Utrecht University

Fault reactivation analysis of the Cleaver Bank High based on 3D seismic Data

Ping Chen
Student Number: 4235916

Abstract

The dominant fault trends in the southern part of Dutch offshore are NW-SE and NE-SW, which formed during the Paleozoic. During post-Carboniferous tectonic phases, only few new faults formed at Rotliegend level, but the pre-existing basement faults were reactivated repeatedly and penetrated into Rotliegend sediments. Under different tectonic regime and stress direction, different trends of basement faults were reactivated from different angles. The high quality of 3D Seismic data allows for an improved fault analysis in Cleaver Bank High, which is located in the central part of Dutch offshore. Five distinct fault trends were recognized at Base Zechstein level, including NW-SE, NNW-SSE, WNW-ESE, NE-SW and N-S. This study determined when the faults were reactivated since the Permian, and found oblique reactivation on pre-existing faults in the study area. This information leads to a better understanding on the structural development. Reactivation of old faults resulted in the formation of new petroleum traps or the destruction of originally exited ones. So the improved understanding of the fault reactivation also helps to decrease the risk of petroleum exploration.

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1. Introduction

The basement of the Netherlands are represent by two separate provinces, namely the Gondwana-derived Avalonia, including the London-Brabant Massif, in the south, and the Caledonian basement in the north (De Jager, 2007). The NW-SE trending faults, which are dominant in the southern half of the Dutch subsurface (Fig.1), may be related to the suture between these two provinces (Coward, 1993; Hollywood and Whorlow, 1993). Although the earliest proved movements along the NW-SE trending faults is in Late Carboniferous times, related to the Variscan Orogeney (Fig.2; Corfield et al., 1996; Ziegler, 1990), this trend could already exist during mid-Paleozoic. The second most common fault trend in the Dutch subsurface is NE-SW. The first evidence for activity of NE-SW trend was found to be in the Variscan phases during Late Carboniferous (Ziegler, 1990). Together with the NW-SE faults, they controlled the sedimentation during Late Carboniferous, when the broad thermal subsidence of the North Sea occurred following the final stage of the Variscan Orogeny (Ziegler, 1990). Both NW-SE and NE-SW faults were reactivated repeatedly after the Permian and penetrated into Rotliegend deposits. Under different tectonic regime and stress direction, different trends of basement faults were reactivated from different angles. Oblique reactivation of old basement faults was recognized in the Southern North Sea (Fig.2; Glennie, 1986; Gibbs, 1986; Corfield et al., 1996). Reactivation of old faults resulted in the formation of new petroleum traps or the destruction of originally exited ones. So a better understanding on the fault reactivation is also significant for petroleum prospect assessment. The aim of this paper is to study the fault patterns and reactivation period and movement sense of each fault trend, to help to unravel the post-Permian tectonic framework.

Recently, a similar analysis at Base Rotliegend level was carried out for the northern Dutch offshore by EBN (Ter Borgh et al., 2016; Fig.3). For this study, I focused on the Cleaver Bank High (Fig.3), located south of the EBN study area and north of the Broad Fourteens Basin. Compared to the area of the EBN study, this area is stronger influenced by WNW-ESE trending reverse faults which were reversed during the Paleogene (Laramide and Pyrenean inversion phases). In this area, a fault analysis already exists at Upper Carboniferous level (Schroot & De Haan, 2003; Fig.5). Schroot and De Haan (2003) compared the fault offsets at intra-Carboniferous level and Base Permian level, and deducted which faults were reactivated since the Permian.

This study focused on the fault network at Base Zechstein level, which is below salt and thus was not decoupled by salt from the older basement faults. These faults have accommodated most of the movements in post-Permian tectonic phases. This study also integrated the seismic data above the salt, including depth map of the base of Triassic and Paleogene sediments, to help understanding the local structural evolution. By studying the structural evolution locally, the possible periods for fault reactivation were determined. By comparing the fault offsets at Base Permian level and Base Zechstein level, faults reactivated during the Permian could be distinguished from those reactivated after the Permian. When a fault has an offset at Base Zechstein level equal to Base Permian level, this fault should be reactivated after the Permian.

Oblique-slip faults could be recognized when they are offsetting other faults. Sandbox experiments show that oblique-slip along the pre-salt structural grain could result in the development of reverse faults and extensional grabens in the post-salt sequence (Oudmayer & de Jager, 1993), which also helps for recognizing oblique-slip faults.

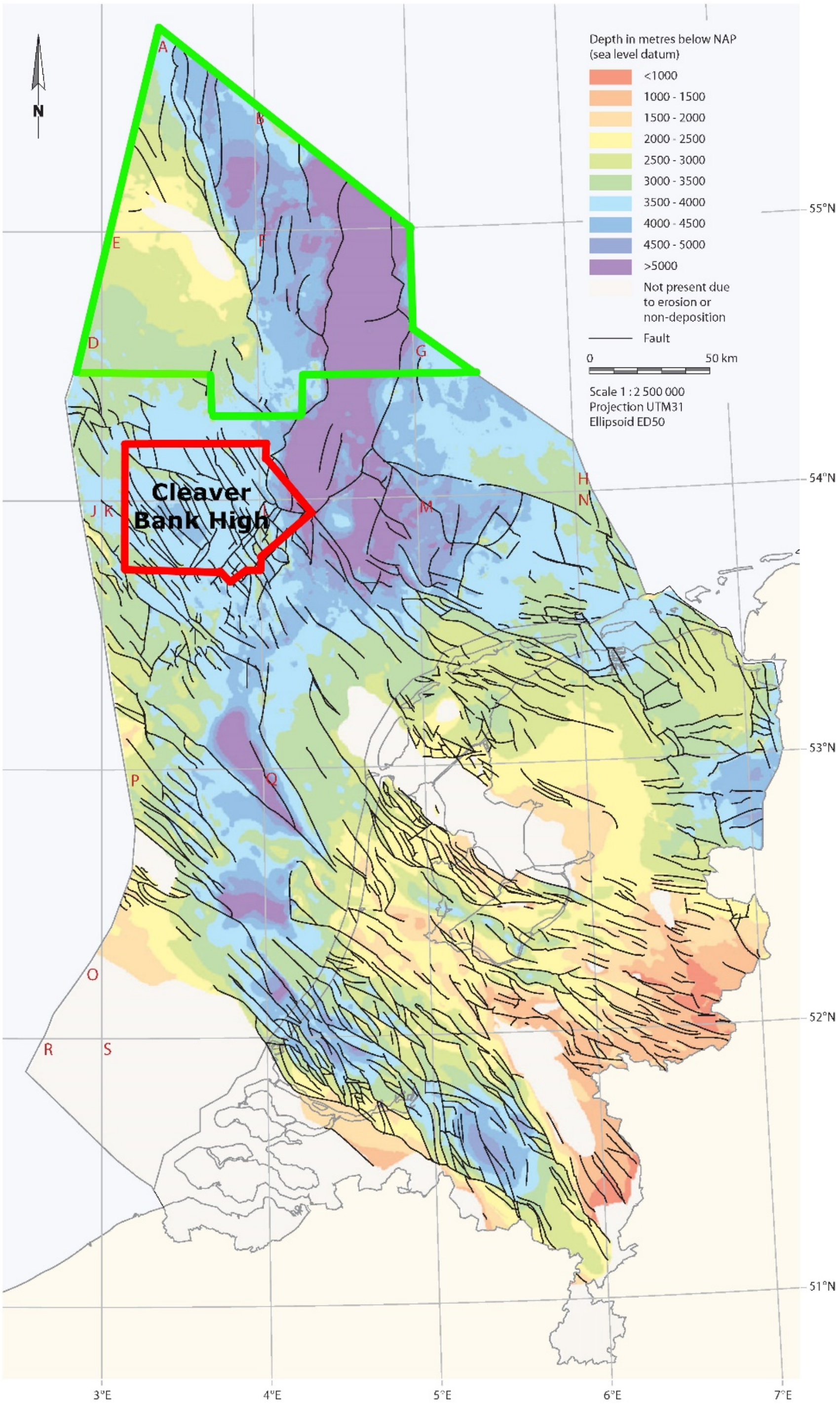

Figure 1. Depth map of the base of the Zechstein Group with general fault information (Duin et al., 2006). Red polygon indicates the location of the study area and green polygon indicates that of the EBN study.

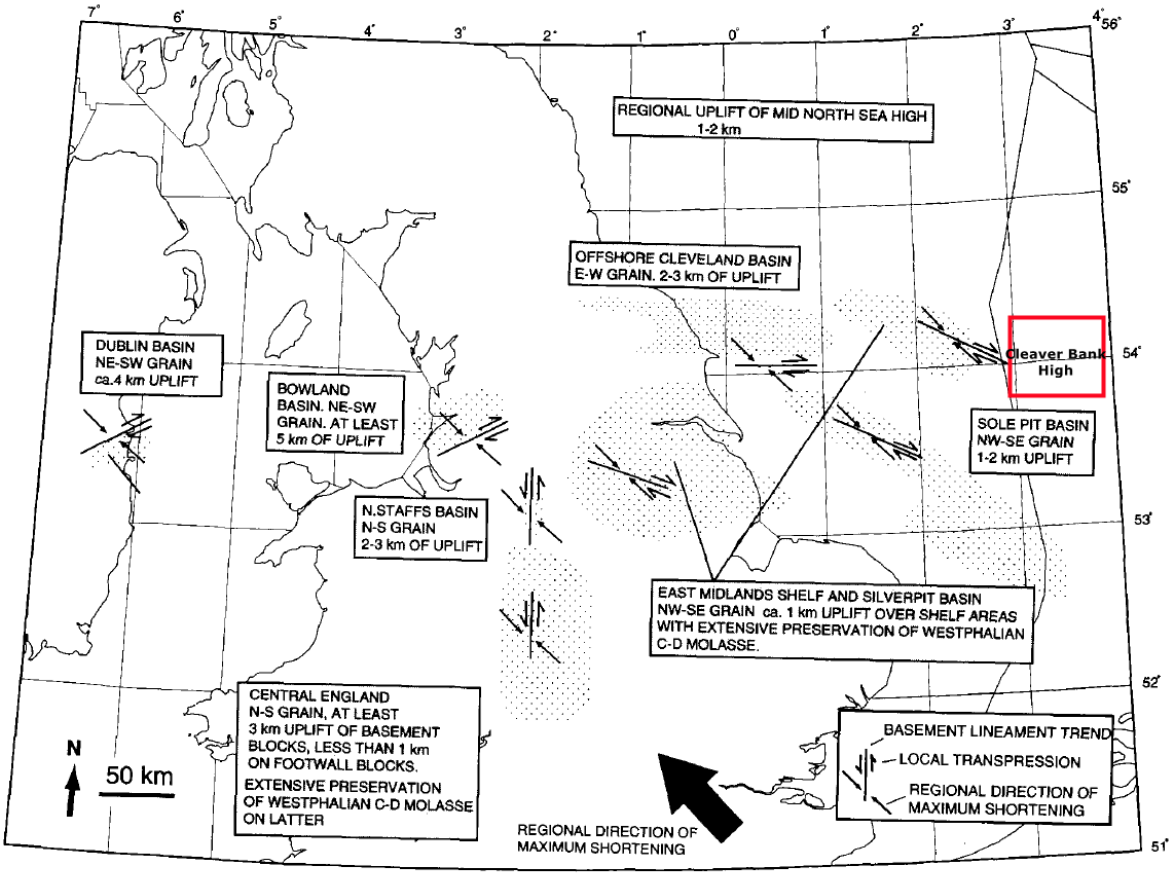

Fig. 13. Summary map illustrating the variation in the amount of tectonic uplift and transpression relative to the regional direction of maximum shortening for inversion on the Variscan foreland.

Figure 2. Summary map illustrating the variation in the amount of tectonic uplift and transpression relative to the regional direction of maximum shortening for the inversion on the Variscan foreland (Corfield et al., 1996). Red rectangle indicates the location of the Cleaver Bank High. The NW-SE faults in the Cleaver Bank High was oblique reactivated during the Late Carboniferous.

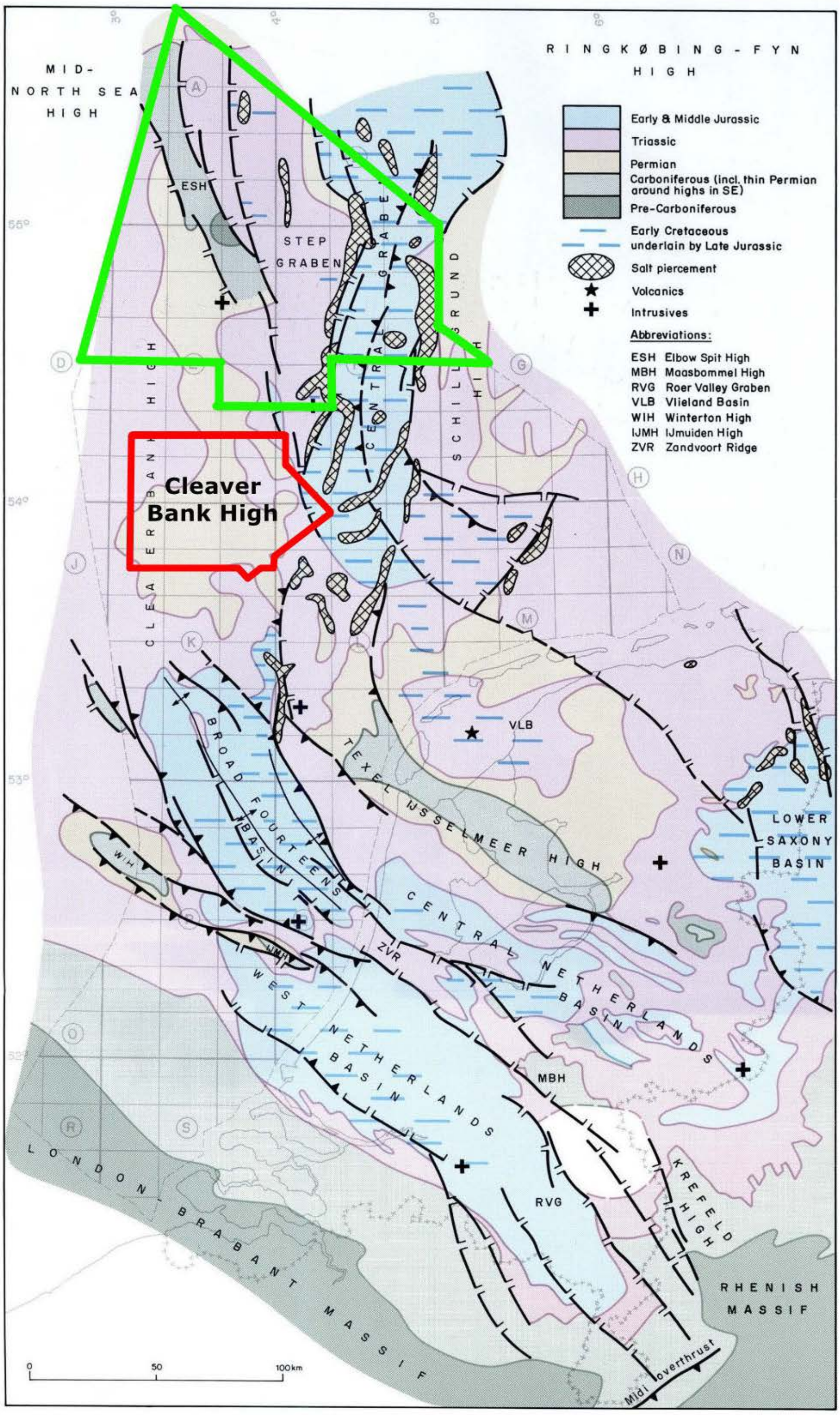

Figure 3. Geological map of the pre-Cretaceous including the Late Jurassic of the Netherlands. (Van Wijhe, 1987). Red polygon indicates the location of the study area and green polygon indicates that of the EBN study.

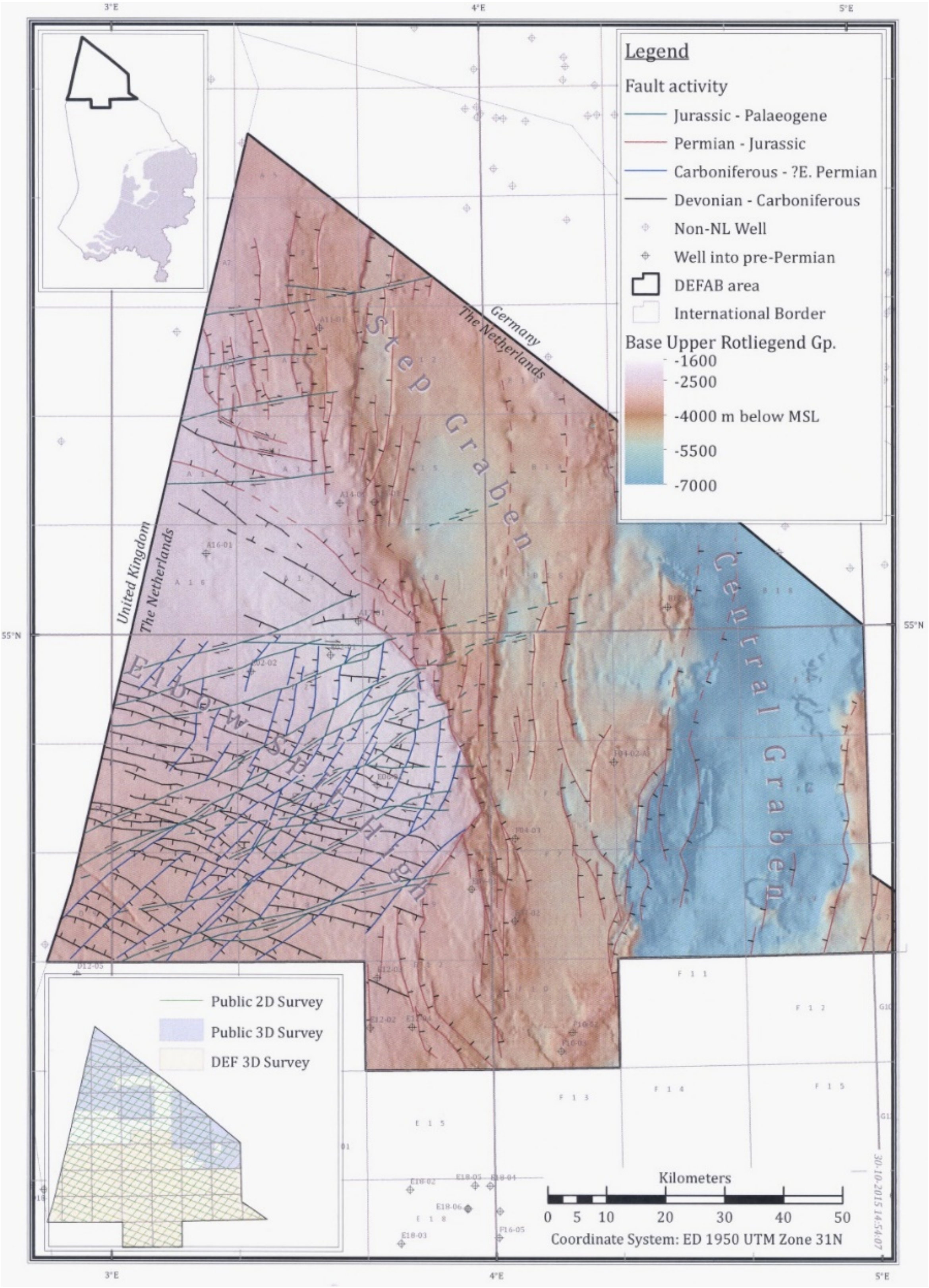

Figure 4. Fault interpretation in Dutch northern offshore in the depth map of the base of Upper Rotliegend Group. Location is also indicated in Fig.1 (Ter Borgh, 2016)

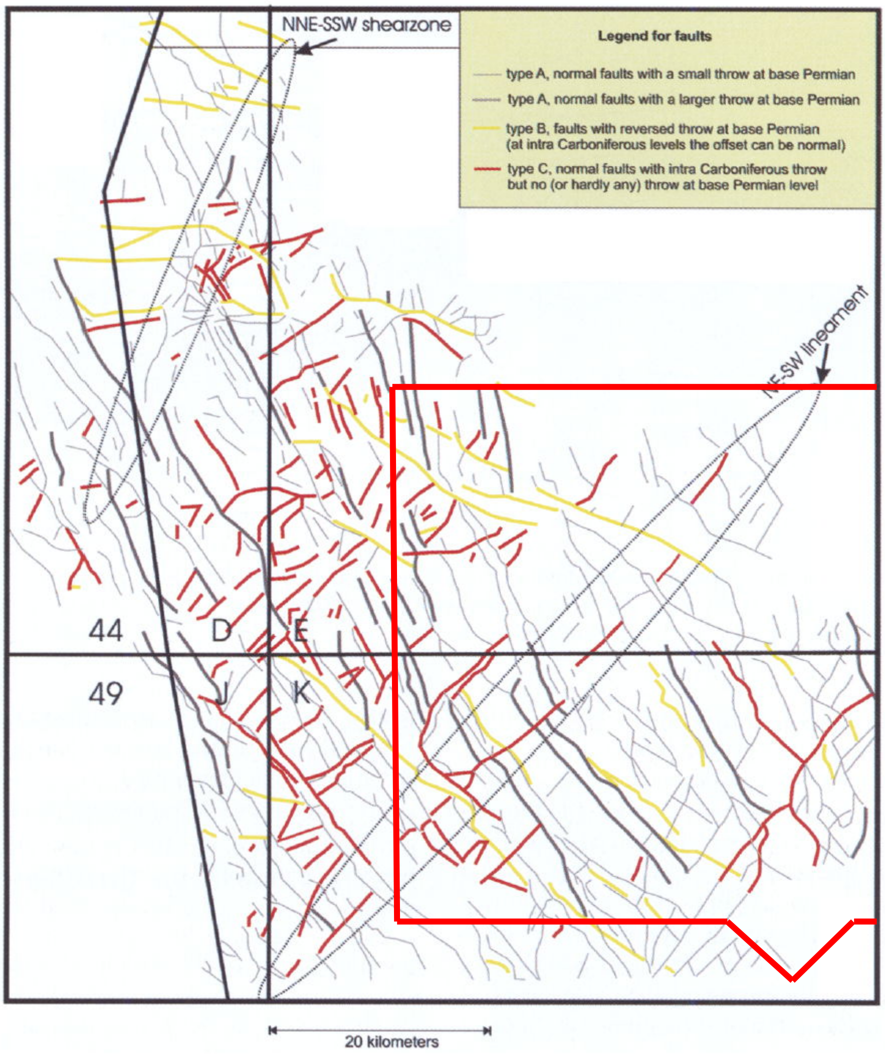

Figure 5. Fault map with the faults at intra-Carboniferous level (Schroot & De Haan, 2003). Red polygon indicates the area within the research area.

2. Geological Setting

The North Sea has experienced multiple tectonic phases since the Carboniferous including Variscan orogeny phases (during the Carboniferous and Permian), Kimmerian rifting phase (during the Late Triassic and Jurassic), and Alpine inversion phases (during the Late Cretaceous and Tertiary) (Fig.6).

The Variscan Orogeny occurred from the Carboniferous to the Early Permian. During the Early Carboniferous, the Rheno-Hercynian Ocean floor was subducted southwards beneath the mid-European terranes (Gondwana-derived microcontinents), which led to the formation of the Variscan Mountains (Franke, 2000). The compressional tectonics was replaced by broad thermal subsidence from Westphalian in the final stage of the Variscan Orogeny (Ziegler, 1990). The sedimentation was fault-controlled predominantly by NW–SE trending faults during the Late Carboniferous (Ziegler, 1990).

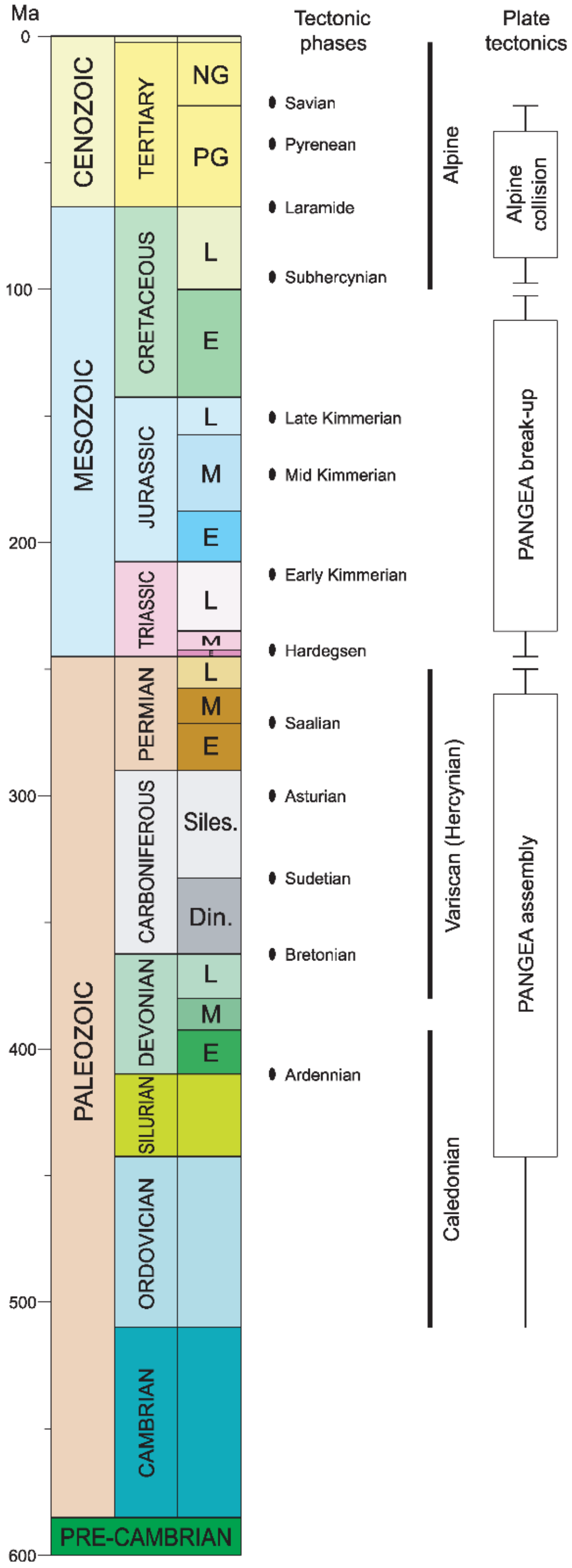

Figure 6. Tectonic phases in the North Sea and their relation to plate-tectonic events (De Jager, 2007).

The Cleaver Bank High (CBH) was developed in the Variscan foreland during the Permo-Carboniferous wrench tectonics (Fig.7) (Ziegler, 1990). The principal horizontal compressional stress-axis rotated from a northerly direction to an east-west direction during the Stephanian and Autunian (Ziegler, 1990). Right-lateral shears were recognized regionally (Ziegler, 1990).

The deposition of the Permian sediments followed the Variscan orogeny. During the Early Permian, rifting events occurred leading to extension, uplift and igneous activity (Ziegler, 1990). Late Carboniferous and Early Permian sediments were absent due to erosion or non-deposition, and the Upper Rotliegend overlies Namurian to Stephanian deposits in most areas of the North Sea (Geluk, 2007). The hiatus is an amalgamation of several unconformities into a single mega-unconformity (Glennie, 2009), which is called Base Permian Unconformity (Geluk, 2005). The Southern Permian Basin developed due to the Late Rotliegend thermal subsidence of the lithosphere north of the Variscan Mountain belt after rifting ceased (Geluk, 2005). Upper Rotliegend sediments were deposited under continental conditions during the Permian in the Southern Permian Basin (Gast et al., 2010).

The Kimmerian rifting is related to the Mesozoic break-up of the Pangea supercontinent (De Jager, 2007). An eastern branch of crustal extension propagated during the Early Triassic into the North Sea area (Ziegler, 1988, 1990). Continued extension in the western rift branch resulted in continental breakup and the opening of the Central Atlantic Ocean during the Middle Jurassic (Ziegler, 1988, 1990). The rifting in the North Sea didn't cease until the end of Early Cretaceous (Ziegler, 1988, 1990).

The Alpine orogenic system developed during the Late Cretaceous, when Africa-Arabia began to converge with Eurasia and the Tethys system of oceanic basins started to close (Ziegler, 1990). Inversion-related uplift of the basins resulted in depositional thinning and erosion of the Upper Cretaceous chalk and Lower Tertiary clastics (De Jager, 2007). The uplift was a continuous process, albeit with several acceleration pulses. These pulses seem to have been simultaneous in most inverted basins (De Jager, 2003): the Subhercynian inversion pulse (the Late Cretaceous), the Laramide inversion pulse (the Paleocene), the Pyrenean inversion pulse (end of the Eocene) and the Savian inversion pulse (end of the Oligocene) (Fig.6; De Jager, 2007).

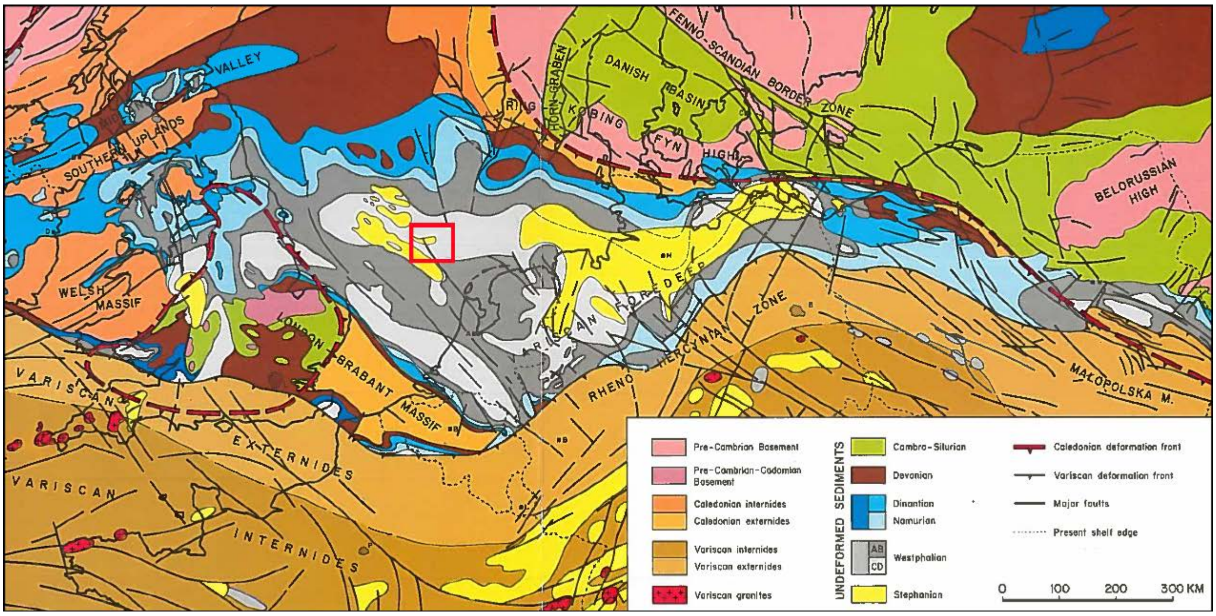

Figure 7. Pre-Permian Geological Map of Western and Central Europe (Ziegler, 1990). Red rectangle indicated the location of the study area.

3. Structural development and stratigraphy of the Cleaver Bank High

The Cleaver Bank High is an area which developed due to Permo-Carboniferous wrench tectonics and has undergone a uniform structural and sedimentological history since then. The most important tectonic phases for Cleaver Bank High after Carboniferous includes the Kimmerian rifting phase from the Late Triassic to the Jurassic, and the Pyrenean and Savian pulses during the Paleogene related to the Alpine inversion.

During the Late Carboniferous, the broad thermal subsidence of the North Sea occurred following the final stage of the Variscan Orogeny. Resulting from the long-term Late Carboniferous subsidence, the top Carboniferous strata are very thick in the Cleaver Bank High (Quirk, 1993). At the end of the Stephanian, more than 1000 m of the Coal Measures sequence were removed by erosion in places on the Cleaver Bank High, leading to the formation of Base Permian Unconformity (Quirk, 1993).

As seen in the thickness map of the Zechstein Group (Fig.8), the Zechstein salt is relatively thin and consistent in the Southeast area of the Cleaver Bank High, while there are many salt domes in the Northwest part. Since the Paleogene Lower North Sea Group was affected by the salt movement as shown in Fig. 9, we could know that the latest salt movement in this area occurred during the Paleogene (Pyrenean and Savian inversion phases).

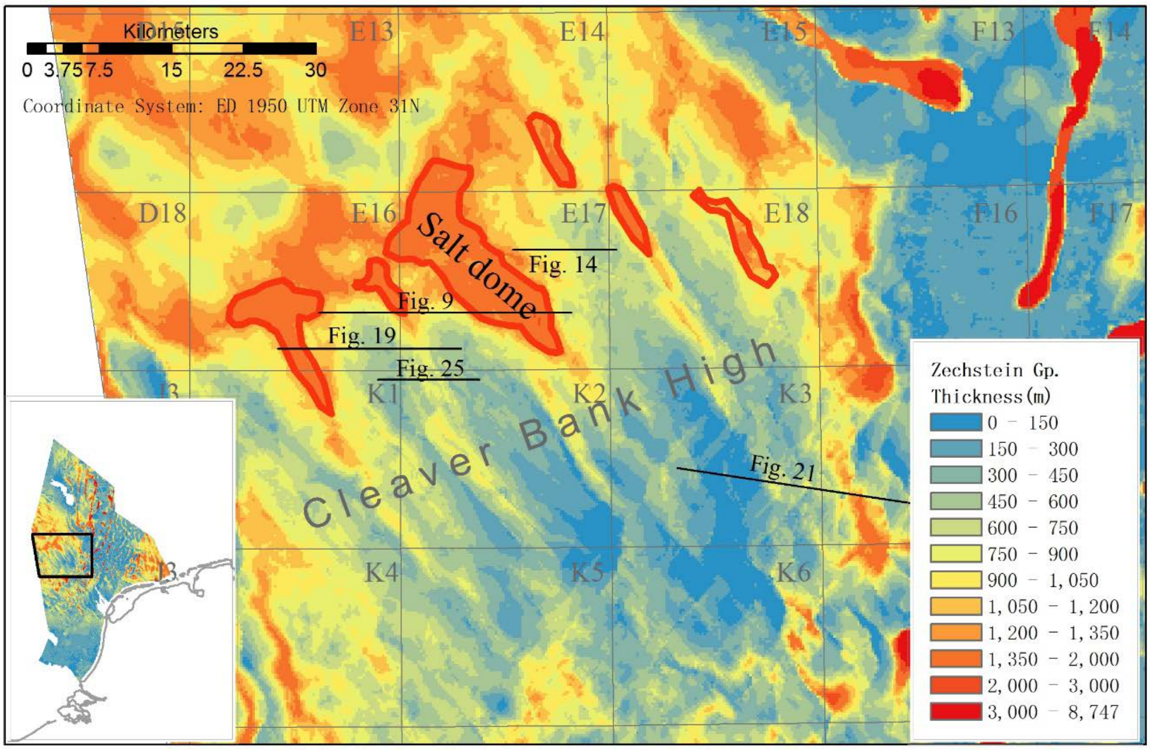

Figure 8. Thickness map of the Zechstein Group. Red Polygon indicates the position of salt domes. (Thickness data source: www.nlog.nl)

During the Middle Jurassic (the Mid Kimmerian phase), most of the Jurassic and Triassic sediments in the Cleaver Bank High were removed by local uplift and subsequent erosion (Duin et al., 2006). The Jurassic deposits are entirely absent here, and the Triassic deposits are only preserved in the northwestern and southeastern part of the Cleaver Bank High area (Fig.10).

Alpine inversion phases have affected the Cleaver Bank High area since the Paleogene. The consistent thickness of the upper Cretaceous Chalk Group in the seismic section (Fig.9) suggests that this area is hardly influenced by the Late Cretaceous Subhercynian pulse during the Alpine inversion. The most important inversion tectonic movements in the Cleaver Bank High are the Mid Paleogene Pyrenean and Late Paleogene Savian pulses. It is suggested by Apatite fission track analysis that the Cleaver Bank High was uplifted during the Mid Paleogene (Pyrenean) (Alberts & Underhill, 1991). And the clear angular unconformity between the Paleogene Lower North Sea Group and the Neogene Upper North Sea Group throughout the Cleaver Bank High area suggests that this area is strongly influenced by the Late Paleogene Savian inversion pulse. The Chalk Group was folded due to the Paleogene inversion phases in this area.

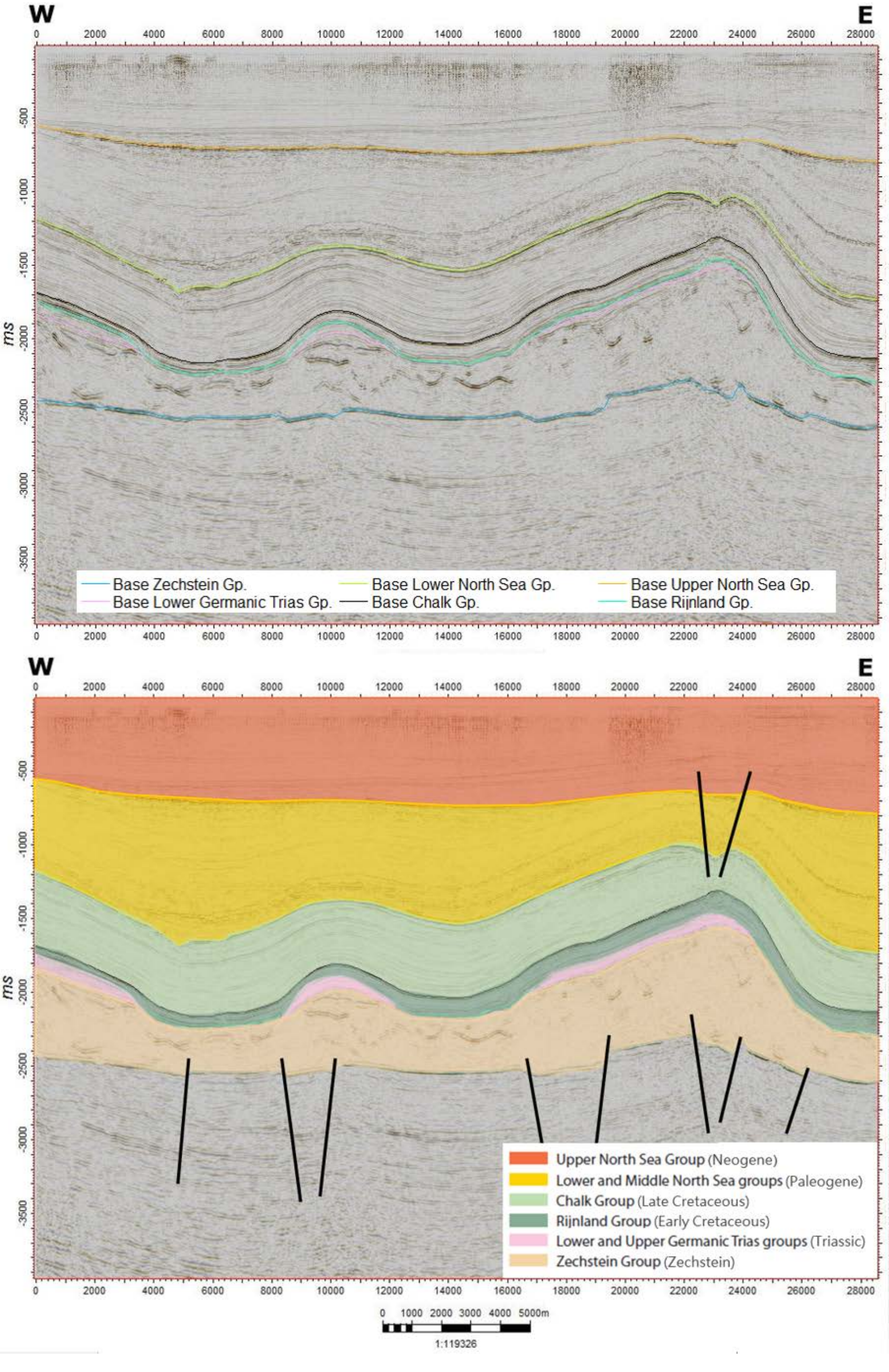

Figure 9. Seismic Section (Location is shown in Fig.8, Fig.10, Fig.17, Fig.18). The Chalk and Rijnland Group are strongly folded. The salt domes and the preserved Lower Germanic Trias Group locate below the peaks of the folds.

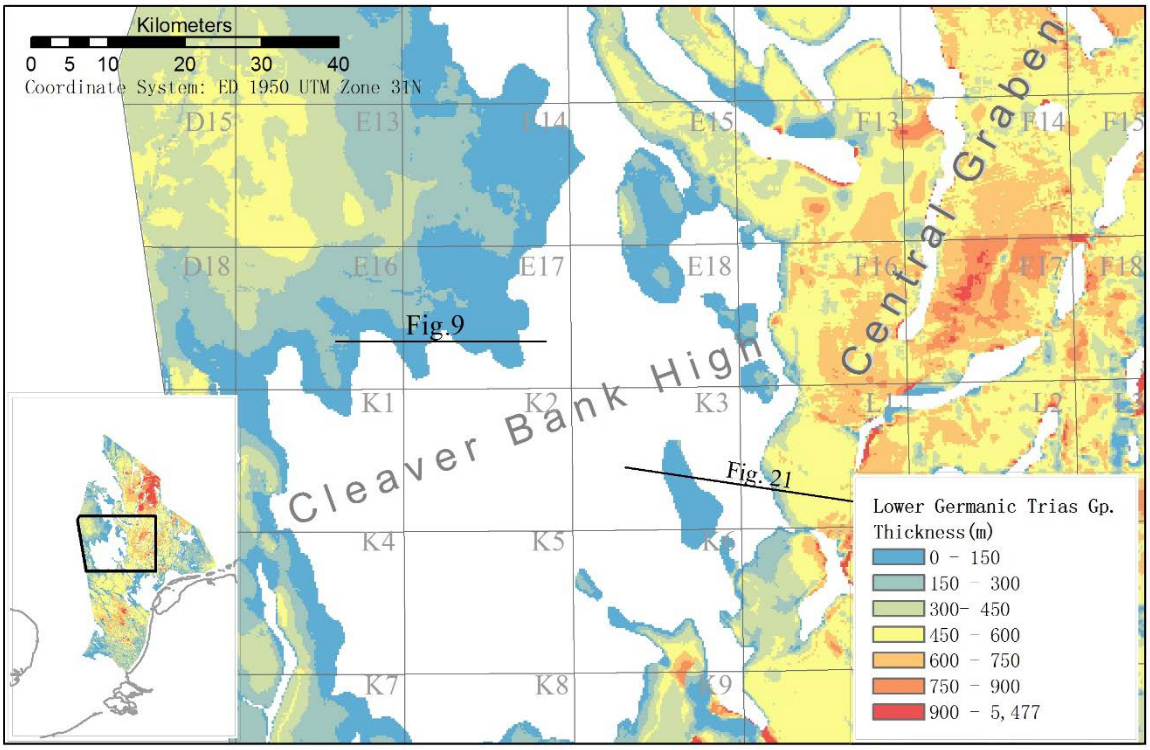

Figure 10. Thickness map of Lower Germanic Trias Group. (Thickness data source: www.nlog.nl).

4. Data and Methodology

4.1 Data

We utilized 3D seismic data from the DINO database to analyze the fault network. The DINO database contains over 135 3D seismic surveys covering around 99.900 km^2, more than 577.000 km 2D seismic lines (analogous & digital lines), and around 5800 non-confidential wells. This study used the public 3D seismic surveys in the Cleaver Bank Area shown in Fig.11b, which was acquired by NAM, PGS and Wintershall during the period 1991–2003. The seismic coverage and the study area is shown in Fig. 11a. The seismic survey in the study area is a high-quality dataset. The database allows an interpretation of the Late Paleozoic (from the Late Carboniferous to the Permian), Mesozoic and Cenozoic successions.

This studies also used the seismic horizons from the v3.0 version of the Digital Geological Model-deep (DGM-deep), which is a regional subsurface layer model covering both the onshore and offshore of the Netherlands. The modelling process was constrained by all publicly free 3D-surveys and 1305 wells from the DINO database. The well locations are shown in Fig.11a. The data is public and was downloaded from the NL Oil and Gas Portal site (www.nlog.nl).

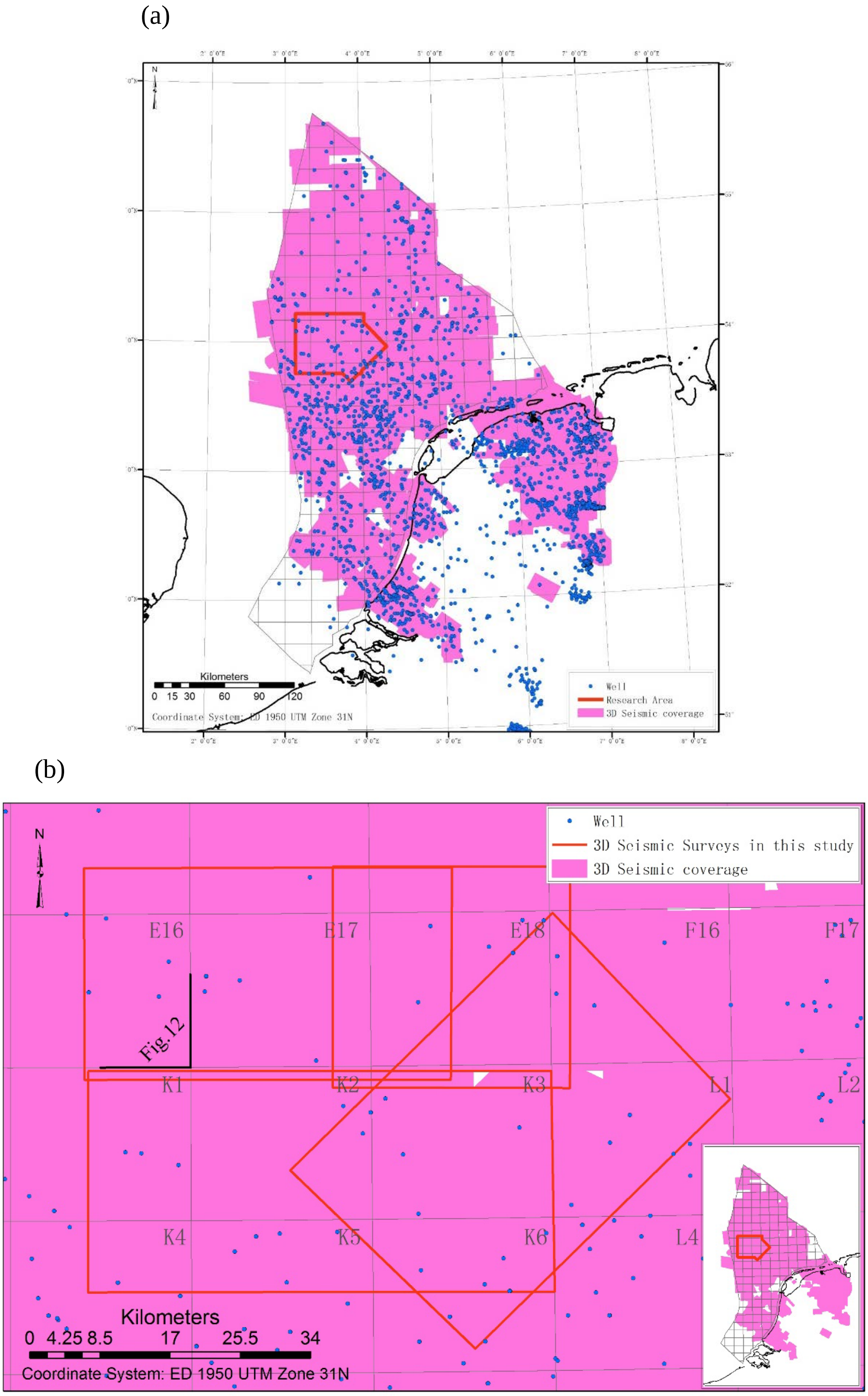

Figure 11. (a) The seismic coverage and well locations of the DINO database, (b) The seismic surveys used in this study (Data Source: www.nlog.nl).

4.2 Quality Control of Data

As shown in Fig.11, this study utilized seismic data from four different seismic surveys. Different seismic surveys have different data phase and polarity. Fig.12 shows the comparison between two intersecting seismic sections from different seismic surveys in study area. As shown in the Fig.12a, the top of Chalk Group is displayed as a blue line in the left section, while it is displayed as a blue-over-red line in the right section. The difference in the data phase resulted in the different display of the same layer in different seismic surveys. And there is a difference of the depth of the same layer between the two sections (Fig.12a), which result in the inconsistency of the 3D seismic data in study area. So quality control is required to vanish the difference before interpreting the data. For this study, the data phase of all the surveys was adjusted to the zero phase of European Polarity. As shown in the Fig.12b, the base of salt is displayed as a blue-over-red line in both the seismic sections after quality control. And a vertical shift was applied to set the depth of the same layer consistent in different seismic surveys.

The key and the first step of assessing seismic data phase and polarity is to identify high-amplitude reflections and to understand their geologic cause. Reflections are generated by acoustic-impedance contrasts, and thus high-amplitude reflections result from large contrasts.

The Seismic data in this study is encoded in the SEGY format. The data is displayed with a balanced double-gradational color scheme using red for positive amplitude and blue for negative amplitude. So the impedance increase is displayed as blue, and impedance decrease is displayed as red.

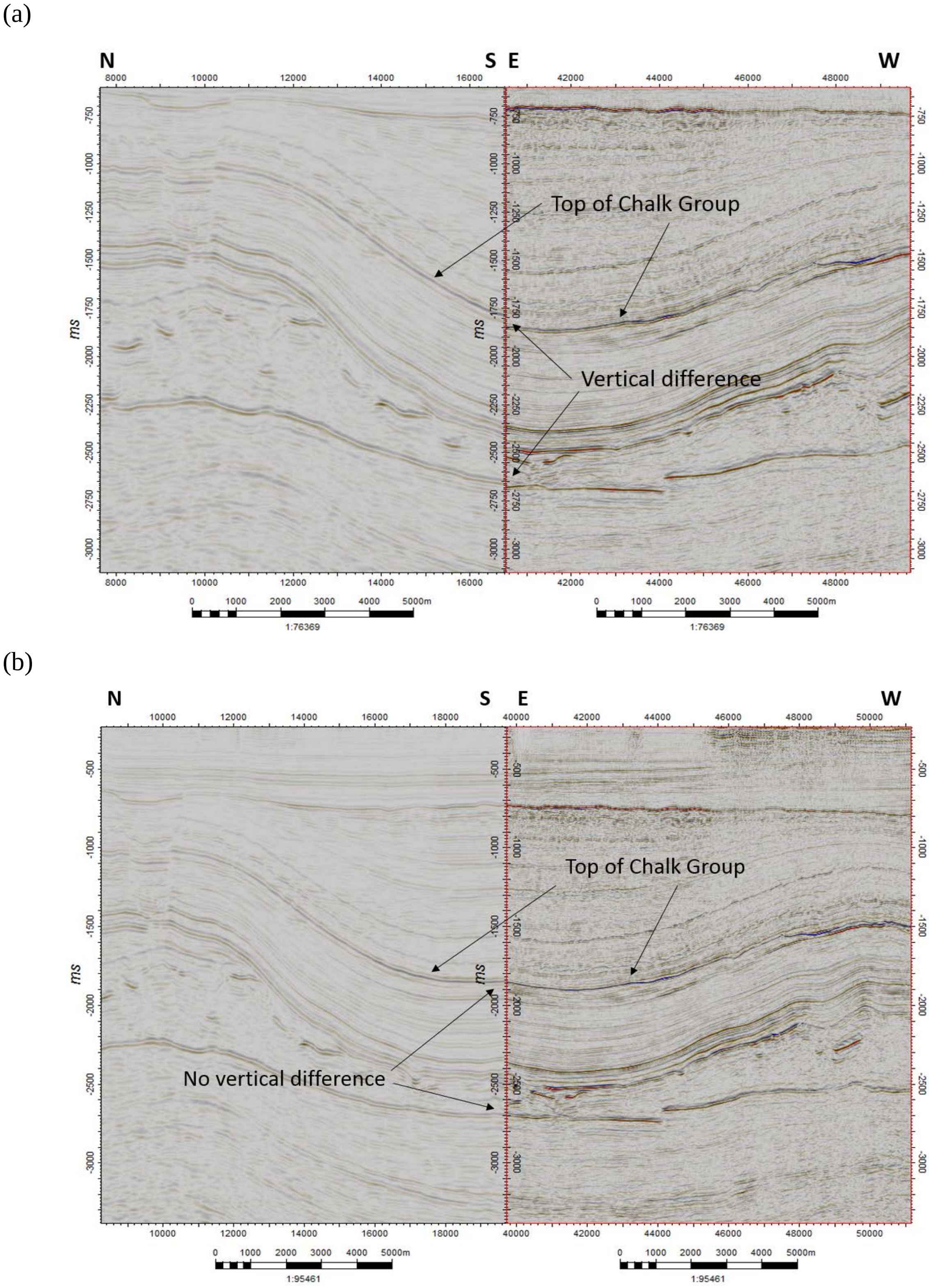

Figure 12. Comparison between two intersecting seismic sections from different seismic surveys (location is shown in Fig.11). (a) Seismic sections before quality control. (b) Seismic sections after quality control.

Brown (2011) concluded all the probable causes of a package of high-amplitude reflections. In the research area, the probable causes include:

Impedance Increase:
    Top of Zechstein salt
    Top of the Chalk Group
Impedance Decrease:
    Base of Zechstein salt
    Base of the Chalk Group
    Top of Westphalian coal
Low-impedance Layer:
    Floaters in Zechstein salt
High-impedance Layer:
    thin salt layer

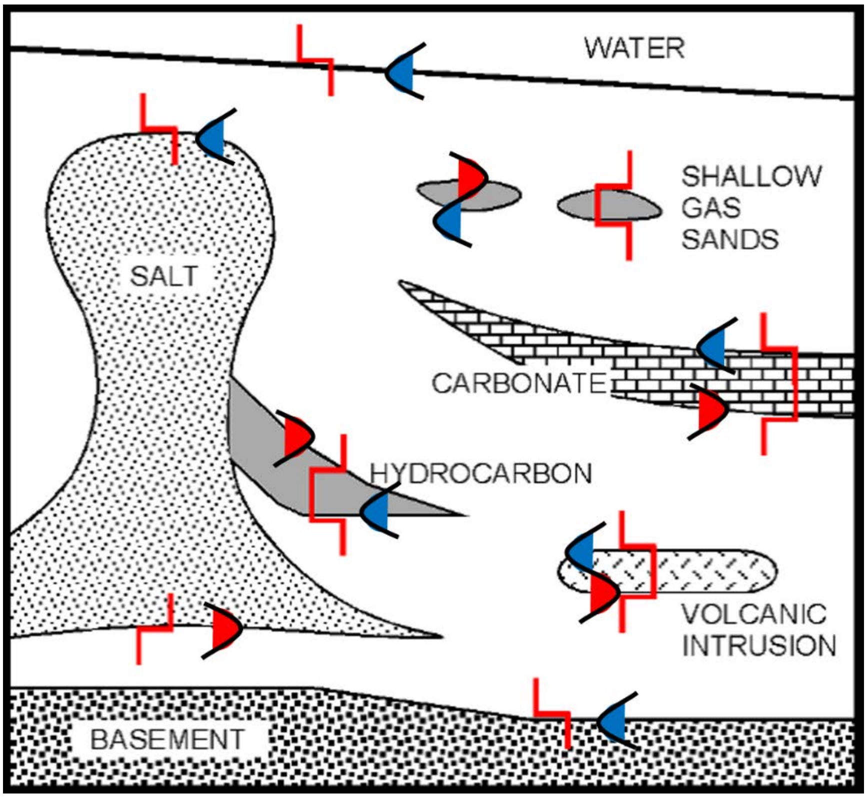

Figure 13. Probable geological cause of high-amplitude reflections (Brown, 2008). Red polyline shows the impedance change in the surfaces, and the waves show how the seismic responses of the surfaces are displayed in Petrel when the data is in the zero phase of European Polarity.

The feature that is generally the most useful is the low-impedance layer. Concerning the Seismic data in the Cleaver Bank High, the floaters in the Zechstein salt are very good indicators for the polarity, and were used for phase accessing in this research. The floaters are large slabs caused by the break-up of the anhydrite layer in the salt (Peryt et. al., 2010). They should be displayed as a blue-over-red line when the data is in the zero phase of European Polarity (Fig.14). The top of the Chalk Group was also used as a reference when it is not easy to find a clear floater in salt. It is displayed as a blue line when the data is in the zero phase of European Polarity (Fig.14).

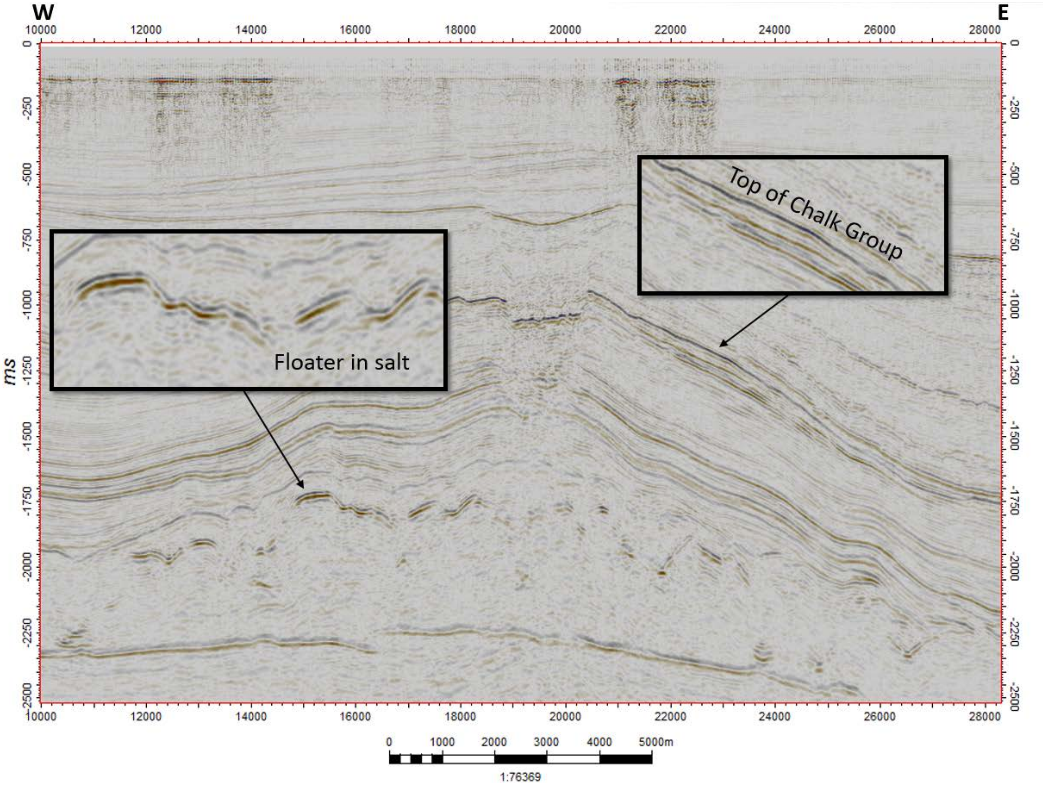

Figure 14. Seismic section in the zero phase of European Polarity after quality control (location is shown in Fig.8, Fig.17 and Fig.18). The floaters are displayed as a blue-over-red line. The top of the Chalk Group is displayed as a blue line.

4.3 Methodology

Before investigating the fault reactivation, a good understanding on the local structural development is required. By studying the structural development locally, I could determine when the normal or reverse movements occurred along the faults. This information is vital for studying the fault reactivation. So I integrated the thickness map of the Lower Germanic Triassic Group (Fig.10) and the Zechstein Group (Fig.15), and the depth map of the base of the Paleogene Lower North Sea Group (Fig.16). By comparing the folding patterns at different level, the compression period and orientation could be roughly determined, which helps to study the fault reactivation.

To study the fault reactivation, I need to map the faults at Base Zechstein level, group them based on their orientation, and look at the relationship between faults. The precise mapping of faults is the precondition of studying fault reactivation. And the relationship between faults is also very important because it helps to identify the strike-slip components along faults. It is not easy to observe the strike-slip component along faults directly in the seismic lines. But when the fault is found to be offsetting other faults, it is easy to see if there is a strike-slip component along it, as shown in Fig.15a. And an oblique-slip fault could be determined, when both a strike-slip component and a normal offset is observed along the fault.

The fault offsets are also significant information for understanding fault reactivation. When faults have reverse offset at Base Zechstein level, they are possible to be reactivated during the Late Jurassic uplift or Paleogene compression. When faults have normal offsets, they could be reactivated during the Permian, Triassic or Jurassic. By comparing the fault offsets at Base Permian level and Base Zechstein level, faults reactivated during the Permian could be distinguished from those reactivated after the Permian. When a fault has a normal offset at Base Zechstein level equal to Base Permian level, this fault should be reactivated after the Permian, as shown in Fig 15b. When it has a normal offset at Base Zechstein level different than Base Permian level, this fault should have been reactivated during the Permian, and was reactivated after the Permian again.

At last I could combine the information of the local structural development, the relationship between faults, and the fault offsets at different level, to determine when the faults were reactivated.

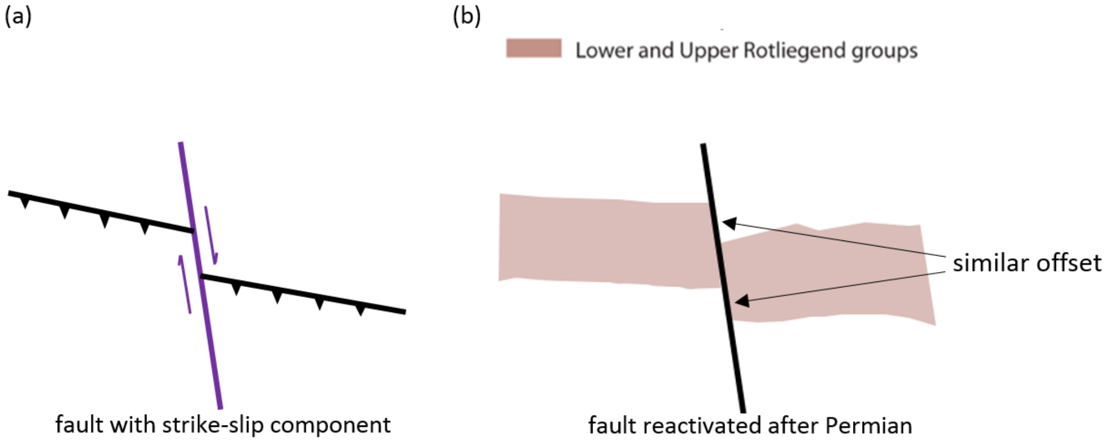

Figure 15. (a) Sketch illustrating how to identify fault with strike-slip component, (b) Sketch illustrating how to identify fault reactivated after Permian.

5. Results

5.1 Base Zechstein fault map of Cleaver Bank High

As seen in the Fig. 16, five distinct fault trends were recognized. They are NNW-SSE, NW-SE, WNW-ESE, N-S and NE-SW. All the fault trends have a very high degree of parallelism. Most of them have a normal offset at Base Zechstein level, except for the WNW-ESE reverse faults. The northwestern part of the Cleaver Bank High is predominantly controlled by:

(1) NNW-SSE faults (purple)

- Length varies from 5 to 35 km
- Normal offset up to 400 m
- Offsetting WNW-ESE faults
- Some are offset by the NE-SW faults, and some are offsetting the NE-SW faults

(2) WNW-ESE faults (black)
  - Length up to 25 km
  - Reverse offset up to 200 m
  - Offset by the NNW-SSE faults

In the southeastern part of Cleaver Bank High, there are:

(3) N-S faults (yellow)
  - Relatively short, from 2 km to 9 km
  - Normal offset from 100 m to 200 m
  - Offsetting the NE-SW faults.

(4) NE-SW (blue)
  - Most of them have a length from 5 to 15 km
  - Normal offset of up to 150 m
  - Some are offset by the NNW-SSE faults, and some are offsetting the NNW-SSE faults

(5) NW-SE (green)
  - Length up to 25 km
  - Normal offset from 50 m to 300 m

(6) NNW-SSE faults[same as (1)]

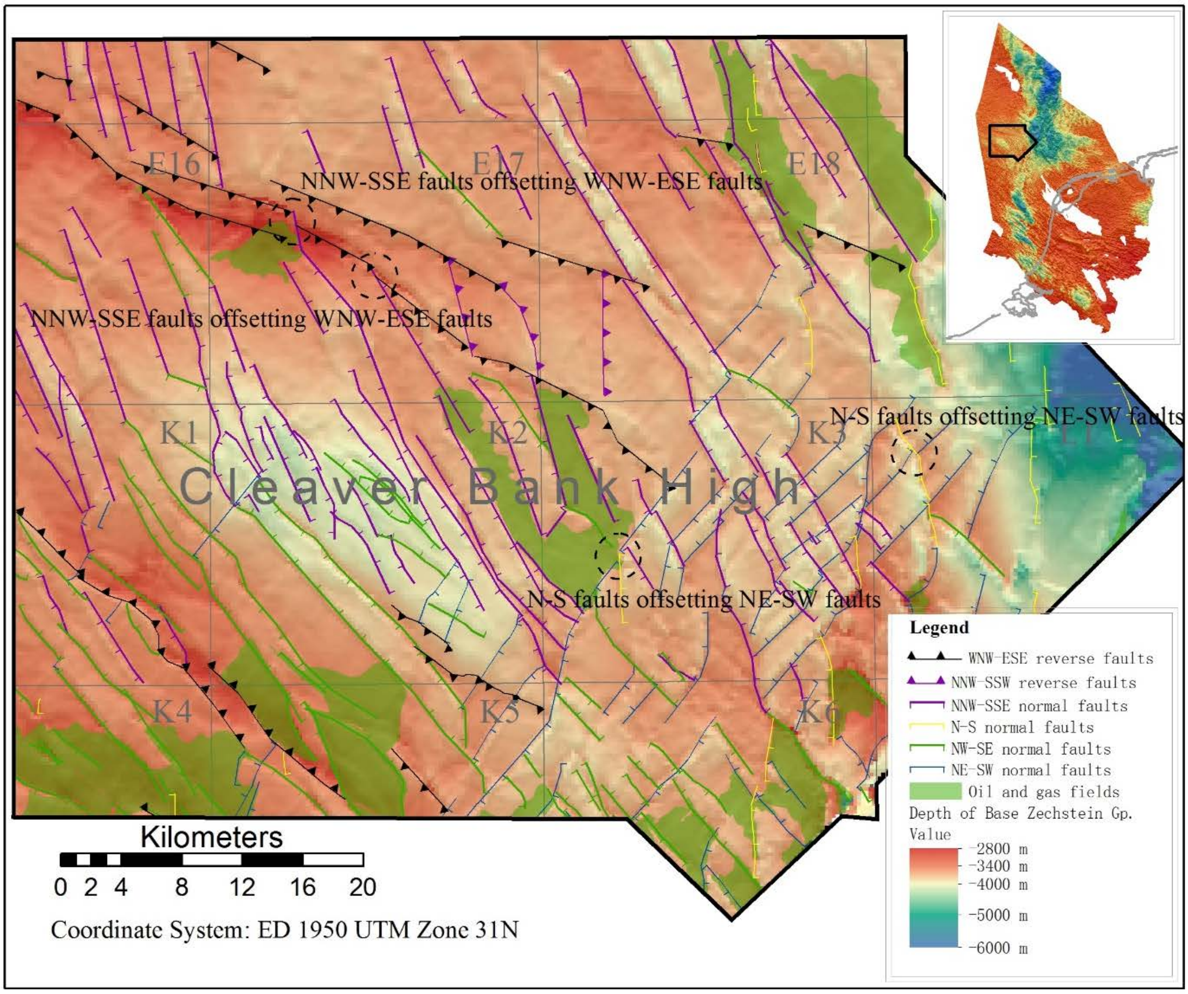

Figure 16. Fault interpretation in the Cleaver Bank High in the depth map of the base of the Zechstein Group (Depth data source: www.nlog.nl).

5.2 Reconstruction of the local Stress regime during the Paleogene

From the thickness map of the Zechstein Group (Fig.17), we can find the orientation of the salt domes to be NW-SE. From the depth map of the base of the Lower North Sea Group (the top of the Chalk Group) (Fig.18), we can see that the Chalk Group (the Late Cretaceous) was strongly folded and the folding axis is also in NW-SE orientation. The Fig.9 illustrates that the folding of the Chalk Group and the Zechstein salt domes occurred in the same period, since the shape of the top Chalk matches with the top Zechstein so well. So the compression have occurred after the Late Cretaceous, when the Chalk Group was deposited. And because the Upper North Sea Group (the Neogene) was not affected, the Chalk Group and Zechstein Group should be deformed before the Neogene. Considering all the information above, the most likely period for the deformation of the Chalk Group and Zechstein Group is the Paleogene (Laramide and Pyrenean inversion phases). Both the folding pattern of the Chalk and the orientation of the Zechstein salt domes are providing support for the interpretation that the compression axis during the Paleogene is in NE-SW direction.

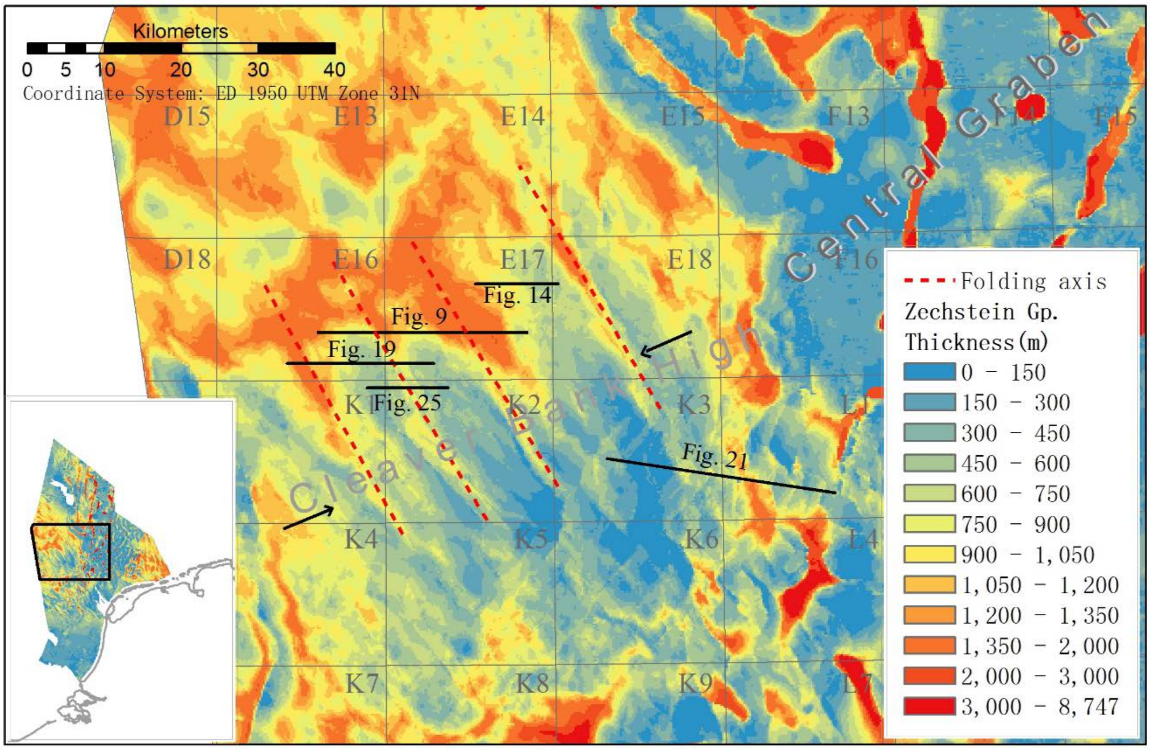

Figure 17. Thickness map of the Zechstein Group. Red dashed lines mark the folding axis of the Zechstein Group, black arrows indicate the compression orientation (Thickness data source: www.nlog.nl).

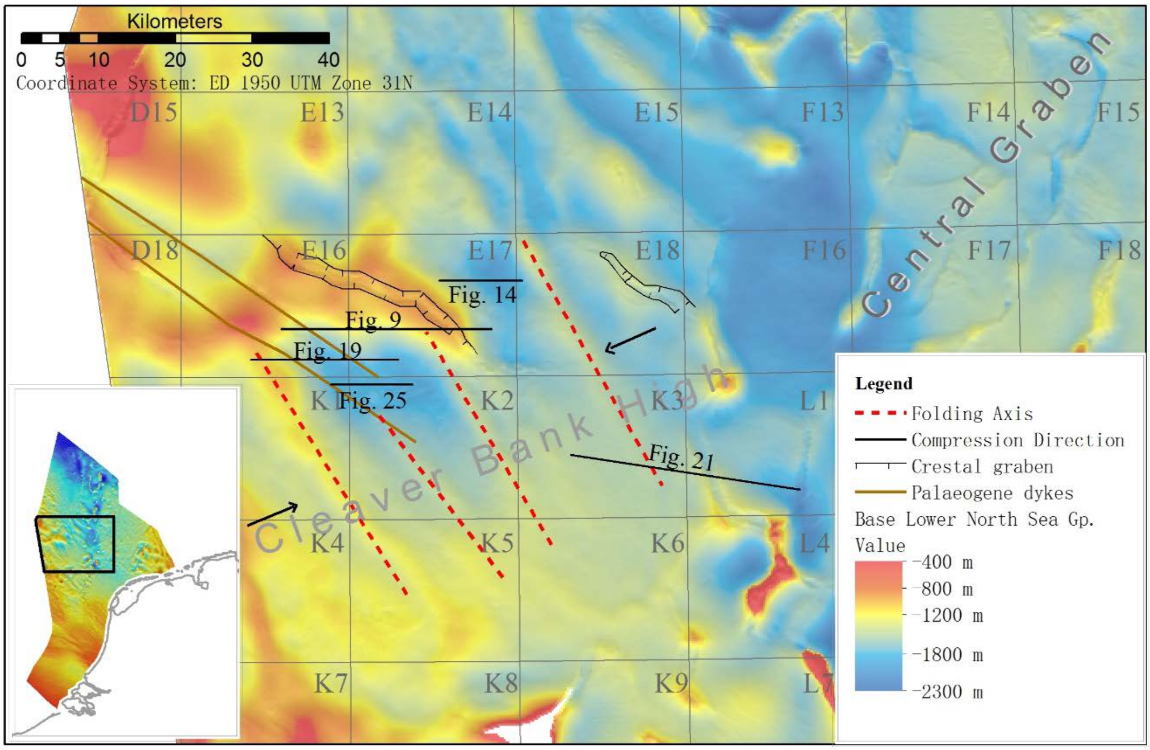

Figure 18. Depth map of the base of the North Sea Group or the top of the Chalk Group. Red dashed lines mark the folding axis of folding Chalk sediments, black arrows indicate the compression orientation (Depth data source: www.nlog.nl).

5.3 Fault reactivation interpretation

For this study, we only consider fault reactivation since the Permian. In most areas of the Cleaver Bank High, the Chalk Group and Rijnland Group are very continuous, and they have a consistent thickness, as shown in Fig. 9. It implies that this area was stable and the faults are not likely to be reactivated during the Cretaceous. The base of the Upper North Sea Group is flat in study area, and it is relatively consistent in thickness (Fig. 9). So it should be stable locally during the Neogene as well. Faults reactivated during the Permian would lead to a difference between the offset at Base Zechstein level and Base Rotliegend level. In this area, I didn’t see any fault reactivated during the Permian. So I also rule out the possibility that faults were reactivated during the Pemian. Considering the reasons above, the most possible periods for the reactivation of faults are the Triassic, Jurassic and Paleogene.

It is difficult to observe which faults were reactivated during the Triassic and Jurassic directly from the seismic sections due to the absent of the Triassic and Jurassic sediments. But we could know that faults are likely to be reactivated during this time when they have normal throws at Base Zechstein level (Fig.19), because normal throws are not likely to occur during the Paleogene compression. The normal faults at Base Zechstein level usually have a similar throw at Base Zechstein level and Base Rotliegend level. It implies that they were not active during the Permian and was reactivated during Triassic or Jurassic. These faults are included in the Fig.20. In the southeastern part of the Cleaver Bank High, there is a small area with preserved

Triassic sediments. In that area, there are two examples of NNW-SSE trending faults which were reactivated and penetrated into the Triassic sediments during the Triassic or Jurassic, as shown in the Fig.21. It further proved that the normal faults at Base Zechstein level are probably to be reactivated during the Triassic or Jurassic. The second left fault in the Fig.21 was reactivated during the Triassic or Jurassic and was reversed during Cretaceous, as it has a normal offset at Base Zechstein level but a reverse offset at Chalk level. It indicated that the faults with a normal offset at Base Zechstein level could also be reactivated during the Late Cretaceous, but the reverse offset is too small to absorb the pre-existing normal offset. The seismic section in Fig.21 located in the boundary between the Cleaver Bank High and the Dutch Central Graben, where the Chalk Group is folded. But the Chalk Group in most areas of Cleaver Bank High is consistent in thickness. So I conclude that it is not likely that the normal faults were reversed during the Cretaceous in other areas of the Cleaver Bank High.

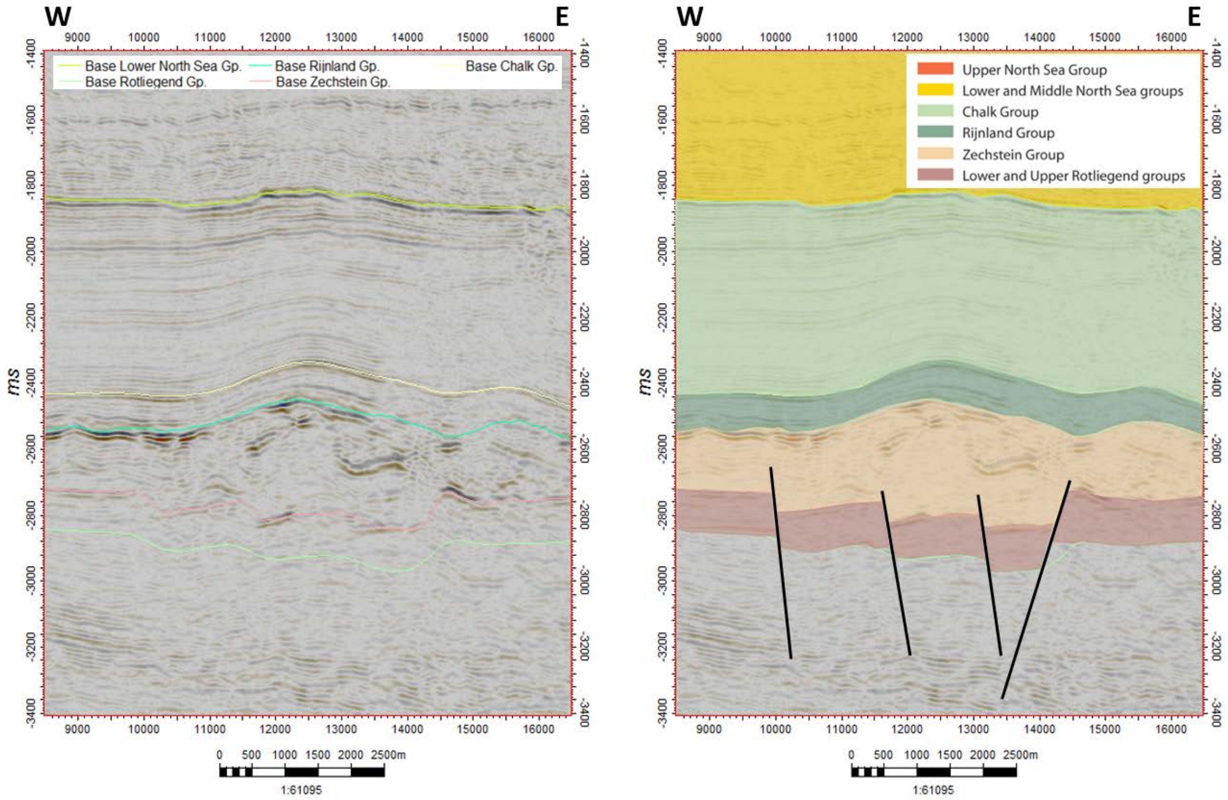

Figure 19. Seismic section shows faults reactivated during the Triassic or Early Jurassic (location is shown in Fig.8, Fig.17 and Fig.18). They have similar offsets at base Zechstein and base Permian level.

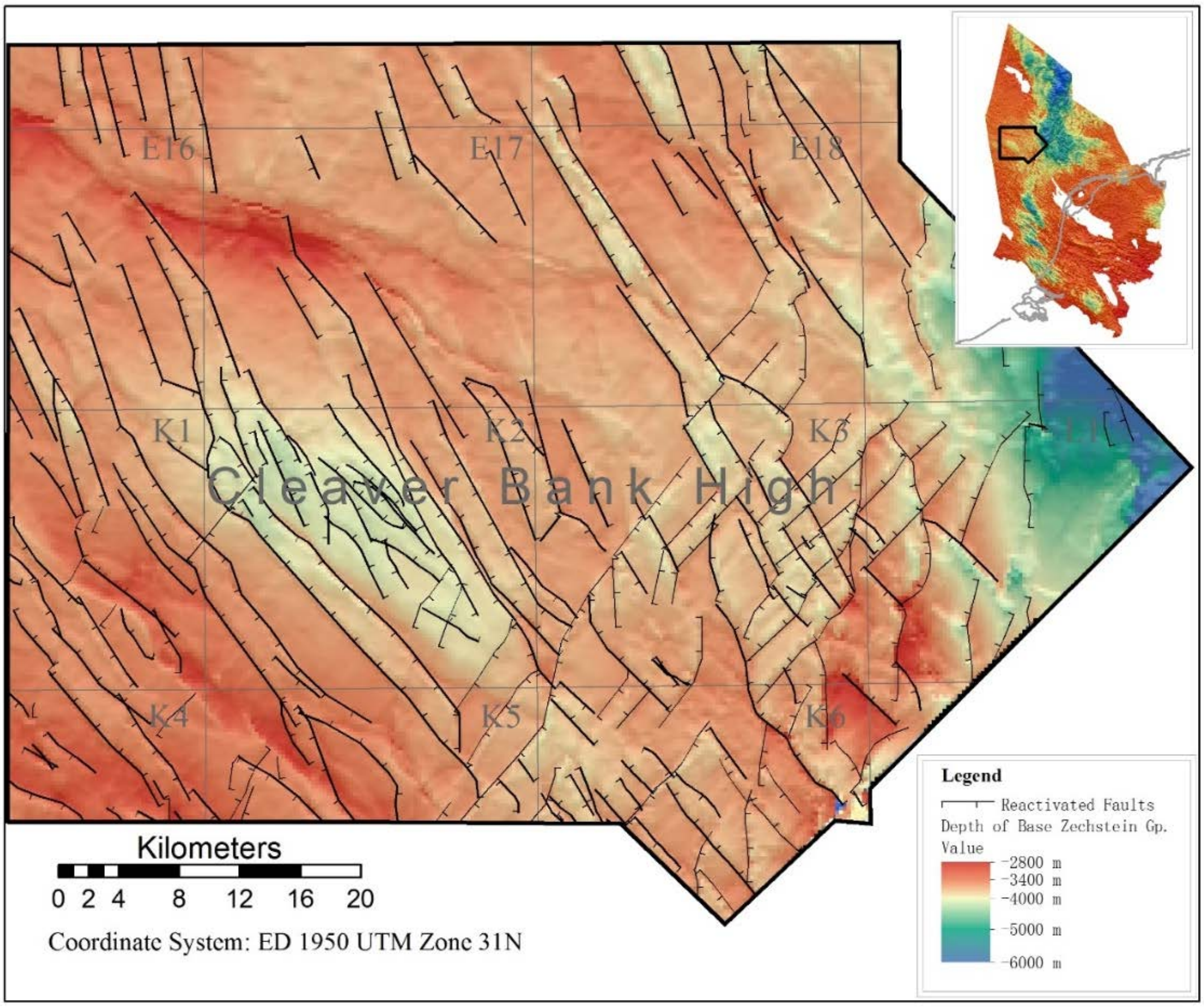

Figure 20. Faults reactivated during the Triassic and Jurassic (Depth data source: www.nlog.nl).

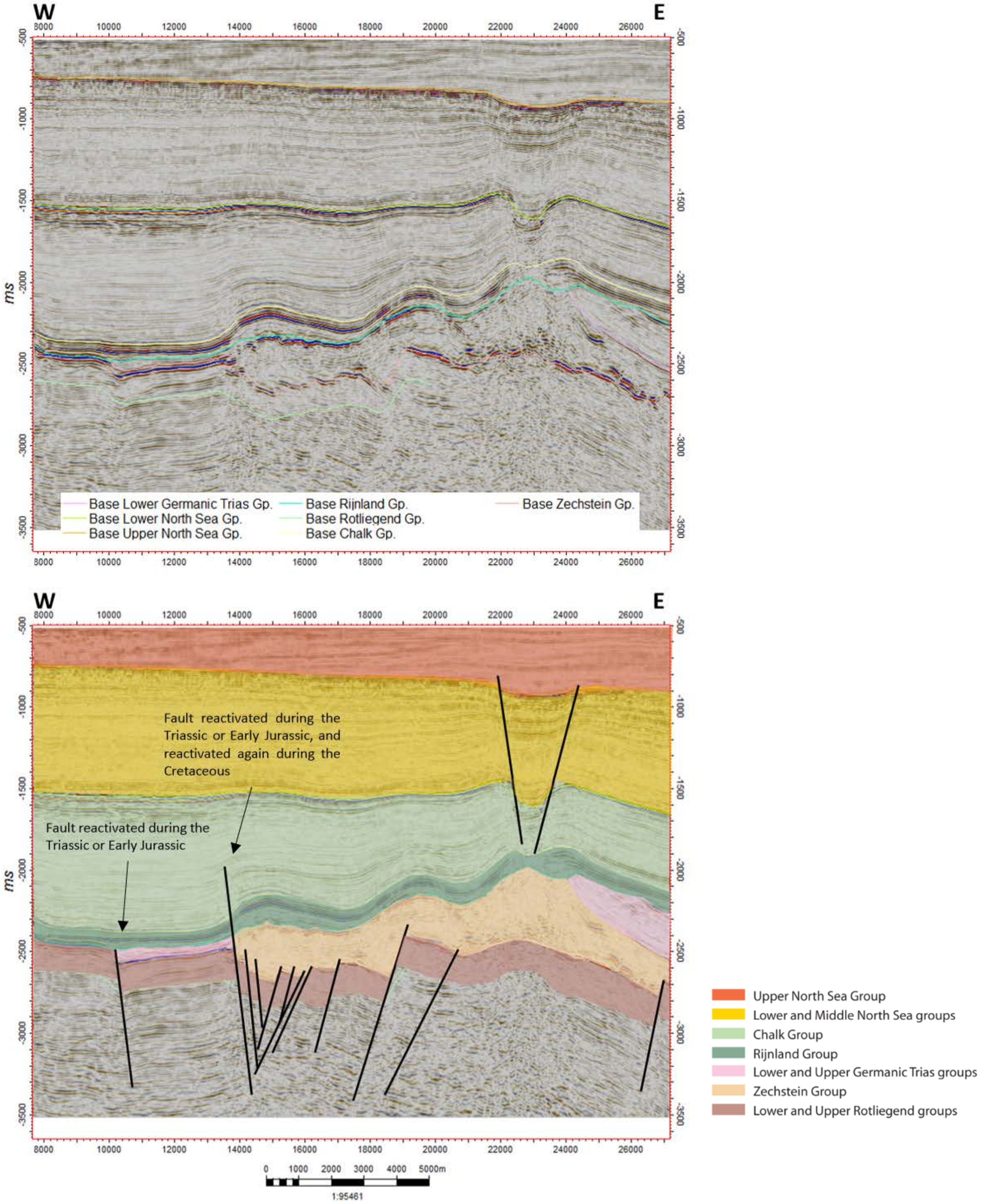

Figure 21. Seismic section (location is shown in Fig.8, Fig.17 and Fig.18) .The first left fault is a NNW-SSE normal trending fault reactivated during the Triassic or Early Jurassic. The second left fault is a NNW-SSE trending fault reactivated as a normal fault during the Triassic or Early Jurassic, and was reversed during the Cretaceous.

The WNW-ESE faults show reverse offsets at Base Zechstein level, and the southern blocks are upthrown relative to the northern block. There are two possible moments when the reverse movements along the WNW-ESE faults occurred. One possibility is during the Middle or Late Jurassic, when the Cleaver Bank High was uplifted locally and the Triassic and Jurassic sediments were removed. Another possibility is during the Paleogene inversion phases (Pyrenean and Savian inversion phases). There is a higher chance that the WNW-ESE faults were reversed during the Paleogene, because the compression direction during the Paleogene is NE-SW, which favors reverse reactivation. Moreover, the Paleogene dykes in this area are parallel to the WNW-ESE faults (Fig. 18). Considering the reasons above, I prefer the interpretation that these WNW-ESE faults were reversed during the Paleogene. When the WNW-ESE faults were reversed, there should be oblique movements along the NNW-SSE faults offsetting them. The WNW-ESE faults and the NNW-SSE faults offsetting them are together included in the Fig. 22.

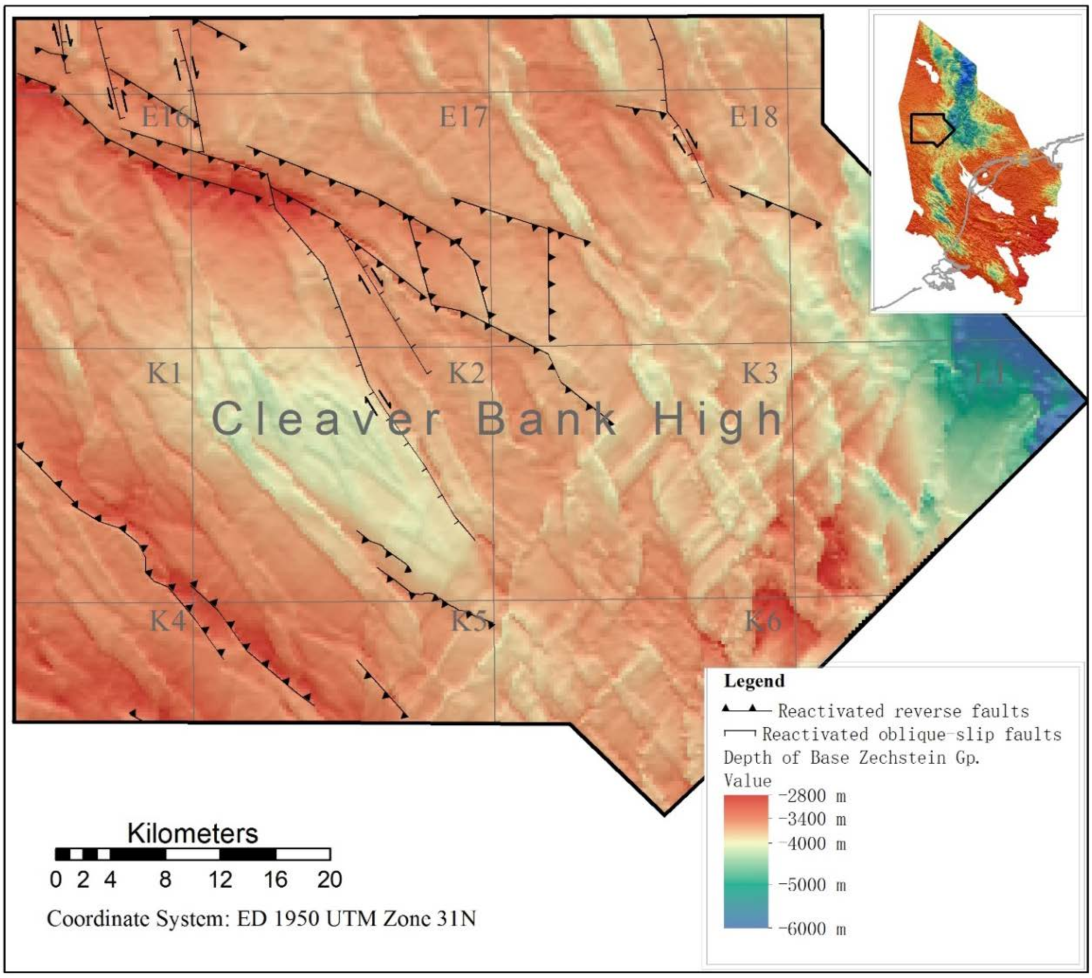

Figure 22. Faults reactivated during the Paleogene (Laramide and Pyrenean inversion phases) (Depth data source: www.nlog.nl).

6. Discussion

6.1 Fault reactivation during the Triassic and Jurassic

Since the Triassic and Jurassic sediments are absent, it is impossible to observe directly from seismic data how the faults were reactivated during this time. But it is known that two extensional phases in the North Sea took place during the Triassic, including Hardegsen (Scythian) and Early Kimmerian (Anisian-Carnian) (Ziegler, 1990). The extensional orientation during the Triassic is W-E, as shown in the Fig. 23 (Kley et al., 2008). Oblique reactivation of NNW-SSE, NW-SE, NE-SW faults could occur in the extension phases during the Triassic. The Early Jurassic were characterized by regional, thermal subsidence (Ziegler, 1990). During the Middle Jurassic, much of the Dutch offshore area was uplifted in conjunction with the development of the thermal Central North Sea Dome (Ziegler, 1990; Underhill & Partington, 1993). During the Late Jurassic, the platforms in Dutch offshore including the Cleaver Bank High were uplifted (De Jager, 2007). It is also indicated in the burial graph (Fig.24) that the Cleaver Bank High was uplifted from 170 Ma to 150 Ma (during the Middle and Late Jurassic). This culminated in the Late Kimmerian Unconformity in the Cleaver Bank High. The entire Jurassic and most of Triassic sediments are absent. So it is not likely that the normal movements along faults occur during the Middle and Late Jurassic.

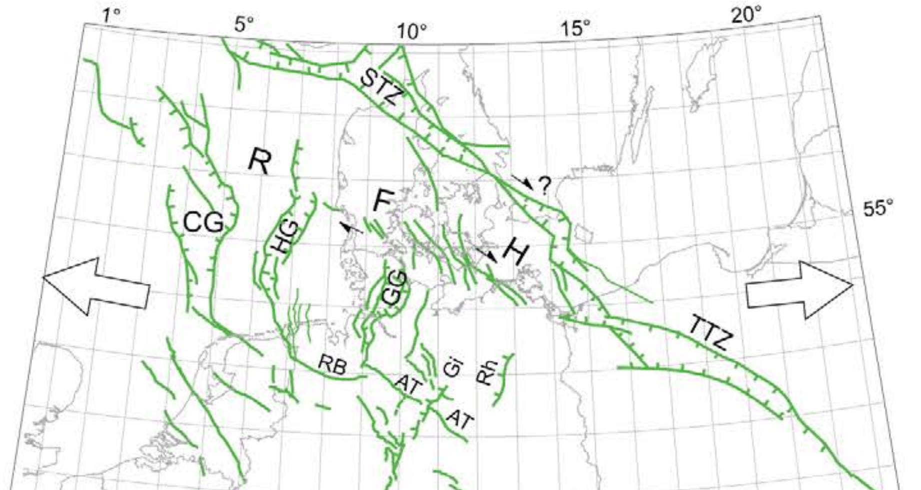

Figure 23. Triassic extension in the Central European Basin System (CEBS). The maps show the overall pattern and extent of fault activity in the Triassic (Kley et al., 2008).

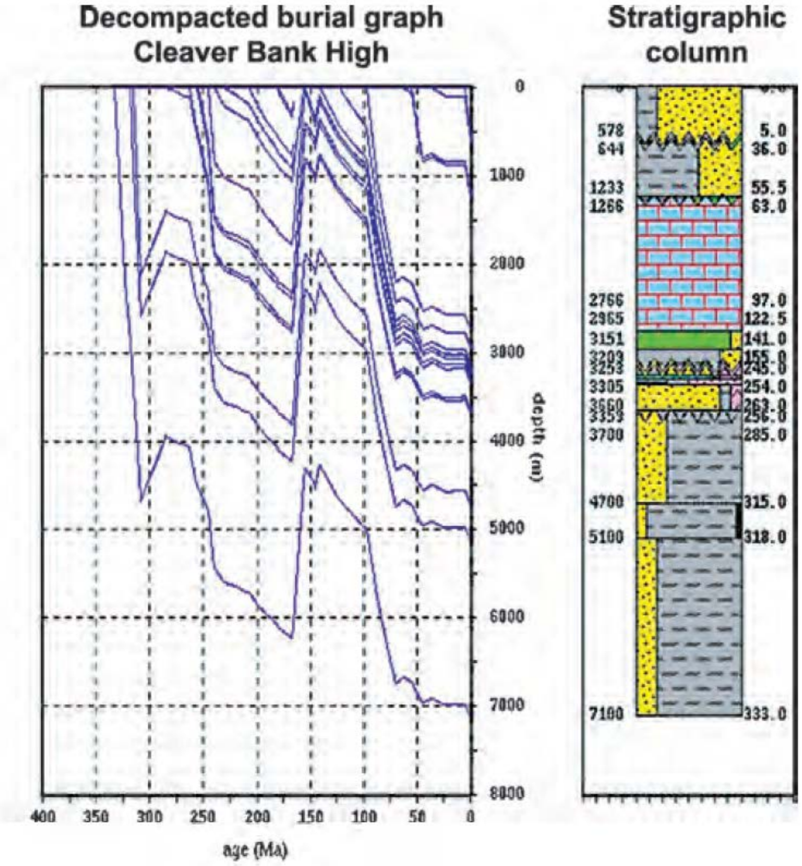

Figure 24. Burial graph of Cleaver Bank High, showing uplift of this platform area during the rifting from 160 to 80 Ma ago, and no indications of Late Cretaceous uplift (De Jager, 2007).

6.2 Oblique-slip

As seen in the Fig.16, the main petroleum fields in the Cleaver Bank High area are bounded by faults, which indicates that the tilted fault blocks are significant traps for petroleum in this area. So an advanced understanding of the fault slip direction could lead to a better understanding of the trap development and a reduction of risk on petroleum prospects. In the Fig. 16, the WNW-ESE faults are represent by the black faults, and the NNW-SSE faults are represent by the purple faults. In the Northwest of the study area, there are several examples that WNW-ESE faults (black) were offset by the NNW-SSE faults (purple) (Fig.16), which implies a strike-slip component along the NNW-SSE faults (purple). The strike-slip component is also supported by the seismic data that show the presence of flower-like fault structures (Fig.25). Considering that the purple faults also have normal throws at the base Zechstein level, they should be oblique-slips with a right-lateral strike-slip component. They could date back to Carboniferous, as the normal offset is found at the intra-Carboniferous level (Schroot & De Haan, 2003). The oblique-slip along the NNW-SSE faults (purple) is likely the result of post-Permian strike-slip faulting and reactivation on the old normal faults. But it is difficult to judge when the strike-slip component came into being. One possibility is during the Triassic when the extensional orientation is oblique to the fault orientation. Another possibility is during the Paleogene (Pyrenean and Savian inversion phases). The reverse movements along the WNW-ESE faults (black) and the oblique movements along the NNW-SSE faults (purple) occurred at the same time, as shown in the Fig.26. I prefer the latter interpretation that the strike-slip movements occurred during the Paleogene, because a crestal graben is observed at the base of the Lower North Sea Group (Fig. 18) above the NNW-SSE faults. The crestal graben was formed during the Paleogene and was active until the Early Neogene, as it has the largest offset in the Lower North Sea Group and its offset gradually decrease upward in the Upper North Sea Group (Fig. 9). Sandbox experiments show that extensional grabens can develop in the post-salt sequence in response to oblique-slip along the pre-salt structural grain (Oudmayer & de Jager, 1993). The observation of the crestal graben above the NNW-SSE faults is consistent with the assumption that the faults were oblique reactivated during the Paleogene. The black WNW-ESE reverse faults together with the purple NNW-SSE oblique-slip faults could form tilted fault blocks, which are very good traps for petroleum, such as the trap of the biggest petroleum field in the Fig. 16.

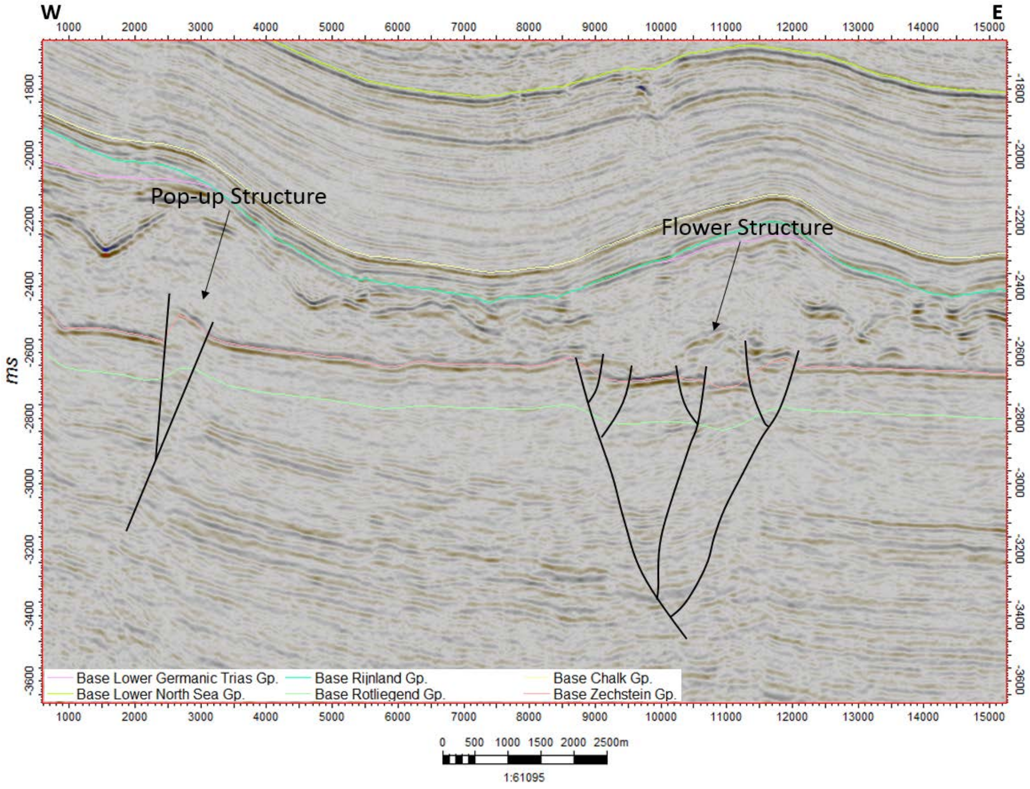

Figure 25. Seismic section (location is shown in Fig.8, Fig.17 and Fig.18). In the left is the pop-up structure following the NNW-SSE and NW-SE fault trends. It formed during the Paleogene compression. In the right is the flower structure along NNW-SSE fault trend. It formed during the Paleogene when the compression orientation is oblique to the fault trend.

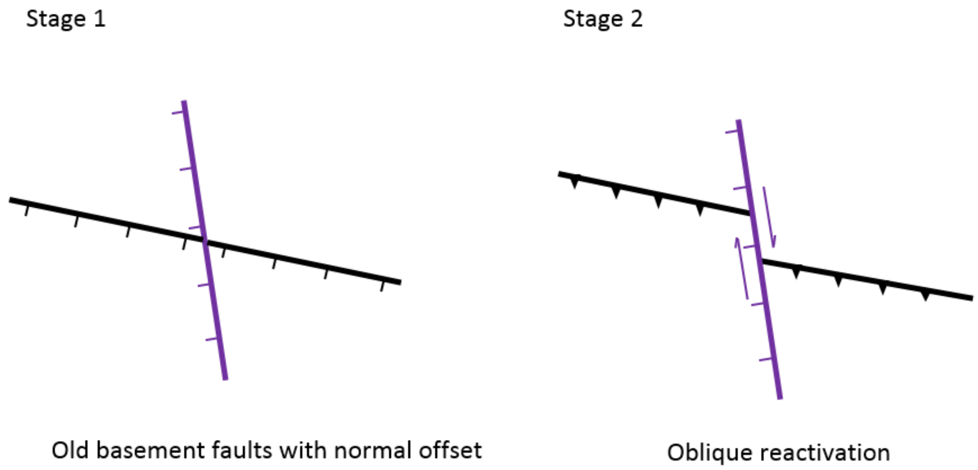

Figure 26. Sketch of a hypothesis of the formation of the oblique-slip NNW-SSE faults (purple). The old normal basement faults were oblique reactivated during the Paleogene. The reverse movements along the WNW-ESE faults (black) and the oblique-slip movements along the NNW-SSE faults (purple) occurred at the same time.

6.3 Comparison with Dutch northern offshore

Although the Cleaver Bank High and Dutch northern offshore have different structural histories, the fault orientation and spacing in these two areas are very similar (Fig.2; Fig.17). It is because few new faults were formed, but pre-existing faults were reactivated and penetrated into Rotliegend sediments. The difference between the two areas is that the Dutch northern offshore is more influenced by the N-S faults parallel to the Step Graben, while the Cleaver Bank High is more influenced by the NW-SE and NNW-SSE faults related to the Caledonia weakness (Coward, 1993; Hollywood and Whorlow, 1993).

7. Conclusion

Faults at Base Zechstein level are mapped based on 3D seismic data in the Cleaver Bank High. Five distinct fault trend were recognized including NW-SE, NNW-SSE, WNW-ESE, NE-SW and N-S. WNW-ESE faults have reverse throws, while other fault trends have normal throws at Base Zechstein level. Strike-slip components along the NNW-SSE faults were indicated by flower structures. Only few new faults formed at Base Zechstein level, but pre-existing faults were reactivated in post-Permian tectonic phases and penetrated into Rotliegend sediments. The folding pattern of the Chalk Group and the orientation of the Zechstein salt domes imply that the Cleaver Bank High were compressed in NE-SW direction during the Paleogene (Laramide and Pyrenean inversion phases), related to the Alpine Orogeny. The consistent thickness of the Chalk Group and Rijnland Group indicated that it is locally stable during Cretaceous. So the reverse movements along WNW-ESE trending faults occurred during the Paleogene rather than

Cretaceous. Oblique reactivation along the NNW-SSE faults also occurred during this time, and led to the formation of tilted fault blocks, which are the most significant traps for petroleum in this area. The most likely time for the normal movements along faults is the Triassic, when extension in W-E direction took place in the Central European Basin System (CEBS).

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