carbonate rocks, sandy layer.

Stratigraphic overview

To better identify changes in thickness, facies and depositional environments, two stratigraphic well correlated overviews were made, one along the strike from the SE to the NW and one perpendicular to the strike from the SSW to the NNE. This will help interpret unconformities, onlaps, faults and pinch outs, whilst further helping explaining basin architecture.

The overviews were made by drawing the lithologies within the zones between wells on a well section panel.

The lithologies were determined based on their gamma ray, density, and neutron signature. These lithologies were drawn onto well section panels containing only their gamma ray.

3.5 Thickness maps

Defining occurrence horizontally

True vertical thickness maps were made based on the thickness of the predetermined zones in the wells. These zones were then used to create an isochore map that displays the initial trends in the thickness of the Zechstein and its zones within the study area. See Appendix C for the Petrel input.

(Sand) thickness maps

First, thickness maps were made based on the zones. The maps were made in Petrel software using the "make surface" feature.

An approximation of Net to gross calculations was calculated to determine the location of sand in the well. A general discrete log was made using a gamma ray cutoff to distinguish between sandstone and claystone.

Sand=if(Gamma_ray<75,1,0)

The formula written above provided an approximation of the net to gross value of sand in the well. This was further used as input for a value of the thickness per zone by integrating these values into each zone. Here the thickness per zone was calculated under attribute operations (see Ap. C. for input.). This provided an approximation of the net sand value within each zone for every well.

Other lithologies within the different zones were only described as either a sand or carbonate or as undefined. This further differentiation was done manually. Interpreted by looking at the neutron/density logs and composite log input.

Sand facies maps were made based on the thickness of the sand within a zone. This thickness was calculated using a discrete attribute. Where the average methods was the thickness, the depth scale was based on the TVD, and the input were the areas where sand was determined using the net to gross calculations.

The values of the thickness of the sand per zone could be extracted from the zone logs and used as input for the thickness map calculations.

The facies maps were made with kriging at an azimuth of 135 degrees and the average value determined at 0 (see Appendix C for an overview of petrel input).

Lastly, reservoir quality maps were made to display areas of possible good reservoir by including known data on the porosity of the NL and Hewett field wells on the sand facies thickness maps.

Limitations

Limitations of using this method for net to gross calculations. The sand calculation is based on the GR and not on a Net sand, these GR values may not be calibrated correctly and are therefore only an estimate of the sand percentage. No porosity measurements are included in this method. As all GR values below 75 are displayed as sand. There is need for manual removal/corrections of other low gamma ray lithologies that could also be displayed as sand, such as carbonates and evaporites.

3.6 Well core data

For this study, core measurement data from 16 Dutch and 3 UK wells were analyzed (Appendix B). The porosity, permeability good sand is determined to be a sand with a porosity above 6% and a permeability above 0.1 millidarcy (mD). For this study permeability values below 0.05 were removed from the dataset as these datapoint are not reliable. Porosity values are reported with up to three significant numbers, permeability values are significant up two decimal places and TVD is recorded in full meters. All well core measurements data were processed using Excel. Here the data-handling and graph plotting was done.

To facilitate comparative analyses, the data were binned by their porosity. Binning was conducted to group data into poro-perm classes for cross plot analysis and reservoir quality assessment. The bins were defined by five percent porosity intervals to capture the trends within these unit. Statistical analysis on the data was done. This includes descriptive statistics (the mean, median and standard deviation) for the binned intervals and the porosity-permeability cross plots regression models using the power law fit. Outliers were identified and evaluated for geological plausibility.

The data was first reprocessed and binned to ensure quality. Afterwards the data was applied for the zones determined in this study based on the TVD data. These new data points were further averaged per zone and per well, and cross plots of porosity permeability and depth-porosity relations were plotted.

3.7 Seismic correlation

To establish a verification of the stratigraphic framework of the Zechstein fringe sandstone, a seismic correlation was performed on a regional scale. This process involved the integration of a 3D seismic section to verify the lateral continuity and thickness variation of the sandstone units.

A seismic line that represented the area was examined to identify major stratigraphic markers and other structural features that represent the edge of the basin. The Fugro5 2012 seismic cube volume 4 was utilized to interpret the facies.

The plan was to further delineate lithological changes within the Fringe facies. By using reflector terminations, onlap, offlap and truncation would be used to infer further depositional dynamics in the basin.

Onlap can be recognized as a reflector that terminates progressive against an inclined surface, where it indicates a transgressive landward migration of a sediment. Offlap on the other hand, is identified as the seismic reflectors shift towards the sea, where they are indicative of a regressive phase and the progradation of a deposit.

4. Results

4.1 Well panels

This study uses well panels to correlate the Zechstein sands. Figure 12 shows the locations of all well sections across the study area that are included. The panels show zones and how they correlate across the areas. The well correlation panels were constructed using data from 121 different wells (see appendix A for overview of wells) to evaluate the thickness and facies variation within the fringe Zechstein. The correlation is based on wireline well log signatures and composite log descriptions. Overall panels the key marker horizons are based on transgressive surfaces, which mostly correlate to the Zechstein cycles 1-4. However, this study introduces a new correlation, not consistent with the original strata, and therefore uses neutral ''Top Zones'' to differentiate the different horizons. For a full description of the zones see chapter 3.4.

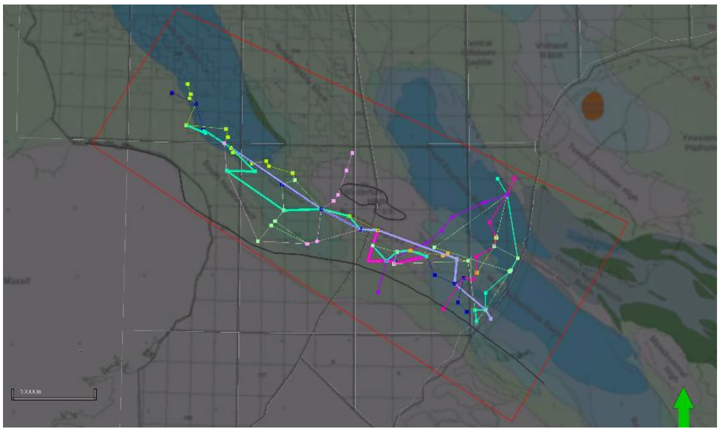

Figure 12 various well section panels indicated with lines across the study area. See appendix A for more detail.

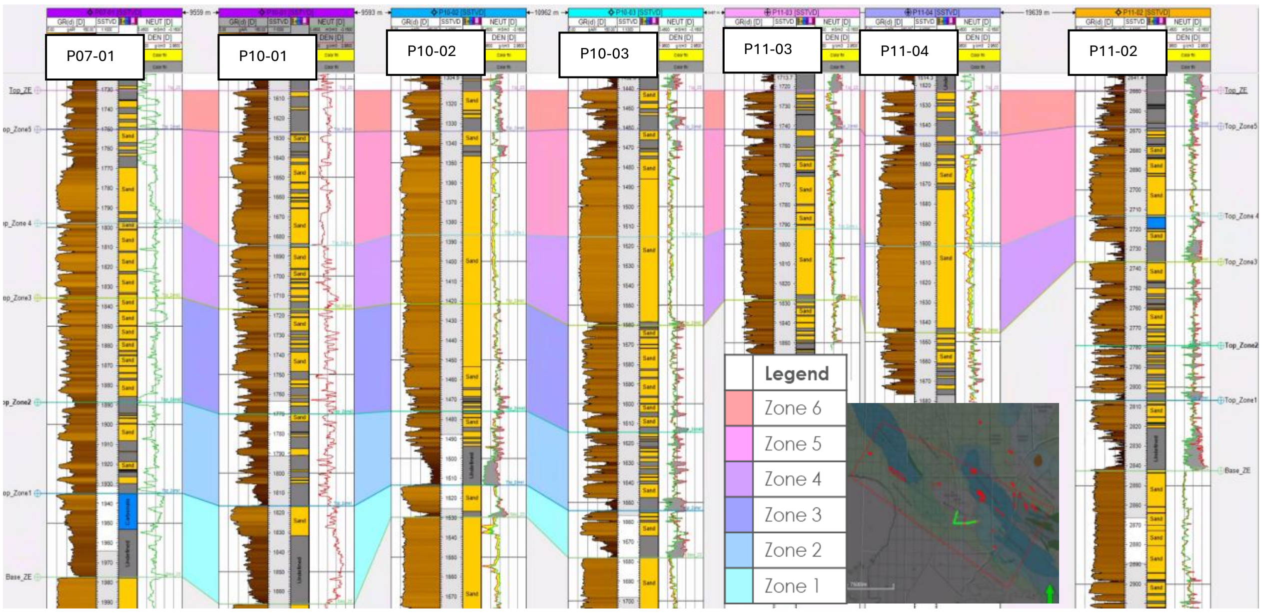

Figure 13 Well correlation of the Nederweert Sandstone in the P10/P11 blocks.

Nederweert sandstone panel

Figure 13 presents well panel ''Nederweert Sandstone'' and highlights an area of the map where the Fringe sandstone is thick. This area is located close to the offshore UK/NL border and therefore provides an ideal location for an in-depth look at the stratigraphy. The panel presents a significant correlation with zones showing a good lateral and thickness continuity. Notably, Zone 1 in well P07-01 differs from the typical lithology observed in other wells, as it is characterized by a carbonate facies rather than the expected sandy facies. Similarly, a localized carbonate is observed in Zone 4 of well P11-02, indicating potential lateral facies variability or localized depositional conditions. Wells P11-03 and P11-04 only intersect Zones 4, 5, and 6, as these wells were not drilled deep enough to depth to capture the full Zechstein sequence. Despite this limitation, the correlatable intervals in these wells support the overall stratigraphic framework and suggest lateral continuity of the upper zones.

Next, two panels are selected as combined, they provide a good representation of the sands of the study area.

Perpendicular to strike panel – depositional setting

Figure 14 shows a well section panel in the Dutch Southern North Sea, perpendicular to the strike. This shows an overall basinward thickening of the strata. Zone 1 undergoes the largest change in thickness as the basin gets filled. Zones 2, 3 and 4 appear to have a good continuous thickness. Notably zone 6 is absent from the well section. Subsequently zone 6 lies directly on top of zone 4.

Along strike UK to NL panel – depositional setting

This panel (Figure 15) reveals a developed lateral continuity of the zones. The thickness of the zones thins towards the East; within the zones it declines from tens of meters to a few meters. Zones 6 and 5 are only present in the four wells most to the West.

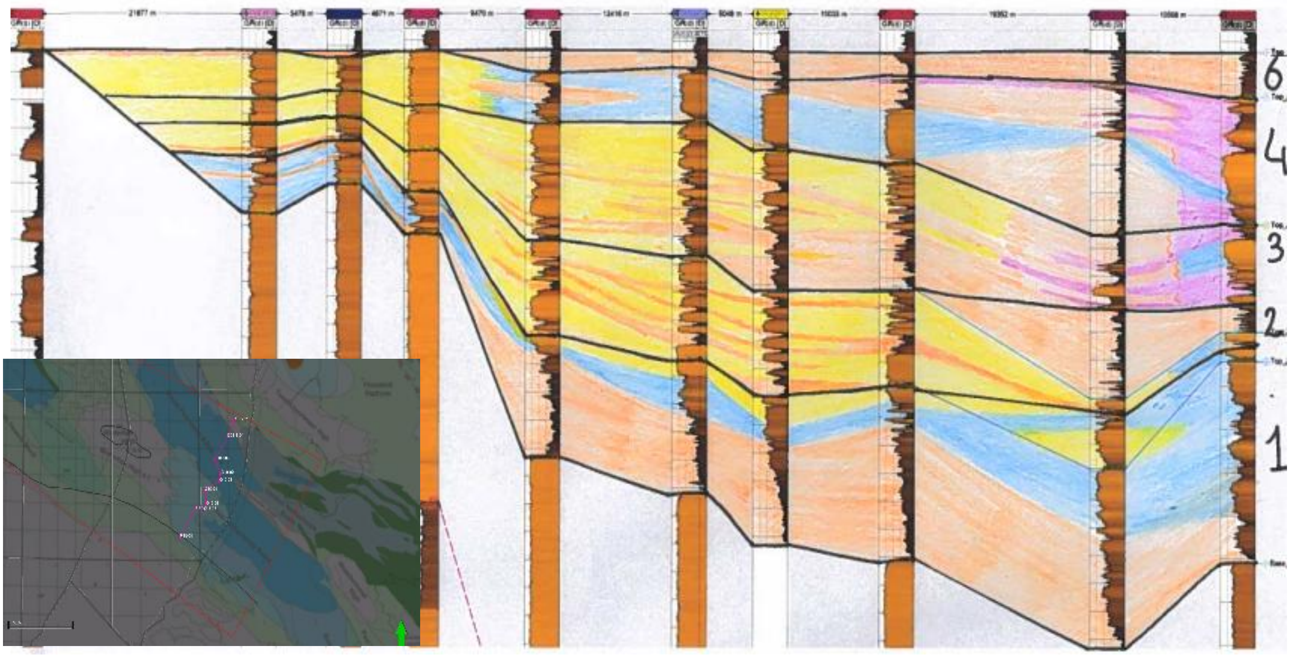

Figure 14 Stratigraphic overview perpendicular to the strike (SSW-NNE). Lithologies are displayed, the numbers on the right correspond with Zones 1-6. Yellow = sandstone, Orange= Clay/siltstone, Blue = carbonates and Purple=evaporites.

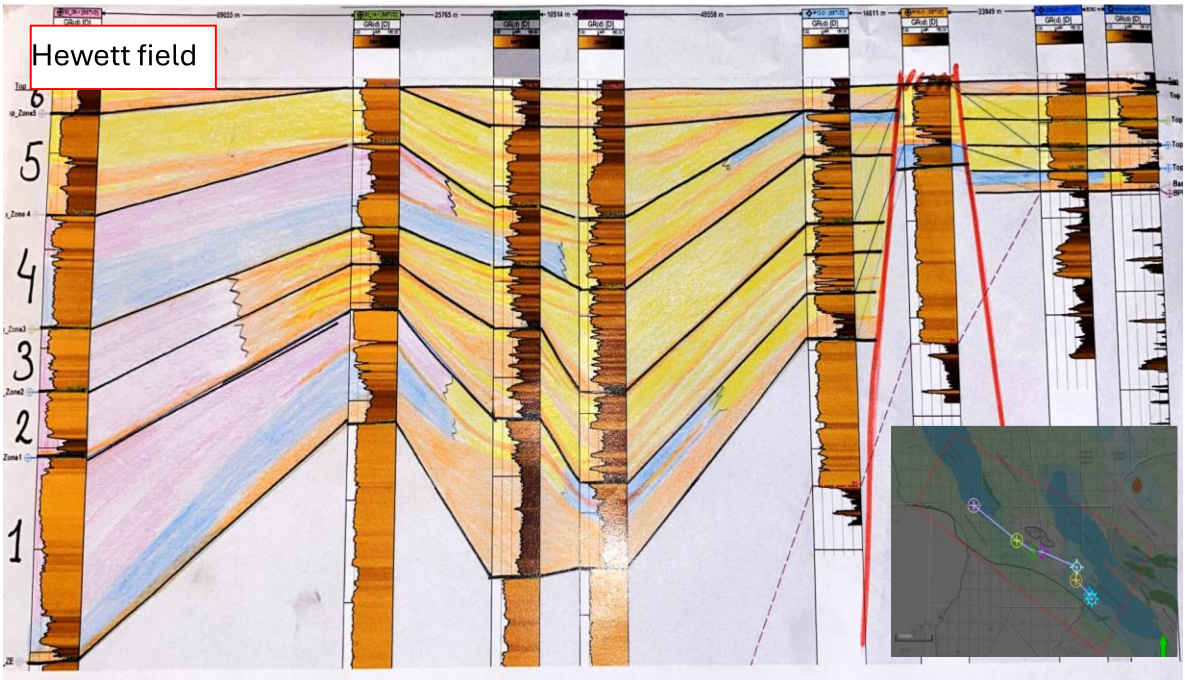

Figure 15 Stratigraphic overview along strike (NW-SE). Lithologies are displayed. The numbers on the left correspond with the Zones 1-6. The left most well is one found in the Hewett field. Yellow = sandstone, Orange= Clay/siltstone, Blue = carbonates and Purple=evaporites.

4.2 Stratigraphic overviews

To better identify changes in thickness, facies, and depositional environments two stratigraphic well correlated overviews were made, one along the strike from the SE to the NW and one perpendicular to the strike from the SSW to the NNE (Figure 16 and 17). This helps interpreting unconformities, onlaps, faults and pinch outs, whilst further helping explaining basin architecture.

The structural changes that happen over the well sections used for the overviews are discussed in chapter 4.1. This section will focus on the lithological changes.

Along strike UK to NL panel

The overview panel (Figure 16) along strike present a lithological sequence around the Hewett field that follow the Zechstein evaporite cycle, whilst moving Eastwards the lithologies become clastic very quickly. Moving from the UK towards the NL, zone 1 to 4 indicate a system that increases in the amount of sandstone. Multiple sand banks appear and disappear within the zones, and some can be followed through the entire overview. Furthermore the sudden appearance of carbonates within Zones 1 and 4 indicate that the system of carbonate precipitation and clastic influx coexists.

Perpendicular to strike panel.

This overview (Figure 17) shows the carbonate facies of zone 1 as it thickens towards the basin. The zone is thin and consists of sands that shale out basinward. Zone 3 shales out towards the basin and further develops into the classic Zechstein evaporites. Zone 4 only presents a sandy facies close to the basin edge and quickly changes to a carbonate platform that progresses to an evaporitic sequence to the North.

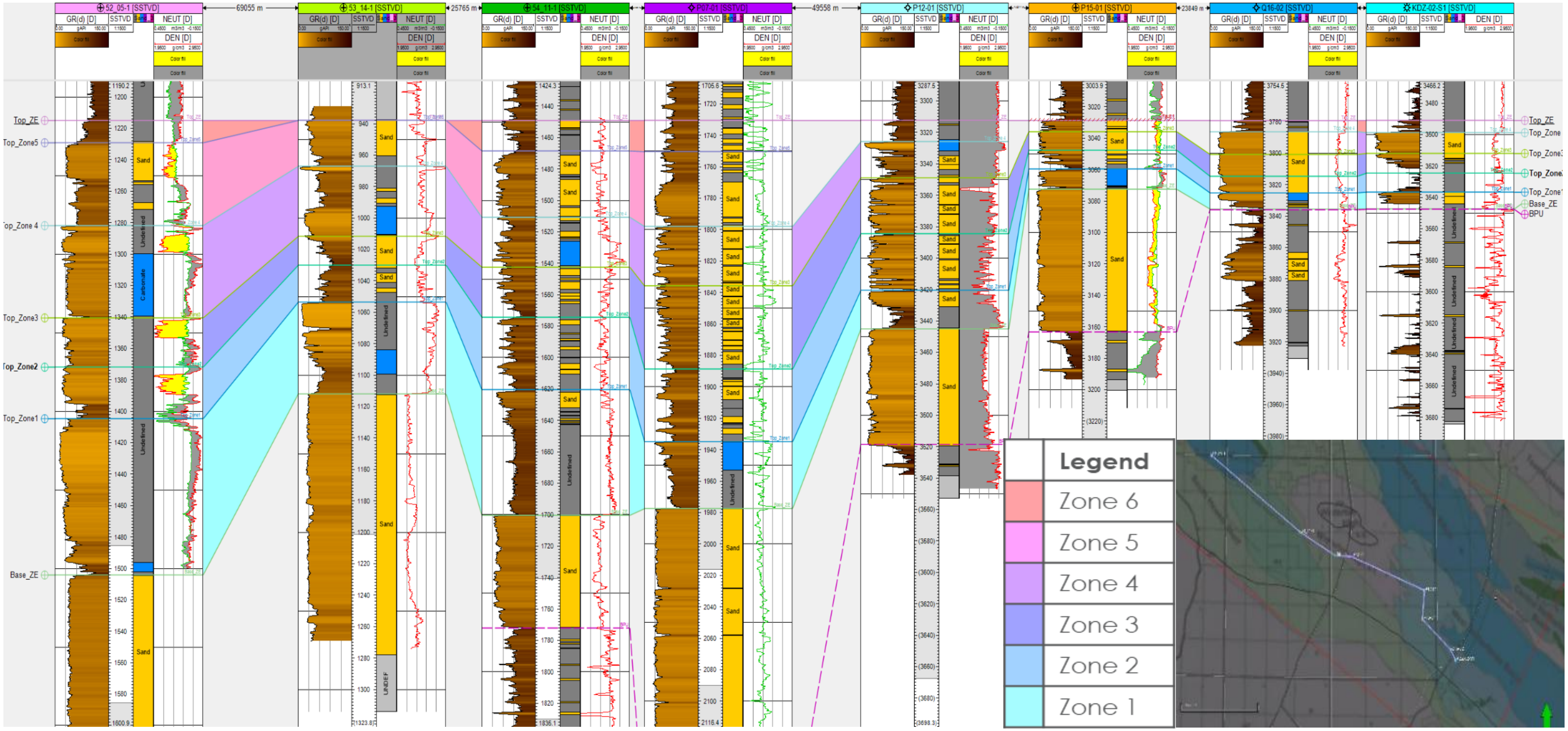

Figure 16 well section panel UK to NL. Along strike.

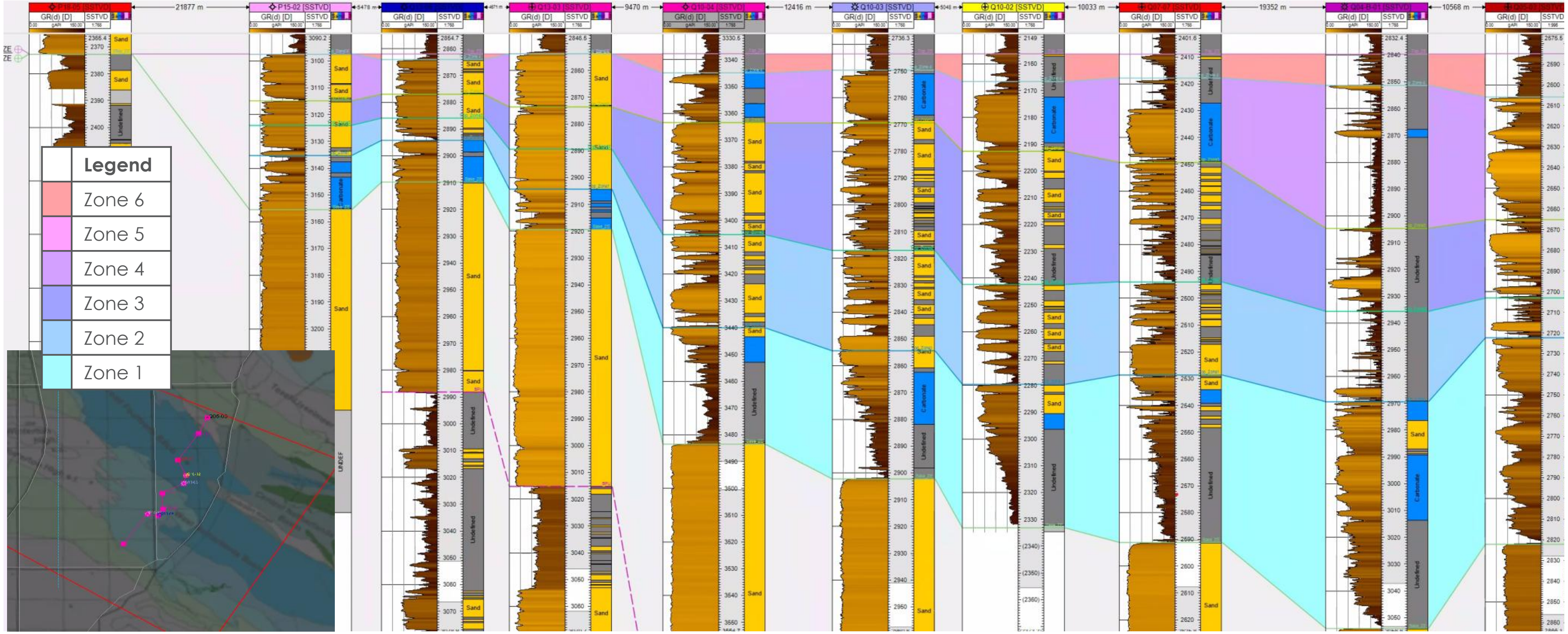

Figure 17 Well section panel perpendicular to the strike. Note that well Q05-03 does not show a lithology as this well did not contain any more sandy facies.

4.3 Core viewing

A visit to the core storage facility at the NAM in Assen was an element of this study, as during the studies there were a lot of inconsistencies about the lithologies of the Zechstein. Therefore, looking at core samples could provide insight into the true rocks that are found.

The only core record of a ZE fringe sandstone is found in well Q16-FA-101-S1 (also known as Q16-07-S1) of the Dutch offshore. Cores 3 and 2 were looked at, these were cored at depths of 3706.02-3689.22 md, and 3688.82-3680.00 md respectively. Figure 18 presents an image of a piece of Core 3 at its deepest.

This study concluded the sequence to start with a Zechstein sandstone with mudclasts on top of Carboniferous shales. This is interpreted to be the base Permian unconformity. After this a marine transgression is shown with clay moving up in a fining upwards sequence indicating a shallow marine setting. Within the sandstone the clear white cement is indicative of anhydrite.

Table 3 displays the top of the zones correlated to the depth in TVD. For the rest of this study the well tops for this well are based on the findings derived from this visit.

Figure 18 image of Q16-07 Core 3 between 3706.02 and 3703.32 mAH source: NLOG (2025). NAM (1989)

Table 3 The proposed new tops of the zones and their related depths. The mAH depth is described in the composite log and the TVDSS depth is as the depth found in the petrell well data.

Top Zone	Depth mAH	Depth TVDSS
Top ZE	3660	3565
Top Zone 4	3668	3568
Top Zone 3	3675	3585
Top Zone 2	3685	3595
Top Zone 1/Base ZE/BPU	3706	3615

4.4 Thickness maps

4.4.1 Gross thickness per zone

Thickness maps were generated across the study area using interpreted well tops based on the determined zones. Maps were produced in both true vertical thickness (TVT) and both isochore gridding and kriging formats were used. Kriging was performed using an anisotropy range with a major direction of 50.000m and a minor direction of 30.000m, with an azimuth of 135 degrees, to capture the depositional strike. Detailed input can be seen in Appendix C.

The Zechstein zones exhibit significant thickness variations across the area, both laterally and vertically. Figure 19 shows the isochore gridded map of the Zechstein Group, illustrating significant thickness variations. The thickest interval occurs in the north, in areas with a presence of thick evaporites. Maximum thicknesses of the entire Zechstein interval of up to hundreds of meters are observed in the area to the north due to a deeper basin and thick evaporitic sequences. The Zechstein Group thins towards the uplifted southern margin where the formation truncated and eventually disappears. These trends are consistent with erosional truncation and a regular basin edge.

Maps of the TVT of each zone within the Zechstein Group are provided, to account for thickness variations within facies (Figure 20). This gives insight into the spread of the zones. These images show the individual zones become thicker towards the North. Some zones show this phenomenon more than other, but the overall trend indicates a thickening northward.

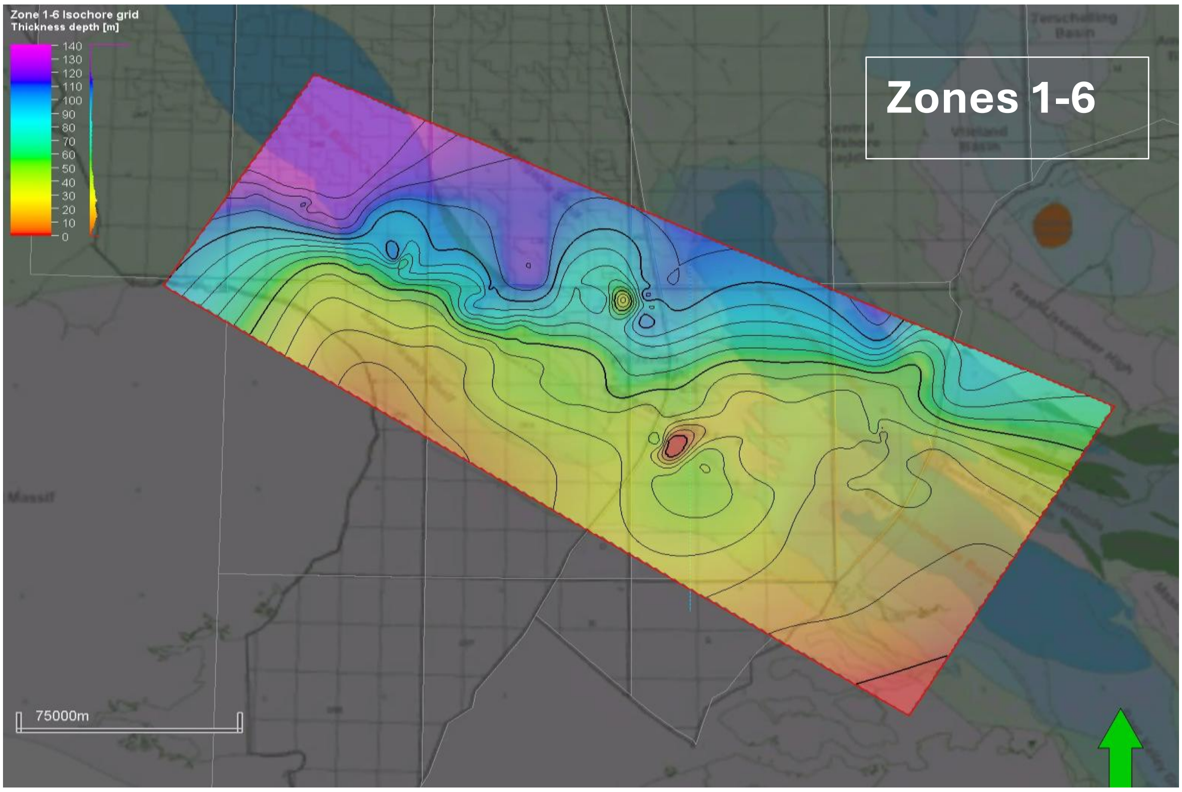

Figure 19 True vertical thickness (TVT) maps of the gross total Zechstein group. Zone 1-6 isochore gridded thickness. scaled 0-140 m. Cool colors indicate thicker intervals

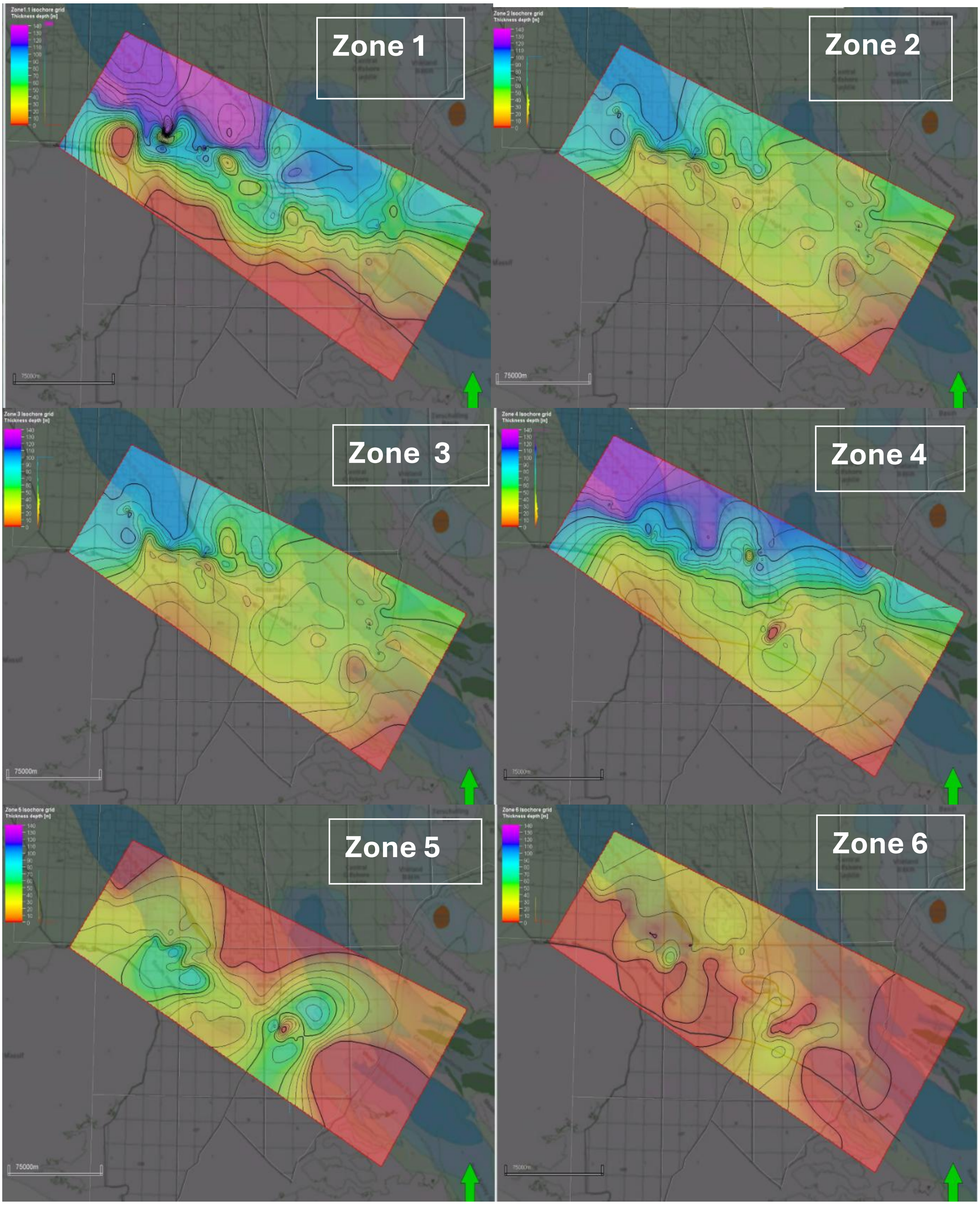

Figure 20 True vertical thickness (TVT) maps of the gross thickness in the zones within the Zechstein group. Isochore gridded thickness maps of zones 1-6. Scaled from 0-140 m. Cool colors indicate thicker intervals.

4.4.2 Net sand thickness

Next, net sand thickness maps are produced. These maps are based on the total thickness of the sand within the zones.

Figure 27 shows the isochore gridded map of the Zechstein formation, illustrating significant thickness variations. The NW-SE belt that runs parallel to the LBM, with shale out- towards the NNE and the depocenter gradually shifting westward. Thinning trends towards the southwest are interpreted because of onlap and erosion.

The maximum thickness of the total sand intervals is up to ~ 70 meters, observed in the area around the P10-P11 wells.

4.5 Well core plug data

A total of 16 NL and 3 UK wells across the study area were analyzed (Figure 21). Core plug data were evaluated to assess porosity, permeability, grain density and true vertical depth (TVDSS). These measurements were used to characterize reservoir quality and to identify trends. An overview of the range in values per well are provided in Table 4.

Table 4 overview of the porosity, permeability, and true vertical depth data. Source: 1 EBN database. 2. Kingsnorth project (2011). Numbers provided show the lowest and highest value if relevant. Measured depth mentioned relates to the Maximum depth of the Zechstein interval.

Well	**Porosity** (%)	**Permeability (mD)**	**Grain Density**	**Measured TVDSS (m)**
P10-01[1]	22.3- 28.0	27-723	-	1722
P11-05[1]	24.8- 29.8	7.0-431	2.65-2.76	1956
P11-04[1]	14.1- 29.5	97 - 1147	2.63-2.68	1602
P12-A-01[1]	25.6-30.1	-	2.48-2.88	3001
P12-12[1]	5.3-7.2	0.17	2.66-2.72	2856
Q10-02[1]	17.5-19.0	85	2.68-2.73	2245
Q11-03[1]	2.5-7.1	0.19- 2.4	2.51-2.69	2623
Q14-02[1]	5.7-6.8	0.23	2.65-269	2793
Q14-03[1]	4.9-7.3	0.07- 0.2	2.68-2.79	2858
Q16-FA-101-S1[1]	5.25-7.3	0.06- 0.08	2.69	3593
48/29-1[2]	26	1100	-	1300
48/29-2[2]	20		-	
48/29-3[2]	22		-	
52/5-1[2]	22		-	
52/5-2[2]	26		-	
52/5-3[2]	20		-	

Figure 21 Overview of the location of the 19 wells that include the core plug data.

Porosity values range from 2.5 to 30 percent, while permeability values range from 0.7 to 1174 mD, indicating a broad range from tight reservoirs to highly permeable zones. Grain density is consistent with lithological expectations of a sandstone with some carbonate or evaporite cement, averaging 2.70 g/cm^3 .

The Raw porosity and permeability data was grouped into 5 percent porosity bins. This was done to analyze the quality of the data. These binned points were plotted next to the raw data to highlight any influence of outliers and clarify the porosity permeability relationship across the dataset.

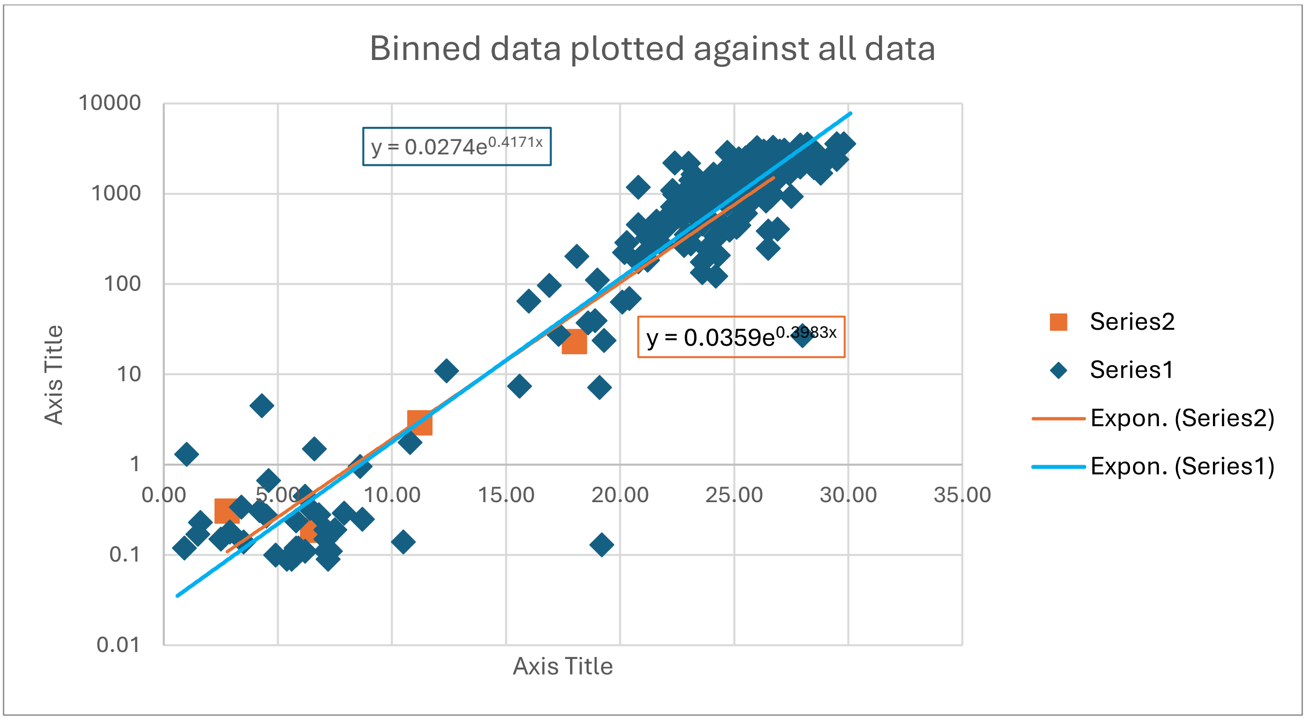

Figure 22 Binned data plotted against all data.

Note that the number of values included in each bin is not equal. An exponential series was calculated for the raw and the binned data. The formulas are $y = 0.0274e^{0.4171x}$ and $y = 0.0359e^{0.3983x}$ respectively. As figure 22 indicates these two trends are similar. Therefore, the influence of outliers is found to be minimal.

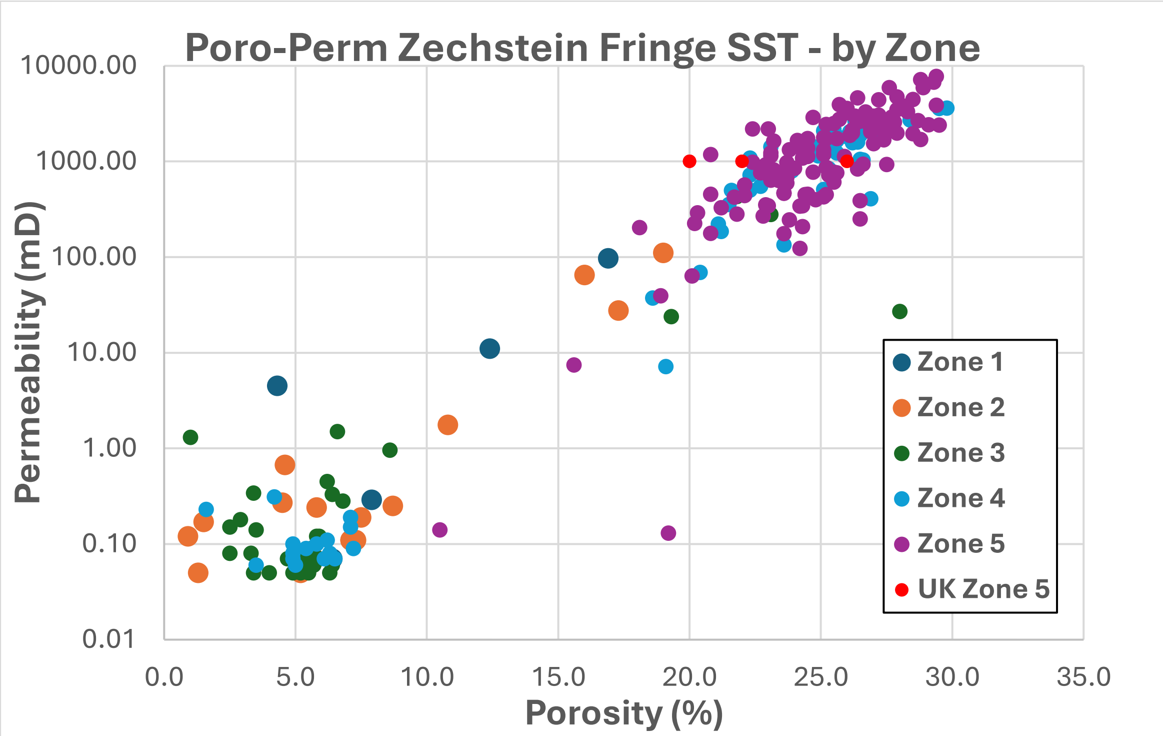

Figure 23 Porosity vs. Permeability cross plot for core plugs, color-coded by zone.

Figure 23 shows the cross plot of porosity and permeability of the Zechstein fringe sandstone per zone. The data displays a logarithmic relationship, which is typical for a siliciclastic reservoir. Higher porosity values (>20%) correspond to permeability values over 100 mD, while tighter porosities (<6%), mostly show values below 1mD. Furthermore, the graph indicates that most samples fall withing the high porosity, low permeability zones correspond with wells of zones 4 and 5.

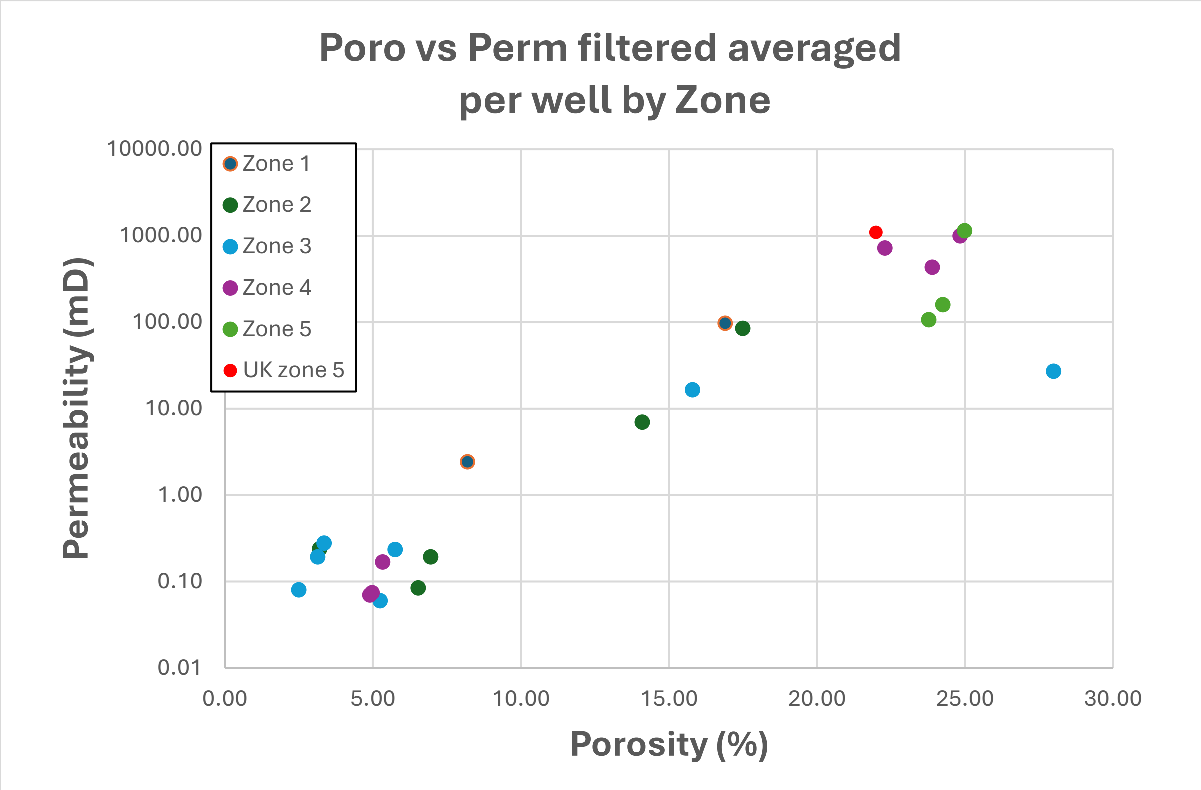

Figure 24 Porosity vs Permeability with values averaged per well per zone

Next, the data was averaged per well per zone. This is depicted in Figure 24, here it shows the cross plot of porosity and permeability of the Zechstein fringe sandstone per zone. The data displays a logarithmic relationship, which is typical for a siliciclastic reservoir.

Higher porosity values (>20%) correspond to permeability values over 100 mD, while tighter porosities (<6%), mostly show values below 1mD.

Furthermore, figure 25 shows the cross plot of porosity and TVD of the Zechstein fringe sandstone averaged per well by zone. The data displays a trend that can be explained by a power law. Overall, there is a clear relationship between the porosity of the sand and its current burial depth. This is an indication for compression.

Higher porosity values (>20%) correspond to a shallower depth of max. 2000m. While tighter rocks (porosity <10%) correlate to depths >2500 m.

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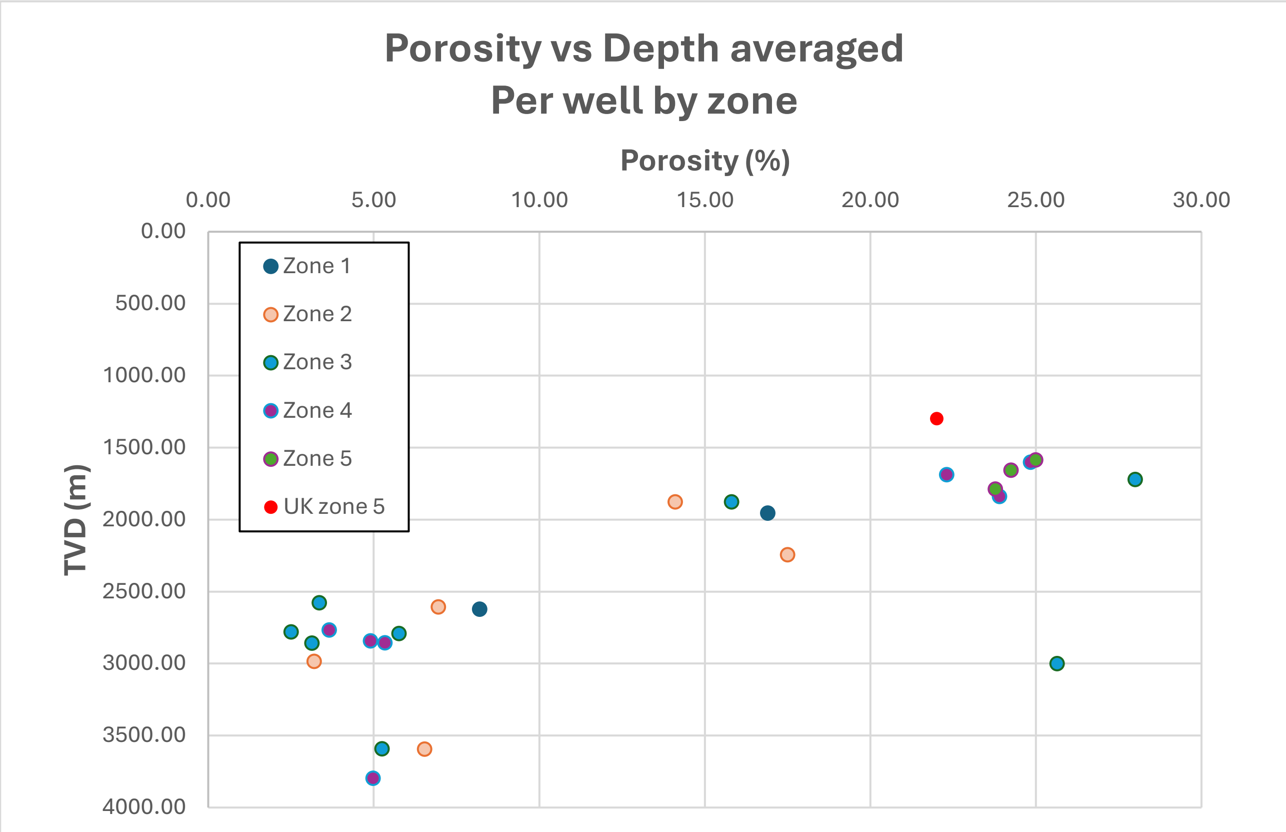

Figure 25 Porosity vs true vertical depth with values averaged per well by zone.

The porosity permeability correlation of each separate zone by well was also plotted (Figure 26). This presents an overview of both the trends visible within each zone, and the distribution of data in each well.

A logarithmic trend can be interpreted from the graphs in all zones. Zone 1 has only 4 datapoints, therefore the trend is not fully reliable. Zones 4 and 5 show many datapoints from well P11-04.

Zones 3 and 4 show two separate clusters one with a low porosity and permeability and one with a high porosity and permeability, these are from wells P12-12, Q14-03 and Q16-02 which all are further from the LBM and are found at a deeper TVD.

The distribution in the wells is poor. Therefore, slight changes in the trends can be wrongly interpreted. However, as the graph of averages per well by zone shows, the overall trend remains the same.

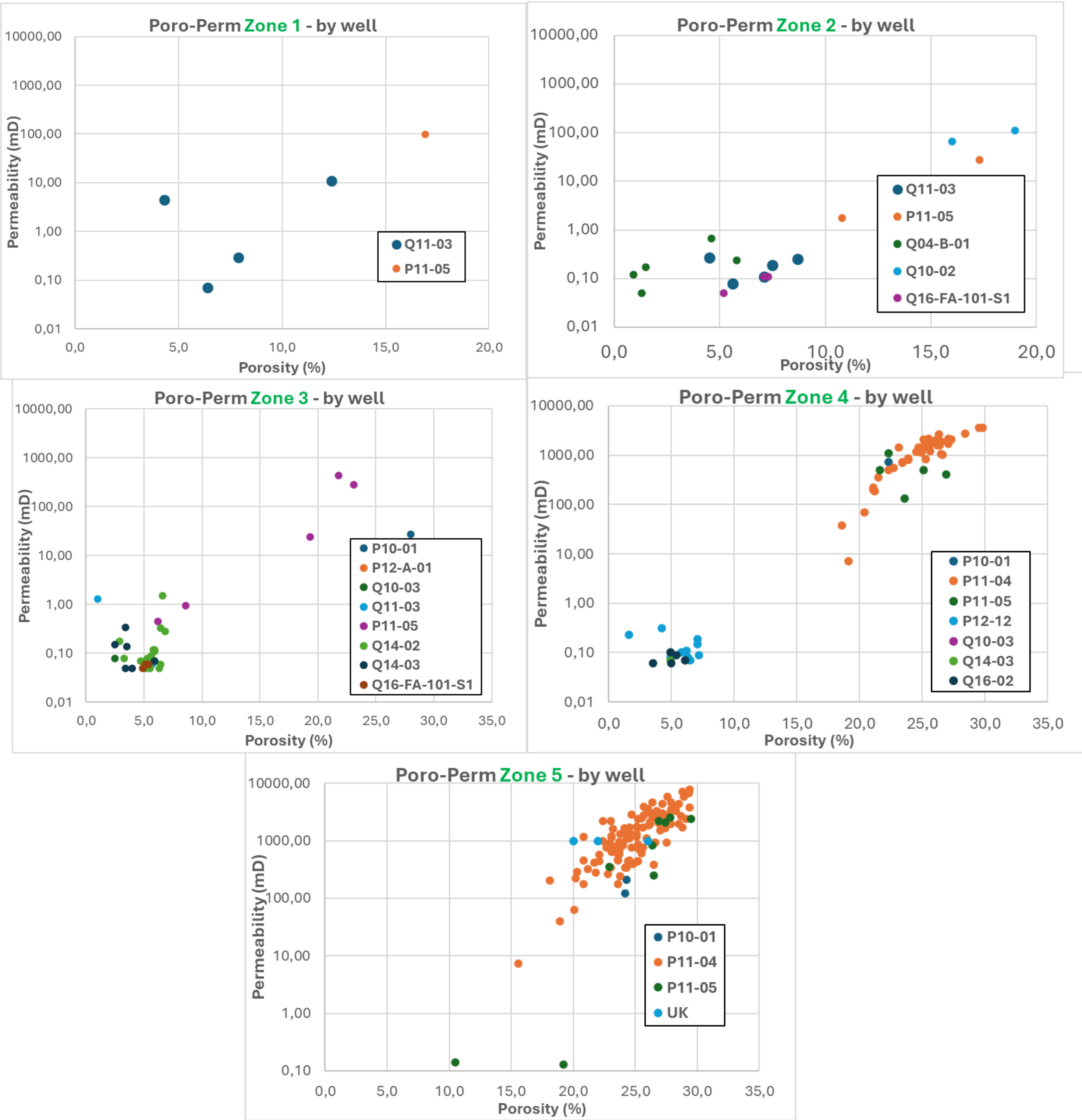

Figure 26 Graphs showing porosity vs permeability of zone 1-5 by well.

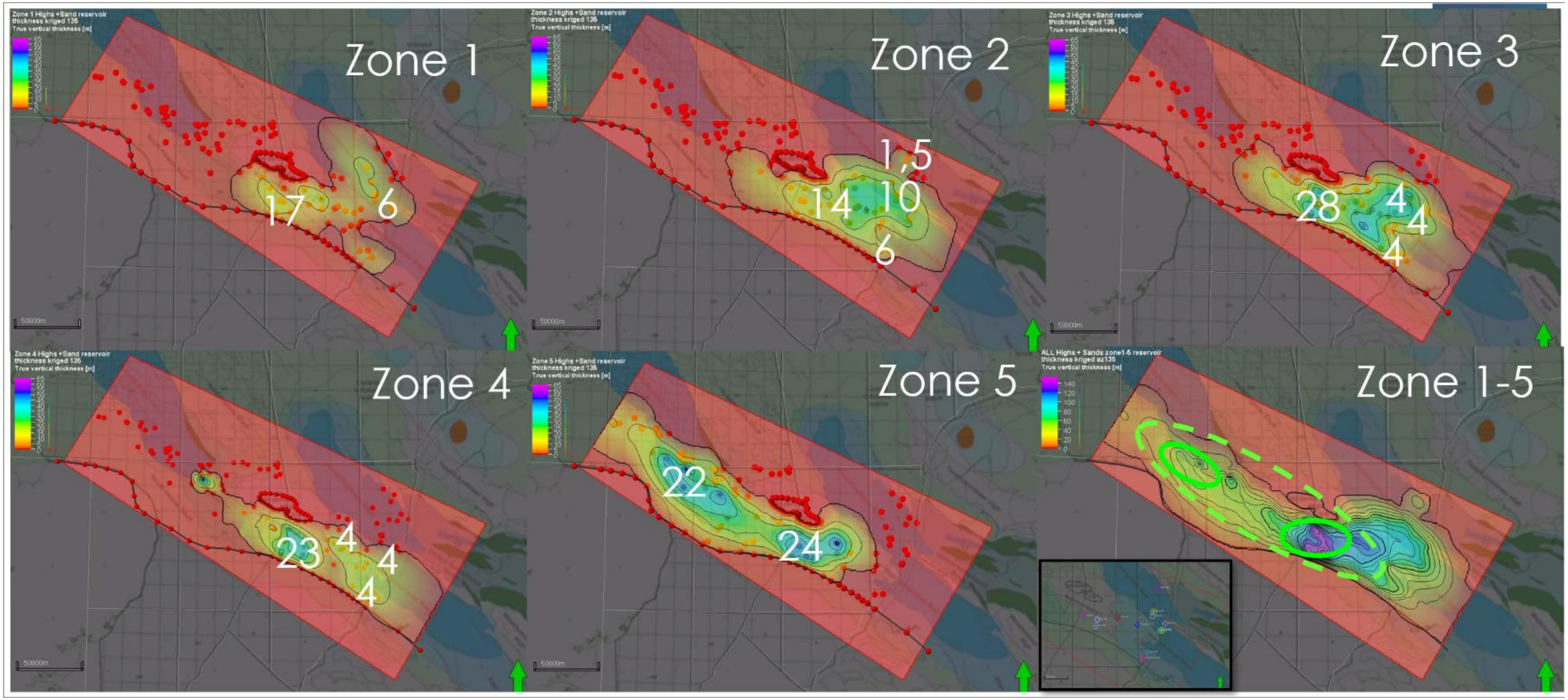

Figure 27 Thickness and Porosity maps of the Sand in Zones 1-5. Modelled using Kriging with an az. 135 degrees, averages taken as zero. Single zones have a depth scale 0-65 m while Zone 1-5 is scaled as 0-140 m. Green circles indicate sweet spots of good reservoir potential. The porosity values on the map are given in percentages.

4.6 Reservoir quality maps

Thickness and porosity maps of the Sand in zones 1-5 were enhanced with given porosity data (Figure 27) . This helped interpret a zone of good reservoir potential, which is displayed in image of Zone 1-5.

The porosity values help indicate regions of good reservoir quality as the results from Chapter 4.5 concluded that a higher porosity is always indicative of a good reservoir quality. Note that, in the Dutch offshore area, all porosities over 10 percent concentrate around the P10-P11 blocks. Other areas display lower values. This indicates a proximal relationship of a good sand to the LBM.

The areas of good reservoir quality are annotated in figure 27 zone 1-5, the full green ovals indicate areas of good porosity where data is present. The dotted green oval represents an area of possible good reservoir quality without the certainty of well core data. This is the region is which more data and research could provide for more prospects.

4.7 Seismic sections

A seismic section interpretation that focused on a SW-NE oriented 2D seismic line crossing the basin margin was interpreted (Figure 28). This was done to investigate the stratigraphical and structural environment of the Zechstein.

The seismic line was flattened on an interpreted Top Zechstein horizon to enhance the correlation and facilitate better recognition of onlap and/or unconformities. An important feature that can be observed on this line is the truncation and pinch out of the Fringe Zechstein and the Rotliegend. The fringe can be identified as a discontinuous deposit near the platform edge. This is shown with a red arrow and are interpreted as an erosional termination against a basin ward thickening wedge.

Variations in seismic impedance are evident across the seismic section and are interpreted to correspond to the lithological boundaries between the formations as described in the introduction. These contrasts help delineate key units, such as the base and the top of the Zechstein.

The quality of this regional seismic data from 1991 posed limitations regarding the validity of the interpretations. This seismic is less effective in resolving finer scale information on the different sandstone zones within the Zechstein due to a modest seismic resolution.

Within this area there are a lot of faults that limit interpretation as the seismic resolution causes uncertainties in following the seismic reflector through discontinuities caused by the faulting.

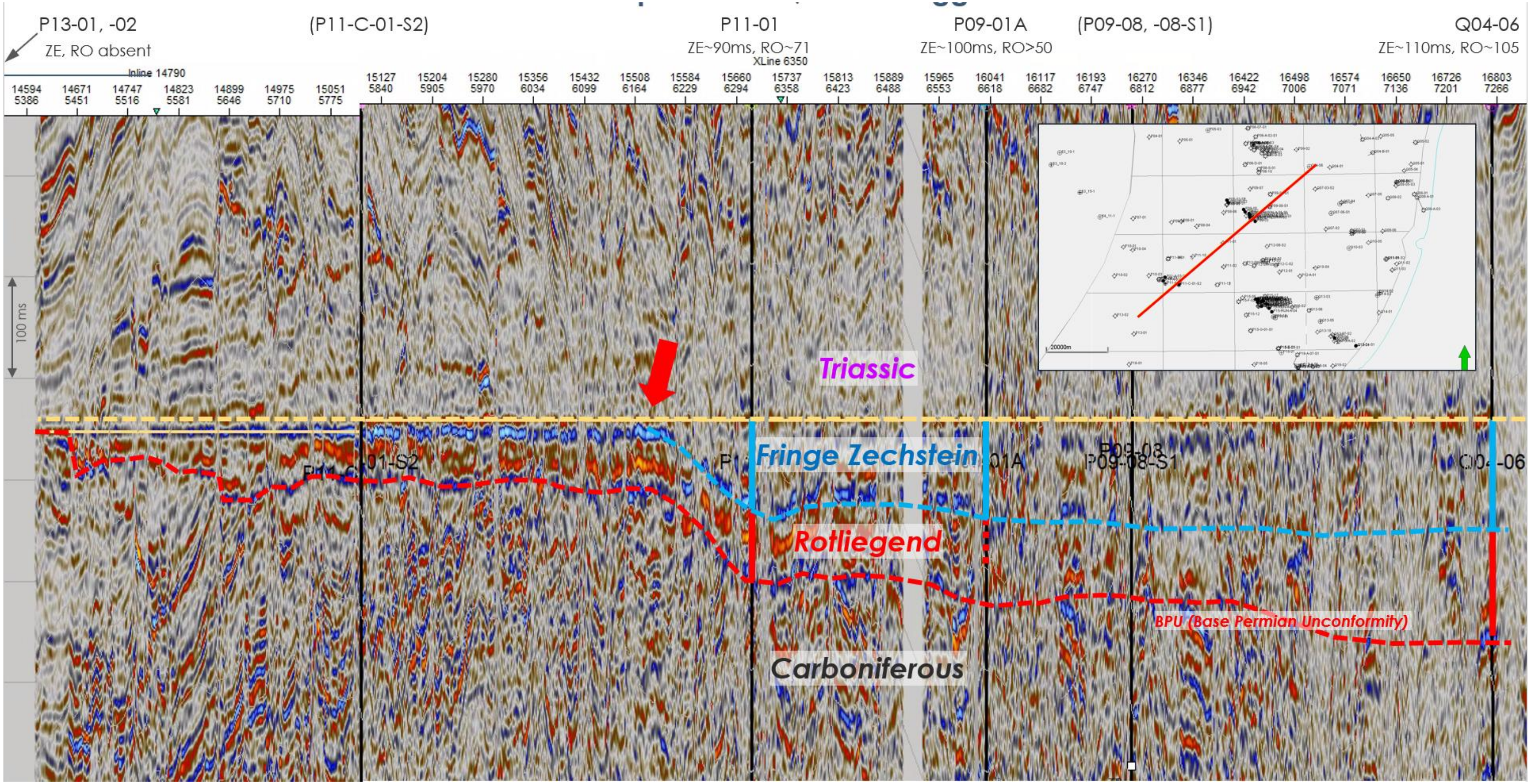

Figure 28 Seismic section of a SW-NE Rotliegend pinchout line. Flattened on ~Top Zechstein; vert. exaggeration 50x. Red arrow indicates truncation/pinch out of the Fringe Zechstein as the Top of the Rotliegend Line MPNI-9101 (1991)

5. Interpretation and Discussion

5.1 Stratigraphic Correlation Inconsistencies: Petrel vs. NLOG

During the well correlations, several inconsistencies were identified when comparing various lithostratigraphic well tops in the NLOG database. When compared to the zones used in this study, they show significant differences. In multiple wells, the Top Zechstein and the Triassic unit boundary determined by NLOG were inconsistent. These discrepancies highlight the challenges of interpreting the Zechstein Fringe Sandstone due to poor formal definition in this region.

Overall, the Fringe sandstone often occurs as a discontinuous sand lens at the margin, complicating regional correlation. Furthermore, the NLOG tops adhere to standardized regional picks whilst this correlation focuses on reservoir scale continuity. As this study required correlations across longer distances, new interpretive uncertainty arose.

Several geological and data related factors can explain these inconsistencies.

121 wells were correlated across the Southern North Sea in both the Netherlands and the UK. Their distribution can be seen in chapter 4.1.

The Zechstein was correlated using ‘’zones’’ which are defined by transgressive surfaces that can be found throughout the entire study area. Two main results will be further discussed as they provide a good synopsis of the area.

Nederweert Sandstone

The “Nederweert Sandstone” panel (Fig. 13) portrays a key region near the UK/NL offshore border where the Zechstein exhibits notable lateral thickness and continuity. However, several inconsistencies in the NLOG database raised need for reconsideration of the local stratigraphic correlation. Table 7 presents a revised interpretation of the newly interpreted top, referring to the original Zechstein nomenclature. This comparison is specific to the “Nederweert Sandstone” region in the P-blocks, as described in the NLOG Stratigraphic Nomenclature. and includes the proposed new well tops as a true vertical depth (TVD) per well.

One of the primary discrepancies identified lies in the classification of strata as depths corresponding to zone 6 in this study. When compared to the NLOG stratigraphy (NLOG, 2025) the rock is most found to be of Triassic origin, typically classifying it as the Nederweert Sandstone. Additional inconsistencies are in the thickness of the ZEZ4S sandstone. In this study, thicknesses were interpreted by following key transgressive surfaces, whereas NLOG displays greater variability in the thickness of ZeZ4S as it merely looks for lithological changes. This different approach underscores the need for a more sequence stratigraphic framework for the marginal sandy Zechstein Facies, particularly in areas of great complexity, such as the Nederweert region, where there are no clear markers to differentiate between Zechstein and Triassic sands. It is proposed to reclassify all “Nederweert” sandstone in this area as Zechstein sandstone.

Table 5 Proposed new tops of the zones and their related official formation and Depth.

Top Zone	**Official Formation**	P07-01 TVD	P10-01 TVD	P10-02 TVD	P10-03 TVD	P11-03 TVD	P11-04 TVD	P11-02 TVD
6	ZEUC	1731	1605	1313	1442	1722	1523	2650
5	ZEZ4S	1750	1627	1334	1461	1742	1546	2668
4	(1)ZEZ3S/ (2)ZE3C	1797 (1)	1685 (1)	1386 (1)	1515 (1)	1793 (1)	1602 (1)	2713 (2)
3	ZEZ2S	1836	1717	1422	1560	1828	1646	2737
2	ZEZ2S	1888	1770	1476	1614	--	--	2779
1	(1)ZEZ1S/ (2)ZEZ1C	1935 (2)	1817 (1)	1514 (1)	1655 (1)	--	--	2807 (1)
Base ZE	--	1977	1866	1530	1678	--	--	2843

Well Q16-FA-101-S1

The visit to the Core store facility at NAM provided insight into the specifics of core Q16-FA-101-S1. This further helped improve the stratigraphic correlation as rock determination gave insight as to the true formations of this core. Therefore, it is important to discuss variations in formations used in the composite log, the NLOG database and this studies correlation.

The composite log described the region to range from 3699 to 3668 md. The log further describes the formation as ZEZFR, Figure 18 image of Q16-07 Core 3 between 3706.02 and 3603.32 m. which corresponds to a general Zechstein fringe facies. Furthermore, it states that below the Zechstein, Carboniferous rocks are found. This would indicate the presence of the base Permian unconformity (BPU). On another note, NLOG found that the Zechstein interval could be found ranging from 3701-3636 md. The formation is further described as an 11 meters thick layer of Kupferschiefer followed by a carbonate and multiple sandstone facies. Below the Zechstein NLOG states that the Permian Slochteren formation is present.

These results are in contrast with the findings of this study. Here, the BPU is found at 3705.57 Md, where it is followed by Fringe sandstone. No indications of the Slochteren Fm nor the Kupferschiefer are found. Furthermore, due to onlap near the basin edge it is most likely that the youngest sands are found in this well instead of fringe sandstone ZEZ1S which is older.

5.2 Relationship with the original Zechstein nomenclature

An essential step in evaluating the reservoir is determining if the zones defined through well correlation can be related to the original Zechstein nomenclature (See introduction).

Based on the well panel correlations in Petrel (See appendix A), he various zones do not neatly correlate with the Zechstein cycles. First, the Zechstein fringe sandstone is a marginal facies that only occurs at the basin edges (Bouroullec & Geel, 2025). Therefore, it often is not captured in the classic evaporitic cycles. Secondly, the lateral facies variability is not considered in the original cycles. As this framework is based on evaporitic sequences of the larger basin, to look regionally, the sands may represent a clastic facies which was deposited during the same time but differs in lithology. This results in a pinch out or even disappearance of sands over short distances making regional correlations when using the Zechstein Z1-Z4 cycles. Literature states that during Z1-Z3, the clastic influx was pushed back to the basin margin, the carbonates were laid down as series of prograding and aggrading sigmoidal bodies (Geluk et al, 1996). As around the LBM extensive sabkhas and mudflats developed, more towards the western offshore sands were deposited under fluvial and estuarine conditions. Third, as thin sands in this region are often dolomitic or anhydritic, the definition of their position within the cycles is often ambiguous.

Lastly, literature and NLOG inconsistencies are prevalent. In some wells, NLOG assigns sands to either a general Zechstein fringe facies (ZEFRS) or even to the Triassic Nederweert sand. The ZEFRS correlations shows that sandy bodies are not always recognized formally. The indication of a Nederweert Sandstone far offshore indicates unclear vertical boundaries (Figure 29). As the contact of sands are often irregular and differentiation between them is irregular.

In general, a partial correlation to the Zechstein nomenclature is possible, as the determined zones represent a marginal Zechstein Clastic system that is not consistently represented in the original cycles. This highlights a need for a supplemental zonation scheme for the edge of the Zechstein units in the Netherlands. Suggested is the use of Zones 1-6 as a practical subdivision framework for regional) correlation (Fig. 29).

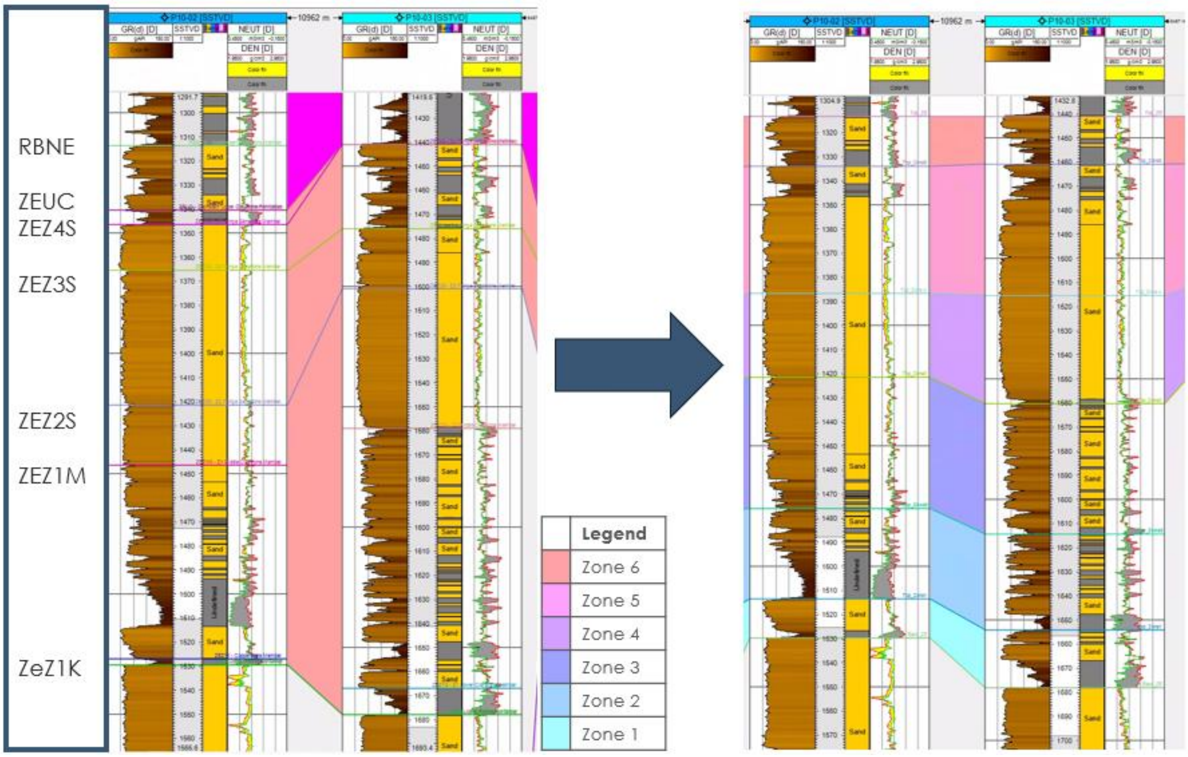

Figure 29 NLOG well tops of well P10-02 and P10-03 vs. Defined Zones.

5.3 Sediment source and transport of the Zechstein Fringe Sandstones.

Understanding the source and transport mechanisms of the Zechstein fringe Sandstone is essential for interpreting its spatial distribution, thickness variation and reservoir quality.

According to literature the deposition of the Zechstein fringe Sandstone could be either due to Uplift and subsequent erosion of the LBM, due to salt halokinesis or due to a sea level drop at the end of the Permian.

The Kingsnorth project (2011) proposed a minor uplift and erosion of the LBM during the late Permian. This caused the local development of the Hewett sandstone. During the Early Triassic, this graded into claystone (Lower Bunter Claystone), deposition of which came to an abrupt halt as the LBM further uplifted and deposited the Bunter Sandstone which consists of sheetflood sands and fluvial channels (Kingsnorth, 2011).

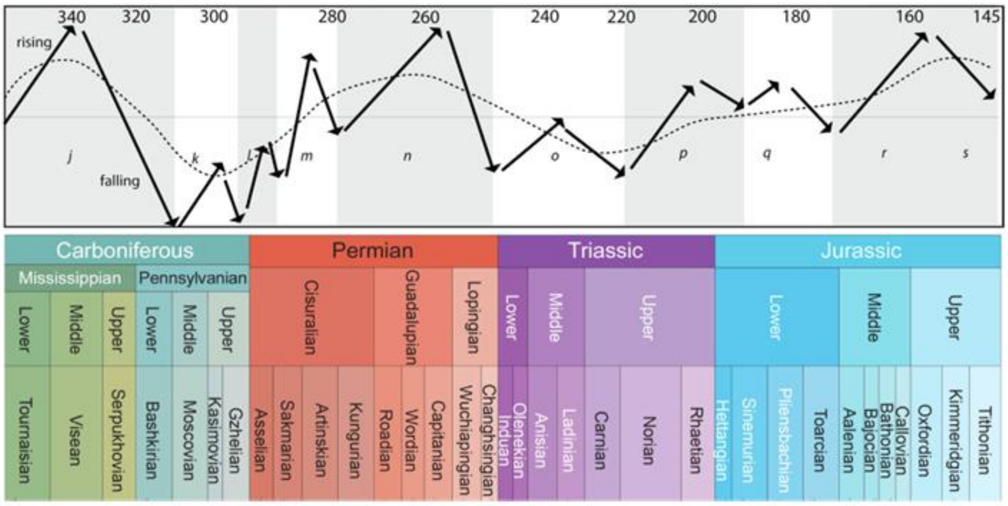

Figure 30 The tectono-glacio-eustasy from the Carboniferous-Jurassic. Up arrows indicate sea level rise and Down arrows indicate a falling sea level. Note the significant sea level drop at the end of the Triassic. (Van der Meer et al., 2022)

Another possible mechanism instead of LBM uplift is that of a sealevel drop, this could have caused the basin margin to be exposed and therefore changing to a shallow marine to continental setting, explaining the deposition of sands.

This is supported by Van Der Meer (2022) as they found notable falls in sea level rise during the late Permian (260-245 Ma) (Figure 30). They state that this is caused by changes in oceanic crustal production, as the Permo-Triassic has been described as a major regression in the Northern hemisphere (van der Meer, 2022).

A study by Maniar (2019) looked at Triassic reservoir of the Nederweert and Volpriehousen sections of well NDW-01, further east. They concluded that the lithofacies that are encountered in the NDW-01 well are related to wadi deposits and that a fluvial system led to the deposition of the Nederweert sandstone member.

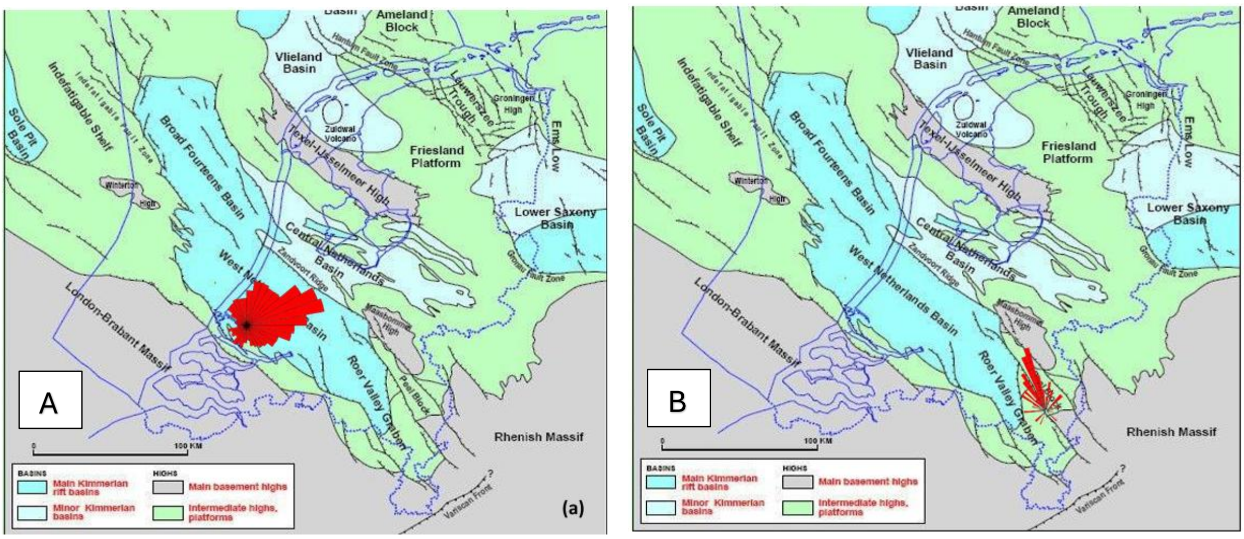

Figure 31 A) Paleoflow direction that led to the deposition of cored Upper bunter sandstones in the Naaldwijk area. B) Paleoflow direction that lead to the deposition of the Nederweert Sandstone in the Roer Valley Graben. Maniar (2019).

The rose diagram of the Nederweert sandstone (Figure 31) shows a bulk transport direction towards the NNW, thus the Rhenish Brabant Massif if considered a likely sediment source. The Upper Bunter sands of the Naaldwijk area (close to the study area) indicates a paleo direction to the ENE, proposing a clastic influx from the LBM (Maniar, 2019).

Another possible mechanism is that of isostatic movement, where the heavy salts of the deep basin exert upward pressure on the basin margin, leading to localized uplift. As the deeper basin of the Zechstein Group consists of thick evaporitic sequences, which are highly ductile over time, their tendency to flow could have caused differential load on the edge of the basin, causing localized uplift. This could have influenced the influx of clastic sediments from the LBM as it created accommodation space (Duin et al., 2006, Geluk, 2005).

Of course, a combination of all mechanisms is most likely, thus further investigation is needed to refine the source and transport mechanisms of the Zechstein Fringe sandstone and to provide an improved definition between the Triassic and Zechstein sands, a detailed study on the paleo direction and depositional environment of the sands is recommended. In addition, a comprehensive sequence stratigraphical analysis on the structure of the sands would provide valuable insight in a more regional context.

5.4 Main controls on reservoir quality

Significant variability in the porosity and permeability of the Zechstein fringe sandstone is the result of a combination of compaction, cementation, and proximity to the source.

As described in the results section on well core data analysis and as indicated by the reservoir quality and thickness maps (see Figure 27), the eastern region of the study area shows low reservoir quality. As the sands in the area are of a low porosity and permeability. There are multiple reasons for the lateral variation inreservoir quality.

The first reason is due to compaction related to burial, which resulted in a denser rock by reorganizing the framework grains. In the eastern part of the study area, the reservoir is buried deeper. Secondly the cementation of anhydrite cement further degrades the reservoir quality in the sands. This is proven by a high grain density over 2,7 g./cm3 that are found in wells in the area (See appendix B). Lastly the more proximal the Sand is to the source (London Brabant Massif), the better quality the sand. This is demonstrated by the depth porosity plot (Figure 25) as this portrays a clear relationship where a shallower sand corresponds with a higher porosity.

5.5 Hewett Sandstone vs Zechstein Fringe Sandstone

One of the main aims was to figure out how the UK Hewett sandstone relates to the NL Zechstein fringe Sandstone. This was done by providing better horizontal and vertical correlations (See Appendix A). Providing stratigraphic overview schemes and comparing porosity and permeability and seismic data.

Vertical and lateral definition

The presence of the Zechstein fringe sandstone can be better defined, both horizontally and vertically as is described in chapters 5.1 and 5.2. here is it concluded that the Hewett sandstone of the UK and the Zechstein fringe sandstone of NL are of the same origin. Geluk et al. (1996) proves this comparison by stating that although the Hewett and Brockelschiefer rocks are considered lowermost Triassic in the UK they are the same as NL Zechstein rocks. And later naming the sandy deposits in the southern offshore a Z4 sandstone/Hewett sandstone (Geluk 2005).

Well core data (poro/perm plots)

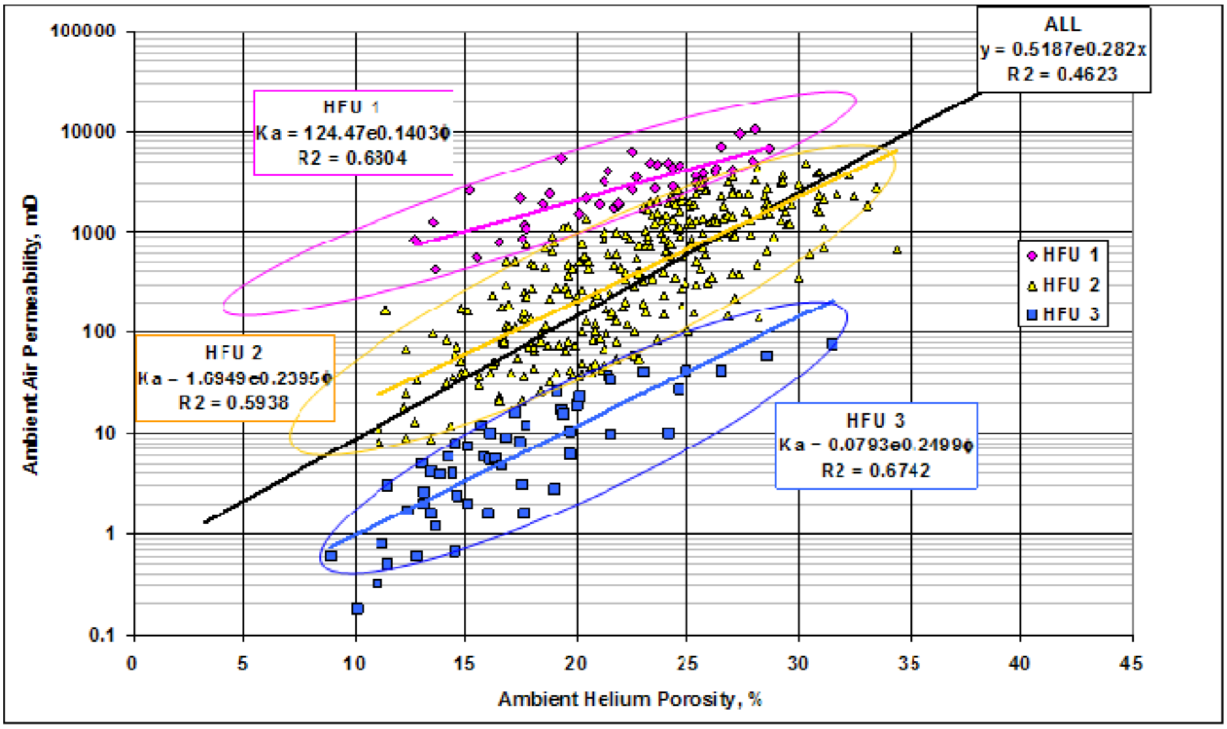

Figure 32 poro-perm plot of the Hewett field sandstone (Kingsnorth 2011)

For comparing the poro-perm data, two datasets were used. The Kingsnorth Project (2011) demonstrates a strong correlation between porosity and permeability (Figure 32), a trend that closely aligns with observations from this study (Figure 27). The high porosity values identified in the P10/P11 area are comparable to those documented in the Hewett field, suggesting similar reservoir characteristics and quality across these regions.

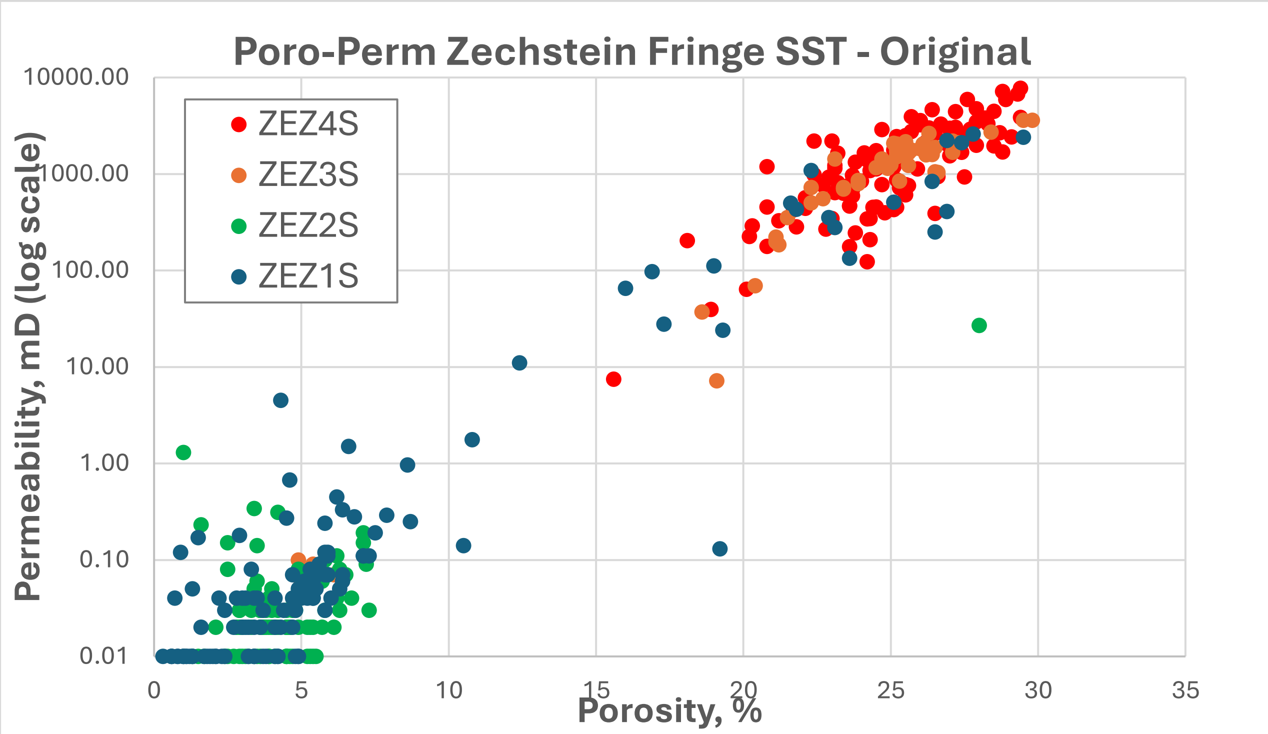

Figure 33 Porosity vs. Permeability cross plot for core plugs, color-coded by stratigraphic interval.

The porosity-permeability cross-plot based on the original Zechstein stratigraphic framework as recorded in the NLOG database (Figure 33) reveals a distinct trend: sands assigned to the ZEZ4S and ZEZ3S intervals consistently exhibit good reservoir quality, whereas those within the ZEZ2S and ZEZ1S intervals demonstrate significantly poorer quality. This pattern is likely attributable to the main compaction mechanism on which it heavily relies.

When comparing the porosity permeability cross-plot of figure 34 with the cross-plot that uses the zones used in this study, there are differences and the distinction between the upper and lower sands becomes less clear.

Overall, when comparing this NLOG dataset to this study, the general trends are significantly similar.

Seismic sections

As previously established, the limited seismic resolution of the available datasets has introduced significant challenges in accurately interpreting both structural features and internal lithological variations. To address these limitations, a comparative analysis of higher-resolution seismic sections from other studies was undertaken.

Chapter 4.7 outlines that the geometry suggests that the Zechstein carbonate or evaporite facies thins toward the basin margin, terminating against pre-existing topography or erosional surfaces developed during subsequent tectonic activity. This lateral termination, or pinchout, represents a key stratigraphic boundary and may have implications for both reservoir distribution and trap development in this part of the basin. It highlights the importance of recognizing marginal Zechstein geometries in frontier exploration areas of the southern Dutch offshore.

A comparative evaluation of the Kingsnorth project (2011) provides additional context. A SW-NE oriented large seismic section of the entire Hewett anticline depicts the full subsurface of the area (Figure 34). This cross section further highlights a proposed top of the Lower Bunter, which, like this study, was inferred due to the absence of a distinct lithological contrast.

Notably, this section does not reveal a clear truncation or pinchout of the Zechstein units. However, it does exhibit a consistent thickening of the Zechstein sequence toward the northeast, consistent with basinward deposition and accommodation space increase. This observation reinforces the interpretation of margin-ward thinning and provides a broader regional framework to interpret stratigraphic variability and reservoir potential within the Zechstein succession.

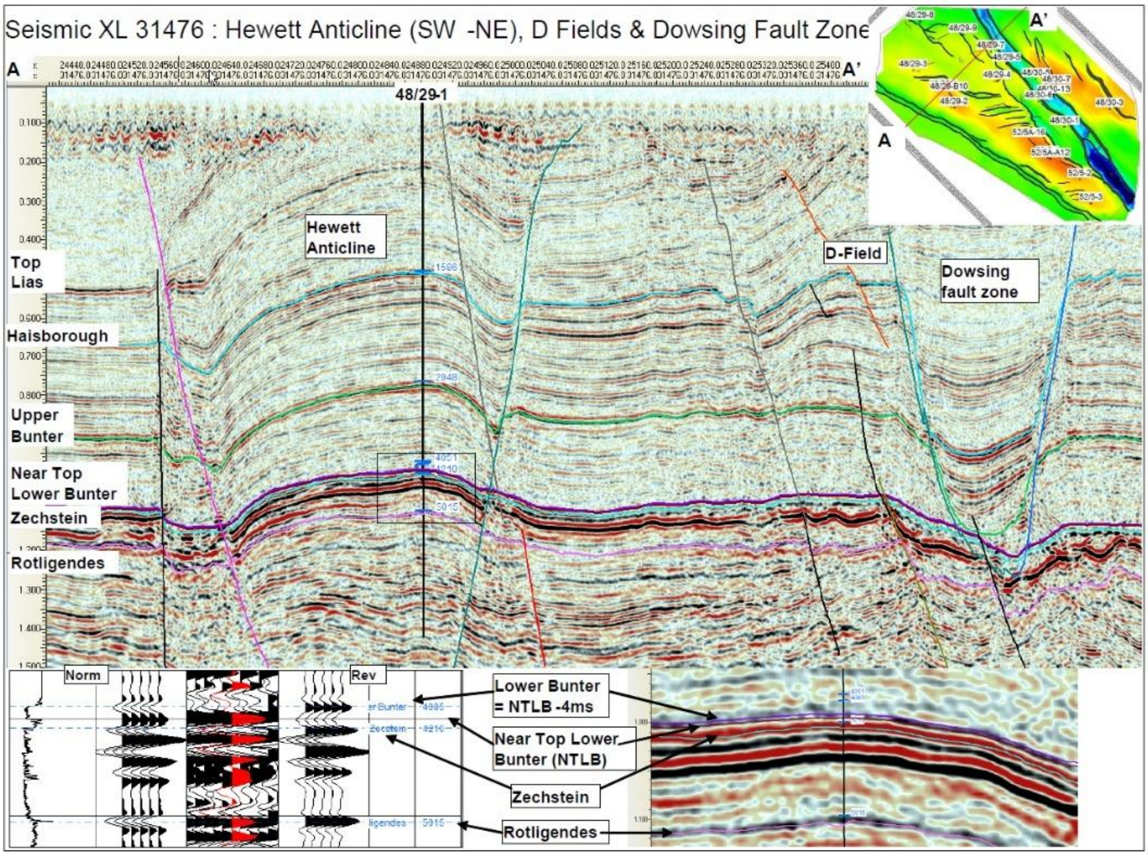

Figure 34 Cross section over Hewett anticline and example of synthetics illustrating Top Lower Bunter Construction. (Kingsnorth, 2011).

6. Conclusion and recommendations

The aim of this internship was to define the occurrence, characteristics, and reservoir potential of the Zechstein Fringe Sandstone in the Netherlands, while exploring its relationship with the Hewett Sandstone in the UK and identifying new areas of good reservoir quality.

Conclusion

It was investigated to determine if the occurrence of the Zechstein Fringe Sandstone in NL could be better defined, both horizontally (on a map) as well as vertically (divided into reservoir units). How the relation between the Zechstein Fringe Sandstone in NL and the Hewett Sandstone in the UK could be explained. What the thickness, facies and reservoir quality of the different units are. And if any new ''sweet spots'' of good reservoir quality in the Zechstein fringe Sandstone could be identified.

The most important conclusions are that:

- The current well-top correlation in the UK and NL area are **not consistent**. Therefore, proposed changes should be sent to TNO.
  - The most important finding here is that the Nederweert Sandstone correlates with ZeZ4S in the area around P10/P11.
- The Hewett Sandstone in the Hewett field **correlates well** with the ZeZ4S sandstone in the areas around P10/P11.
- There are "**Sweet Spots**'' found in the area in and around the P10-P11 blocks.
- Reservoir quality of the Fringe sand is influenced through multiple factors including the current **burial depth, anhydrite cement** and the **proximity** to the source of the sands.
- Verification on seismics (using non confidential data) proved to be **difficult,** therefore it is suggested to use newly acquired 3D seismics in the P10/P11 area, for further search of new prospects.

The full story of the area is as follows: After the Zechstein transgression, the eastern part of the study area shows a limited influx of sand coming from the south. During the Zechstein, the depocenter shifted westwards, and more and better quality sand arrived from the London-Brabant Massif in the Southwest. This higher quality sand, called the Hewett sandstone in the UK, occurs in the Netherlands around blocks P10 and P11. Dutch nomenclature recommends assigning this sandstone to the Permian, rather than the Triassic, as is customary in the UK. The 'Nederweert sandstone', is suggested by TNO in some wells in the P blocks, most likely belongs to the upper Zechstein. Therefore, we propose to revise this in NLOG.

The question remains whether the sands of the Zechstein fully fit into the cyclicity of the original Zechstein seismics.

Implications:

This research has led to insights into the thickness and distribution of the ZE Fringe sandstones in the UK and NL offshore region, thereby contributing to reservoir evaluation for EBN and partners. Moreover, it has enhanced our understanding of the occurrence and distribution of the Hewett and Fringe sands in the UK and NL. Furthermore, this study has provided insights into the geological history of the Zechstein fringe sands and surrounding regions

Follow up recommendations

To provide an improved definition between the Triassic and Zechstein sands, a detailed study on the paleo direction and depositional environment of the sands is recommended. In addition, a comprehensive sequence stratigraphical analysis on the structure of the sands would provide valuable insight in a more regional context.

To further research the area the depositional pattern of the sands could be modeled using a modeling program such as Dionysos. This could provide insights into the sediment transport pathways, facies distribution and further defining reservoir quality.

The main recommendation is to focus efforts on the Zechstein fringe sandstone on better seismic data for further prospect development in the P10/P11 area.

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Appendixes

Appendix A – Well section panels

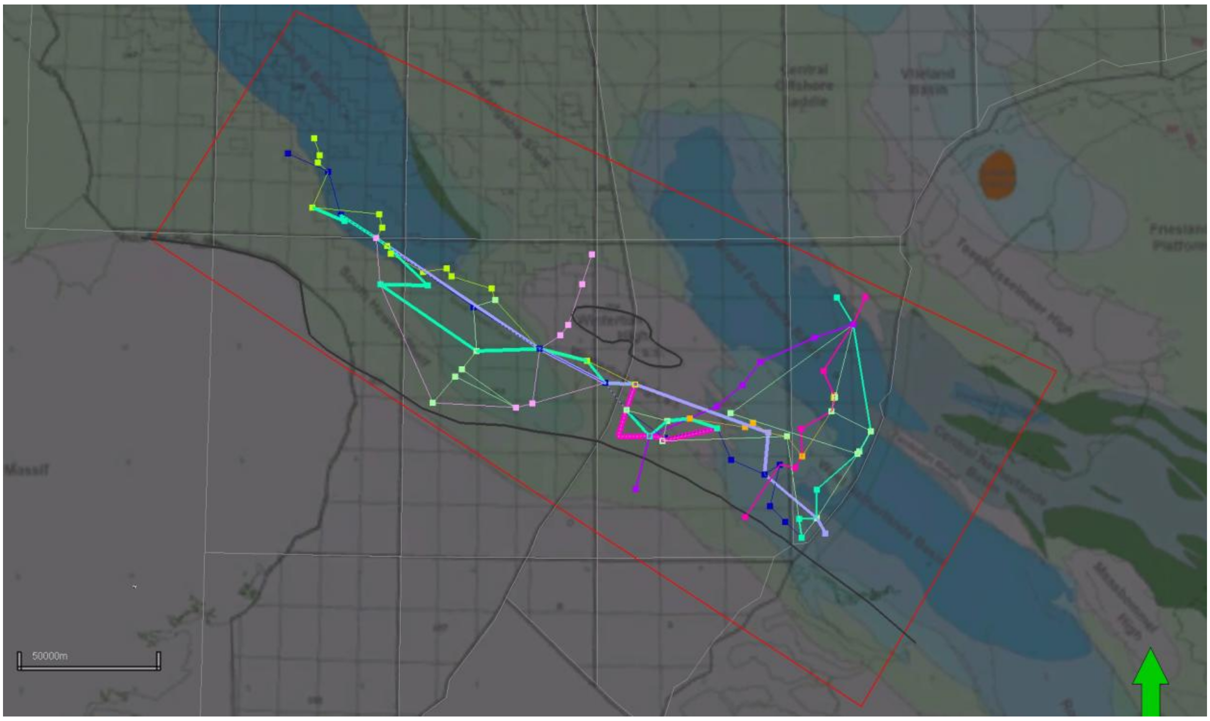


Figure 34 Overview image presenting well section panels within the study area (Figs. 38-49)

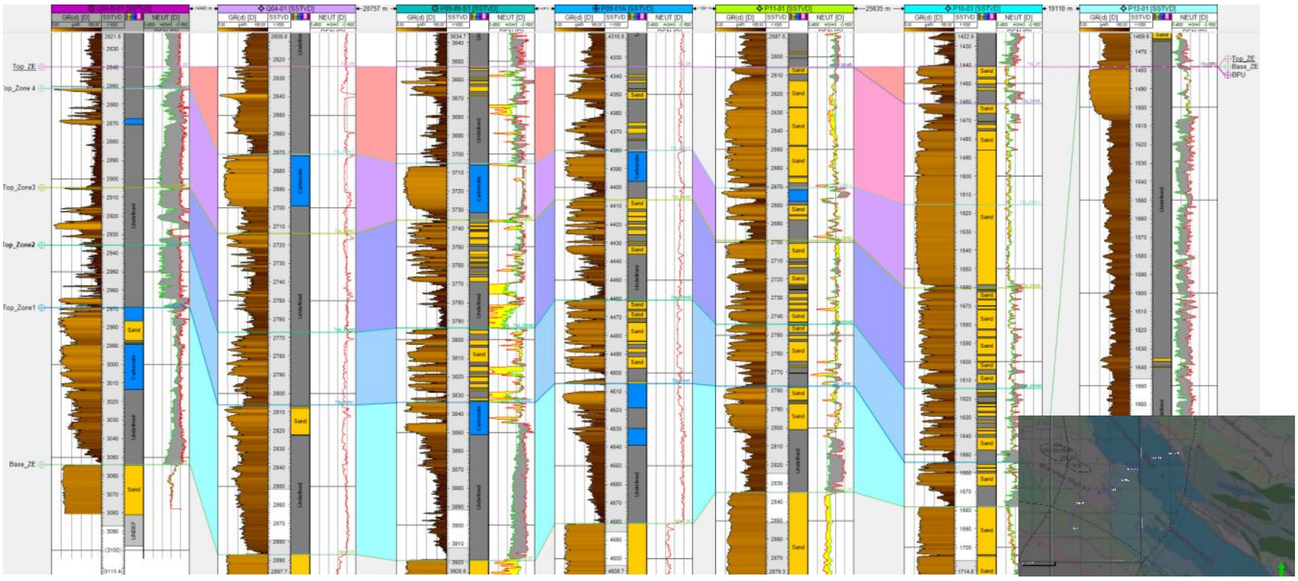


Figure 35 Well panel NE-SE west with a relative scale of 1.000.000.

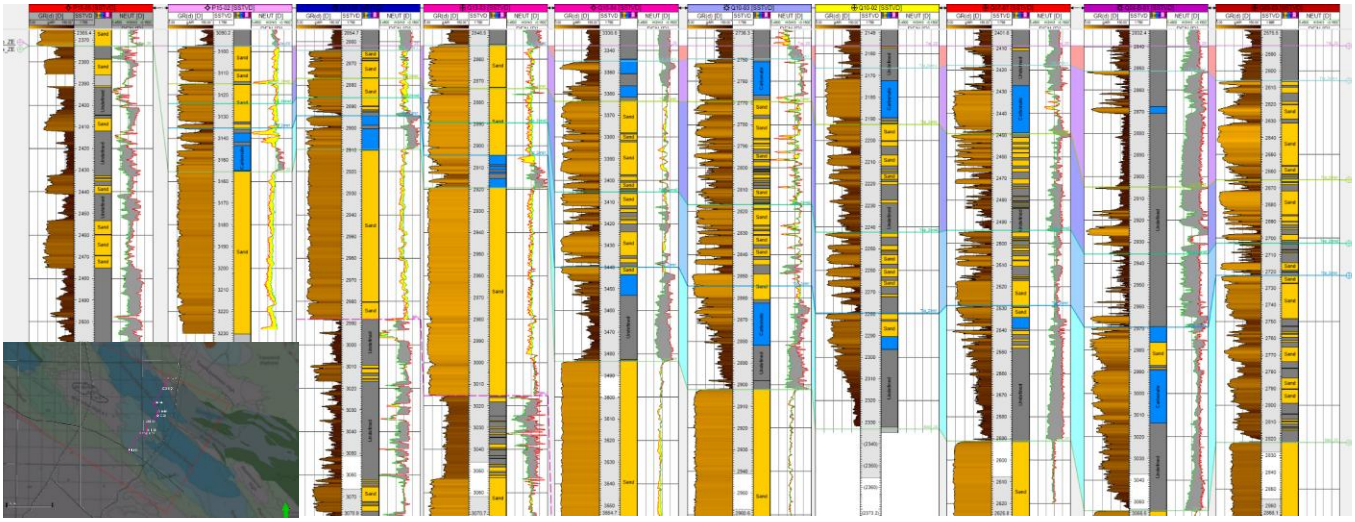


Figure 36 Well section panel SW-NE mid   with a relative scale of 2.5000.000

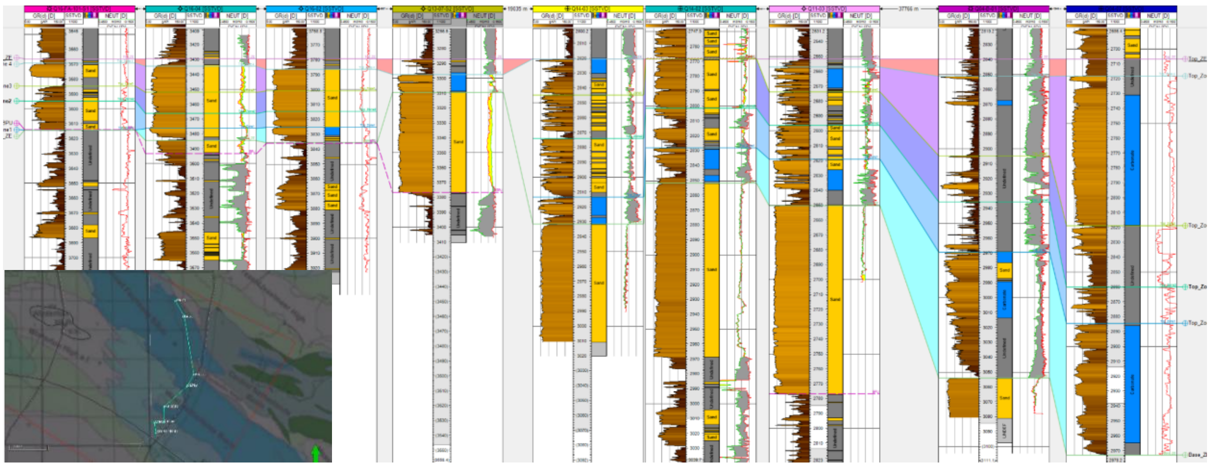


Figure 37 well section panel with a S-N East relative scale of 1.000.000.

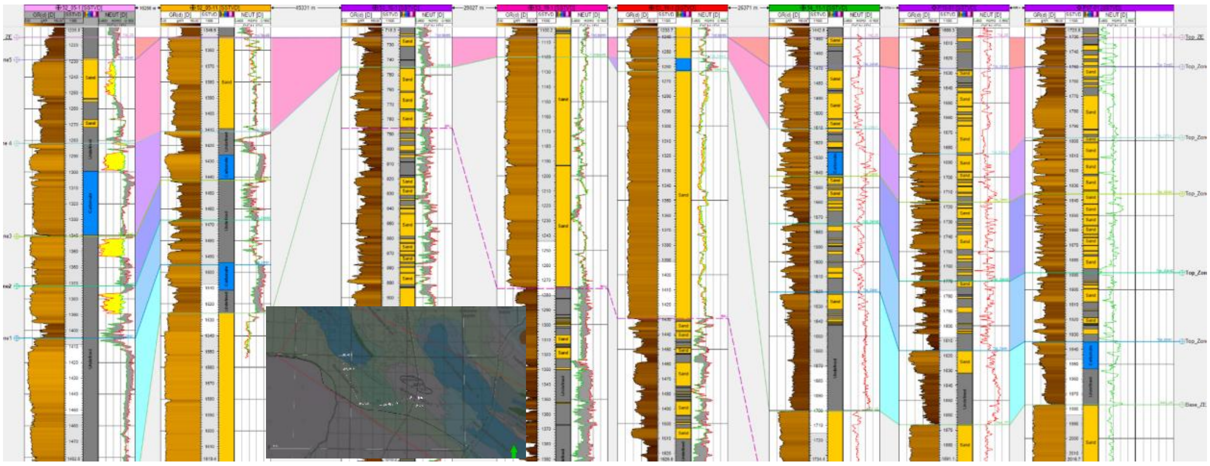


Figure 38 Well section panel UK EW-south with a relative scale 1.000.000.

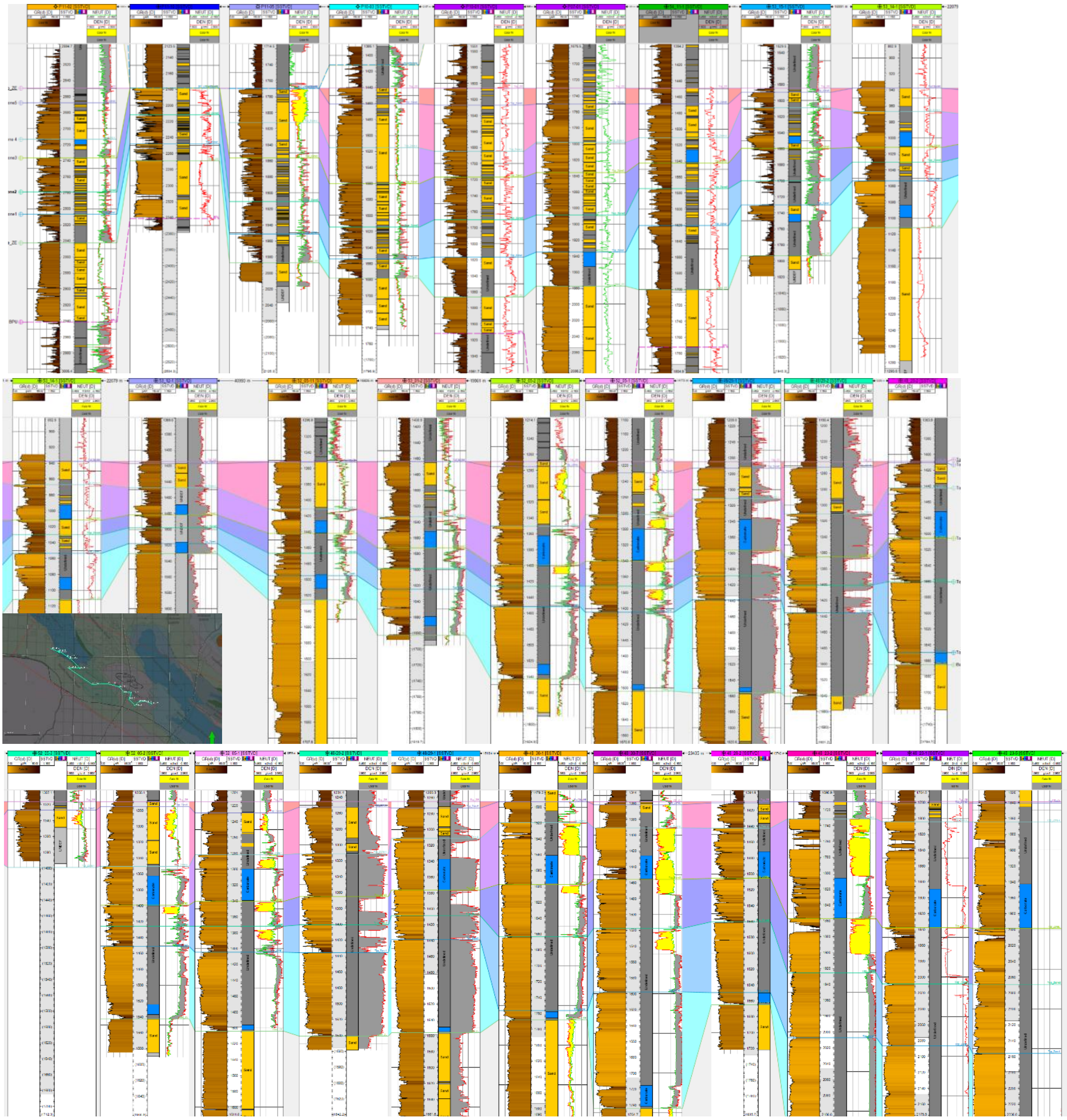


Figure 39 well section panel NL to UK with a relative scale of 1.000.000. Panel goes from the East to the West.

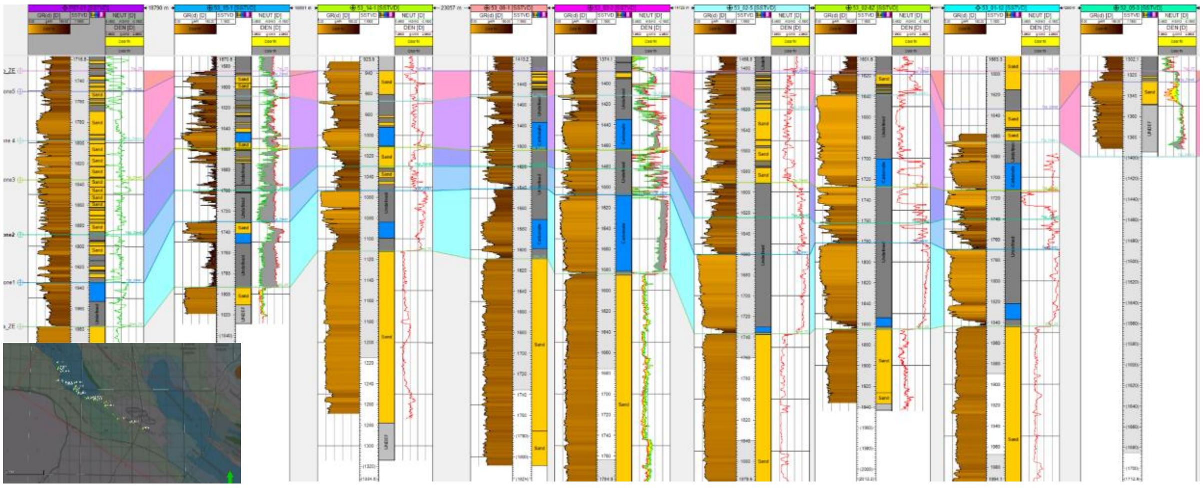


Figure 40 well section panel X-section 2 with a relative scale of 1.000.000

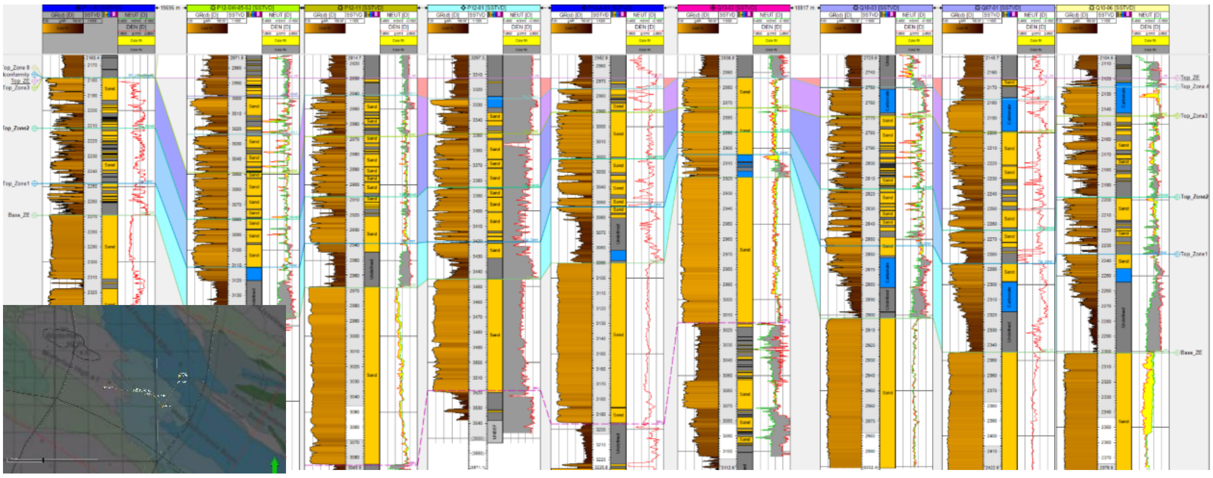


Figure 41 well section panel X-section 3 with a relative scale of 1.000.000.

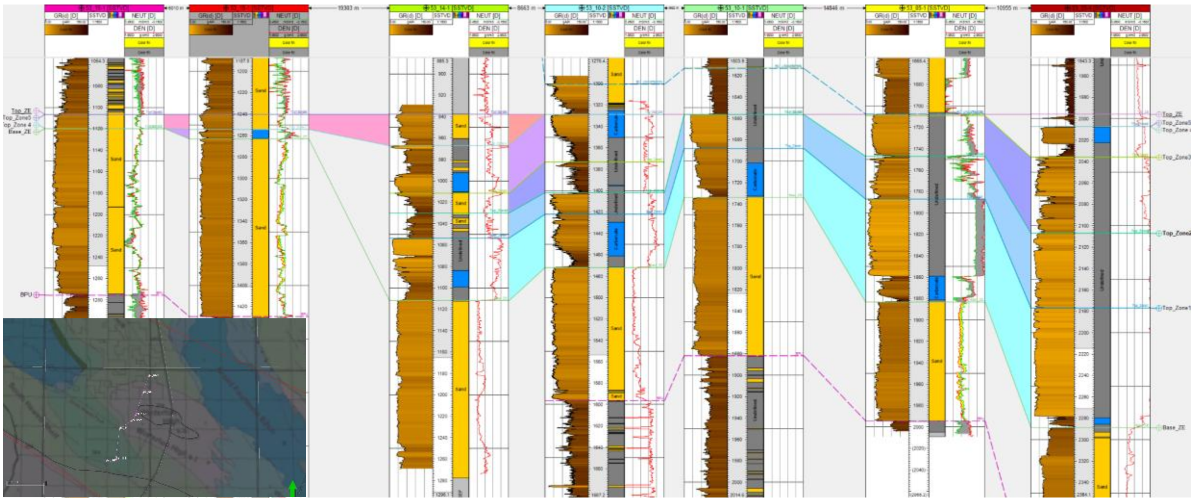


Figure 42 well section panel UK-NS-east with a relative scale of 400.000.

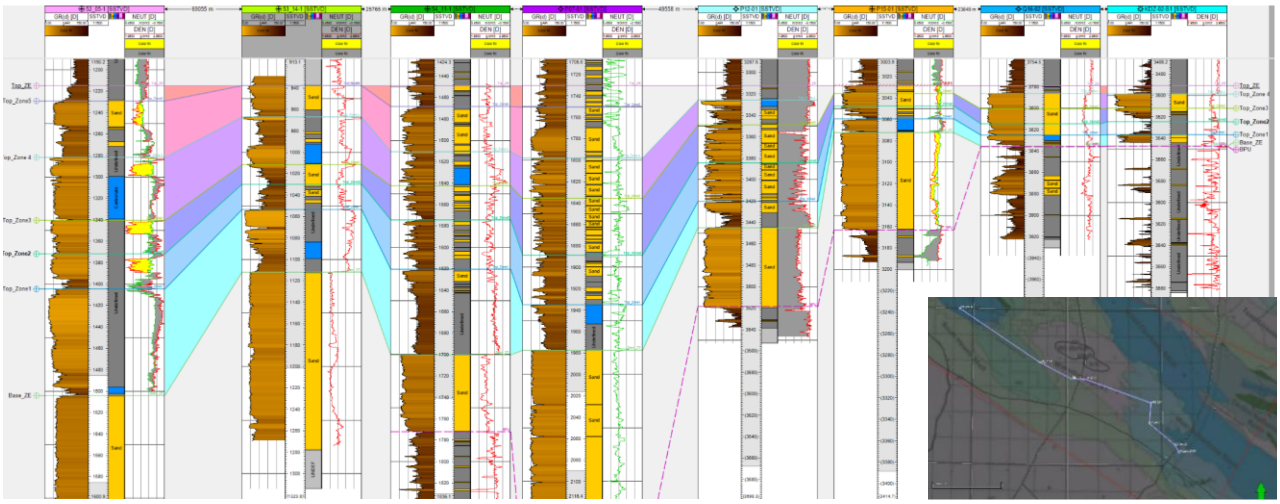


Figure 43 well section panel as in chapter 8 with a relative scale of 1.500.000.

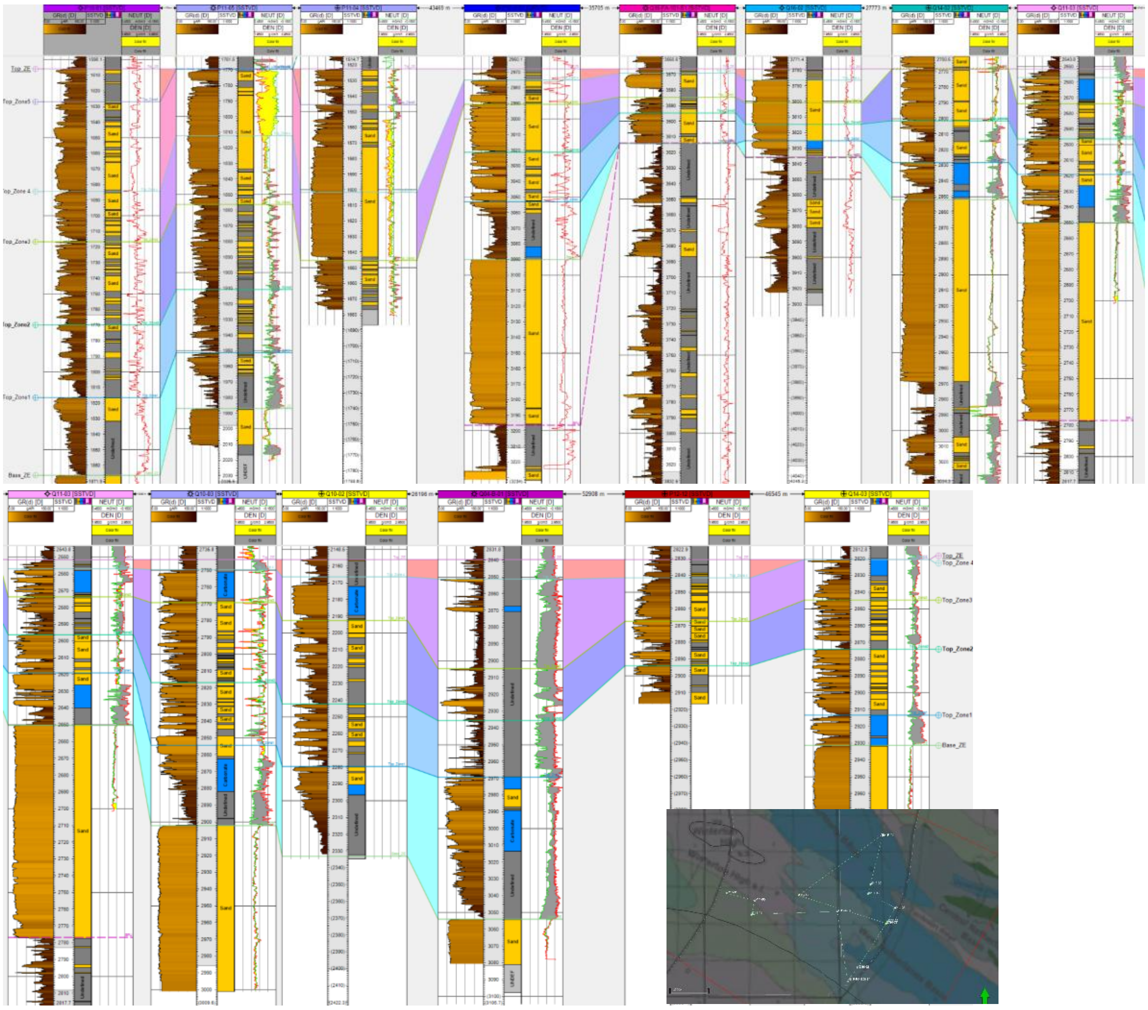


Figure 44 well section panel of good sands with a relative scale of 15.000.000.

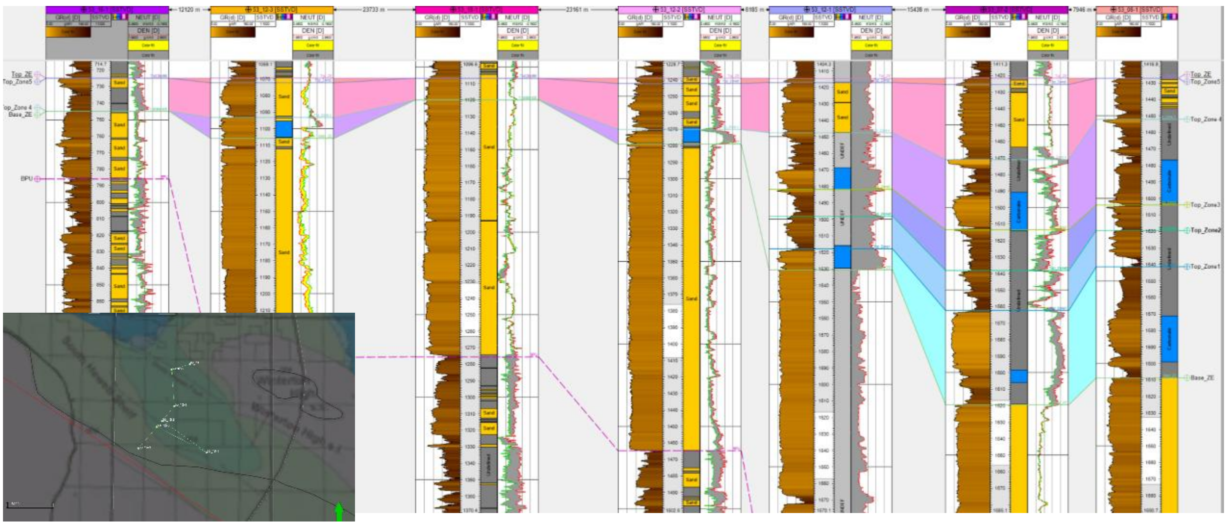


Figure 45 UK-NS mid relative scale 500.000 1 image horizontal 10000

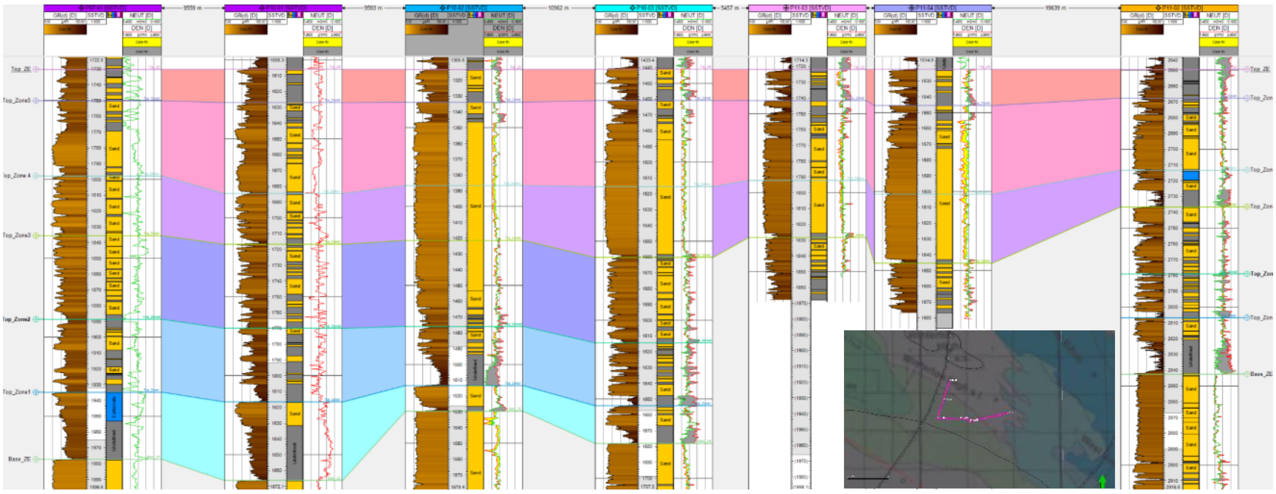


Figure 46 Nederweert relative scale 250.000

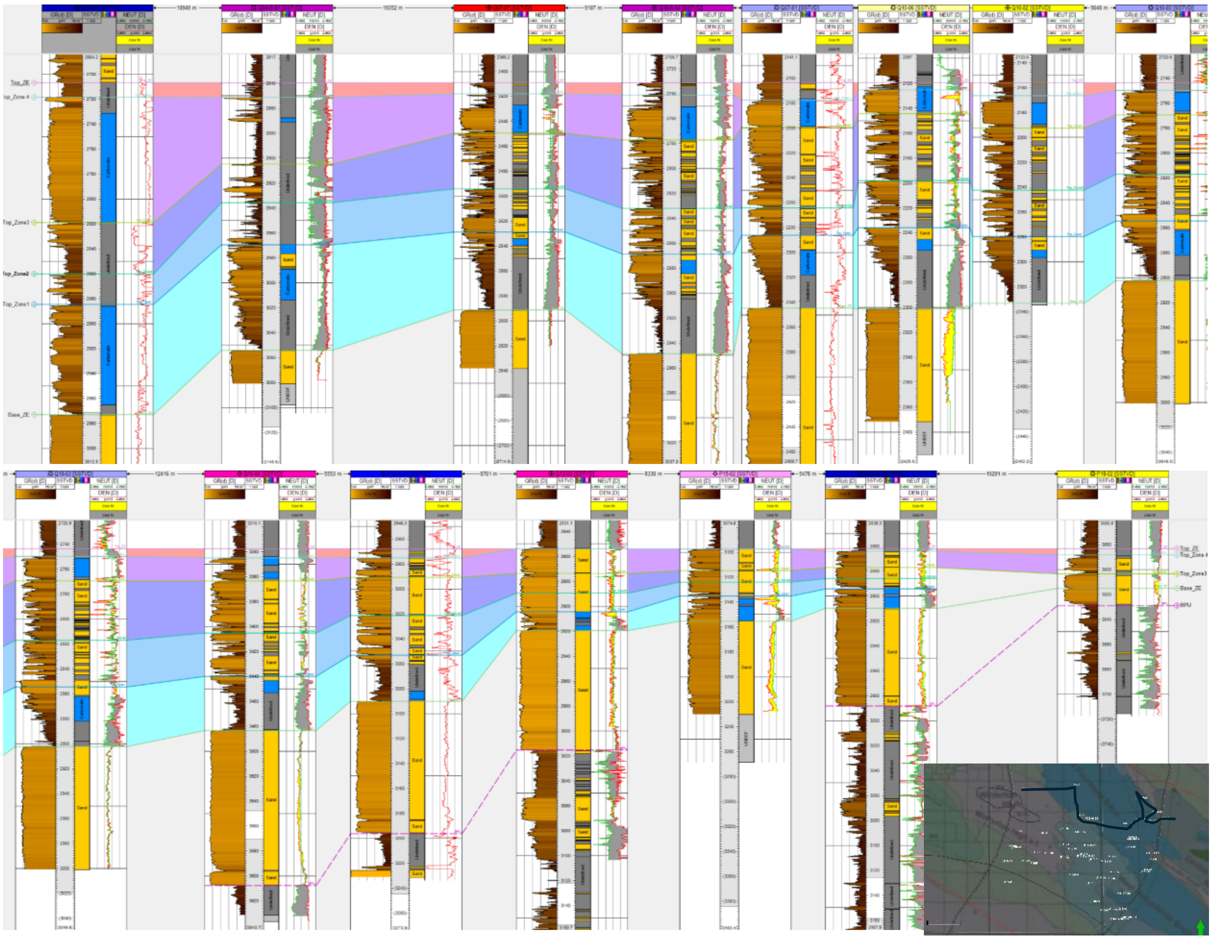
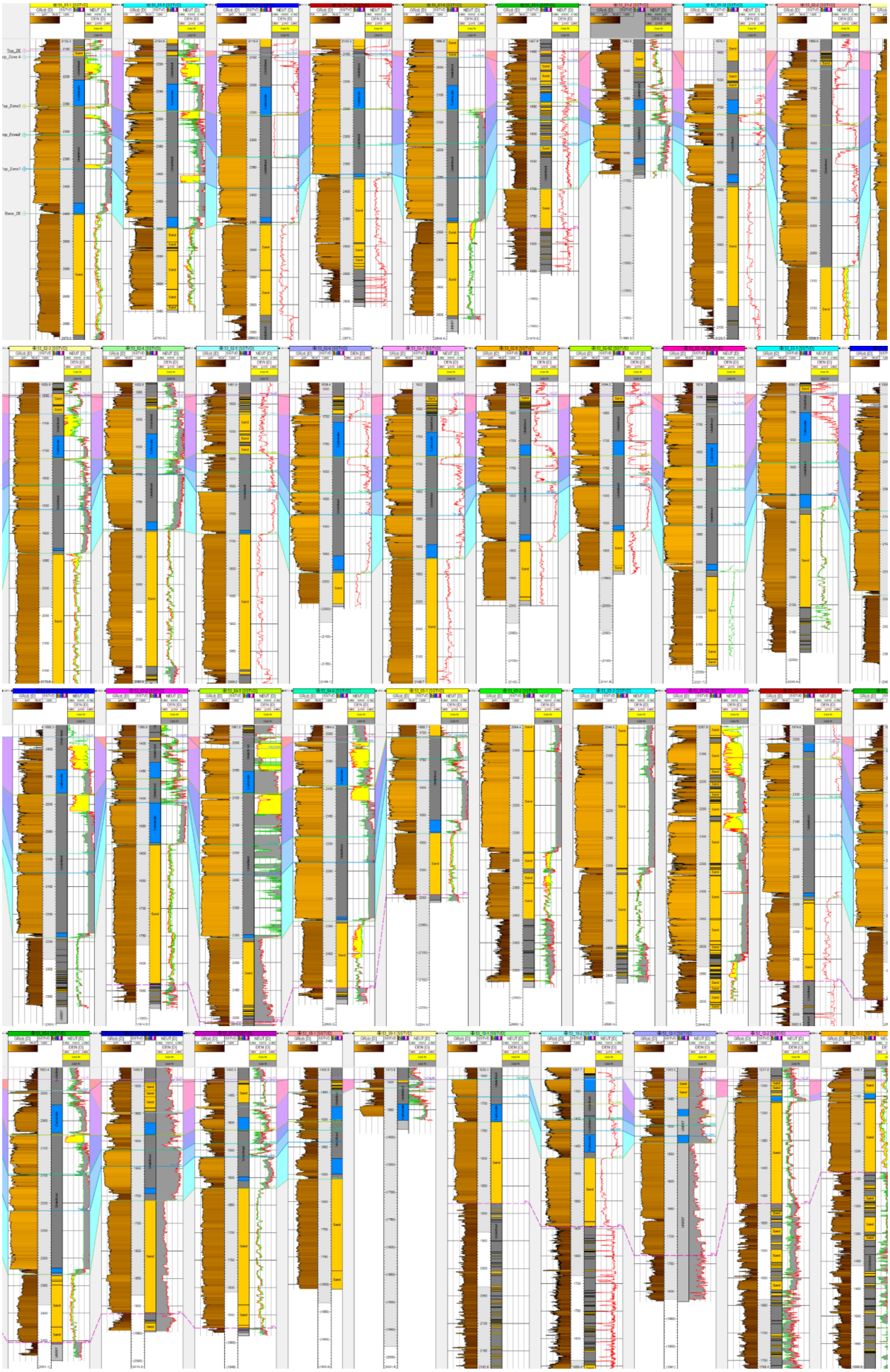


Figure 47 Top of NL relative scale 1.500.000



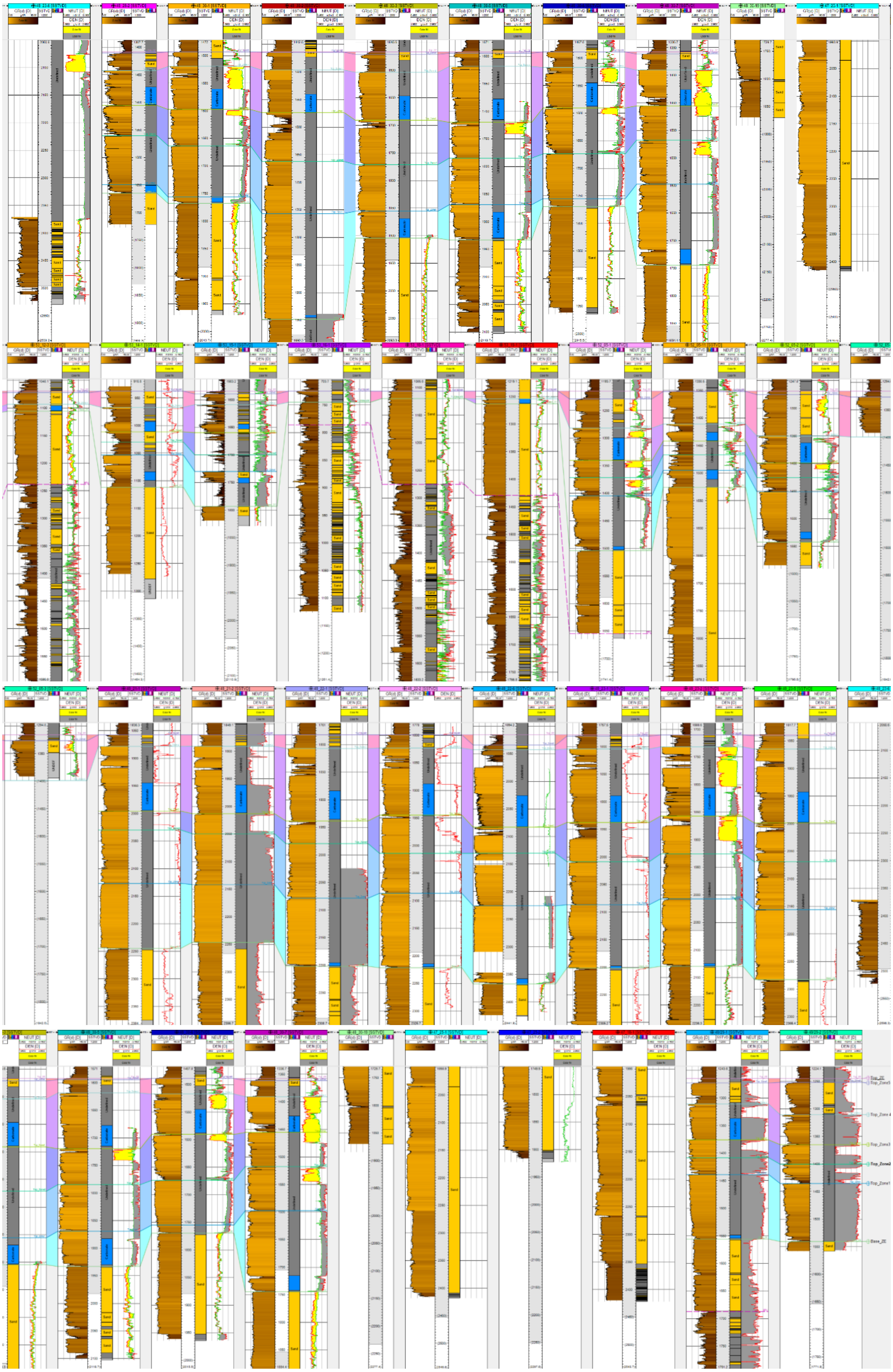


Figure 48 well section panel of all UK wells in an random order. With a constant scale of 10.

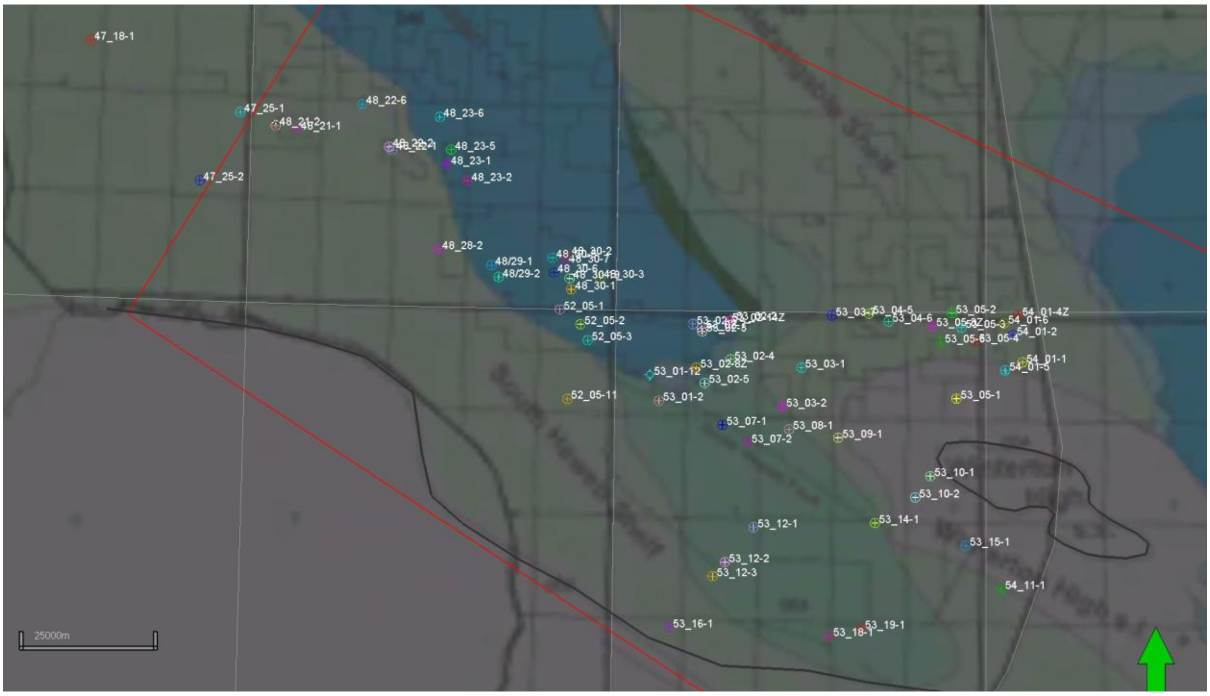
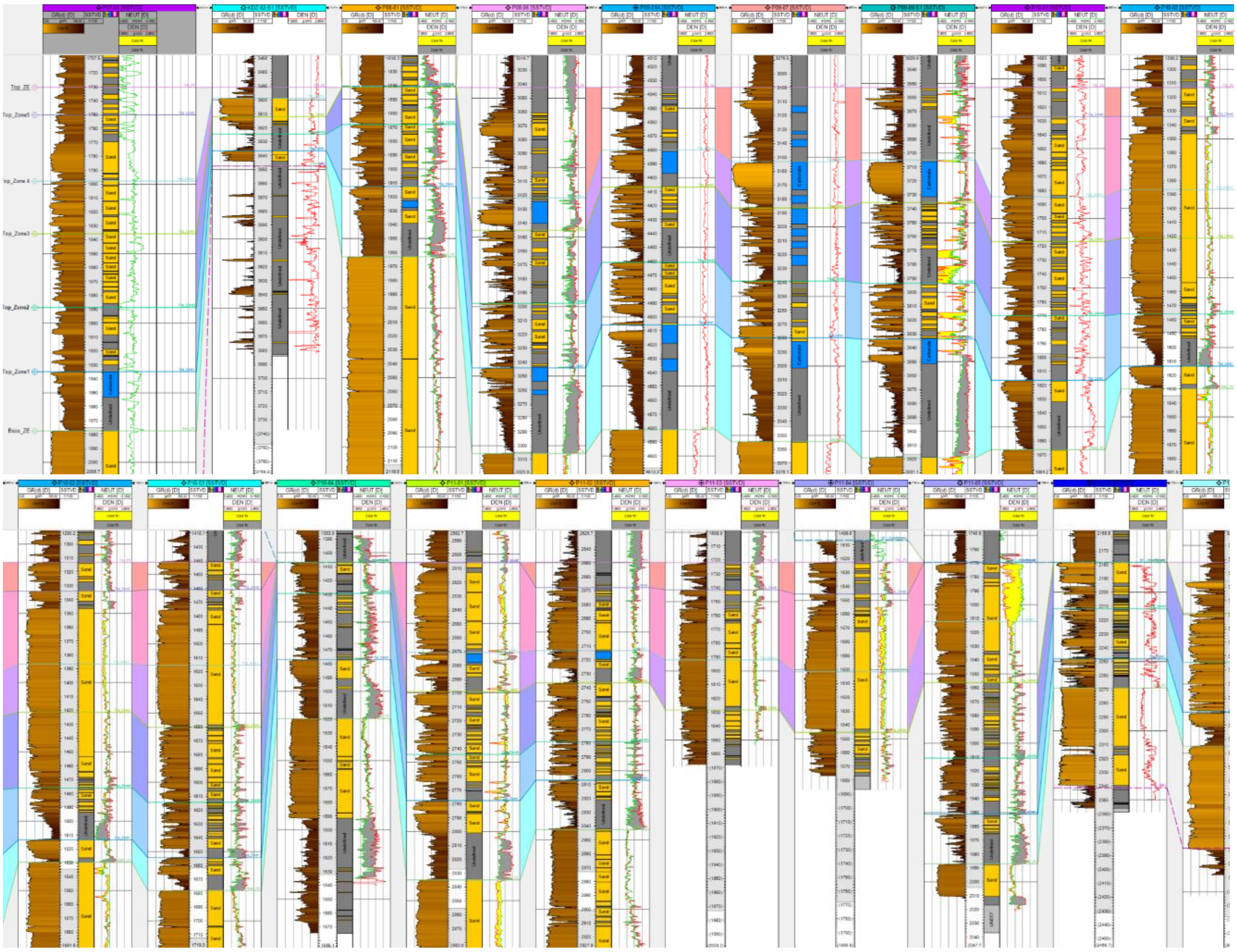
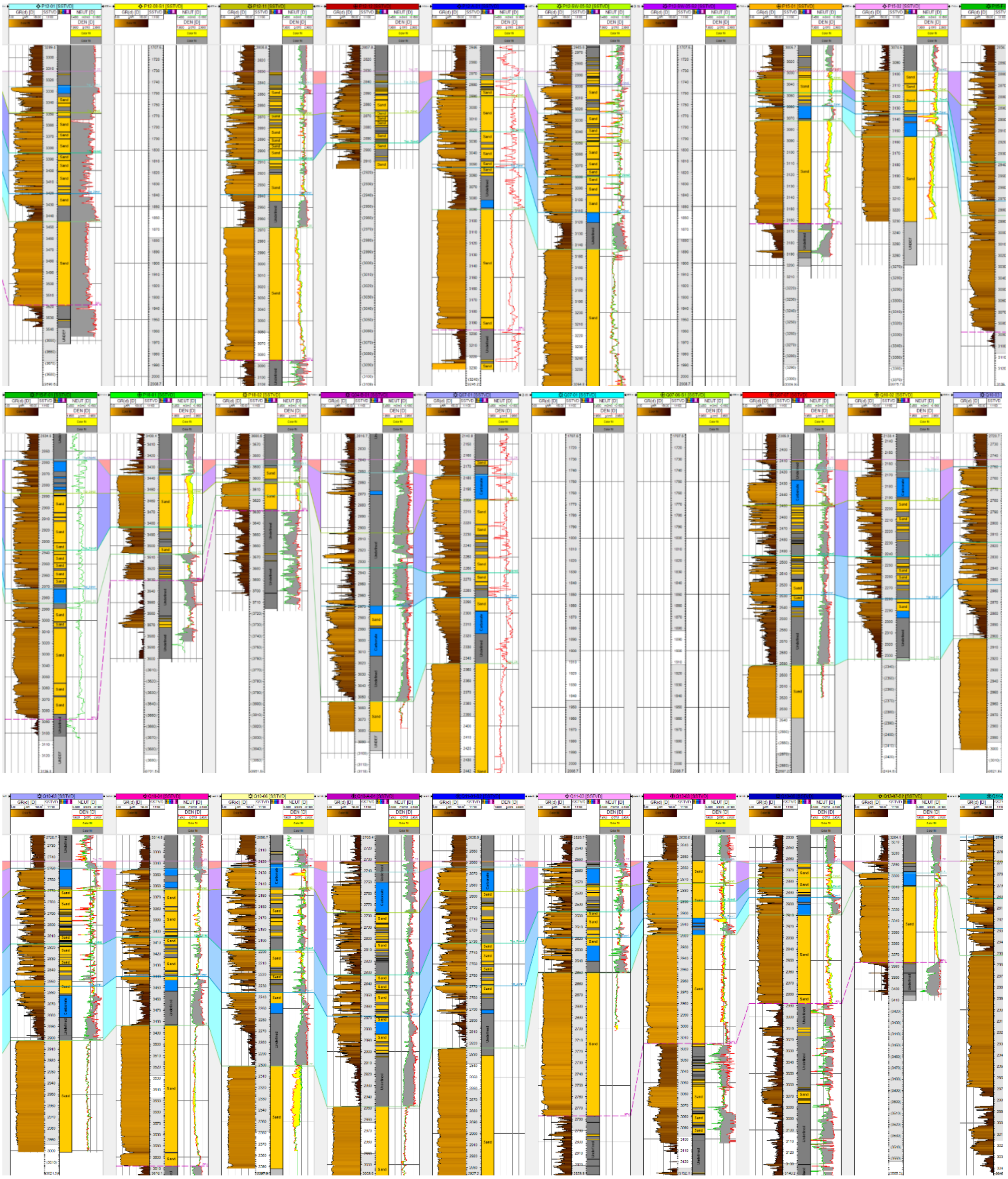


Figure 49 Overview of all wells included in well section panel of all UK wells in random order.





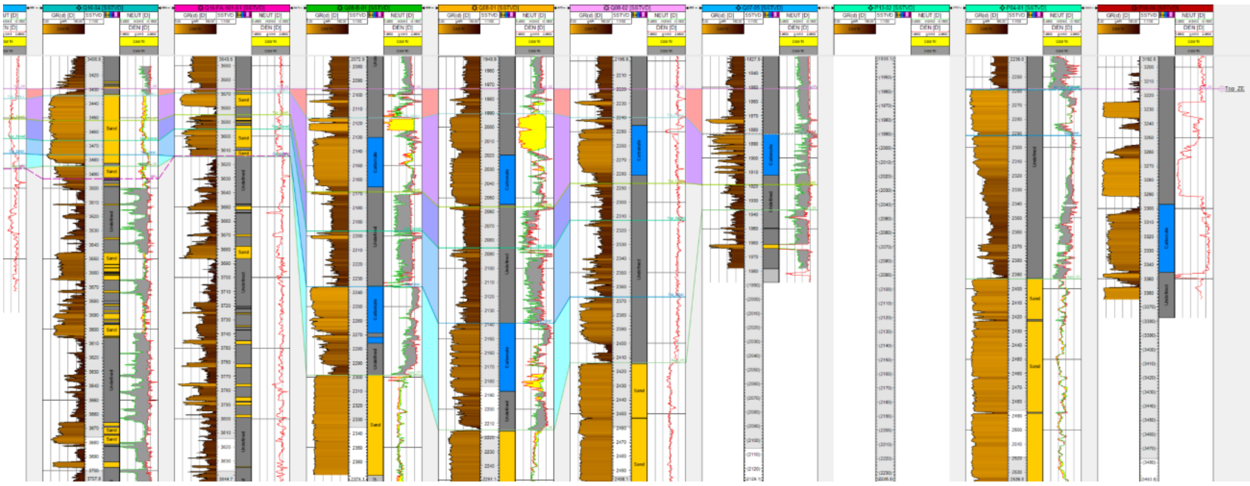


Figure 50 Well section panel of NL in a random order. With a constant scale of factor 10

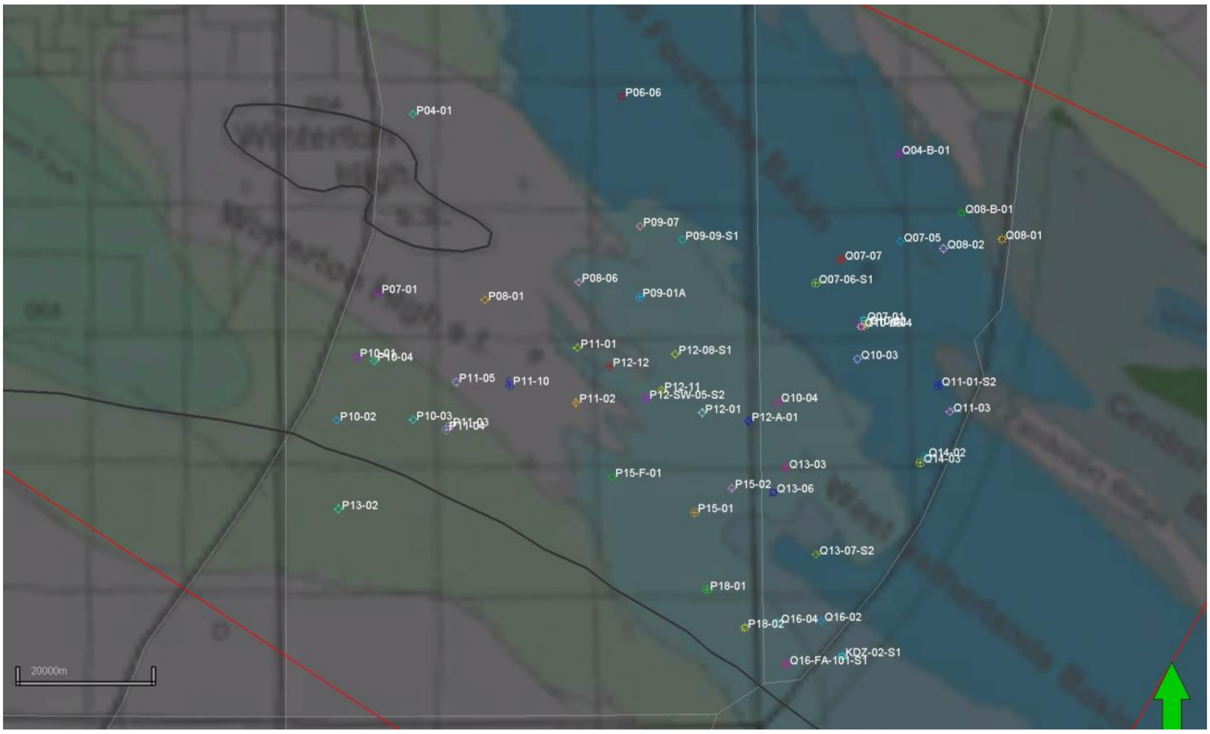


Figure 51 Overview of all wells included in well section panel of all NL wells in a random order.

Appendix B – Poro/Perm input

Table 6 Filtered averages per zone per well. Red data indicates a possible unreliable dataset.

Well name:	Depth mTVSS	Porosity, %	Hor. permeability, mD	My Zone	Sample number
P10-01	1721	28.00	27.00	3	1
P10-01	1688	22.30	723	4	1
P10-01	1657	24.25	159	5	2
P11-04	1602	24.84	997	4	48
P11-04	1586	24.99	1147	5	109
P11-05	1956	16.90	97	1	1
P11-05	1877	14.10	6.98	2	2
P11-05	1877	15.80	16.55	3	5
P11-05	1840	23.90	431	4	5
P11-05	1789	23.78	107	5	9
P12-12	2855	5.33	0.17	4	6
P12-A-01	3000	25.63		3	
Q04-B-01	2985	3.20	0.24	2	4
Q10-02	2245	17.50	84	2	2
Q10-03	2781	2.50	0.08	3	1
Q10-03	2768	3.65		4	
Q11-03	2622	8.20	2.43	1	3
Q11-03	2607	6.95	0.19	2	4
Q11-03	2578	3.35	0.28	3	2
Q14-02	2793	5.76	0.23	3	7
Q14-03	2858	3.13	0.19	3	3
Q14-03	2842	4.90	0.07	4	1
Q16-02	3796	4.98	0.07	4	5
Q16-FA-101-S1	3594	6.53	0.08	2	3
Q16-FA-101-S1	3593	5.25	0.06	3	2
UK	1300	22.0	1100	5	3

Table 7 Overview of input of porosity binning.

Binning of porosity	Depth mTVSS (m)	Porosity, %	Hor. permeability, mD	Sample number
0 to 5 %	2849.81	2.78	0.305020904	99
5 t 10%	2741.85	6.53	0.186979114	31
10 to 15%	2116.12	11.23	2.9	3
15 to 20%	1818.61	18.00	23.00329609	11
20 to 25%	1633.02	23.00	559.0924546	75
25 to 30 %	1640.46	26.73	1850.820952	80

Appendix C – Petrel input

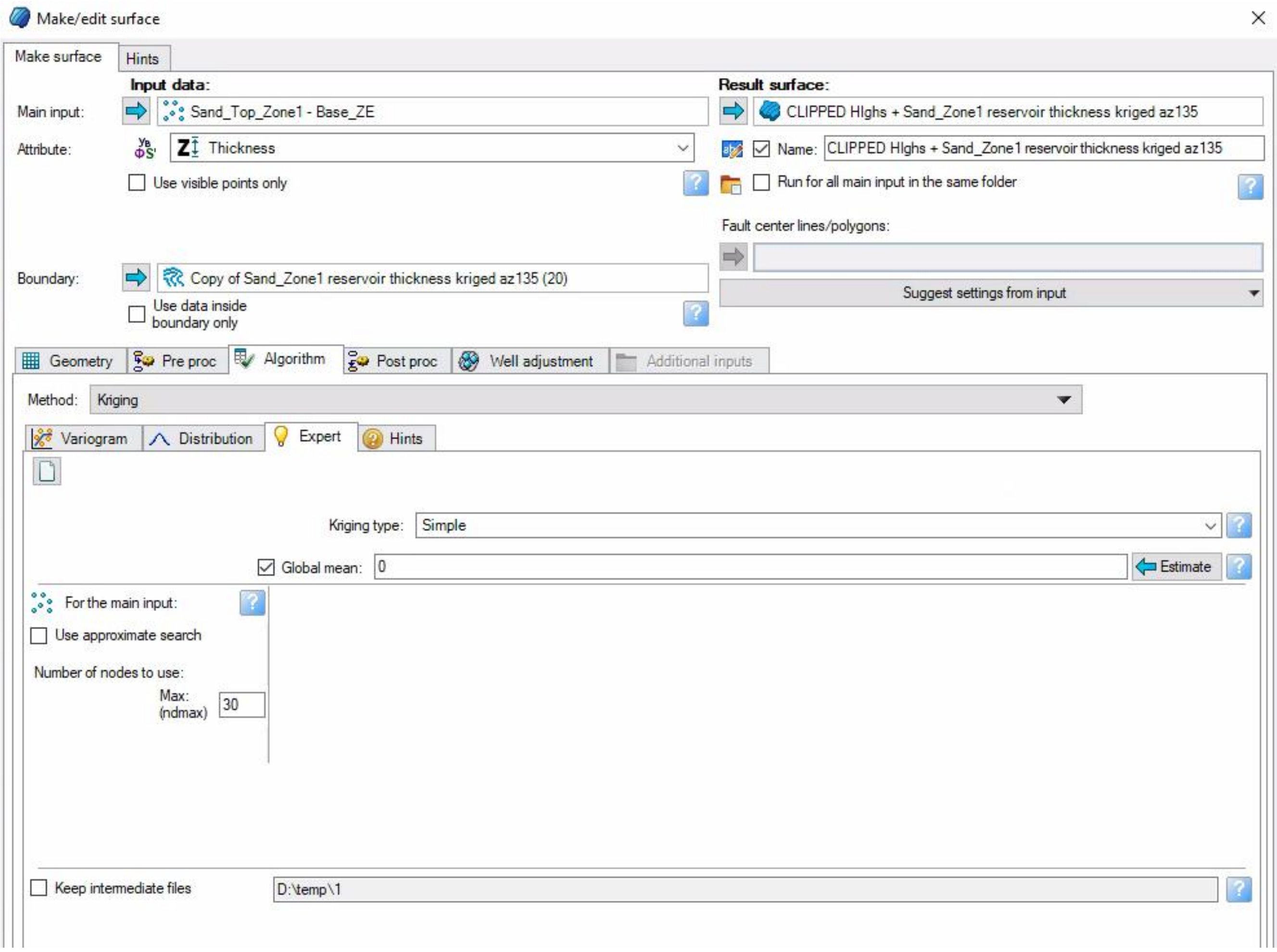


Figure 52 settings for petrel input of a kriged map with a global mean of 0. Application: net sandstone maps (Fig. 27).

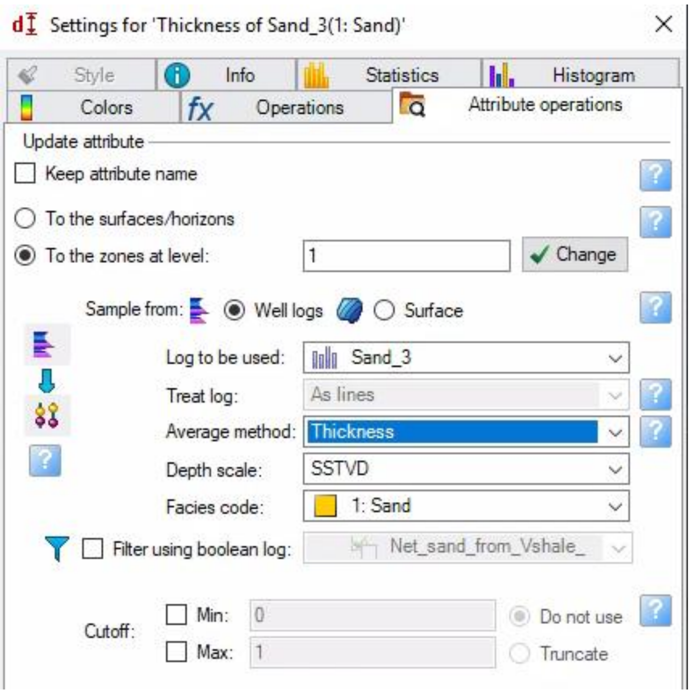


Figure 53 Settings input for the calculating of the presence of sand in each well.

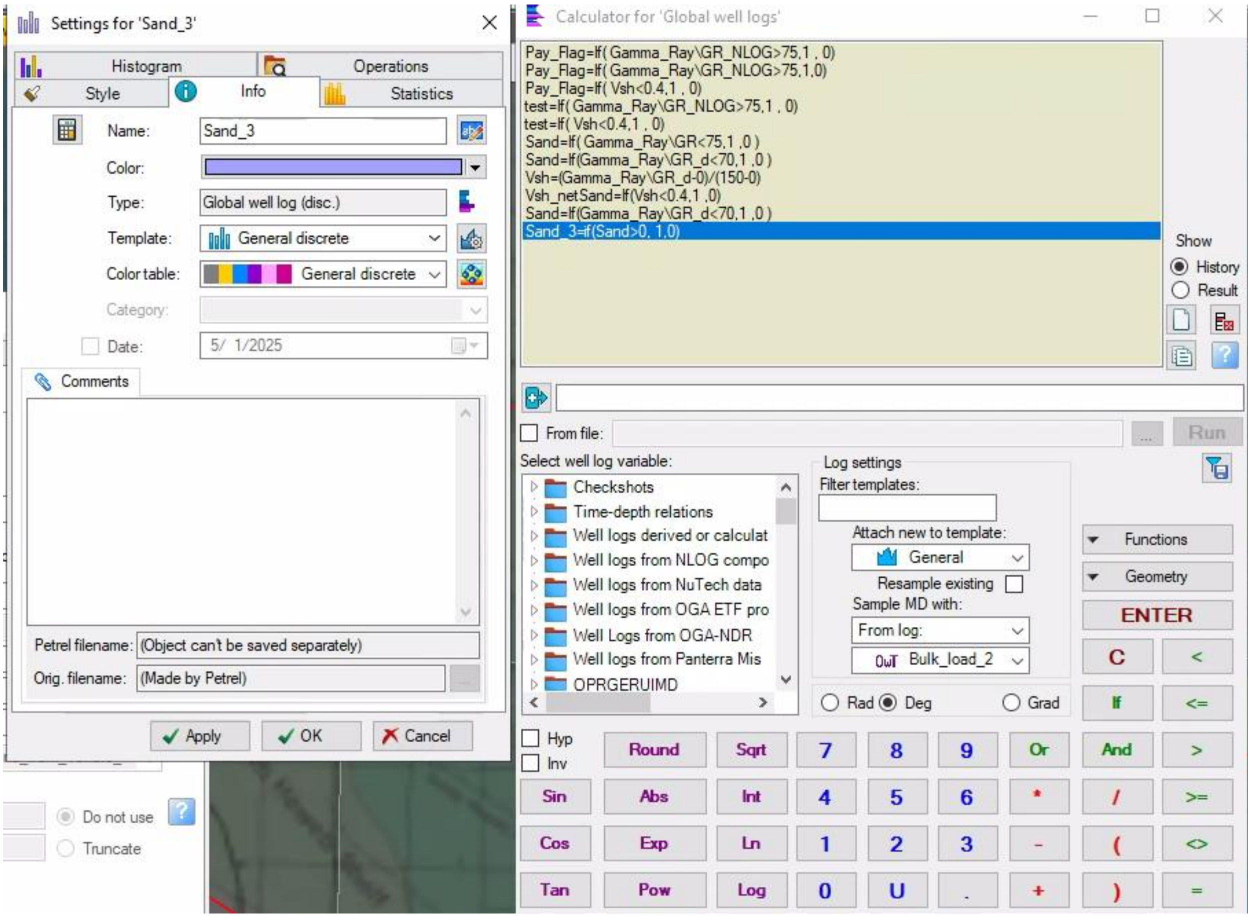


Figure 54 Settings input for the calculating of the thickness of the sand within each zone