The Hantum Fault

Thickening of Rotliegend sediments related to the activity of the Hantum Fault

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Abstract

This study investigates the potential Rotliegend thickness trends in the hanging-wall block of the NW-SE trending Hantum Fault in the north of the Netherlands. Three hypotheses are tested; 1) the fault is younger than the Rotliegend, 2) an onlapping model, and 3) a syn-tectonic model. Thickness maps of the Rotliegend are made based on well data and seismic interpretation of the fault and the Top and Base Rotliegend horizons, emphasising the offshore L6 block. The results reveal a thickening of Rotliegend in the hanging-wall part on the onshore segment of the Hantum Fault. However, towards the L-blocks, a thicker Rotliegend trend on the hanging-wall block is not observed. Thickness maps, based on well data, even suggest a thinning of the Rotliegend in the hanging wall in the L6 block. Structural fault analyses suggest that the Hantum Fault is part of a more complex system consisting of at least four distinct parts, which may be responsible for the variability in hanging-wall sediment thickness. The Hantum Fault's complex history includes creating up to 1000 meters of throw of the Rotliegend and continued throw in younger units despite decoupling in the Zechstein salt, because, above the fault there always remained a zone of weakness. The southernmost part of the Hantum Fault, likely the oldest, was active during Rotliegend deposition and caused syn-tectonic thickening of the hanging wall. The rest of the fault exhibited no signs of syn-tectonic thickening or onlapping, suggesting that the fault is younger in those parts than the Rotliegend sediments and, therefore, had no influence on sediment thickness. Due to the different character of the onshore part of the Hantum Fault, the part of the Lauwerszee Through, there is suggested that this part of the fault actually belongs to a fault that goes straight to the north, rather than the Hantum Fault, which branches to the left.

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1. Introduction

The Hantum Fault is a normal fault that runs from the Lauwerszee Trough towards the offshore L-blocks in the North Sea (Fig. 1). The NW-SE trending fault divides the Terschelling Basin and the Vlieland Basin offshore and onshore it is situated on the west side of the Lauwerszee trough, which separates the Friesland Platform from the Groningen High.

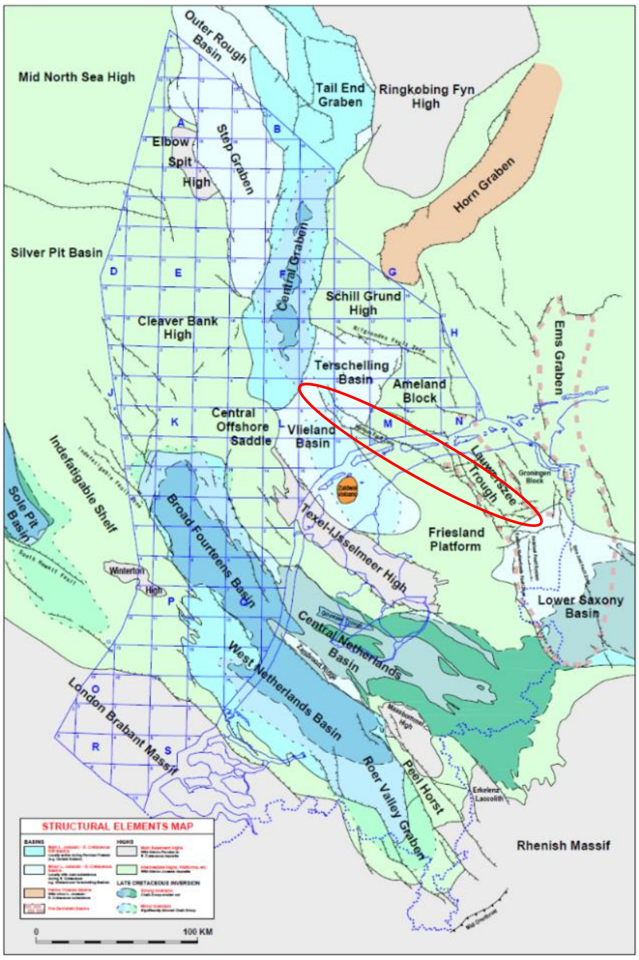


Figure 1. *Structural elements map of the Netherlands showing Mid and Late Kimmerian (Jurassic and Early Cretaceous) basins, highs and platforms (de Jager, 2007). The Hantum Fault Zone and a part of the Lauwerszee through are annotated with a red ellipse.*

This report examines the potential relationship between the thickness of the Rotliegend sediments and the Hantum Fault. There are three hypotheses: 1) the Hantum fault did not affect the deposition of the Rotliegend sediments (Fig. 2a), 2) Rotliegend sediments may have onlapped against a pre-existing high associated with the Hantum fault, causing thickness varieties (Fig. 2b), 3) the fault may have been active during deposition of the Rotliegend sediments which possibly controlled the thickness in the hanging wall block of the fault, a process called ‘syn-tectonic thickening’ (Fig. 2c).

The thickening of Rotliegend sediments in hypotheses 2 and 3 may have resulted in the development of thicker reservoir rocks of the Upper Rotliegend in the hanging wall block of the Hantum fault. Rotliegend sandstones represent the main gas reservoirs in the Netherlands (Grötsch and Gaupp, 2011). Therefore it is essential to know more about the thickness of these Rotliegend sediments in the hanging-wall block of the Hantum fault.

A study by Gast and Gundlach (2006) shows evidence for thicker Rotliegend deposition in hanging-wall blocks in Germany. Locally, synsedimentary grabens controlled facies distribution during Rotliegend times. Upper Rotliegend sediment accumulation and preservation potential are favoured in paleo hanging-wall positions in Germany (Vackiner et al., 2011). A pattern of horst and grabens may continue from Germany towards the western border of the Southern Permian Basin in England, across the Netherlands, with additional Rotliegend sandstones in the hanging wall blocks (George & Berry, 1997; Gast & Gundlach, 2006).

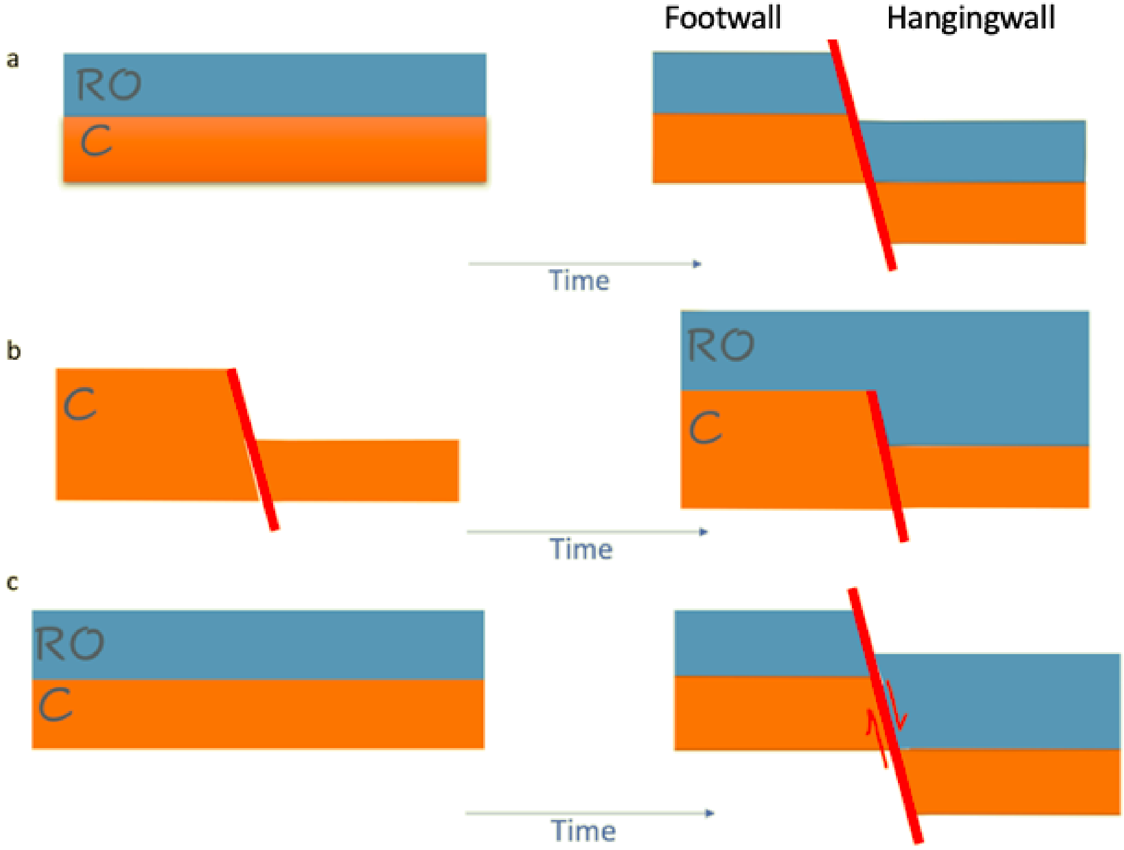


Figure 2. *Different hypotheses how the Hantum Fault has affected the Rotliegend sediment deposition. RO: Rotliegend Group, C: Carboniferous.*

a. *Hypotheses 1 – Hantum fault is younger. Constant thickness in hangingwall and footwall.*

b. *Hypotheses 2 – onlapping model. Before deposition of Rotliegend the Hantum fault was active which caused relief before deposition.*

c. *Hypotheses 3 – Syn-depositional model. The Hantum fault was active during Rotliegend which caused more accommodation space for Rotliegend sediments.*

Also, from the Netherlands, there is evidence that Upper Rotliegend sediment deposition responds to synsedimentary tectonics in the southern North Sea Basin (George & Berry, 1997). Moreover, in the north of the Netherlands (onshore), there is evidence for syn-tectonic thickening of the Upper Rotliegend group, for example, in the Lauwerszee Through area. For example, Mijnlieff & Geluk (2011) suggest a clear relation between the thickness of the Lower Slochteren Member and the Hantum-Lauwerszee Trough. However, if there is a trend of this thickening from the Lauwerszee Trough towards the offshore Hantum Fault is not known. Possibly there is a thickening trend of Upper Rotliegend rocks towards the offshore L-blocks in the hanging wall of the Hantum Fault Zone.

1.1 Aim of the study

This project aims to investigate the Upper Rotliegend thickness trends around the Hantum Fault Zone, emphasising potential hanging wall thickening in the L-blocks. To achieve this aim, the following objectives need to be met:

1) Determine if there is evidence for thickening of the Upper Rotliegend around the Hantum Fault Zone in the Lauwerszee Trough (NL onshore), where abundant well data are available;
2) Map the Hantum Fault Zone on 3D-seismic, from the Lauwerszee Trough towards Ameland, the M07 and M08 blocks, and the L06 and L09 blocks;
3) Check on onshore 3D-seismic whether the different Rotliegend units can be recognised: Lower Slochteren Sandstone (ROSLL) – Ameland Claystone (ROCLA) - Upper Slochteren Sandstone (ROSLU)– Ten Boer Claystone (ROCLT).
4) Find out if there is a trend of thickening of Upper Rotliegend sediments in the hanging wall of the Hantum Fault Zone, from the onshore towards the offshore L-blocks.
5) Evaluate possible hanging-wall thickness trends with a structural interpretation of the Hantum Fault

This research will lead to insights into the thickness, and distribution of the Rotliegend Group in the offshore L-blocks, thereby contributing to evaluating gas prospectivity for EBN and offshore operators. Moreover, it aims to enhance our understanding of the occurrence of thickness variations within the Rotliegend Group in the Netherlands, in line with observations from Germany. If thickening is identified across the Hantum Fault, it may also have occurred along other regional faults, advancing our understanding of tectonic events during the Permian era. Furthermore, the application lies in the potential for evidence to be gathered to support thicker reservoir development, ultimately resulting in higher expected volumes for some gas prospects. Lastly, the research will provide insights into the structural geology and geological history of the Hantum Fault and the surrounding region.

1.2 Study area

A study area of ~15000 km^2 was defined, which covers the full Hantum Fault as defined by the structural map of the Netherlands of de Jager (2007) (Fig. 1). The study area partly covers onshore provinces of Fryslân and Groningen and the offshore M- and L-blocks (Fig. 3). The research area of ~750 km^2, where the emphasis lies, was also determined.

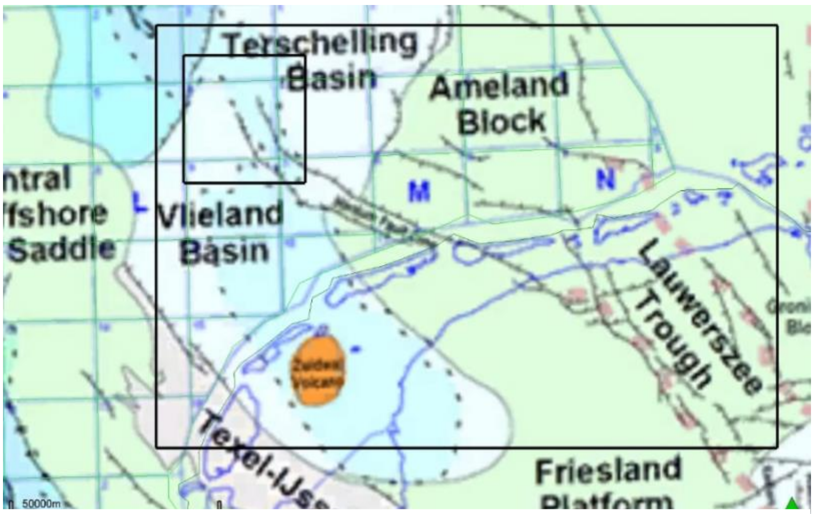


Figure 3. *Study area (big rectangle) and study area where the emphasis lies (smaller square).*

2. Geological setting

2.1 The Rotliegend Group

The tectonics and stratigraphy of the Rotliegend Group in the Netherlands have been particularly well studied (e.g. Ziegler, 1990; Verdier, 1996; Geluk, 2007; Van Ojik, 2011). However, the relationship between the thickness of Rotliegend sediments and the Hantum Fault has never been studied.

The Rotliegend Group in the Netherlands comprises mainly fine-grained clastics and evaporites in the offshore and sandstones in the onshore area (Geluk, 2007). The formation was preserved between the London-Brabant Massif and the Rhenish Massif in the south and the Mid North Sea High and Ringkobing-Fyn Hygh in the north (Fig. 4).

The Rotliegend Group was deposited in the Late Permian (~263 – 257 Ma) over a large area of the UK, Dutch, Danish and German parts of the Southern Permian Basin (Grotsch and Gaupp, 2011). The Permian in the Netherlands has been divided into the Lower Rotliegend volcanic rocks, which have a limited distribution in the Netherlands, the Upper Rotliegend Group and the Zechstein Group (Geluk, 2007). This report focuses on the Upper Rotliegend Group, which consists mainly of clastics and is deposited over a large area of the Netherlands and the UK, Danish and German parts of the Southern Permian Basin (Geluk, 2007).

During the deposition of the Upper Rotliegend clastics, the climate in the Netherlands was arid, like the present-day Sahara. River systems transported sediments from the Variscan mountain belt in the south towards the north; for this reason, finer-grained material was transported further north in the offshore Netherlands, and the coarse-grained material stayed more south in the onshore Netherlands. Eastern winds reworked all the deposited material, which developed aeolian dune belts, for example, the Groningen high. More northwards, the dune landscape becomes a playa landscape (Geluk, 2005).

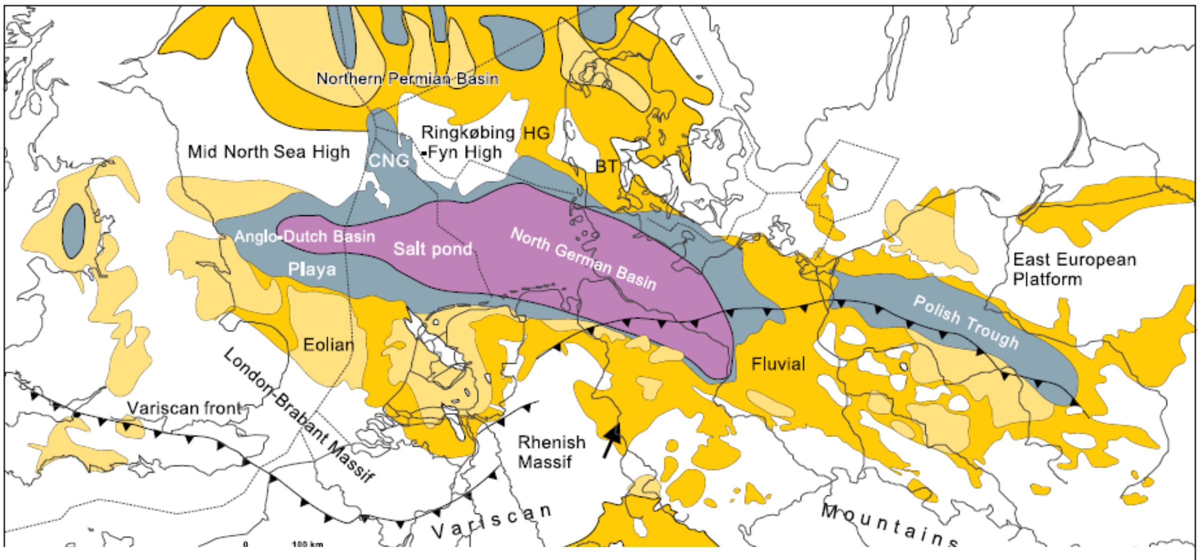


Figure. 4. *Present-day distribution and facies map of the Upper Rotliegend Group (late Middle to early Late Permian) in the Southern Permian Basin (Geluk, 2005). BT: Bramble Trough; CNG: Central North Sea Graben; HG: Horn Graben. (After Geluk, 2007).*

This resulted in the Upper Rotliegend Group with different members; the Slochteren Formation (ROSL), mainly conglomerates and sandstones of aeolian origin, and the Silverpit Formation (ROCL), mainly claystones, siltstones and evaporites of playa origin. These formations are each other's lateral equivalents. Where the Slochteren and Silverpit formation interfinger, the Slochteren Formation splits up in the Lower- and Upper Slochteren sandstones, separated by the clay- and siltstones of the Ameland member (ROCLA). South of the pinchout line of the Ameland Member, the Upper and Lower Slochteren Members can no longer be distinguished as separate units (Geluk, 2007; van Ojik, 2021) (Fig. 5).

2.2 The Base Permian Unconformity

The Late Carboniferous and Early Permian are characterised by great erosion through the Asturian inversion phase (Late Carboniferous) and Early Permian thermal uplift, which led to a hiatus of (parts of) the Late Carboniferous and the entire Early Permian of 40 to 60 Ma in most places, as can be seen on the subcrop map of the Base Permian Unconformity (Fig. 6) (Geluk, 2005; van Buggenum & Den Hartog Jager, 2007). The most eroded areas were the high areas, these areas where the biggest hiatus lies often reappeared as horsts in later times. The less eroded areas, where a smaller hiatus lies, often reappear as grabens. This assumes that there is a structural correspondence between the high and low areas at the time of the Base Permian, like, for example, the Lauwerszee through (van Buggenum & Den Hartog Jager, 2007; Geluk, 2007; De Jager, 2007). For this reason, the Upper Rotliegend sandstones are deposited on the topography developed by weathering the subcropping Carboniferous units, coal-bearing lows and sand-prone ridges (Geluk & Mijnlieff, 2001) (Fig. 6).

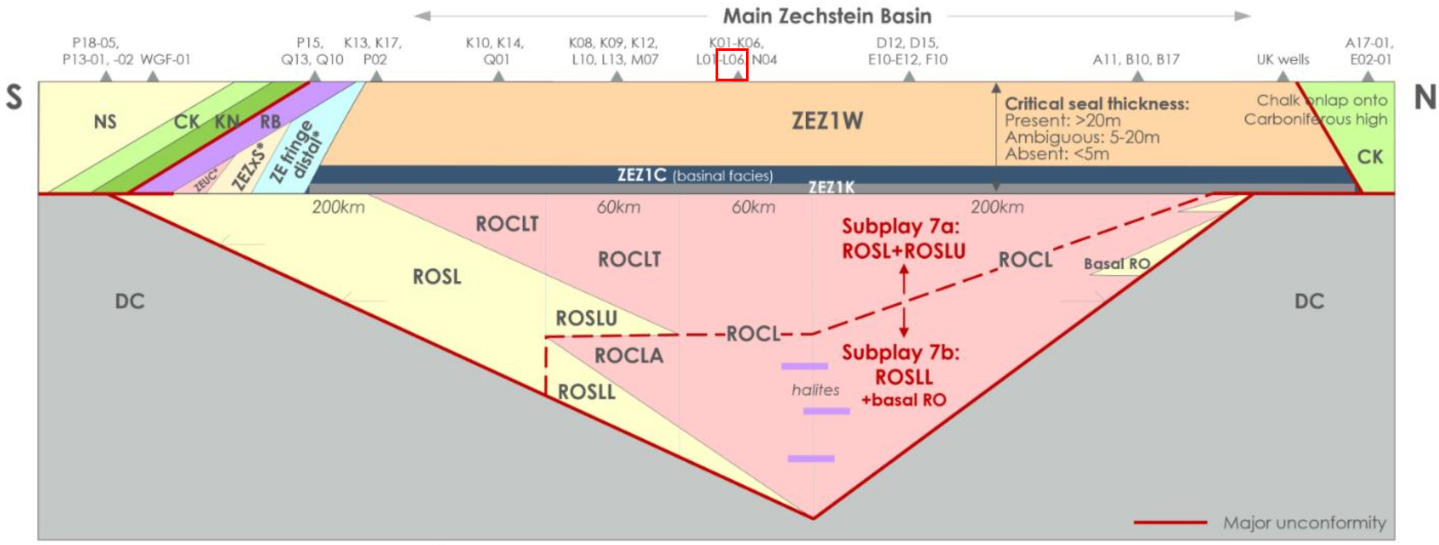


Figure 5. *Stratigraphic scheme of the Upper Rotliegend in the Netherlands illustrating the vertical and lateral distribution of the Upper- and Lower Slochteren sandstones with an indication where block L06 lies. NS: North Sea Groups, CK: Chalk Group, KN: Rijnland Group, RB: Lower Germanic Trias Group, ROSL: Slochteren FM., ROSLU: Upper Slochteren Mb., ROCLT: Ten Boer Claystone Mb., ROCLA: Ameland Claystone Mb., ROCL: Silverpit Formation, ZE: Zechstein Group, ZEZ1K: Coppershale Mb., ZEZ1C: Z1 Carbonate Mb., ZEZ1W: ZZ1 Anhydrite Mb., ZEZxS: Zechstein Fringe Sandstone Members (Z1-Z4), ZEUC: Zechstein Upper Claystone Mb. (After van Ojik et al., 2021).*

2.3 The Hantum Fault Zone

The NW-SE fault zone that separates the Vlieland basin from the Terschelling basin and practically connects to the south to the Lauwerszee Through which divides the Groningen high from the Friesland platform is defined as the Hantum Fault Zone (Fig. 1) (de Jager, 2007). The Hantum Fault, as well as the Mid Netherlands fault zone, belong to a family of NW-SE trending faults that probably date back to the times when Avalonia merged against Laurussia (de Jager, 2007). Probably, the southern part of the Hantum Fault, where it is still called the Lauwerszee Through, represents a pre-existing NW-SE structural trend since the subcrop map of the top of the Base Permian Unconformity shows the juxtaposition of Carboniferous units of different ages (Fig. 6) (van Buggenum & Den Hartog Jager, 2007). This suggests activity on the southern part of the Hantum Fault during the Base Permian uplift.

The Hantum Fault shows evidence of repeated reactivation throughout geological history. For example:

1) The Early Permian witnessed strike-slip deformation, while a conjugate set of NE-SW to NNE-SSW faults (like the Hantum Fault) developed regionally (Ziegler, 1990).

2) the map of Zechstein salt structures illustrates a trend of salt structures along the Hantum Fault, which may have resulted from the fault's activity and caused a weakness in the earth's crust (Fokker et al., 2007). Moreover, Cretaceous and younger strata fault maps reveal that NW-SE trending faults experienced reactivation during these times (De Jager, 2007).

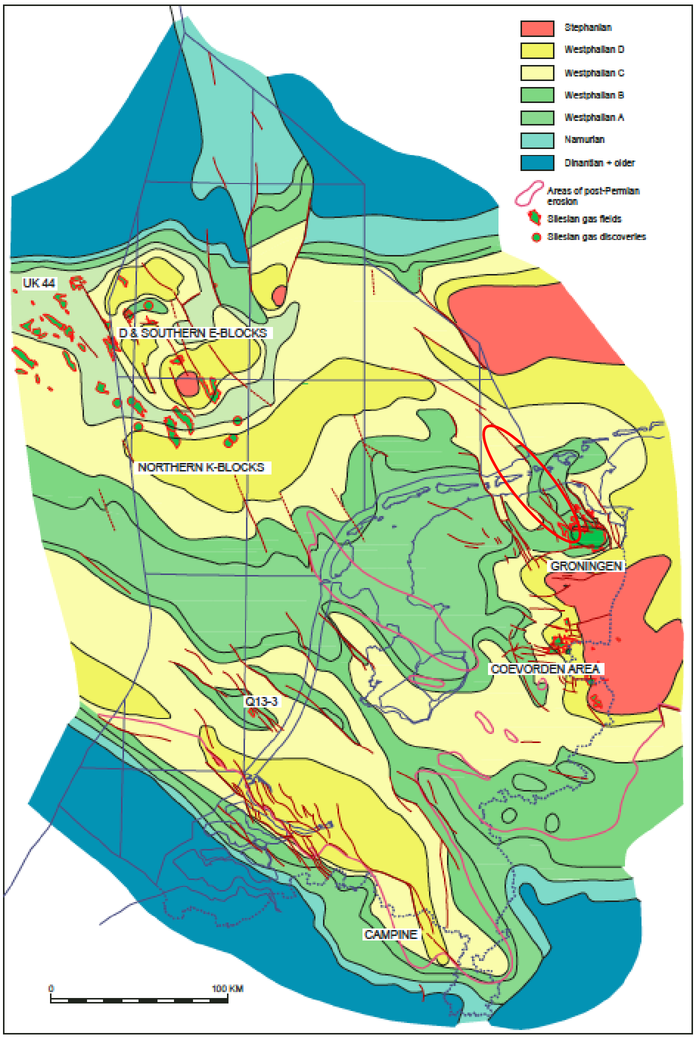


Figure 6. *Subcrop map of the Base Permian Unconformity (van Buggenum & Den Hartog Jager, 2007). At the position of the Hantum Fault (shown with a red elipse) there is a difference in the ae of the Carboniferous in the Lauwerszee Through, Westphalian A is deposited next to Westphalian C or B. This gives reason to think that the Lauwerszee Through part of the Hantum Fault is a pre-existing weakness in the earth's crust.*

3. Data and methods

3.1 Timeline

This section provides an overview of the data and methods utilised in this project. A visual representation of the project timeline is presented in figure 7, illustrating the various stages of the project, which are described in further detail below.

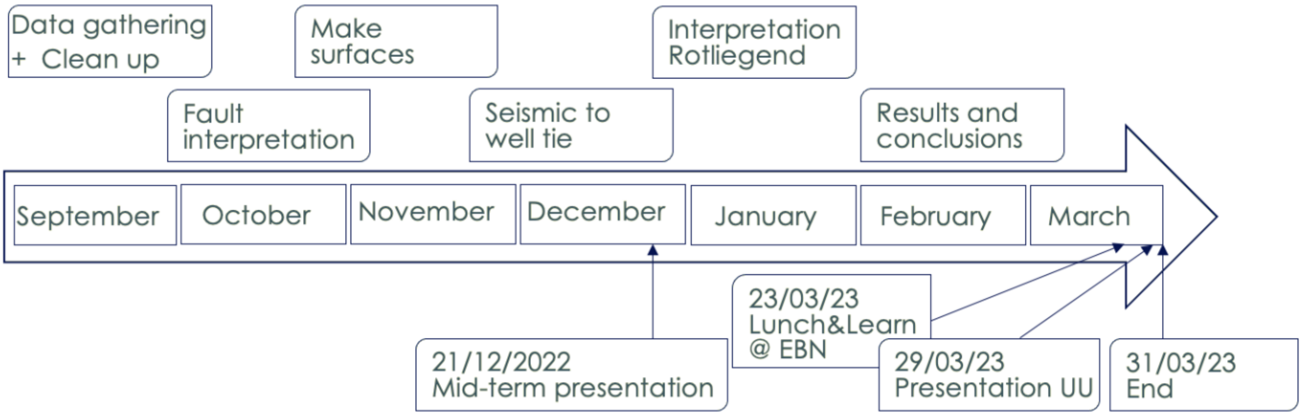


Figure 7*. Timeline showing various stages of the project.*

3.2 Petrel software

The Hantum Fault and the upper and lower boundaries of the Rotliegend Group in the study area were interpreted using the Petrel software (Schlumberger) with a license obtained from EBN. The software version utilised was 2020 (2020.5), which was updated to 2022 (2022.3) in December. Subsequent horizons are interpreted with the help of existing data from the TNO-Horizons (see TNO Horizons).

The EBN standard convention was used in all seismic data (Fig. 8):

- An increase in acoustic impedance (hard kick) results in a negative amplitude and is displayed as a through, which is a red seismic loop.
- A decrease in acoustic impedance (soft kick) results in a positive amplitude and is displayed as a peak which is a blue seismic loop.

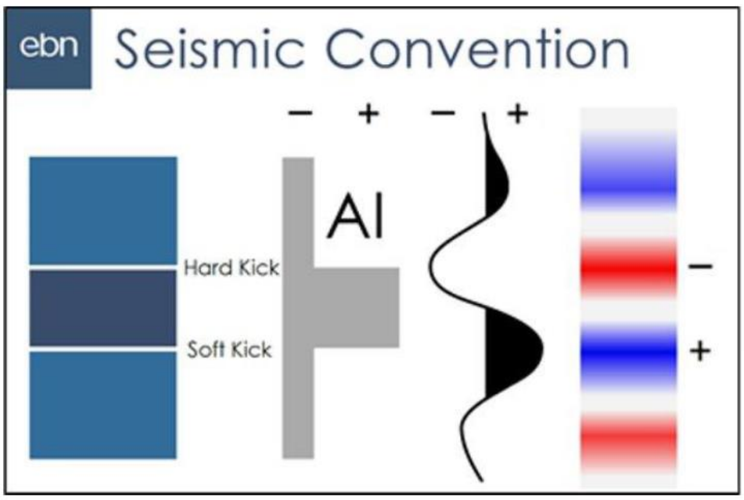


Figure 8. *EBN standard convention for seismic surveys. A blue loop represents a peak, and a red loop a through.*

3.3 Data

Seismic surveys

Multiple 3D seismic surveys were conducted in the study area. A quality-based selection resulted in the selection of five 3D seismic surveys, which cover together the whole Hantum Fault (Fig. 9). These surveys are accessible through the EBN database, except for the NAM 1992 surveys, which were downloaded from TNO (www.nlog.nl) and imported into the EBN database.

Well data

Within the study area, 142 boreholes containing lithostratigraphic information on the Rotliegend Group are available (Fig. 9). These wells feature a density, gamma-ray and sonic log. In addition, the well tops have been ascribed based on the subdivision of the Rotliegend Group TNO (2021).

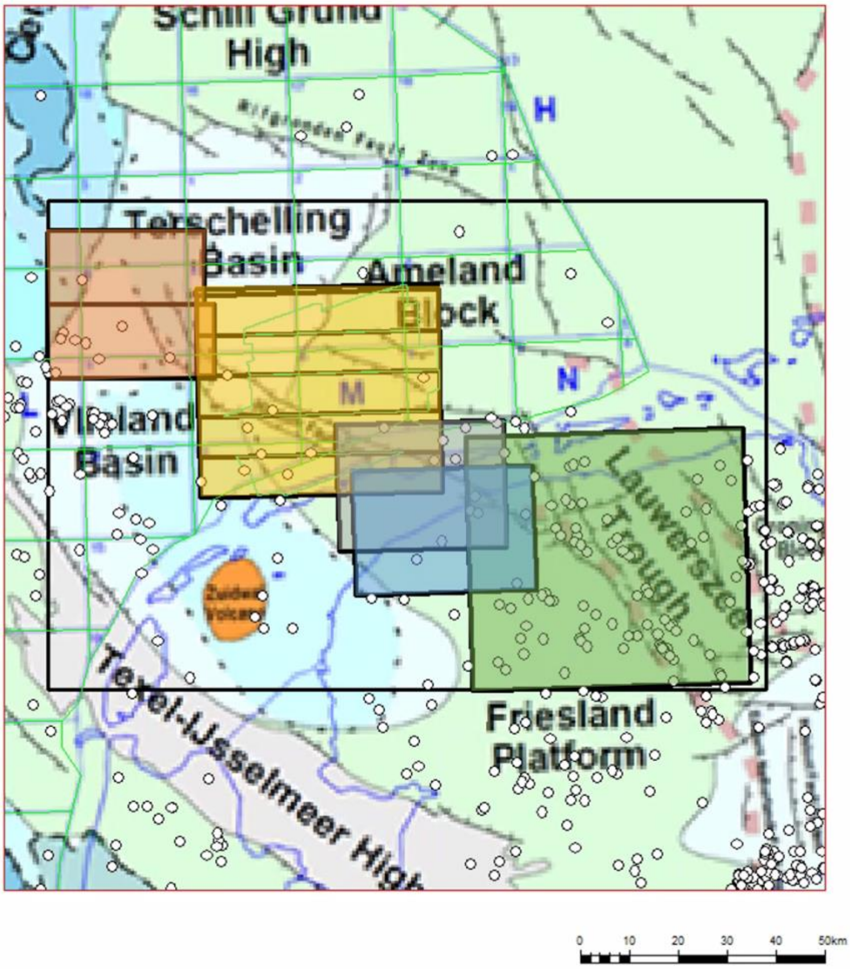


Figure 9. *The black rectangle shows the research area for this study. The smaller rectangle are the eight 3D seismic surveys used for this study which cover the full Hantum Fault Zone together with a 2D survey in the East of the study area. The white dots represent the wells with Rotliegend well data in the study area and around.*

Colors:

-L06_PSDM_WIN_2007 - orange
-M08_PSTM_NAM_2001 – yellow
-Friesland-10355_PSDM_NAM_2017 – Green
-L3NAM1992A - blue
-L3NAM1992C – grey

All surveys are provided in TWT, L06_PSDM_WIN_2007 also in Depth.

Clean up data

The best result can be made with well data that is equally spread over the study area. However, the wells are not equally spread because most wells are located where in the past, hydrocarbons were drilled. This has led to many wells concentrated in one place instead of equally spread well data over the study area. For this reason, this needed some adjustment and a ‘Clean-up data workflow’ was developed.

Clean-up data workflow

1. Wells with a number above four are excluded, these wells are all relatively close together, and this is to prevent data gathering in one specific place.
2. Wells which have determined a fault within the Rotliegend are excluded.
3. Wells that do not reach the top of the Carboniferous are excluded
4. Wells with an inclination above 60 degrees within the Rotliegend are excluded as true vertical thickness may become unreliable due to the isochore effect.
5. Suspected errors are always checked with the NLOG database and, according to this, adjusted.

TNO horizons

In this project, horizons provided by TNO are used. These horizons come from the DGM-deep V5 dataset for both on- and offshore locations. In this project these horizons are referred to as the 'TNO horizons'.

3.4 Fault interpretation

Using the horizons provided by TNO, the Hantum Fault was interpreted throughout the study area using the fault interpretation toolbox in Petrel. Although the research area featured multiple faults, the Hantum Fault was presumed to possess the most significant offset. Following this, the faults interpreted via seismic data were integrated, and a 3D fault model was created utilising fault pillars. This model yielded as a structural framework fault model, which served as the foundation for various maps and further fault analysis conducted throughout the project.

3.5 Thickness maps from well data

True vertical thickness maps based on well data in the study area are being made to anticipate thickness trends. This will result in an isochore map where initial Rotliegend thickness trends can be identified. The interpreted Hantum fault will play a role in the algorithm that makes the surface of the data in Petrel to give the most realistic view.

3.6 Seismic-to-well tie

Well-logs are recorded in-depth and seismic reflectors are recorded in time, so synthetics need to link the depth (z) of a specific seismic reflector to the seismic two-way travel time (s). These wells are chosen because they had the following criteria:

- There is a relatively thick Rotliegend Group
- The well has a reliable part of the Carboniferous
- There is a sonic log
- There is a density log
- Top Z2A (Zechstein) is defined by TNO and visible in the seismic survey
- The logs are modern (from after 1980)
- The seismic survey around the well is of sufficient quality
- The division between hanging-wall- and footwall wells.

It has been decided to make synthetics of wells M07-04, M08-01 and L09-07-S1 (Fig. 10). M08-01 lies in the hanging wall of the Hantum Fault, and M07-04 and L09-07-S1 in the footwall of the Hantum Fault. Synthetics were made by using the seismic-well-tie process in Petrel.

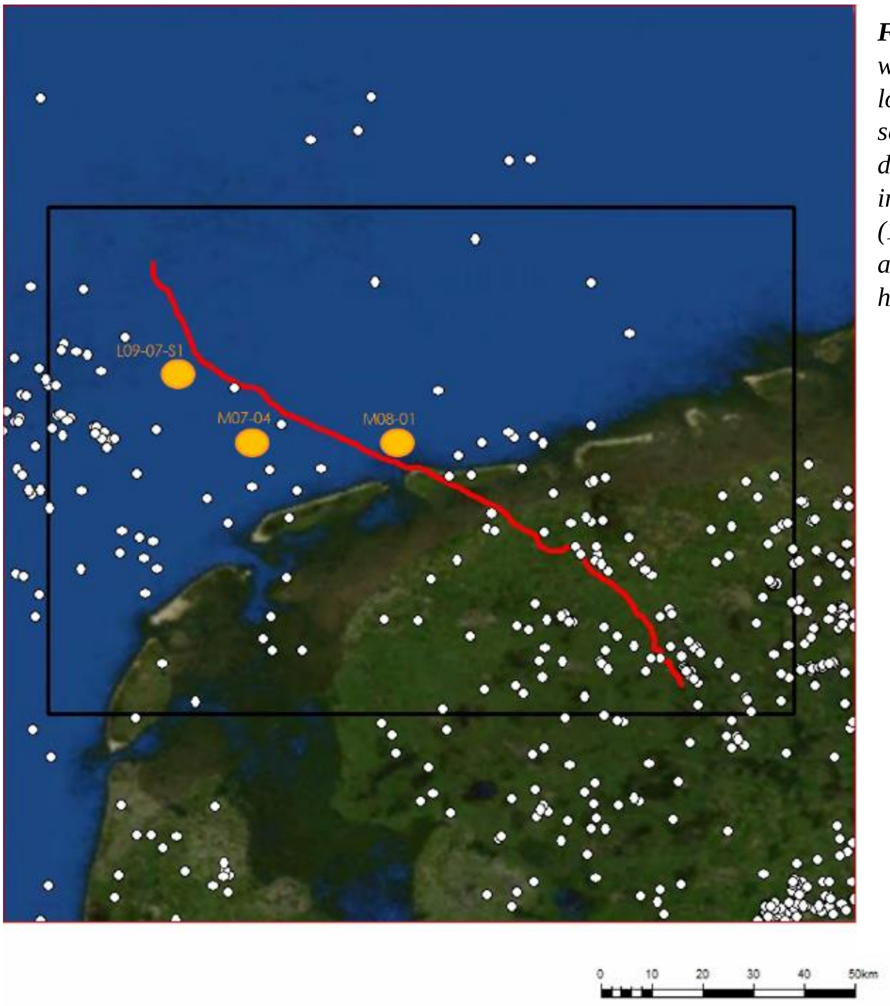


***Figure 10**. Displayed with an orange circle the location of wells where seismic-to-well-tie is done: L09-07-S1 (1992) in the footwall, M07-04 (1989) in the footwall and M08-01 (1982) in the hanging-wall.*

3.7 Interpretation Rotliegend

In order to identify thickness trends of the Rotliegend in proximity to the Hantum Fault, a thorough seismic interpretation of the top and base of the Rotliegend is necessary. Therefore, the synthetics of M08-01 and L09-07-S1 were utilised to perform seismic interpretation of the top and base of the Rotliegend seismic surveys featured in figure 9. Upon evaluation of all seismic surveys, an isopach map of the Rotliegend will be generated, enabling an assessment of the impact of the Hantum Fault zone on the thickness of the Rotliegend.

4. Results

4.1 Fault interpretation

The depth of the Hantum Fault within the Rotliegend Group follows the depth trend of the Rotliegend group itself, with increasing depth from the onshore to the offshore L-blocks. Specifically, the depth of the fault onshore ranges between 2750 and 3250 meters, while at the offshore L-blocks, located at the end of the fault, the depth ranges from 3750 to 5000 meters below the surface (see Fig. 11). As the depth of the fault, the throw varies as well. The throw is almost a kilometre onshore and decreases to the L-blocks. Further analyses of the fault throw will be conducted in the subsequent analysis section.
Often, above the interpreted Hantum Fault, Zechstein salt movement (diapirism) took place, which could have been triggered by the fault. A fault is visible in the younger stratigraphic units, as shown in figure 12. However, there is a decoupling in the Zechstein salt.

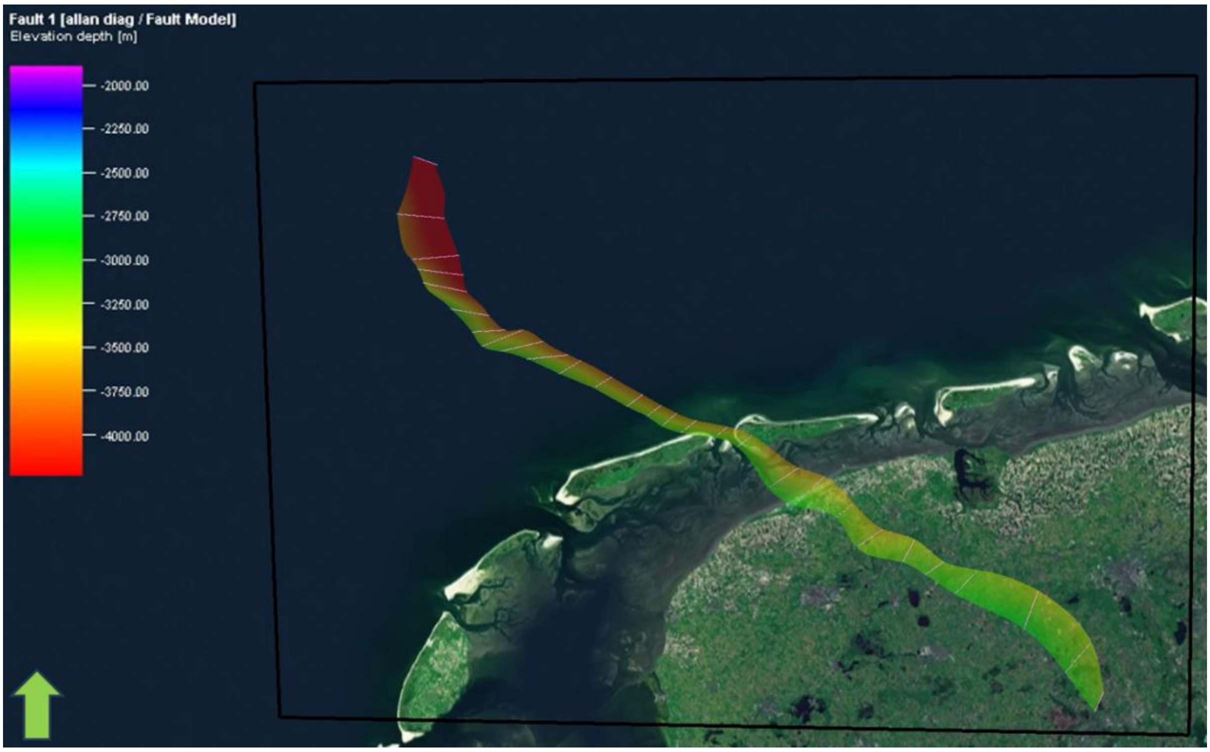
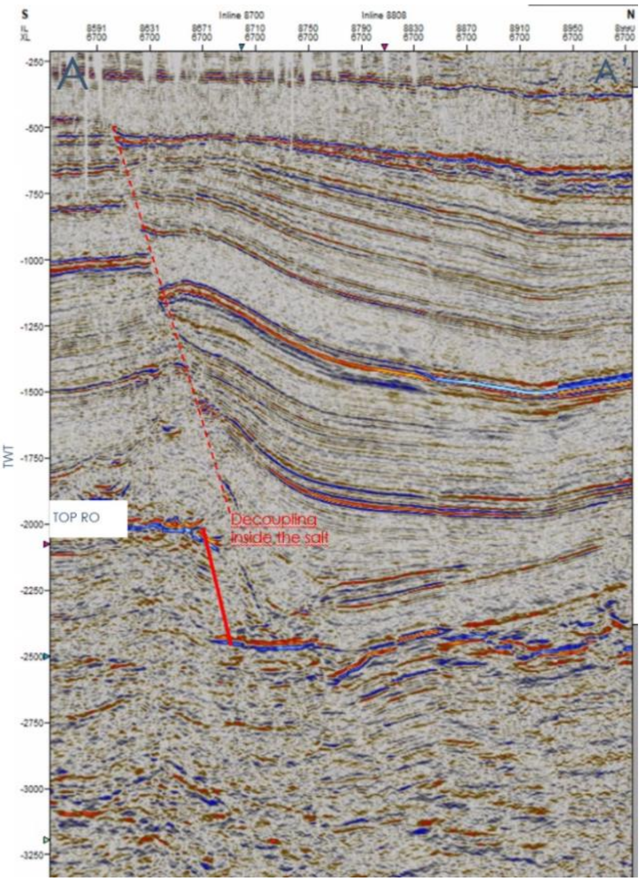


Figure 11. *Distribution of the Hantum Fault across the Rotliegend in the study area interpreted with fault pillars at the depth of the Rotliegend as defined by the TNO horizons. This fault interpretation is used in the project for several analysis and referred to as the structural framework as the fault.*



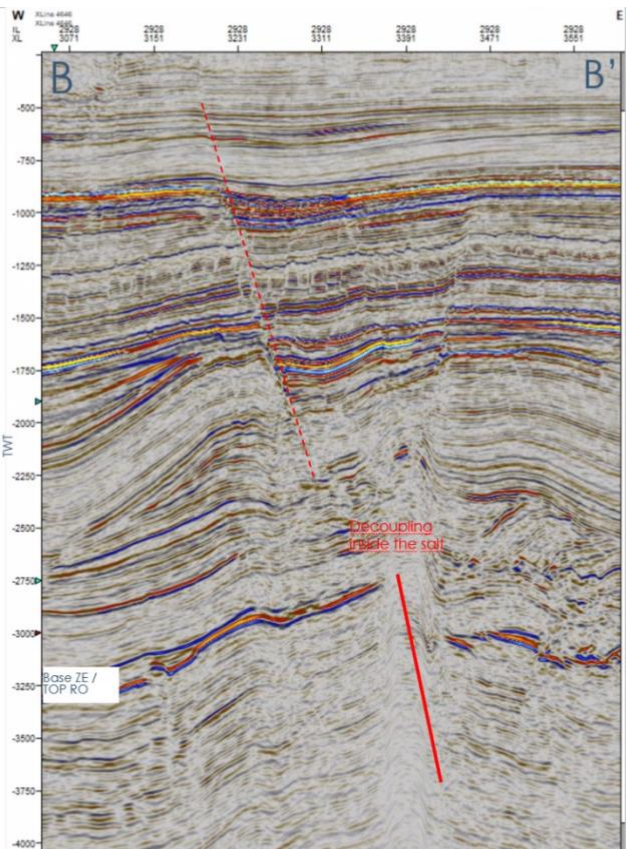


Figure 12. *Seismic lines which show the Hantum Fault. A-A' shows the Hantum Fault in the onshore part (see added map for location), and B-B' shows the Hantum Fault interpretation in the L-blocks. The dotted line represents the interpretation through the younger units up to the North Sea groups. There is a decoupling of the fault in the Zechstein salt due to the ductile characteristics of salt in the underground.*

4.2 Thickness maps based on well data

The cleaned thickness data were gridded in Petrel using convergent gridding with the Hantum Fault structural framework from figure 11 included. This reveals a distinct thickening in the onshore hanging wall. In contrast, the thickening in the offshore hanging wall cannot be accurately determined from this dataset. Instead, the well data suggests thinning of the Rotliegend Group in the hanging wall in the offshore L-blocks (Figure 13). Additionally, the thickness map of the ROSLL indicates thickening in the north of the fault in the L block hanging wall; however, it should be noted that there is limited well data available in this area (Figure 14). Given the scarcity of well data in the offshore L and M blocks, seismic interpretation is required to comprehensively understand the Rotliegend thickening or thinning around the Hantum Fault. These initial findings underscore the need for further investigation into the Hantum Fault and the Rotliegend Group in thickness trends, which can be achieved through seismic interpretation.

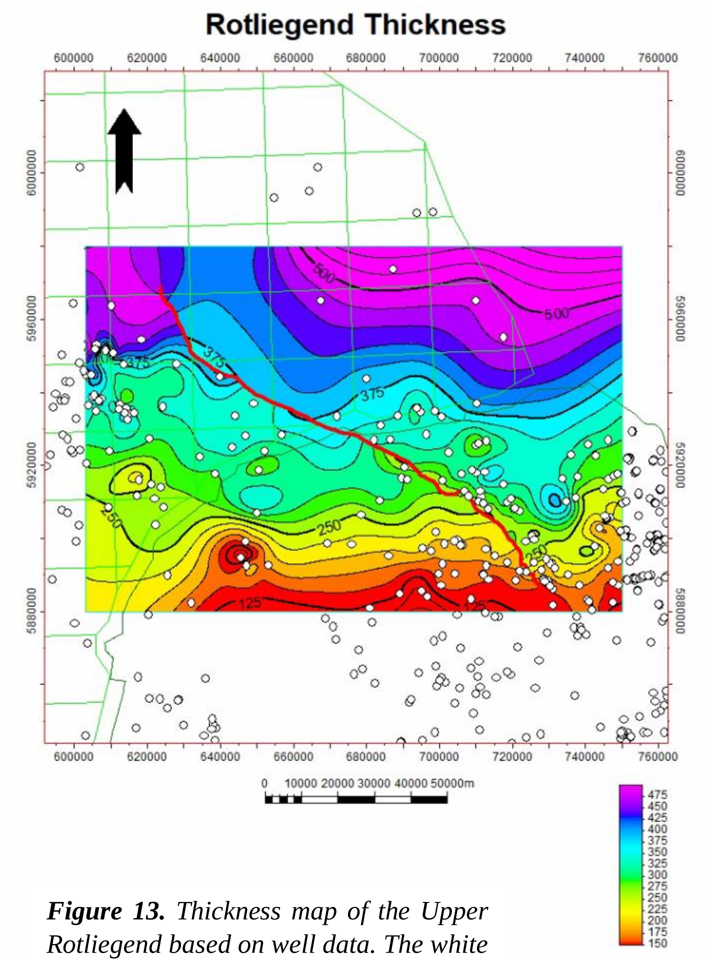


Figure 13. Thickness map of the Upper Rotliegend based on well data. The white dots are well data points; the red line is the interpreted Hantum Fault. Onshore, there is a prominent thicker Rotliegend Group in the hanging wall of the fault compared to the footwall. Offshore the opposite effect can be found; there seems to be a thicker footwall in the far northwest of the study area. Note that the well data is not evenly spread.

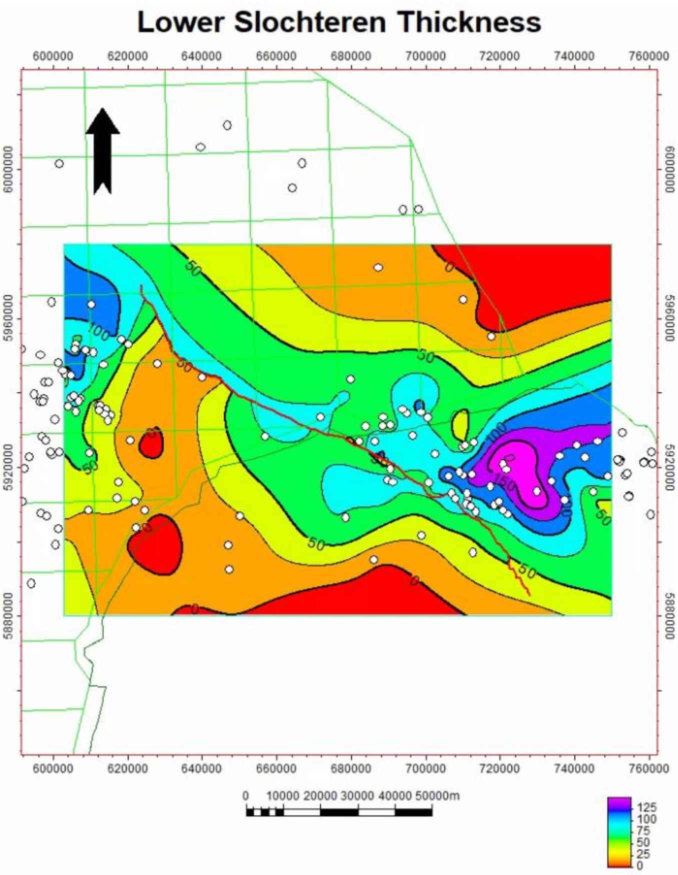


Figure 14. Thickness map of the Lower Slochteren Formation of the Rotliegend Group (ROSLL) based on well data. The white dots are well data points; the red line is the interpreted Hantum Fault. This figure shows a thicker Lower Slochteren Member in the whole hanging wall of the area.

4.3 Seismic to well tie

Seismic-to-well ties were performed for three wells in the study area to correlate the top and base of the Rotliegend Group. The top of the Rotliegend was defined by a peak, a blue loop and was relatively easy to find due to the strong acoustic impedance with the overlying Zechstein salt. However, the base Rotliegend proved problematic to well tie due to the weak acoustic impedance contrast and its status as an unconformity rather than a specific horizon (Fig 15).

For improved understanding of the lithologies, several relevant Rotliegend cores were inspected at the NAM corehouse in Assen. Among them, L09-03 is located in the study area, in the footwall of the Hantum fault. The cored interval includes the Base Permian Unconformity, with Basal Rotliegend conglomerates overlying Carboniferous claystones. These different lithologies happen to have similar impedance, therefore this unconformity is poorly visible on seismic (Fig. 16).

Based on the challenges encountered in well tying the base Rotliegend, a decision was made only to interpret this horizon in depth for the L06_PSDM_WIN_2007 survey. This survey was selected because it is also provided in depth, and therefore the interpretation could be made without the need for well tie control points. In addition, the interpretation of the base Rotliegend in depth for the L6 survey will provide valuable insights into the thickness trends of the Rotliegend Group around the Hantum Fault in the smaller study area where the emphasis of this project lies.

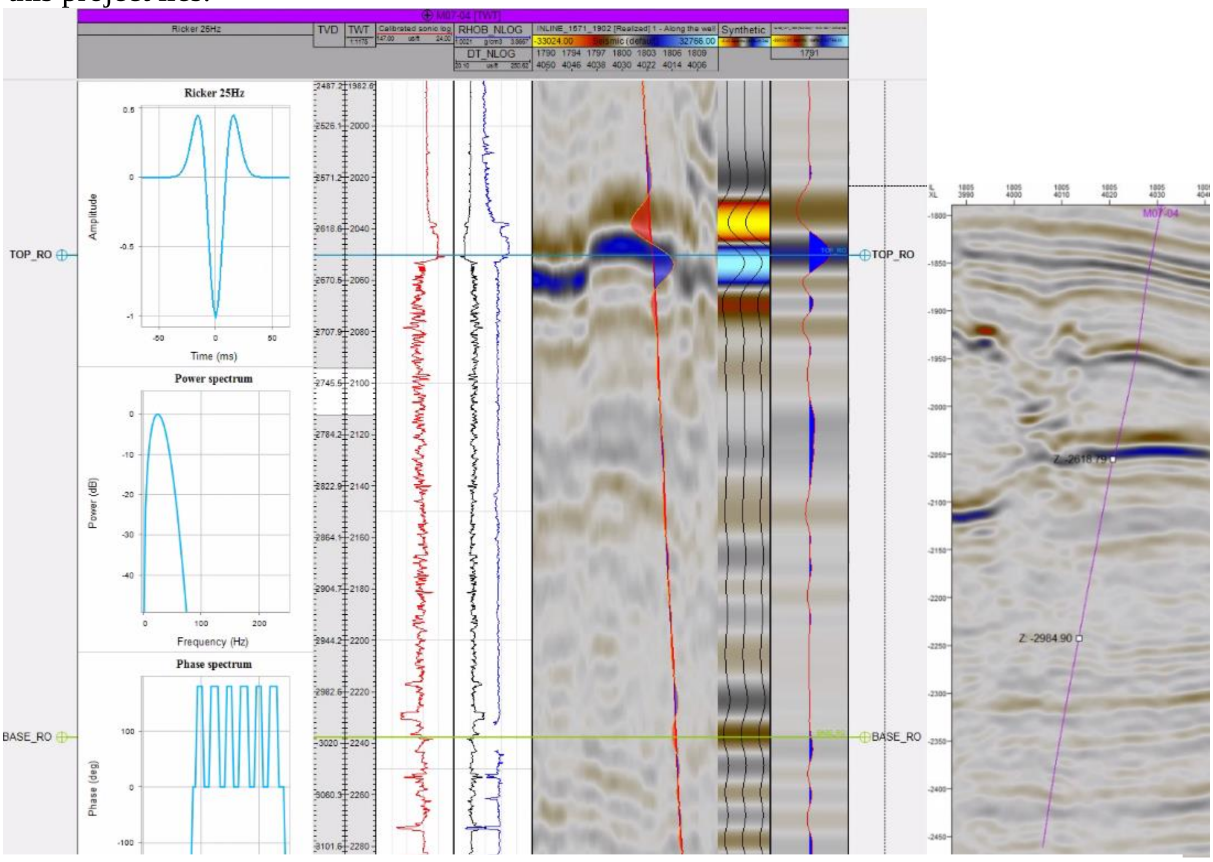
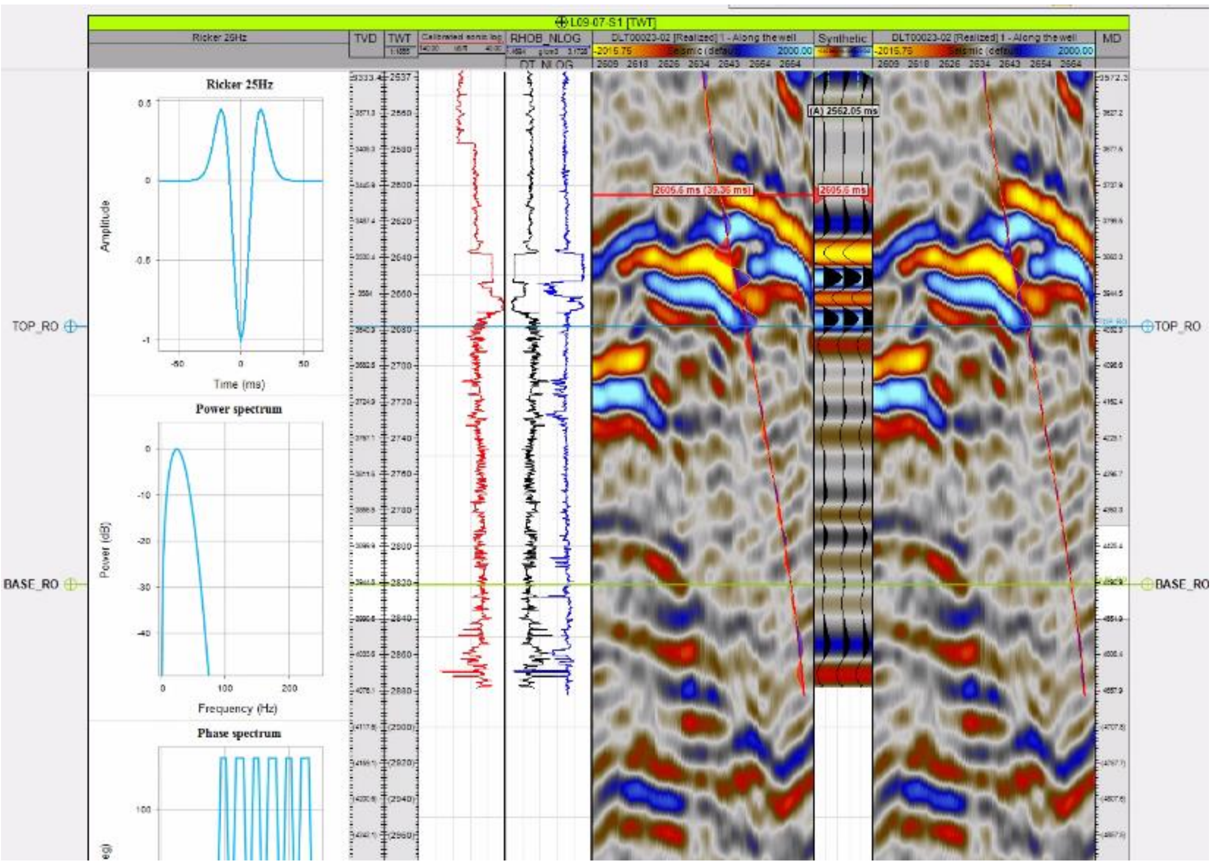


__Figure 15a__. Seismic to well tie of M07-04 with its adjacent seismic line. The Top Rotliegend is indicated by a distinct blue reflector in both the seismic survey and the synthetic, while the Base Rotliegend is indicated by a red reflector in the synthetic. However, the survey does not provide clear differentiation of the Base Rotliegend reflector. Location of this well can be found in figure 10.



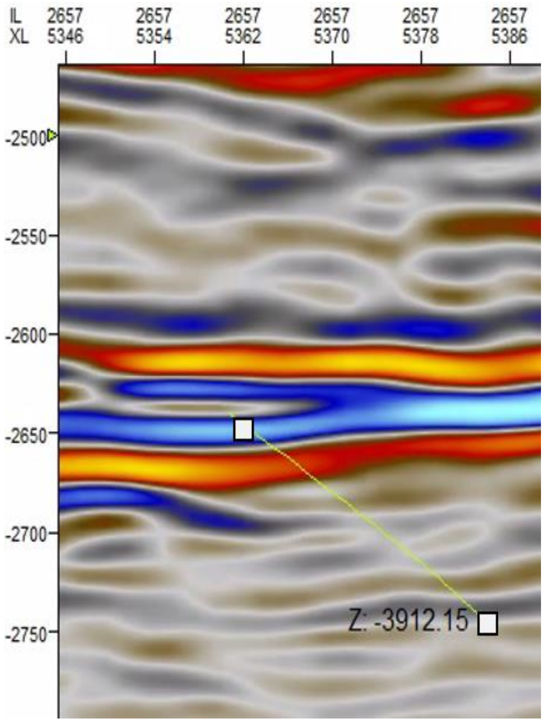
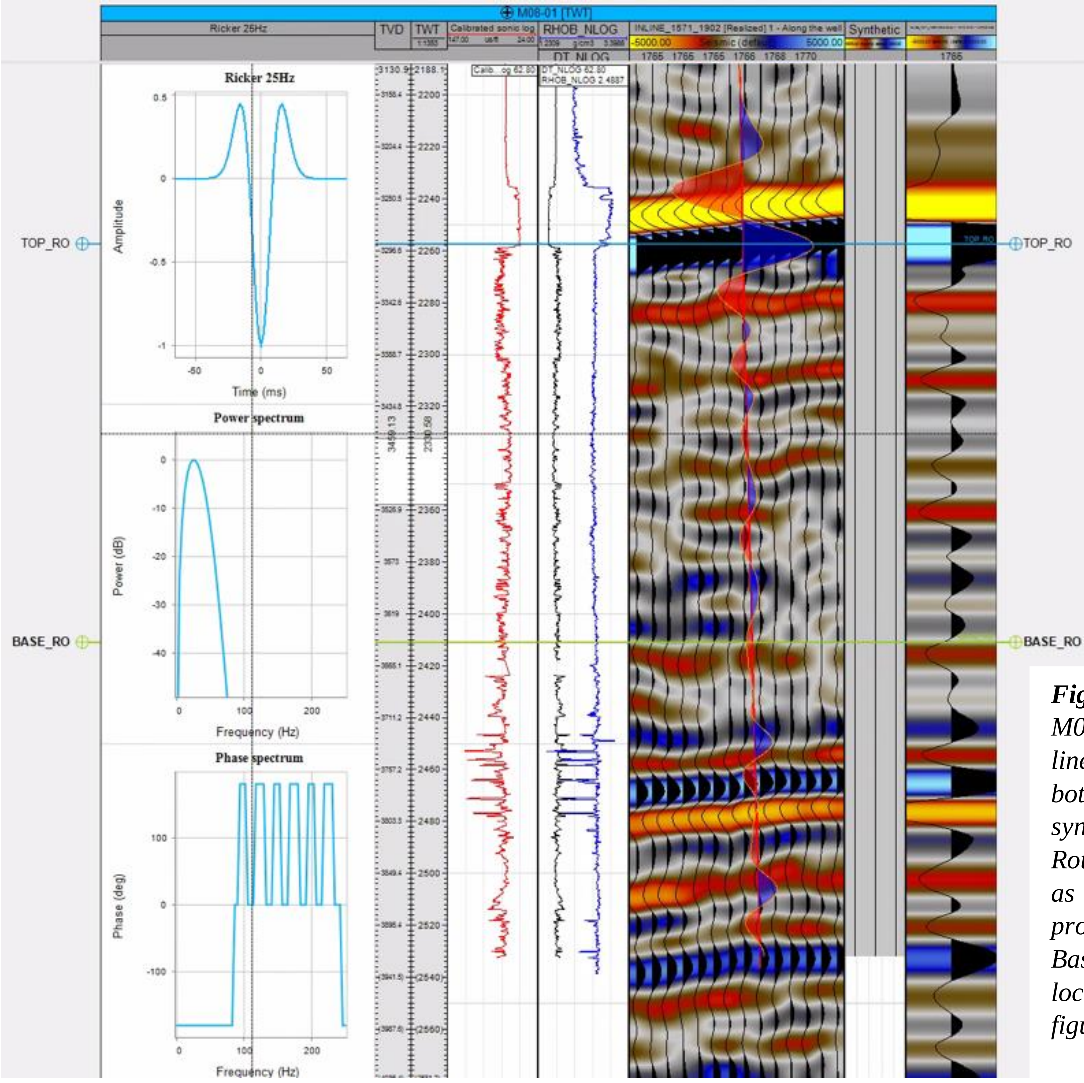


***Figure 15b**. Seismic to well tie of L09-07-S1 with its adjacent seismic line. The Top Rotliegend is indicated by a distinct blue reflector in both the seismic survey and the synthetic. The seismic survey does give a red reflector around the position of the Base Rotliegend, however this is not visible in the synthetic, also the logs do not give a clear distinction. Location of this well can be found in figure 10.*



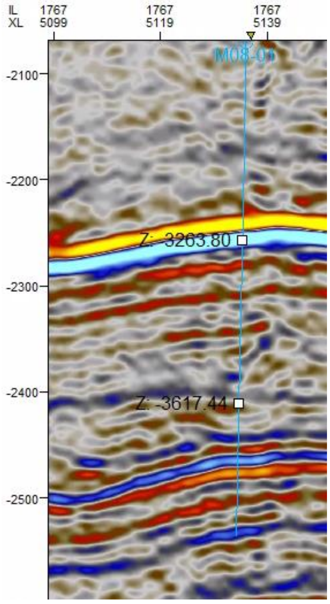
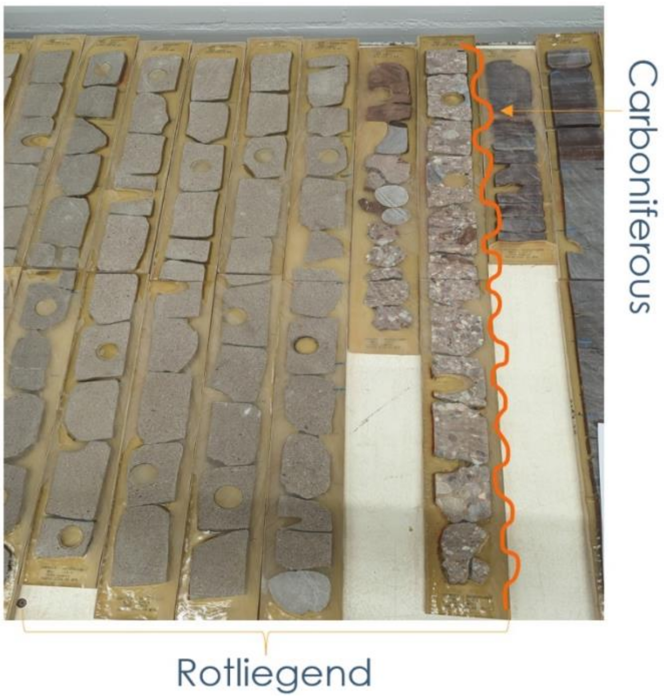


Figure 15c. *Seismic to well tie of M08-01 with its adjacent seismic line. A distinct blue reflector in both the seismic survey and the synthetic indicates the Top Rotliegend. However, the survey, as well as the synthetic, does not provide clear differentiation of the Base Rotliegend reflector. The location of this well can be found in figure 10.*

Figure 16. *Core slabs from well L09-03, with a contimitous section across the Base Permian Unconformity, from the NAM corehouse. The Base Permian Unconformity is highlighted in orange. The Carboniferous section is identified by its dark grey colour, while the Rotliegend is characterised by its red/grey colour and coarse-grained nature at the base of the formation. In certain intervals, the grain size reaches approximately 5 centimetres.*

The photo was taken by Odin van Oord, and there is permission to use it.



4.4 Seismic interpretation of the Rotliegend Group

The Top Rotliegend is defined by a peak, a blue loop and is relatively easy to find; also, due to the strong reflectivity of Top ZEZ2A (base Zechstein salt), a strong trough and thus a red reflector which usually directly overlies the Top Rotliegend blue peak loop. The Base of the Rotliegend is an unconformity. Therefore it displays lateral variations in polarity and amplitude, which makes it harder to interpret, as can be seen from the seismic to well tie (Fig. 15). However, the Carboniferous is recognisable by strong reflectors related to coal layers, which tells something about where the Base Rotliegend must approximately lie. On all the selected seismic surveys, the Top Rotliegend has been interpreted. For the M08 survey, the seismic interpretation of Oord (in progress) was used. This interpretation is then added with the TNO horizons to make a whole Top Rotliegend interpretation surface of the study area. This then converses from time to depth with a velocity model that TNO made: VELMOD-4 (Fig. 17). From the depth of the Top Rotliegend map, it becomes clear that the Hantum Fault affected the deposition of the Rotliegend, the Top Rotliegend horizon lies deeper in the hanging-wall of the fault than in the footwall of the fault, especially in the south and middle section of the fault this effect is visible. Towards the north, in the L-blocks, where the emphasis of this study lies, the throw at Rotliegend level becomes smaller; see Chapter 5 for details.

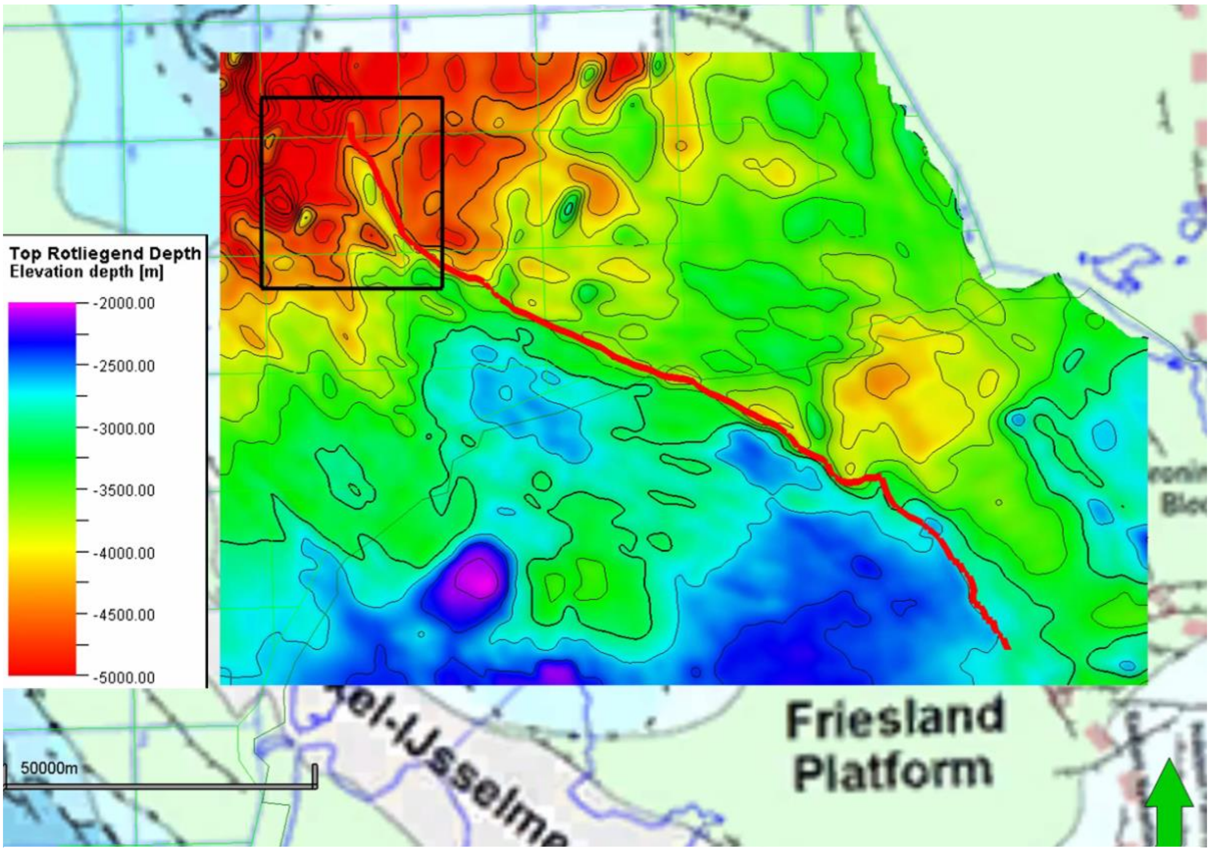


Figure 17. *Top Rotliegend surface in depth made with interpretation in time, added with the TNO horizons and then converted to depth with a velocity model specially made for this project. The Top Rotliegend lies deeper in the hanging wall of the Hantum Fault, except for the L-block, where the emphasis of this study lies.*

Interpreting the Base Rotliegend was more challenging due to the less clear seismic reflector compared to the Top Rotliegend (Fig. 15). The Base Rotliegend interpretation of the whole study area was not feasible within the given project timeframe. Therefore, it was decided to focus only on interpreting the Base Rotliegend in the part of the research area where the emphasis lies in achieving the best results for the project. In this area, the Base Rotliegend interpretation was interpreted on the L6 survey in depth, for which a specific workflow was established.

The Base Rotliegend was interpreted on specific lines within the L6 depth survey. To get the best results, instead of using the top Rotliegend surface from the interpretation in time that was conversed to depth, the Top Rotliegend was interpreted at the same lines as the Base Rotliegend. After doing the Top Rotliegend very precisely, this interpretation is flattened. With the help of the seismic to well-tie position of the Base Rotliegend, the Base Rotliegend horizon could be picked (Fig 18).

After interpreting ±50 lines of Top and Base Rotliegend on the L6 surveys, a detailed surface could be made of these interpretations, shown in figure 19. Where the interpreted lines lie is shown in figure 20. With these two surfaces, the thickness of the Rotliegend in this area could be determined; this is shown in figure 21. There is no direct effect of the Hantum Fault on the thickness of the Rotliegend in this area. This result based on seismic data gives a different result than the thickness map based on well data (Fig. 13). This is due to the scarcity of well data in the area, especially in the hanging wall of the Hantum Fault in the L-blocks. Therefore the map based on seismic interpretation data is more reliable.

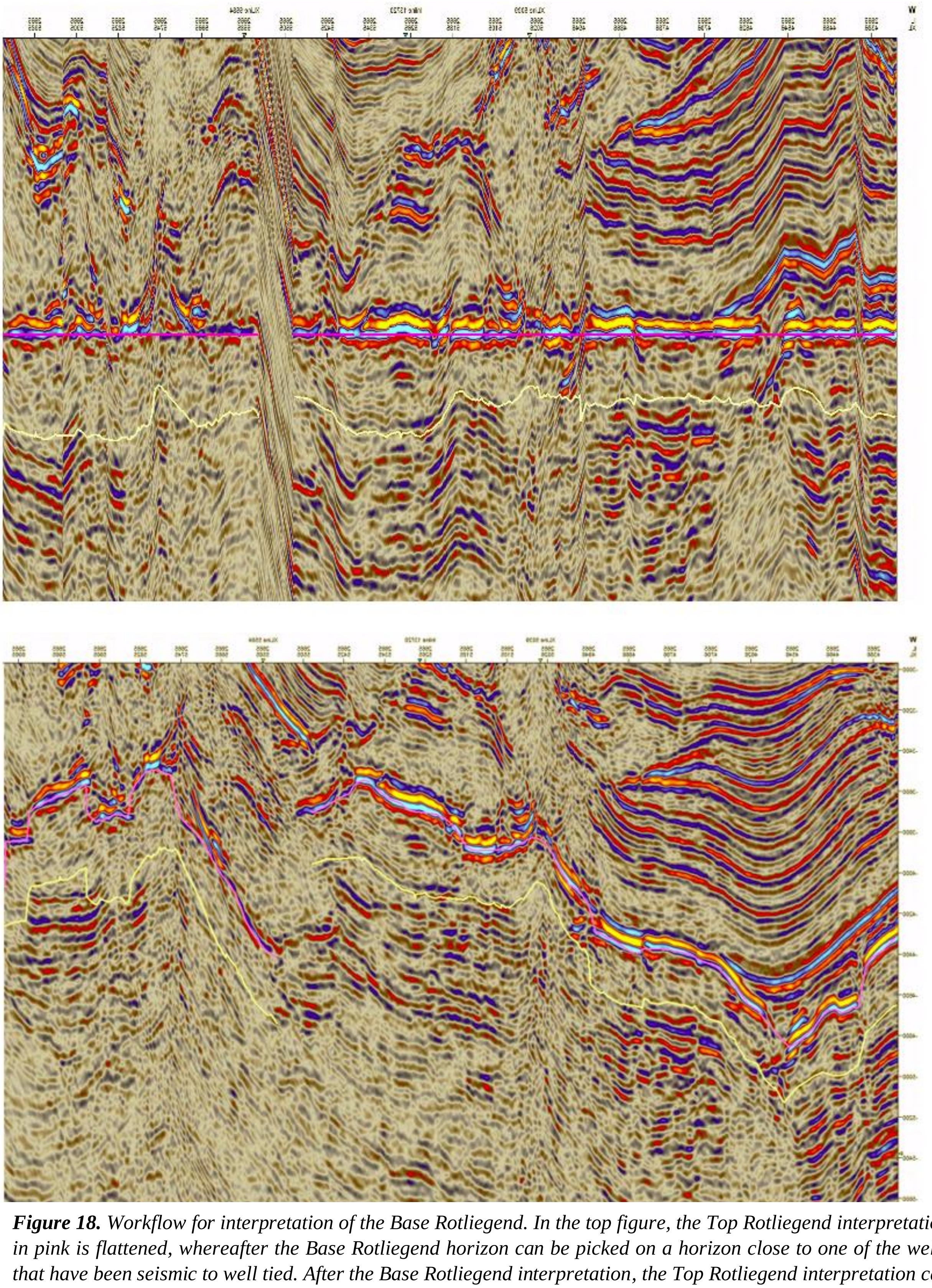
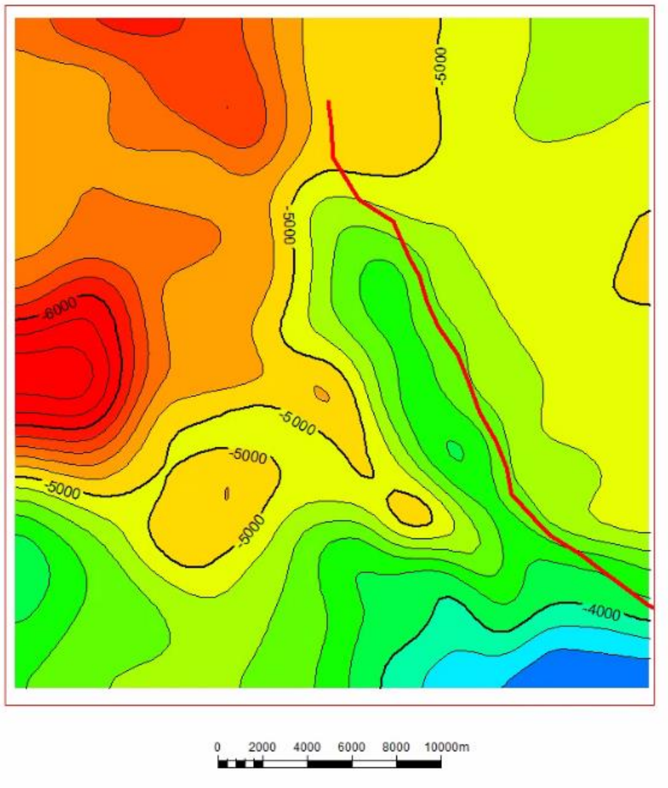


Figure 18. *Workflow for interpretation of the Base Rotliegend. In the top figure, the Top Rotliegend interpretation in pink is flattened, whereafter the Base Rotliegend horizon can be picked on a horizon close to one of the wells that have been seismic to well tied. After the Base Rotliegend interpretation, the Top Rotliegend interpretation can be unflattened.*



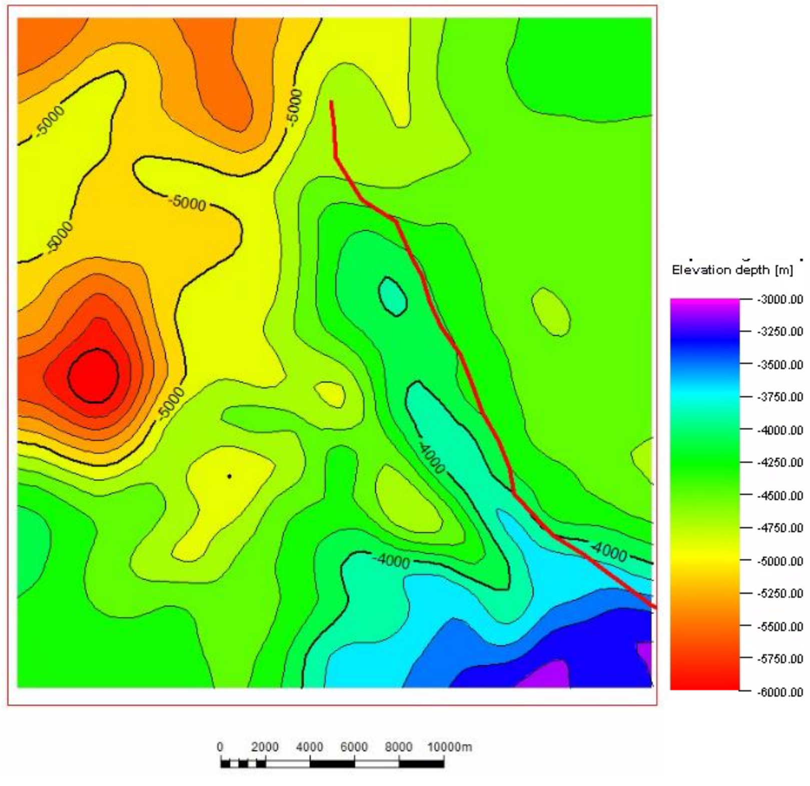


__Figure 19.__ The top figure shows the Top Rotliegend depth map, and the bottom figure the Base Rotliegend depth map interpret in depth. It seems like there is an effect of the Hantum Fault, displayed in red, in the footwall the Rotliegend lies for both the Top Rotliegend, and the Base Rotliegend, deeper.

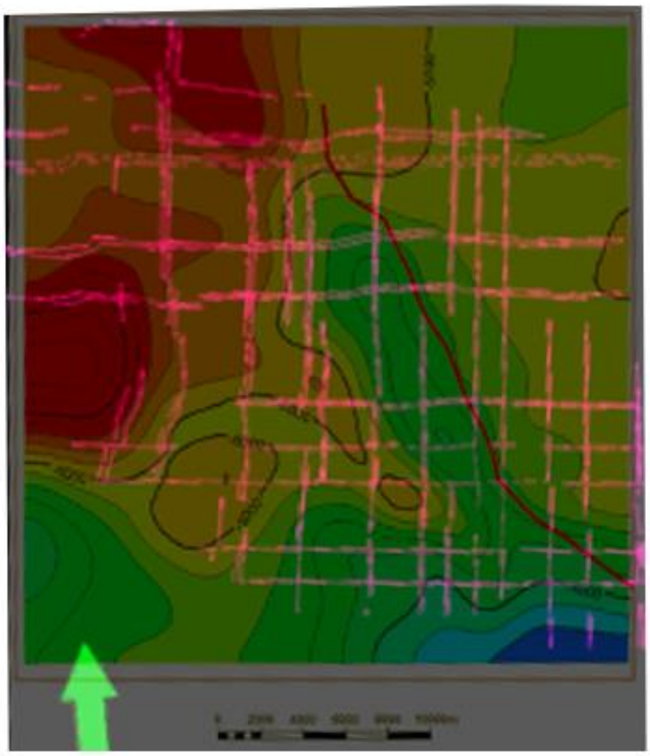


Figure 20. *The interpreted linesof the Top and Base Rotliegend shown on the Top Rotliegend surface. Based on this interpretation the surfaces of figure 18,19 and 21 are made.*

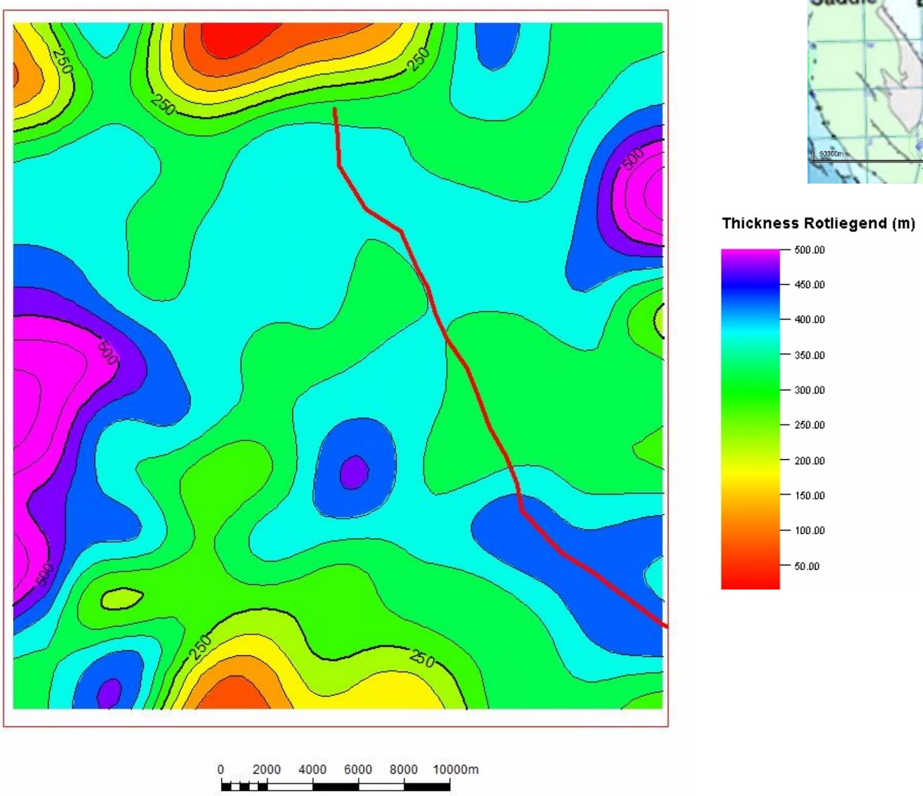
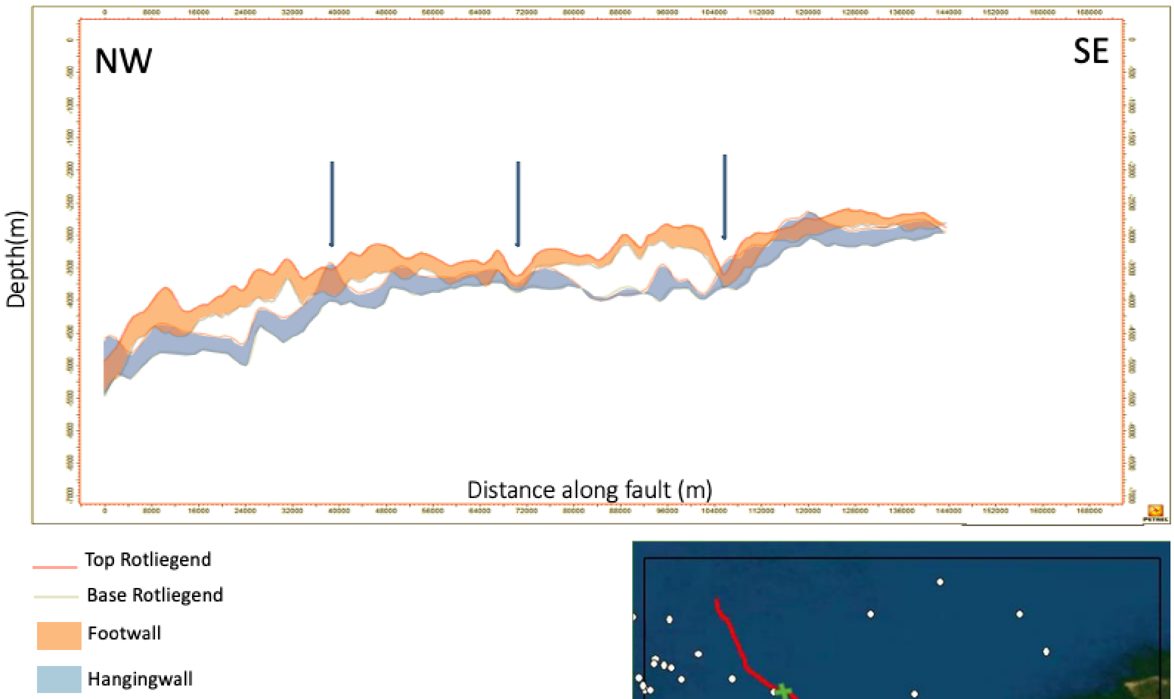


Figure 21. *Thickness map of the Rotliegend in the L6 block, based on depth seismic interpretation of the Top and Base Rotliegend. There is no clear relationship between the Hantum Fault and the thickness.*

4.5 Allan mapping

The structural framework of the Hantum Fault, as interpreted in this study and described in figure 11, was used to extract Allan diagrams of the Hantum Fault. Allan (1989) introduced a graphical technique for mapping the relative positions of stratigraphical cut-offs in both the footwall and the hanging wall across a fault. This technique produces a 2D diagram of the 3D fault surface, showing the relationship across the fault surface for the hanging wall or footwall and the stratigraphical horizon it intersects with. To make the diagram of the intersecting footwall through the Rotliegend, 1000 meters was subtracted from the x and y position of the Hantum Fault. For the hanging wall, the opposite was done: 1000 meters were added to the x and y positions of the fault. This 1000 meters is the projection distance of the fault, which is crucial for accounting for the complete effect of the Hantum Fault. Considering the scale and complexity of this fault zone, employing a smaller value might lead to erroneous results. Therefore, it is necessary to incorporate the entire fault zone to assess its impact on the Rotliegend accurately, with 1000 meters distance of the fault this is ensured. The Allan diagram of the Hantum Fault was made using Top Rotliegend and Base Rotliegend interpretation (Fig. 22). It shows that the throw of the Hantum Fault varies laterally. There are three distinct points where the footwall and hanging wall come into contact.



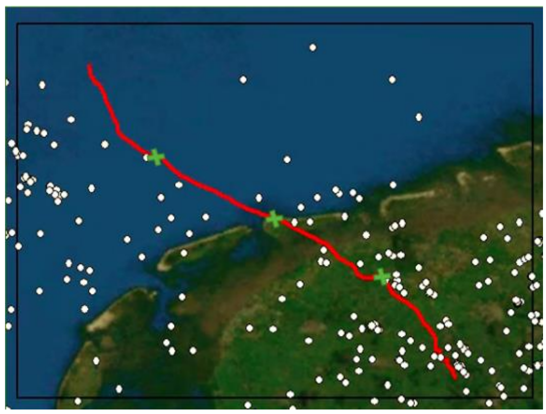


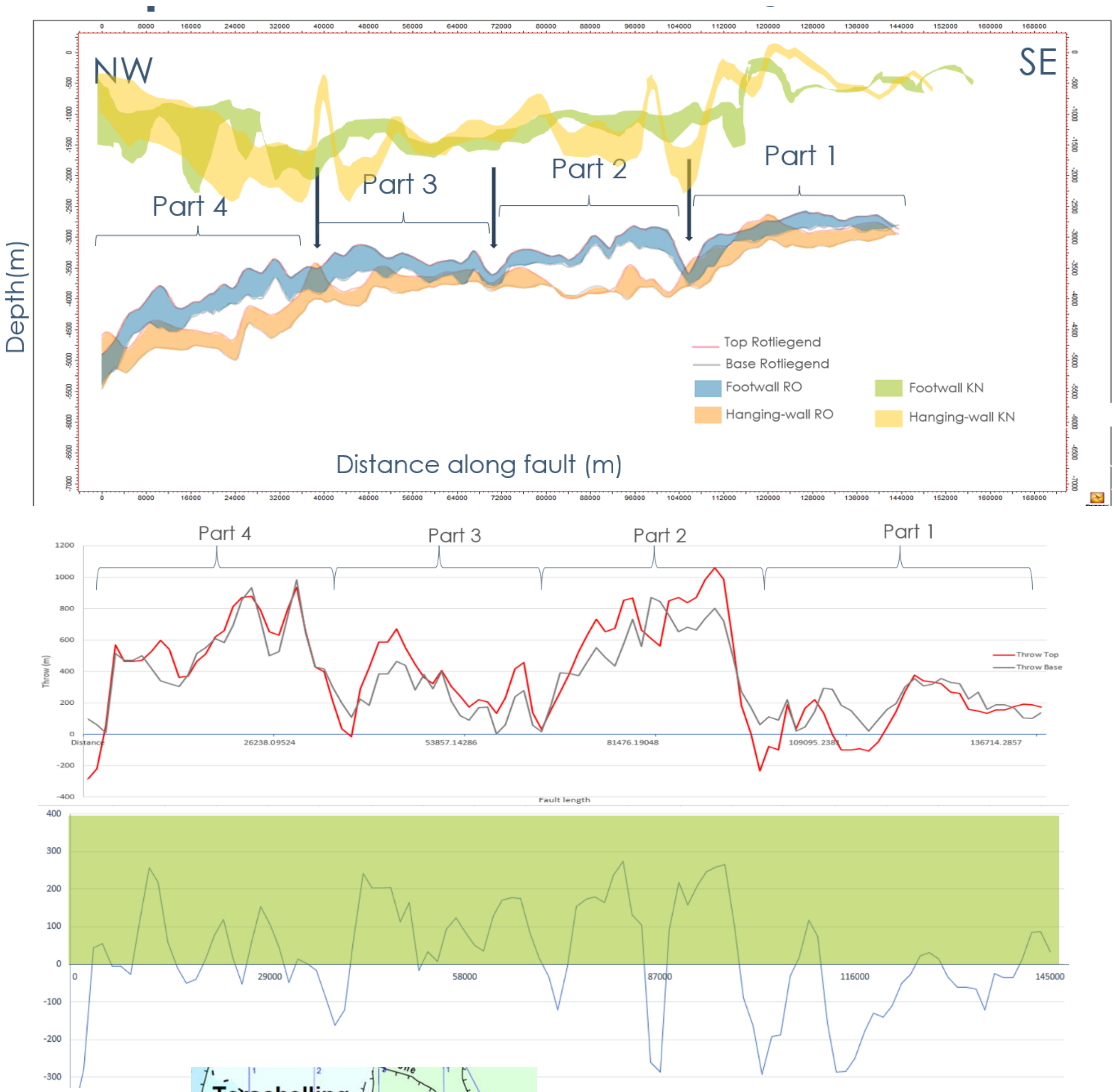
Figure 22. *Allan diagram for the Hantum Fault with the footwall and the hanging wall of the Rotliegend, map is for reference. Arrows indicate where the footwall and hanging wall come into contact, on the map this is indicated with green crosses.*

5. Discussion

5.1 Fault analysis

The relative positions of the top and base Rotliegend in both the footwall and the hanging wall across the Hantum Fault can be determined by analysing the pattern in the Allan diagram (Fig. 22). The three points where the footwall and hanging wall come into contact indicate zero throw. The throw of a fault is zero at the fault tips and has its maximum in the centre of the fault (Kim and Sanderson, 2005); therefore, the results allow identification of four fault parts, parts 1, 2, 3, and 4. To investigate this effect more, throw profiles have been made. The throw calculation was performed by subtracting the hanging wall depth from the footwall depth for the top and base of the Rotliegend. As shown in the Allan diagram, the four parts of the Hantum Fault are also visible in the throw profile (Fig. 23). The Hantum Fault has the smallest throw in the south, onshore, in the diagram part 1. The largest throw is reached in parts 2 and 3, especially in part 2, where the throw reaches over a kilometre. Part 2 is partly onshore and partly offshore and part 3 lies in the M-blocks. In part 4, in the L-blocks, the most northern part of the Hantum Fault, the throw is similar to part 2; however, in part 4 the top and base of the Rotliegend do have the same character, unlike in part 2 where the top has a larger throw than the base of the Rotliegend.

The difference between the throw of the Base Rotliegend horizon and the throw of the Top Rotliegend horizon indicates possible syn-tectonic sedimentation of the Rotliegend around the Hantum Fault. The graph aligns with the previous findings, indicating that there is likely no syn-tectonic thickening in the Rotliegend of block L, which is depicted in part 4 of the diagram (Fig. 23). However, it should be noted that this diagram does not rule out the possibility of syn-tectonic thickening in parts 1, 2 and 3 of the fault.



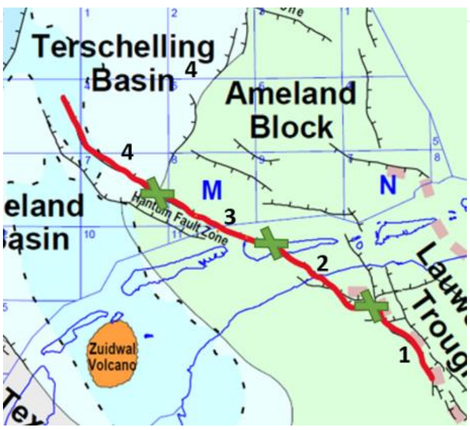
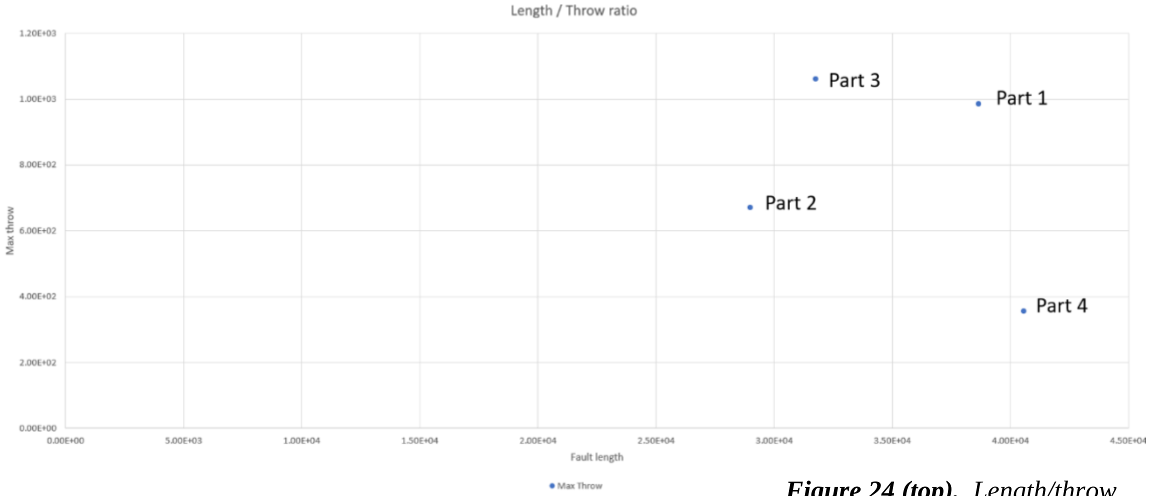


Figure 23. The top graph is the Allan diagram for the Hantum Fault with the footwall and the hanging wall of the Rotliegend in it and of an interval in the Cretaceous, the Rijnland Group. The middle graph shows the throw diagram for the Hantum Fault and the bottom graph shows the ratio between Top Rotliegend throw and Base Rotliegend throw of the Hantum Fault. In the Allan diagram four different parts are recognized which can be traced back in the throw diagram and are visible on the map of the figure, the crosses match the arrows. The green part in the bottom graph represents the part where the throw in the Top Rotliegend is larger than the throw in the Base Rotliegend at the same location.

Length/throw relation

The length of the fault has a typical relationship with its displacement (Barnett et al., 1987). More specifically, there is a different relation between length and displacement for different fault types. Therefore, from the length/displacement ratio, there could be determined whether a fault is normal, reverse, or strike-slip in character (Kim & Sanderson, 2005). It is important to note that there is a distinction between fault displacement and throw. Displacement occurs along the fault surface, while throw represents the vertical displacement. The Hantum Fault has an average angle of approximately 60 degrees. For example, for a throw of 1000 meters the displacement along the Hantum Fault would be 1150 meters which is in the similar order of magnitude which can be considered negligible.

This length/throw relationship has also been determined for the Hantum Fault (Fig. 24). A graph was created by Kim and Sanderson (2005) that plotted length/displacement ratios from various studies and determined a fitting line for normal faults (Fig. 25). The segments of the Hantum Fault fit in the model of normal faults. However, the part of the fault onshore seems to have a different character, although still close to the fitting line for normal.



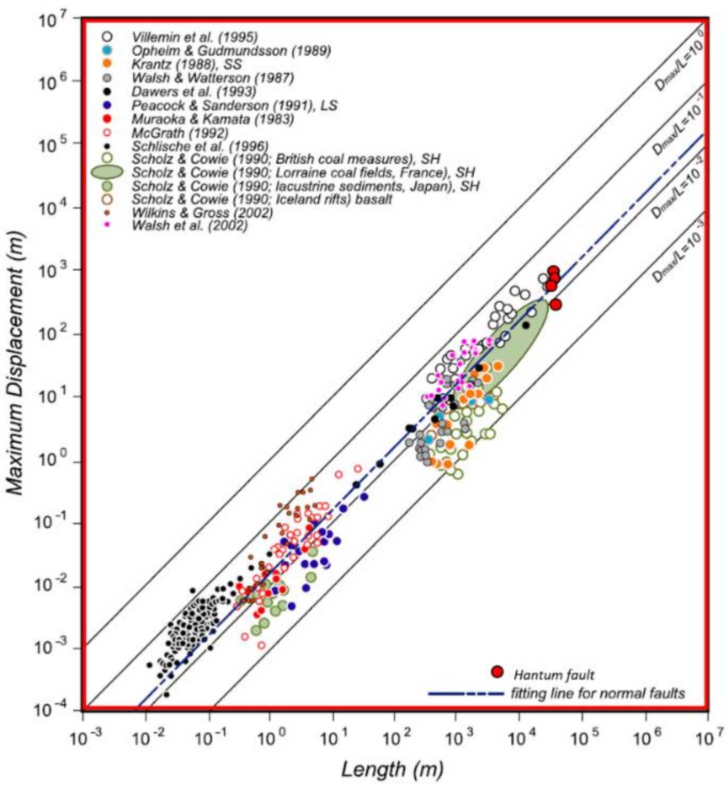


Figure 24 (top). *Length/throw ratio of the four segments of the Hantum Fault, as shown in figure 21.*

Figure 25 (left). *This graph shows the relation between length and displacement for normal faults. The blue dotted line shows the fitting line for normal faults. The Hantum Fault parts from figure 22 are plotted on this graph in red. With this, there can be concluded that the Hantum Fault segments are indeed normal, rather than strike-slip. Graph modified after Kim & Sanderson (2005).*

5.2 Geological history of the Hantum Fault

The four parts identified in the Rotliegend Allan diagram may have distinct tectonic histories. One hypothesis is that these parts may have merged later in geological time. However, this theory is refuted when a Cretaceous horizon is added to the Allan diagram. It exhibits a different and more pronounced trend that does not align with the previously identified four segments (Fig. 23). Including a Cretaceous horizon in the Allan diagram portrays the fault at a subsequent geological time. However, by doing this, there should be noted that there probably is a decoupling of the fault in the Zechstein salt, as seen in (Fig. 12). However, at roughly the position of the Hantum Fault in the Rotliegend, there is, despite the decoupling in the Zechstein salt, a weakness, this is why the Hantum Fault continues into younger units. By also computing the throw of the Cretaceous horizon from the Hantum Fault, a similar trend to the throw graphs of the Rotliegend horizons appears to exist (Fig. 26). This observation suggests that the Hantum Fault persisted during the Cretaceous, which agrees with the observation of decoupling of the fault in the Zechstein salt (Fig. 12). Despite additional cutoffs from the Hantum Fault in the Allan diagram, the throw direction trend remains consistent.

Figure 26. *The throw profile of the Rotliegend, added with the throw profile of the Rijnland Group, from the Cretaceous. These graphs show the same trends, they are different, but the main trends are the same, only less pronounced in the Cretaceous horizons. The blue line represents the Top of the Rijnland or the Base Chalk, and the orange line is the throw of the Base of the Rijnland.*

By inspecting the structural element map of de Jager (2007) and the throw pattern with the different parts of the Hantum Fault, it becomes evident that the zero offset points are positioned at the locations of new faults that intersect the assigned Hantum Fault, or a change in the strike of the fault (Fig. 23). A branch between part three and part four separates the Terschelling Basin from the Ameland block. Additionally, the fault changes strike between parts two and three and between parts one and two. Although the Hantum Fault seems to have a more straightforward trajectory between part one and two, it actually deviates to the left. It is plausible to contend that the first part of the Hantum Fault, which lies onshore, corresponds to the fault that follows a straight path.

Based on this, it becomes feasible to provide answers to the various hypotheses depicted in figure 2. Is the Hantum Fault younger than the Rotliegend group (hypothesis 1), is there a pre-existing relief, which could be caused by the Hantum Fault in earlier times, which caused thickening of the Rotliegend in the hanging wall, the onlap model (hypothesis 2), or was there fault movement while depositing the Rotliegend sediments which caused thickening in the hanging wall as well (hypothesis 3). From the thickness map based on seismic interpretation in the L-blocks (Fig. 21), there can be concluded that there is no trend of thickening towards the offshore L blocks; therefore, for the L blocks, hypothesis 1 yields. Furthermore, for the onshore part of the fault, the part where the Hanging wall is thicker, based on well data of figure 13, hypothesis 3, the syn-depositional model, is much more plausible due to the difference in thickness between the footwall and hanging wall and the fault analyses. Hypothesis 2 is a possible explanation in the Lauwerszee Through. Mijnlieff & Geluk (2011) describe that Rotliegend sediments may have onlapped against a pre-existing high, the Groningen high, associated with the Hantum Fault, causing thickness varieties. They suggest a clear relation between the thickness of the Lower Slochteren sandstone and the Hantum-Lauwerszee Trough. However, further study towards this onlap-thickening in combination with the Hantum Fault needs to be done.

Pre-Carboniferous structural trends already determined where Rotliegend would become thicker in the future. In the L-blocks, the fault is probably younger than the Upper Rotliegend deposition, since there is no effect at that position in the subcrop map of the Base Permian Unconformity (Fig. 6). The onshore part of the fault, the part of the Lauwerszee Through, is visible on this subcrop map and is, therefore, the oldest part of the Hantum Fault. Another reason to think that this first part of the fault is connected to the fault that goes straight to the north (instead of branching to the left as the Hantum Fault does) is that this is also indicated on the subcrop map of the Base Permian Unconformity (Fig. 6). This prompts the question as to why the left-branching part of the Hantum Fault has been designated, rather than the straight part which appears to align more consistently with the Base Permian Subcrop map and the fault analysis presented in this study.

5.3 Limitations and recommendations

The current methodology used in the Allan diagram, which involves adding offset in X- and Y-direction from the central fault polygon to measure the depths in the hanging wall, and subtracting the same for the footwall, does not account for the angle of the fault. A more precise approach can be utilised to capture this feature accurately. However, the current method provides a satisfactory analysis for this study.

It would be interesting to investigate the thickness trends around the Hantum Fault in the M-blocks further in part 2 and 3 (Fig. 23). For this study, the time was not sufficient to fully interpret the Base Rotliegend in the whole research area, but with the interpretation of the Base Rotliegend, a thickness map of this area can be made as well. There can be determined if there is a thicker hanging wall.

To enhance the understanding of the development of the Hantum Fault, it is recommended to incorporate additional geological units in the Allan diagram, such as the Carboniferous and the Triassic. The inclusion of such units would make the structural analyses considerably more informative. In the present study, the Rijnland horizons from the TNO horizons were used. However, it should be noted that the interpretation of these horizons is not remarkably detailed. The onshore part of the Hantum Fault goes straight into another fault; it would be interesting to investigate this fault in relationship with the Rotliegend more and the Hantum Fault more.

6. Conclusions

- Based on well data there evidence found for thickening of the Upper Rotliegend around the Hantum Fault Zone in the Lauwerszee Through.
- Different Rotliegend units cannot be recognised in the studied area due to the low impedance in the seismic data.
- Based on seismic interpretation data, there is no relationship between the Hantum Fault and the thickness of the Rotliegend in the hanging wall in the offshore L blocks. Therefore there is no evidence for more sandstone reservoir in the hanging wall.
- The Hantum Fault can be divided into four parts with different tectonic histories.
- The Hantum Fault has a complex geological history. Within this history, the fault has created throw up to 1000 meters in the Rotliegend, and also, in younger units, there is still throw above the Hantum Fault, with decoupling in the Zechstein salts. This is because the position of the Hantum Fault has always been a weakness zone in the earth.
- Onshore, it is most likely that syn-tectonic thickening of Upper Rotliegend sediments in the hanging wall has occurred. However, this phenomenon has no trend towards the offshore L blocks. The offshore part of the Hantum fault is younger than the onshore part of the Hantum Fault.
- The onshore part of the Hantum Fault has a different character than the rest of the fault. This is possibly not even connected to the rest of the Hantum Fault but rather to a fault that goes straight to the north.

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I want to thank EBN for giving me the opportunity of doing my master's internship at an exciting and relevant company in the midst of the energy transition business. During this internship, I not only learned about the Hantum Fault and the Rotliegend thickness trends, but I also learned how it is to work at such a company, a valuable experience I can take with me.

I thank my supervisor from the University of Utrecht, Hans. Thank you for the project's structural input; it added context to the thickness variations and took the study to a higher level.

Next, I thank my supervisors at EBN, Daan, and Maazen.

Thank you, Daan, for your knowledge of the geology of the Netherlands, sometimes, it felt like I was talking to an encyclopaedia; genuinely impressive how much you know of the Netherlands' subsurface. It was really nice working together with you.

Thank you, Maazen, for your openness to questions and critical comments.

I also want to thank the rest of the exploration team: Anke, Bas, Edward, Kees, Johannes, Marloes, Merel, and Sabine for making me feel like part of the team for the last seven months. Furthermore, I would like to thank everyone on the second floor of EBN, with whom I laughed and chatted at the coffee machine when I needed a break from the seismic interpretation windows.

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