VU University Amsterdam

Master Thesis

Fault Mapping and Reconstruction of the Structural History of the Dutch Central Graben

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Abstract

This paper presents the results of a study focused on the structural development of the Dutch Central Graben and aims to provide a comprehensive description of the structural history of the main structural elements. The study makes use of the recently acquired NL-DEF-3D multi-client seismic survey which was designed to provide modern 3D long offset seismic data on large parts of the D, E and F blocks covering over 6,000 km^2. The improved the imaging of the deepest parts of the Dutch northern offshore allows the identification of deep seated fault relations and improved insight into salt activity phases.

The data shows the existence of an intra-Carboniferous angular unconformity in a large part of the Step Graben. Based on both literature and well control the unconformity can be identified to be of Stephanian age, with Stephanian sequences onlapping onto strongly tilted late Westphalian strata. It is the first time a base Stephanian unconformity is identified on seismic in the Dutch offshore but it confirms earlier predictions.

The seismic profiles show a pre-Permian fault system already active at the site of the Dutch Central Graben. A few of these faults were reactivated during Triassic rifting phases. Thickness maps of Triassic strata together with cross fault thickness variations indicate fault activity already during Early Triassic times, much earlier than conventionally thought.

Several different models explaining features observed from the seismic data and describing the deformation history of the Dutch Central Graben have been analyzed. It followed that a model of moderate Triassic rifting, Late Jurassic rifting and Late Cretaceous inversion tectonics together with major halokinesis from Triassic times onward, fits best with the observation.

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Chapter 1

Background

1.1 Introduction

In recent years several deep subsurface mapping projects of the on- and offshore Dutch subsurface have been initiated, aimed at increasing the regional geological knowledge of the Dutch subsurface. In 2004 the NCP-1 project (Nederlands Continentaal Plat, Netherlands Continental Shelf) was carried out by TNO (Geological Survey of The Netherlands) on the Dutch offshore to provide a general geological framework for further studies [10]. The NCP-2 project which was initiated in 2005 and finished in 2010 provided a more detailed description on seven offshore areas [17] as 3D seismic coverage steadily increased. In 2012 EBN (Energie Beheer Nederland) initiated the DEFAB study which comprises the A, B, C, D and F quadrants of the Dutch northern offshore as this area remained one of the last areas of relatively poor seismic coverage.

The DEFAB regional mapping project is part of a large scale exploration project which aims to screen all possible petroleum plays and reevaluate remaining hydrocarbon prospectivity of this under-explored area. The study makes use of the recently acquired NL-DEF-3D multi-client seismic survey acquired by Fugro. This survey was designed to provide modern 3D long offset seismic data on large parts of the D, E and F blocks and covers over 6,000 km^2 spanning the area between the eastern and western offshore borders. It has 10 seconds of seismic data and has significantly improved the imaging of the deepest parts of the Dutch northern offshore.

Following decades of relatively "easy" production and steady production rates, reserves are currently in decline and it is becoming increasingly difficult to replace these volumes. If we continue the current trend, industry will gradually reduce the level of investment in exploration and development and the production from small fields will decline from 30 BCM per year to 10 BCM in 2030. It is hoped the results from the DEFAB regional mapping project will stimulate the industry to invest in development of this area and will help to realize EBN's ambition to counter the current decreasing production trend and to increase production from small fields to 30 BCM by 2030.

1.2 Objectives

The study presented in this paper focuses on the structural development of part of the DEFAB study area in the Northern North Sea and aims to provide a comprehensive description of the structural history of the main structural elements. The recently completed 3D DEF survey is used as key dataset. The availability of such regional and deep dataset creates the opportunity to study the regional structural development of the area. Improved imaging allows the identification of deep seated faults and to unravel the timing of both fault activity and halokinesis. Four major pieces of work have been carried out:

- Seismic mapping of the major fault trends
- Creating a 3D fault model to visualize the relation between structure and deposition
- Test the applicability of the structural reconstruction tool ezValidator
- Reconstruction of the structural history and compare the results with literature

This data has subsequently been used to answer the following research questions related to the development of the Central Graben the surrounding highs:

- Which structural element developed first, the Dutch Central Graben or the Step Graben?
- When were the bounding faults of the Graben active, was there reactivation and if so when?
- Was the Elbow Spit High (ESH) already a stable high when the Central Graben developed?
- When did the salt start moving and when was the major salt pillowing/ diapiring?

1.3 Geological Framework

The sedimentary succession in the North sea is part of a large intracratonic sedimentary basin [17][28]. It has its origin already in the Paleozoic as sediments filled the Variscan/Appalacian foreland basin[12] formed north of the collision zone between Laurussia and Avalonia. This basin evolved into the intra continental southern Permian basin in late Paleozoic times and later became the site of major crustal extension, characterized by a complex structural history comprising of several active stages throughout the Mesozoic [32]. The part of the Central North Sea Graben, situated in the northern area of the Dutch offshore can be considered as the southern limb of this Mesozoic rift system. It runs from quadrant B in a north-south direction to the northern blocks of quadrant L, has a width of approximately 35 km and reaches a maximum depth in excess of 9 km.

The presence Zechstein salt profoundly affected the post Permian structural development of many of the sub basins in the southern and central segments of the North Sea rift system [15][23]. Regional extension, compression and differential sediment loading triggered salt flow, producing a variety of salt structures such as pillows, active and passive diapirs, both during and after rifting. Furthermore, salt plays an important role in the generation, reactivation and propagation of faults in the under and overburden [24]. When the salt layer is thick enough it can impede the upward propagation of deep seated faults through the overlying sedimentary cover and supra salt faults are not directly linked to sub-salt faults. Instead, unlinked or semi-linked faults form in the sedimentary cover above the sub-salt faults [24].

During the late Mesozoic and throughout the Cenozoic the Southern North Sea basin continued to subside as a post rift sag basin and is characterized by the gradual infill with clastic material[12]. The Paleocene succession in the Southern North Sea reflects deposition in a shallow marine environment. From Oligocene to Pleistocene times the eastern north sea basin was filled by a large fluvial system of which the drainage area comprised the Fennoscandian and Baltic areas. Prograding sequences gradually filled the subsiding Southern North Sea basin and covered the Mesozoic structural elements.

1.4 Study Area

The DEFAB study area is located approximately 185 Km north of Den Helder (Figure 1.1) and covers an area of more than 14.000 km^2 spanning the largest part of the D, E and F quadrants. This structural mapping project was concentrated on parts of the Central Graben (CG), the Step Graben (SG) and part of the Elbow Spit High (ESH) covered by the 3D DEF survey (approximately 6500 km^2). As the covered area over the CG was limited, areas north and south of the CG were mapped using other available seismic surveys.

1.5 Structure

In the next chapter section first the regional tectonic and stratigraphic framework are reviewed using the latest available publications. In Chapter 3 the available seismic and well data is presented and the methods used for seismic interpretation and well correlation are explained. Chapter 4 shows the results of the fault

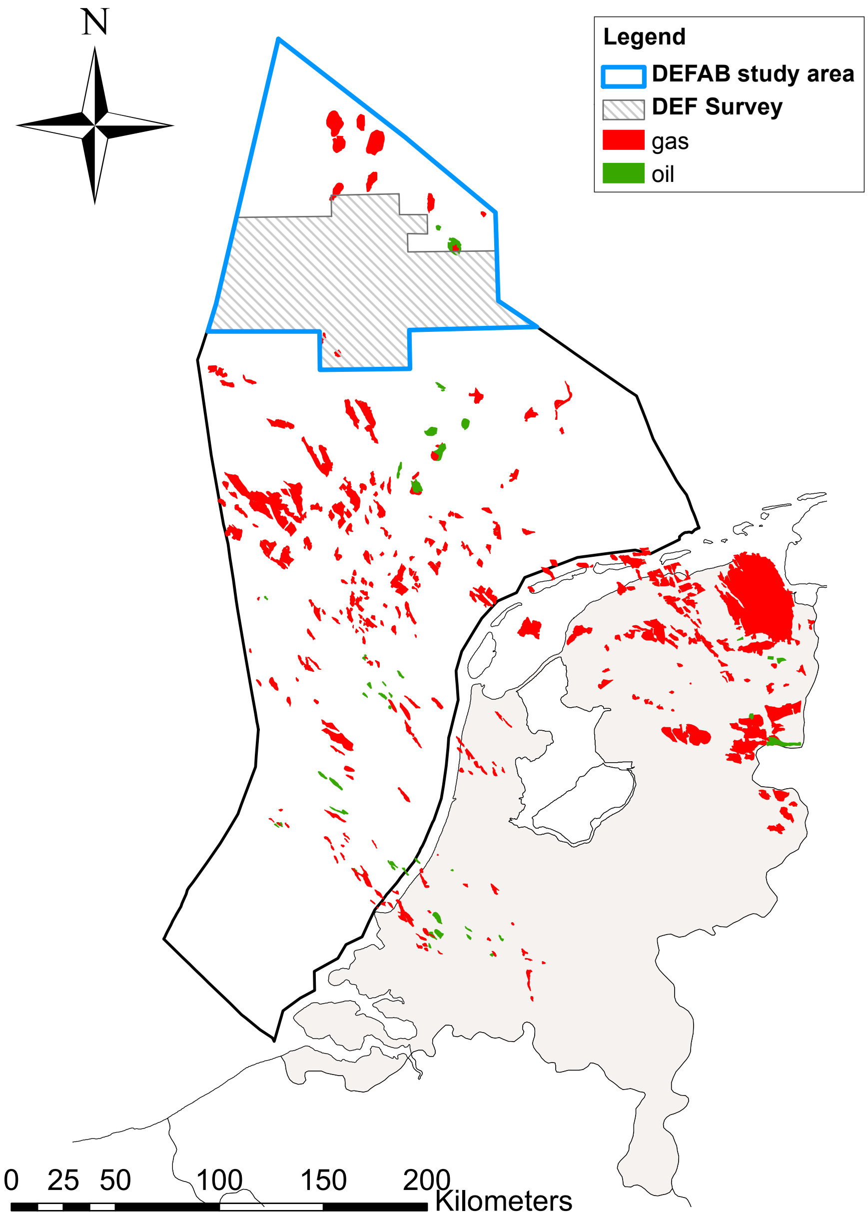

Figure 1.1: This map shows the location of the DEFAB study area (blue) and the 3D DEF survey (shaded)

mapping project which are displayed in a selection of several E-W orientated cross sections through the study area accompanied by a number of thickness maps of the main stratigraphic intervals. In Chapter 5 the results are interpreted and in the next chapter the interpretations are discussed and the application of the structural reconstruction tool is reviewed. In the final chapter the main conclusions are summarized.

Chapter 2

Regional Tectonic and Stratigraphic Framework

2.1 Introduction

The North Sea is part of the large North West intracratonic European basin stretching from the Atlantic shelf through the North Sea to eastern England, The Netherlands, Denmark, Germany and Poland [30]. This large basin is bordered to the north east by the Fennoscandian Precambrian shield, to the west by the Scottish Caledonides, to the south by the remnants of the late Paleozoic Variscan fold belt and to the east by the Russian platform.

It has been the site of several large scale tectonic events that had a profound effect on the evolution of the area. Two important stages of deformation are the Caledonian and the Variscan/Hercinyan orogeny [3][28][32]. The stresses induced by these events led to the development of pronounced Paleozoic lines of weakness developing mainly along NE-SW Caledonide and NW-SE Trans-European Fault Zone trends [11]. Subsequently in the Mesozoicum the area was subjected to multiple phases of extention [6][12]. The Triassic to Jurassic rift geometry was profoundly affected by the old Paleozoic lineaments. The principal effect of these Paleozoic lineaments has been to offset the development of extensional sub-basins within the rift in an en echelon fashion [11][29]

2.2 Regional Tectonic Evolution

2.2.1 Pre-Carboniferous

Figure 2.1 shows the plate tectonic setting during the late Ordovician and early Silurian. During this time the continents Laurentia and Baltica were colliding [22], gradually closing the intermediate Thornquist ocean[18]. At around 420 to 400 Ma, a mico continent derived from Grondwanna, the terrane of Avalonia, arrived from te south and took part in the collision. This micro continent joined

Baltica in a soft docking event at the end of the Ordovician, slowly closing both the Thornquist and Iapetus oceans. East Avalonia formed the southern part of the British isles, the southern North Sea and parts of Denmark and northern Germany. Behind the northward moving Avalonian plate the Rheic Ocean opened [31]. Besides Avalonia, multiple small continental fragments split from the Grondwanna super continent, slowly accreting and forming the western and central part of Europe. Most of these micro continents were bordered by oceanic crust. Most of the oceanic lithosphere was subducted during the accretion but small remnants of the former continental margins are still observed today.

In the Devonian, following the collision of Avalonia with Baltica, the oceanic plate of the Rheic ocean south of Avalonia started to subduct both northward under the Avalonian plate and southward under Grondwanna [19]. As the subduction continued, gradually closing the Rheic ocean, Grondwanna progressed north towards the Laurentia-Baltica-Avalonia complex which would later form the nappe complex of the Variscan Mountains. During this time (late Devonian to early Carboniferous) the plate tectonic regime in the area of present North Sea changed to extension [1][26][31].

A possible cause of this change was the initiation back ark extension in the Rhenohercynian Basin to the south east of the Netherlands. The result were a series of WNW-ESE and NNW-SSE orientated fault blocks developing as pronounced half grabens [28][31]. However, an alternative theory has been proposed stating that the late Caledonian movements and the convergence of Grondwanna with the Northern continent complex caused Baltica-Avalonia to be expulsed to the east, inducing E-W extension in the southern North Sea area [7]. Regardless of the exact mechanism it has been suggested by others that in this structural grain the Proto-Dutch Central Graben can already be recognized [28][31]

2.2.2 Carboniferous

During the Carboniferous the northward drift of Grondwanna induced the development of a large scale trust front and caused flexural subsidence north of this area [4]. Namurian sediments were deposited in the deep foreland basin but as the deformation front migrated northward the sediments, far to the south of the study area, where deformed into major thrust and nappe complexes. Igneous intrusives and extrusives suggest that a subduction zone was present south of the deformation front, dipping southward under the Avalonian plate. Further north, closer to the study area, the impact of the fold belt was less severe and deformation less pronounced. There is no direct evidence of large scale fault formation related to the Variscan compression reaching the Netherlands [28]. The active faults seem to be extensional rather than compressional. The Carboniferous strata are however folded during the latest stage of the Variscan tectonic phase. Deformation on either side of the Variscan front is accommodated in different ways. The area south of the front are characterized by short wave-length

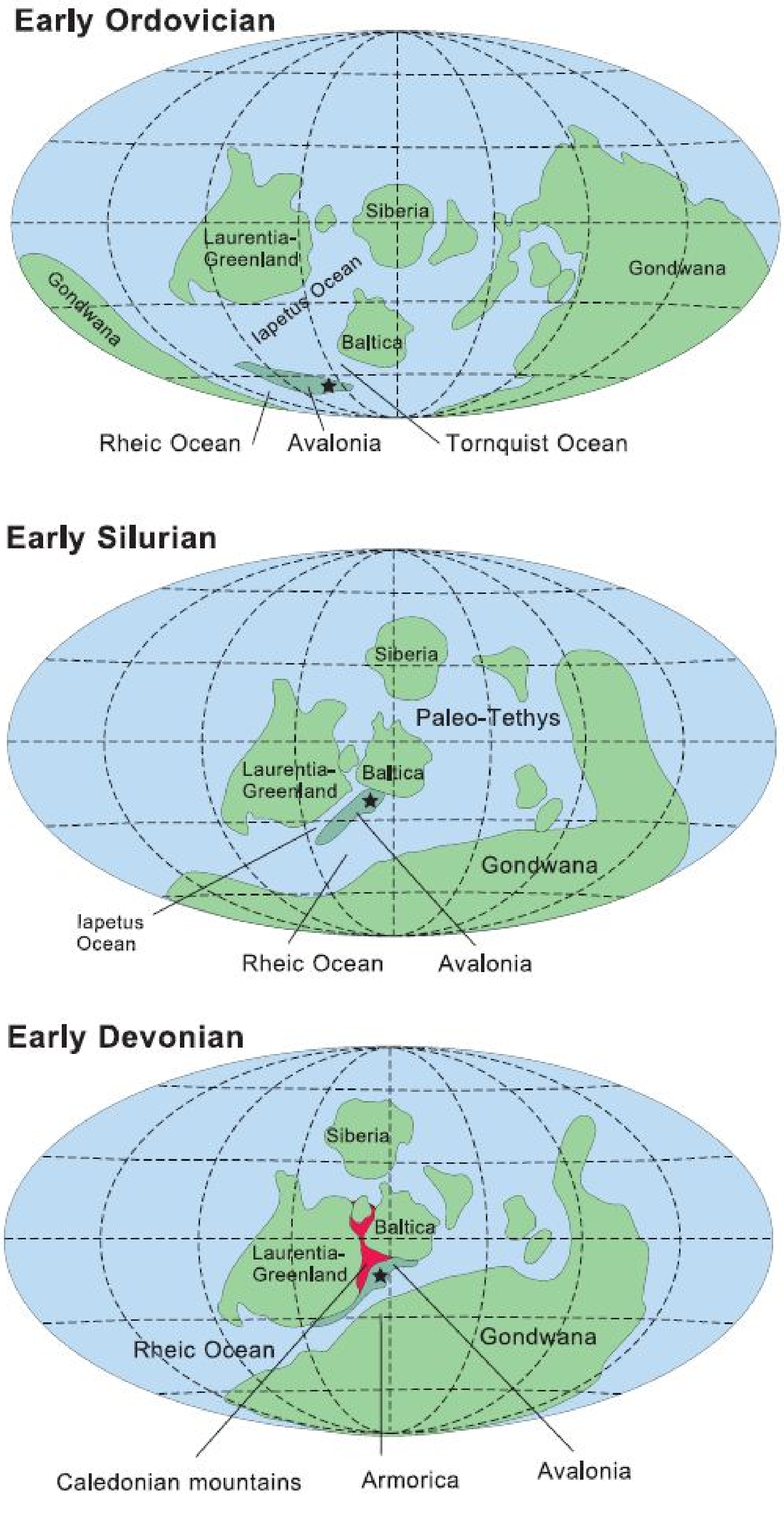

Figure 2.1: Plate-tectonic reconstruction illustrating the northward drift of Avalonia, the collision with Baltica and Laurentia and the subsequent collision of Grondwanna initiating the Variscan orogeny (From [28])

folding and thrust faulting whilst the the north, including the Dutch subsurface is characterized by long wave-length folding.

Besides the flexural subsidence along the southern margin of the North West European Carboniferous basin there are indications of an early Carboniferous rifting event of which the post rift thermal subsidence caused additional subsidence. Others state that an additional Namurian rifting event is needed in order to explain the accumulation of the very thick Carboniferous sequence [17].

2.2.3 Permian

At the end of the Carboniferous, convergence halted and the Trans-European Fault Zone now marks the maximum lateral extend of the Variscan Bohemian massif [6] [31]. At this time the Variscan maintain belt started to collapse and this was associated with post-orogenic tectonism and a regional extension [32]. The westward movement of the African continent transferred additional strain to north west Europe. This resulted in normal and strike-slip features striking NW-SE together with a NE-SW to NNE-SSW conjugate system. These features are associated with the reactivation of the pre-existing structural grain established already during mid Paleozoic times. Thermal uplift caused much of the older Carboniferous series to be severely eroded and the resulting angular unconformity can easily be identified on seismics. Interestingly the subcrop pattern at this Base Permian Unconformity (BPU) already reveals, amongst others, the outlines of the later West Netherlands basin and Dutch Central Graben. [12][28][31].

During the early Permian widespread extrusive magmatism is observed throughout the Southern Permian Basin [12]. The intense volcanic activity was not only limited to the surface but large mafic intrusions have been inferred to have been injected into the stretched crust, inducing hight amplitude reflections on deep seismic profiles. It is not known whether this period of intense activity was the result of a build-up of heat in the lithosphere or the result of a mantel plume. Some have suggested this period was responsible for the stable character of the Mid North Sea High (MNSH) and Ringkobing Fynn High (RFH) during subsequent extensional phases as magmatic underplating thickened and strengthened the underlying crust[21]. The linear alignment of the highs may record the trajectory of the mantel plume beneath the continental lithosphere during this time[18]. Others [28] indicated an earlier development already during the early Devonian as new seismic imaging shows Late Devonian red beds onlapping against the highs.

Regional subsidence caused sedimentation to resume in the Middle Permian. The North Sea area became part of a large sedimentary basin trending E-W [12]. The basin was divided into the Northern- and Southern-Permian separated by the Mid North Sea High and the Ringkobing-Fyn High. During this time several minor tectonic pulses are recognized [13] and are thought to herald the start of the break up of the Pangaea super continent. Subsidence rates were high and caused the area to subside to well below sea level. In late Permian the depression was catastrophically flooded by seawater and subsequent cycles of sea-level change and evaporation left large amounts of evaporites in the basin.

2.2.4 Triassic

During the Triassic the break-up of the Pangaea super continent continued and would eventually result in the continent arrangement as we know it today. Within the Triassic two tectonic pulses are recognized resulting in large regional unconformities, namely the Hardegesen phase and the Early Kimmerian phase [28][31]. Both are comprised of several short lived rift pulses, each represented by an unconformity. These phases had a profound effect on the structure of the Permian basin and sediment dispersal.

Analysis of basement fault patterns had led to the believe that the main direction of extension was directed E-W [28] and initiated the formation of the Dutch Central Graben. However, others have proposed NE-SW extension [6] and a lateral shear system resulting in graben formation. The main rifts were situated further east, focusing in the Gluckstadt and Horn Graben where a thick sequence of lower Triassic sediments accumulated. Subsidence patters show the focus of the extension moving from east to west while the same time older structural highs became the site of strong regional uplift.

The Early Kimmerian phase is believed to be the onset of the main fault movement in the Dutch Central Graben [28] and it is thought that deep seated faulting triggered the movement of the Zechstein salt at this moment as the southern most extension of the Dutch Central Graben shows rim synclines filled with late Triassic sediments. Next to the N-S trending fault system a WNW trending system developed, cutting into The Netherlands swell, a large dome shaped high that existed during late Triassic through late Jurassic.

2.2.5 Jurassic

The break-up of the Pangaea super continent, that was already initiated during the Triassic, continued in to the Jurassic. After the Hardegesen and the Early Kimmerian extensional phases the Jurassic was characterized by two more tectonic phases. The first phase was the Mid Kimmerian rift phase lasting from approximately Aalenian (early Middle Jurassic) to Oxfordian (early Late Jurassic). The second phase was the Late Kimmerian rift phase (Late Jurassic) and is thought to have produced the main syn rift sequences of the Jurassic. During these rift phases extensive halokinesis controlled the sedimentation patterns and fault geometries. the onset of halokinesis is thought to have been triggered by tectonic activity as the salt walls often follow major sub salt fault systems

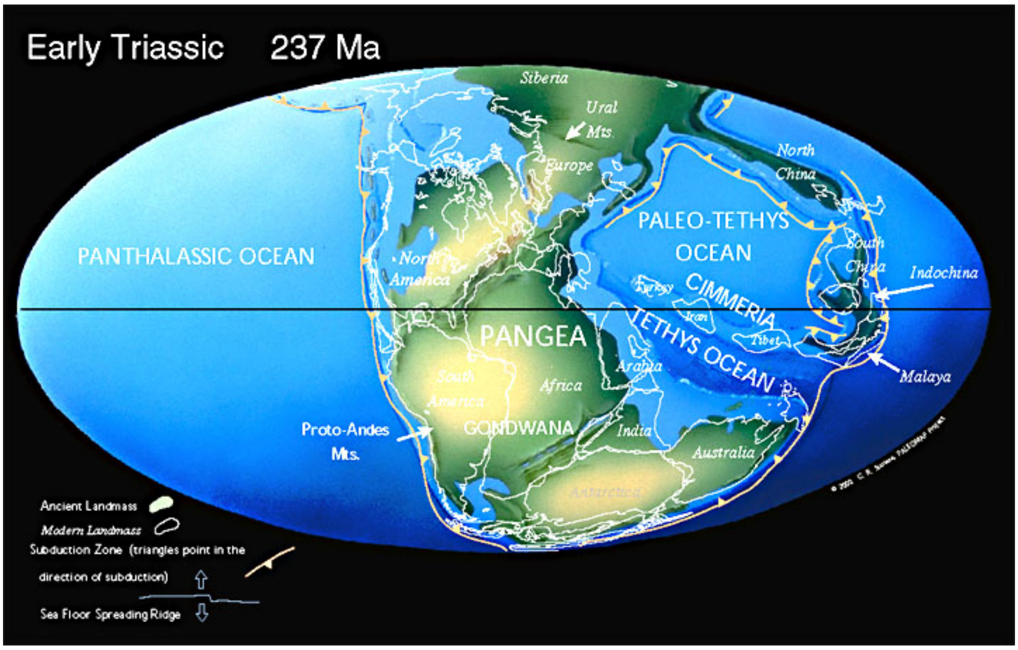

Figure 2.2: Plate-tectonic setting during the Early Triassic. It shows the position of the North Sea basin situated in a land locked position, north of the Variscan collision zone

[28]. The periods in between these phases was characterized by regional thermal subsidence.

The extensional regime induced the formation of several graben systems with different orientations. The bounding faults of the Dutch Central Graben were orientated N-S and are though to be perpendicular to the E-W direction of extension. [28]. This caused the pre-existing structural grain to be reactivated during the two consecutive Jurassic phases. Another clearly expressed graben system is the NW-SE trending system of tilted half grabens. Including the Roer Valley graben, The West Netherlands Basin, The Central Netherlands Basin and the Broad Fourteens Basin. It is thought that these basins follow older structural trends as they are not aligned with the assumed E-W extensional regime. It is believed that most fault movements were trans-tensional with a dextral strike slip component. However, only at a few locations this expected trend was actually observed.

An important structural feature developing during the Mid Kimmerian phase was the Central North Sea Dome that resulted in regional uplift of the area. It is interpreted as a crustal thermal anomaly preceding the active rift phases and, because of its spatial extend and temporal dimensions, involving both the lithosphere and astenosphere[14]. Its center was situated north of the Netherlands at the position of the later triple junction, half way between Scotland and

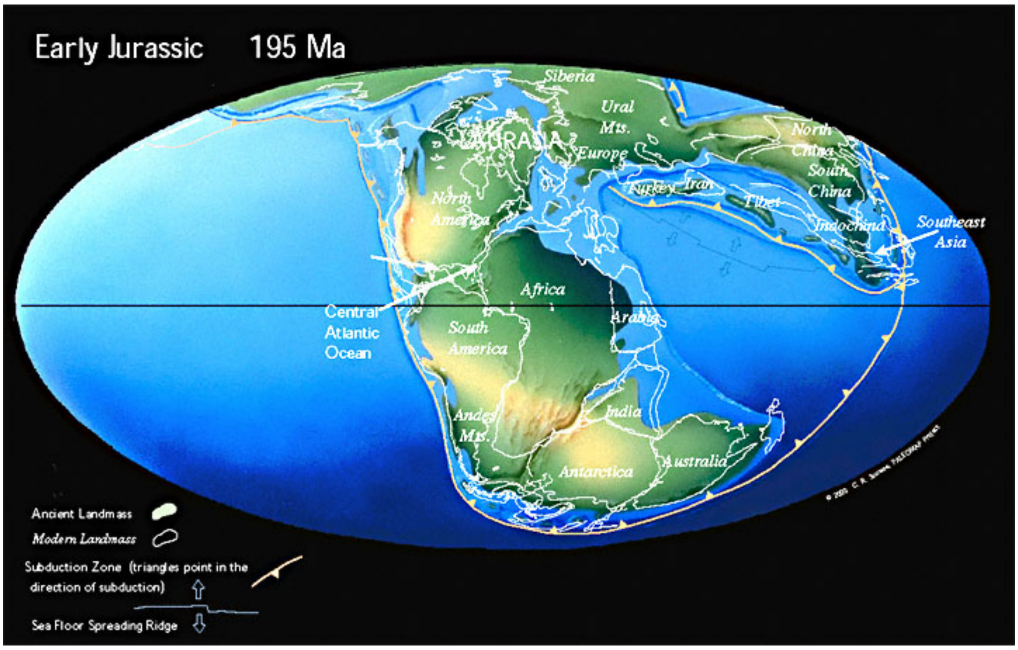

Figure 2.3: Plate-tectonic setting during the Early Jurassic. It shows the flooded continental margins of Europe causing widespread marine conditions at the site of the North Sea Basin

Norway [9]. The doming front gradually shifted southwards into the Central Graben Dome (Early Jurassic) and later into the Friesland Dome (early late Jurassic) and as a result the erosion and non deposition related to the uplift increases toward the north. The position of these domes correlates with the main rift axis of the later Central Graben. As a result of dome formation and erosion the larger part of the Lower Jurassic sediments have been removed, with the exception of the basinal areas [28][9]. The following Upper Jurassic sediments are mainly deposited within the Dutch Central Graben as it evolved as a topographic low centered within the mostly sub aerial Central Graben Dome. Sedimentation patterns show a gradual transgression throughout the Jurassic as the sea approached from the north, alternating with several stages of northward progradation of continental siliciclastic sediments.

2.2.6 Cretaceous

The late Kimmerian rift pulse generated a differentiation into rapidly subsiding basins and high platform areas and this topography lasted throughout the Early Cretaceous. This period was characterized by a gradual regional thermal subsidence as a result of Late Jurassic rifting [28][27]. It records the end of the failed North Sea rift and the transfer of extension out onto the Atlantic margin. The regional subsidence was accompanied by a gradual a step by step southward transgression where periods of marine transgression alternated with periods of siliciclastic terrestrial progradation. Ongoing subsidence eventually submerged the siliciclastic terrestrial progradation. Ongoing subsidence eventually submerged the siliciclastic source areas and a calcareous sedimentation prevailed during the second half of the Cretaceous. In the Dutch offshore Late Cretaceous chalks and marls reach a maximum thickness in the order of 1000 m.

Important tectonic pulses occurred in response to multiple compressional phases and resulted in the inversion of the former Jurassic basins. The first inversion phase is referred to as the Sub Hercynian tectonic phase. After this pulse a period of decreased tectonic activity commenced during which the major inversion axes were apparently overstepped by Maastrichtian and Danian chalks. The inversion movements accelerated again during the Laramide deformation phase. The direction of compression was believed to be approximately N-S and particularly affected are the NW-SE trending basins south of the Dutch Central Graben where inversion was most severe [28]. Older faults were reactivated as reverse faults, locally giving rise to over-thrusting. As a result large parts of the inverted basin fills were eroded whilst sedimentation continued in the adjacent basins [25] The Dutch Central Graben was subjected to minor inversion as the inversion effect diminished to the north, but nevertheless anticlinal inversion structures are clearly visible on seismic. It is generally assumed that these compressional phases were the result of Alpine foreland compression ([32]) although some uncertainties around the exact driving mechanism still remain.

2.3 Tertiary

Following the Late Cretaceous Laramide compressional phase that caused local inversion structures the area was regionally covered by Late Paleocene and Early Eocene marine silisiclastics that transgressed during a tectonic quiet period [28]. It covered the deeply eroded basin sequences in response to what is believed to be a a eustatic rise in sea level and the regional post-rift subsidence of the North Sea Basin [12]. During the Late Eocene renewed uplift affected the areas around the West Netherlands Basin and the Broad Fourteens Basin [28] . This uplift was thought to be related to the Pyrenean tectonic phases. Pyreneyan compressive tectonics involved uplift and erosion of the southern onshore and extended westward into the offshore. However, there are no indications that deformation reached as far as the Dutch Central Graben. These inversion pulses were believed to be only minor compared to the sub-Hercynian and Laramide deformations. Transgressive Oligocene marine sequences are covered by Miocene and younger series separated by an unconformity as Late Oligocene sediments are generally absent and Mid Oligocene series are only partly present [28]. This interruption at the end of the Oligocene is related to the Savian phase of inversion [12]. In some areas the Late Oligocene unconformity has been slightly deformed due to reactivation of diapiric salt structures. It is not known if this movement

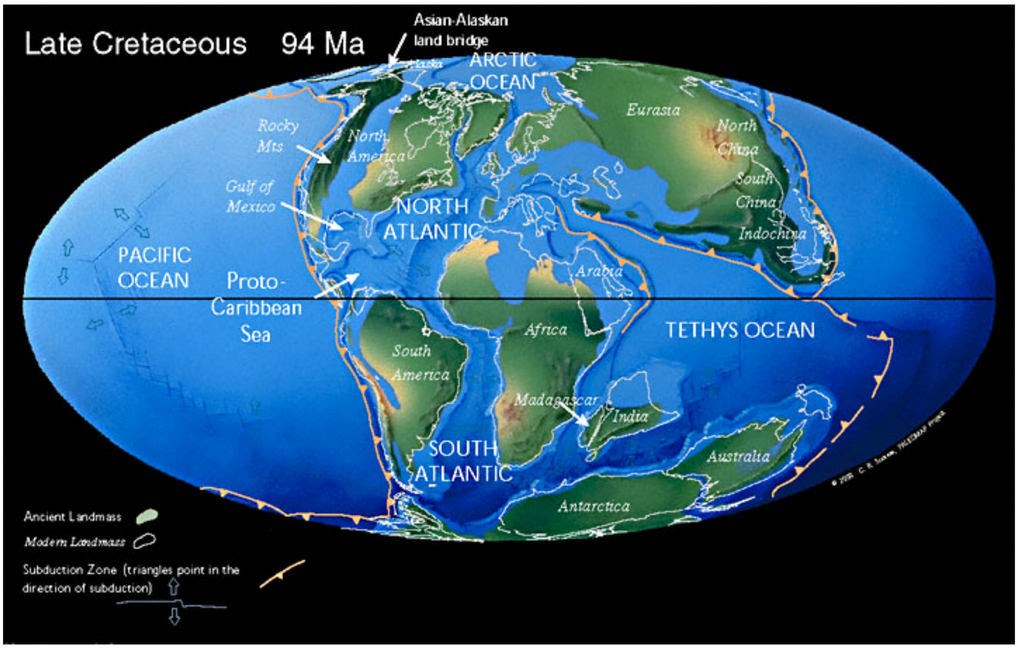

Figure 2.4: Plate-tectonic setting during the Late Cretaceous. It shows the flooded continental margins of Europe causing renewed marine conditions at the site of the North Sea Basin

was related to a tectonic event involving crustal extension. During the Miocene regional subsidence continued over the North Sea Basin and the paleo-water depth slowly increased [12]. In the Neogene the Iridanos delta system prograded from the east. It was sourced from the Fennoscandian border and brought large amount of clastic sediments into the North Sea basin.

2.4 Structural Elements

The main structural elements discussed in this report are listed below. The nomenclature and exact location of these elements have often been the subject of revision. The current division is based on the latest classification [17] distinguishing elements in terms of highs, platforms and basins ,in terms of uniform deformation history and based on it sedimentary cover (Figure 2.5). The main structural elements relevant for this study are discussed below

Dutch Central Graben (DCG)
The Dutch Central Graben represents the southern most extension of the large Mesozoic rift system formed during Triassic and Jurassic Times [6][32], although indications are that this area was already a low during Carboniferous times [28]. It is bounded by extensive basinal faults with large offsets separating it from the

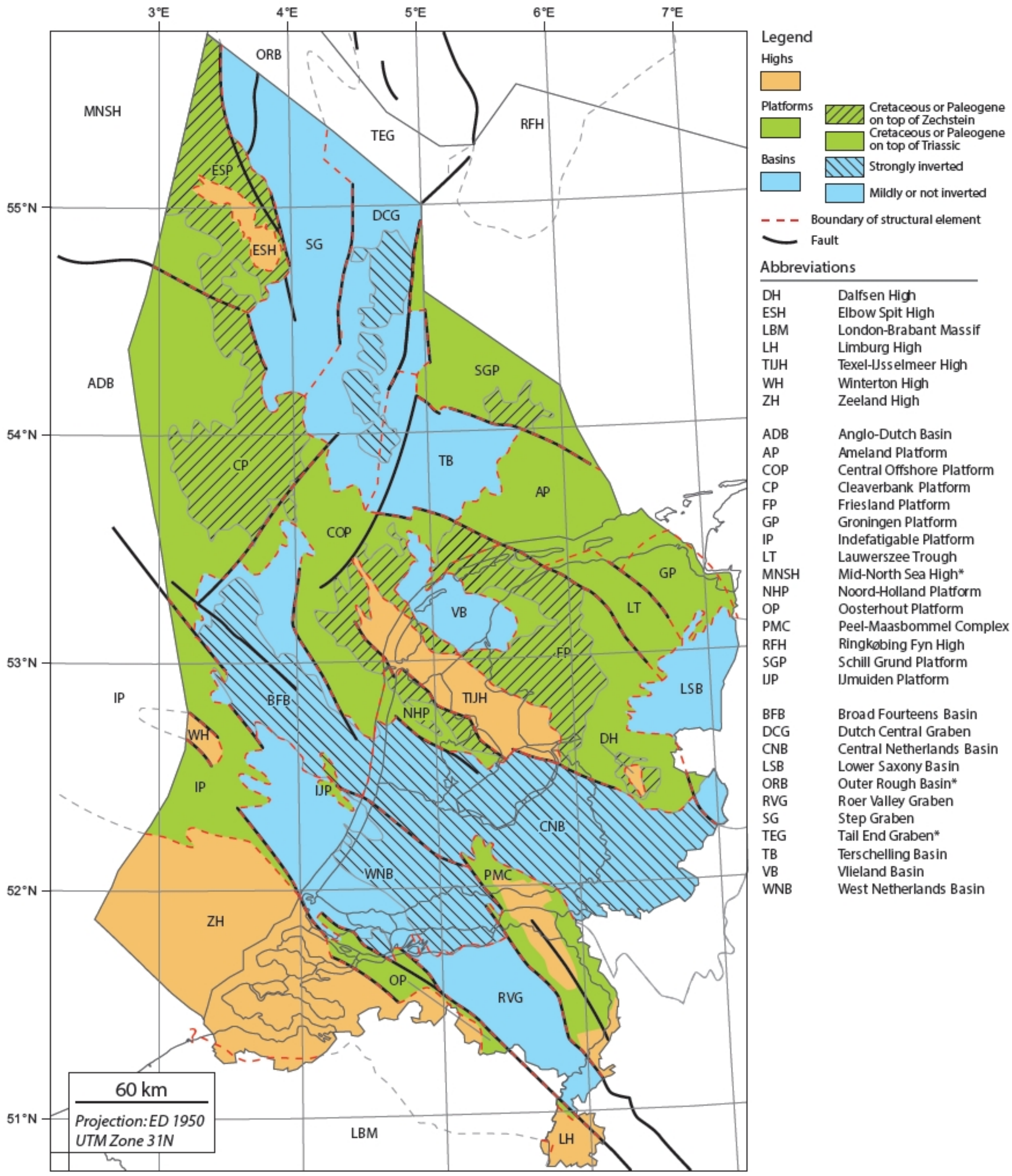

Figure 2.5: This map shows the main structural elements recognized in the Dutch on- and off-shore. From [28]

Schill Grund Platform to the east and the Step Graben to the west. The graben in characterized by thick sequences of Triassic and Jurassic deposits after which inversion removed most of the subsequent Upper Cretaceous Chalk group. Also the deeper Zechstein salts played a major role in the formation and deformation of the main depocenters as salt swells and diapirs developed [8].

Elbow Spit High (ESH)
The Elbow Spit High is part of the Mid North Sea High and is situated on the western limits of the Dutch offshore. It has been a structural high since the Devonian and at present Upper Cretaceous is directly overlying much older Carboniferous and Devonian deposits. [28]. Devonian units onlap onto the western flank and also later Carboniferous units appear to thin towards the high. Magmatic underplating was already put forward as a possible explanation for the stability of this and other platforms throughout geological history [18]. Whether underplating really occurred and if this happened in one or multiple phases in the Devonian and Permian is unknown.

Elbow Spit platform (ESP)
The Elbow spit Platform together with the ESH can be considered as the eastern extension of the Mid North Sea High (MNSH) and is covered by Cretaceous and in the south Triassic deposits overlying Permian rocks. Its eastern boundary is marked by the SG boundary fault and to the west it is bordered by the Cleaver Bank High (CBH, not discussed), where the thickness of the Permian sediments increases significantly.

Ringkobing Fynn High (RFH)
The Ringkbing-Fynn High has, like the other highs, relatively shallow basement rocks as compared to the surrounding platform area. It has been thought that it formed during an early Permian rifting event and remained a structural high throughout the Triassic. The western fraction of the high is bounded by the Dutch Central Graben in the West and the Horn Graben in the East. It is situated in the German offshore and continues north into Danish territory. The thin sedimentary cover mainly consists of thin Mesozoic and tertiary rock [5].

Schill Grund Platform/High (SGH)
The Schill Grund Platform, also known as the Schill Grund High forms the eastern boundary of the DCG. At its southern end it is bordered by the Rifgronden fault marking the northern edge of the Terschelling basin. Towards the north this platform continues into the Ringkobing Fynn High.

Step Graben (SG)
The Step Graben is bordered by the DCG in the east and in the west by the Elbow Spit High, the Elbow Spit Platform and the Cleaverbank Platform. It

is not nearly as deep as the DCG but forms a terrace like feature west of the graben. Lower Triassic deposits are present as well as part of the Upper Triassic. Jurassic however is only deposited or preserved locally. It is though that most of the Jurassic sediments where removed during the late Mid-Kimmerian thermal uplift. The late Jurassic to Early Cretaceous inversion affecting the DCG caused mild to no deformation on the SG [12].

Terschelling Basin (TB)

The Terschelling Basin is situated south east of the DCG an is bordered by the WNW-ESE trending Rifgronden fault zone marking the transition to the SGH in the north. In the south it is bordered by the Hantum fault zone. Both normal boundary faults were active in the Late Jurassic and created the TB. Furthermore The fault zone is composed of two fault systems. A WNW-ESE synthetic strike slip system and a NW-SE antithetic strike slip system [28] In contrast to the DCG, most of the Upper Cretaceous Chalk Group is preserved in this area due to the relatively mild effects of late Cretaceous inversion.

Chapter 3

Data and Methods

3.1 Introduction

The following chapter provides an overview of the general work flow and the available data used for the structural interpretation is briefly discussed. The seismic data is property of EBN but most of the well data is readily available through the public database Nederland Olie en Gas (NLOG). Besides standard seismic interpretation software an additional software package was used named ezValidator. This software package was used to make several fault reconstructions to help solve structural issues and will be discussed later.

3.2 Available Data

The main dataset used for seismic interpretation was the 2011 3D DEF survey (courtesy of Fugro) and a regional interpretation of the main horizons and main faults in the study area was available for the study. The 3D survey has more than 10 seconds of seismic data and has significantly improved the imaging of the deepest parts of the Dutch northern offshore. During the course of the project it was decided to extend the interpretation north of the DEF area into the older ZE3FUG2002A survey and south into the Terracube-2011. The relatively small ZE3FUG2002A survey holds approximately 6 seconds of seismic data. The Terracube is capable of imaging up to 5 or 6 seconds but is comprised of several older surveys with different specifications.

The well data available for this project comprises of more than 300 wells (Within the D, E and F quadrants). Some are still confidential whilst others are publicly available.

3.3 Seismic Interpretation

Interpretation focused on identifying the major faults within the DEF area (Figure 2.1). That is, faults with large offsets and faults important for the evolution of the previously defined structural elements. The faults were then labeled according to their timing. With the help of this fault model and the unfaulting software ezValidator a reconstruction of the structural history was put forward.

The main stratigraphic boundaries (lower North Sea Group, Chalk Group, Rijnland Group, Schieland Group, Altena Group, Triassic and the Zechstein) had already been mapped on this data within the framework of the DEFAB project that started already in 2012. In some areas this interpretation was re-evaluated and in addition, new tops were interpreted where needed, to provide more detailed information on sedimentary evolution inbetween the main horizons.

The seismic horizons were converted into surfaces and subsequently converted into the depth domain using the regional Velmod velocity model provided by TNO. The resulting model in depth was then used as an input to create several thickness maps, used to recognize and evaluate the main depocenters per stratigraphic unit.

Furthermore, a preliminary fault model of the DEF area was used as a basis for the subsequent fault modeling. New faults were mapped and several existing faults were re-interpreted in more detail. In addition, the fault interpretation was extended north and south of the original fault model.

For seismic interpretation the Petrel E and P software platform was used. The applied modeling work flow is common practice in oil and gas exploration and includes regional stratigraphic interpretation and fault interpretation in time domain.

3.4 Fault Reconstruction

3.4.1 ezValidator

One of the objectives of this study was to evaluate the use of ezValidator [20] as a tool for reconstruction in a regional setting. The software was used to infer the original geometries before faulting occurred. To start, a seismic image (standard image files) must be loaded into to the ezValidator environment. This seismic image is overlain by a mesh that can be moved along previously defined faults to remove the throw matching seismic character and stratigraphy across the fault plane. The amount of throw can be defined manually using a tip point, a seismic correlation in the form of anchor points or an horizon correlation. The amount of throw can vary along fault planes but this can be solved by inserting multiple seismic correlation points. Tip points and horizons correlations are inserted automatically whilst anchor points must be specified by dragging the seismic image with the anchor point until the seismic character matches across the fault.

Furthermore, the software is able to remove folds by flattening the image on one or more manually interpreted horizons. The unfolding respects bed thickness and fault/horizon intersection angles around the unfolded horizon(s) but further away from the fault and the horizon the image can be deformed to correct for volume issues. Unconformities can be pointed out by selecting an interpreted horizon as such. This will cause a separation of the overlying units during deformation (if necessary) creating gaps in places where overlap would occur in the reconstructed section. In some cases check shot data from NLOG was used to convert additional wells (depth) into time domain in order to identify which specific seismic horizons should be correlated on both sides of the fault.

3.4.2 Manual Reconstruction

A number of cross-sections representative for the general structure of the DCG (see next Chapter) have been reconstructed manually. Fault relationships and thickness changes in sedimentary sequences have been interpreted to indicate the approximate timing of fault movement, halokinesis and unconformities. These interpretations are then used in a schematic reconstruction of several cross-sections throughout time. These are not true palinspastic reconstructions but must be regarded as reconstruction to represent the approximate regional evolution in a schematic way.

The remainder of this report contains information that is (temporarily) confidential.