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Author: Birgitte Kverneland	…………………………………………… (signature of author)

Faculty supervisor: Alejandro Escalona

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Triassic Reservoir potential in the greater Oda and Ula fields area, North Sea

by

Birgitte Kverneland

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Abstract

Triassic reservoir potential in the grater Oda and Ula fields area, North sea

Birgitte Kverneland, MSc

The University of Stavanger, 2019

Supervisor: Alejandro Escalona and Lars Aamodt

The objective of this thesis is to improve the understanding of the lateral distribution of the sandstones of the Skagerrak Fm, by using 3D seismic data and wells in the greater Oda and Ula field area. The Oda and Ula fields are located in the salt province in the Central Graben. Consequently, salt tectonics played an important role in the deposition of the Skagerrak Fm sands, resulting in a large lateral variation in thickness and facies. The composition of the salt also has a large impact on the supra-salt structural style, and furthermore the sedimentation of the Skagerrak Fm.

The interaction between salt tectonics and sedimentation is investigated in order to understand how salt related subsidence or uplift acted as depocenters for sedimentation. The main aim is to understand the facies distribution, to further build a conceptual model for sandstone fairways, and ultimately point to areas where there can be good quality reservoir potential in the Triassic.

Most wells in the salt province are placed in an interpod setting where the Skagerrak Fm is very thin or absent, since it has not traditionally been the main target. However, it is a proven working play, and is being produced in the Ula Field. It is therefore likely that there are commercial accumulations of oil other places as well in the Triassic section in the area.

Two different salt regimes has been defined, where one salt unit is mobile and halite-dominated. The other salt unit is interbedded with carbonates and anhydrite, and consequently a lot more viscous and non-mobile. The two salt regimes result in different subsalt structural style. The mobile salt unit result in a pod-area where accommodation space is created next to large salt structures, where the Skagerrak Fm sandstone can be deposited and preserved. In contrast, in the area of the non-mobile unit the Triassic thickness is relatively constant and the Top Triassic surface has a gentle topography.

The Skagerrak Fm is a part of a regional fluvial alluvial system, and is locally interpreted to be in a braided streams depositional environment with ephemeral lakes. Rivers have been directed into the pods, where there has been accommodation space for sediments to be deposited, and it is suggested that there is a good Triassic reservoir potential within the pods. The interpod area is farther away from the channel feeder, well logs show less developed sand packages and has possibly lower reservoir potential.

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1. Introduction

1.1 Motivation

The study area is located in the Central Graben in the North Sea, where important structural elements are the Cod Terrace and the Sørvestlandet High (Figure 1). This area has been studied in several decades, since the 1970's when petroleum exploration started in this area. Traditionally, the exploration has been targeting the Ula sandstone Fm of Late Jurassic Age, the Chalk formations Tor and Ekofisk, of Late Cretaceous to early Paleocene age, and the Forties Fm of Paleocene age (Gowers, 1995).

The Triassic has rarely been the main target, but the Triassic Skagerrak Fm play model was proven on the Ula Field in 1981, and recent well results have confirmed the Skagerrak Fm sandstones as potential reservoir in the area. Several discoveries in the UK sector close to the study area have proven oil or gas condensate from Late Triassic sandstones of the Skagerrak Fm (Figure 1) (Fisher and Mudge, 1998).

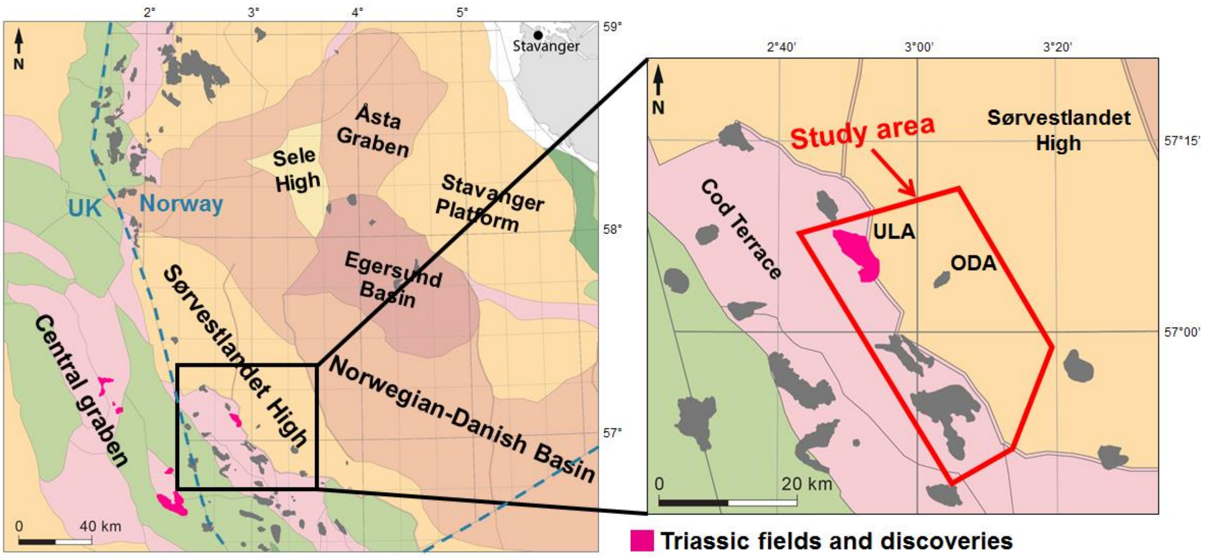


Figure 1: Approximate location of study area and the main structural elements in the neighborhood. Triassic fields and discoveries are shown in pink. Modified after NPD factpages and Evans et al., (2003).

Relatively little effort has been invested in understanding the Triassic stratigraphy on the Norwegian sector (Evans et al., 2003). The lateral distribution of the Skagerrak Sandstone is poorly understood and it is probably underexplored, on the NCS in this area. Figure 2 is a lithostratigraphic correlation of the Skagerrak Fm showing variations in thickness and GR log character. In well 8/10-4 S, the Triassic consists of shales only, while in the other wells good quality sandstone packages up to 20 meters are present. These variations are a result of the paleogeography, likely to be controlled by salt tectonics and faulting in the area.

Given the focus on the Ula Fm and chalk plays, most of the wells in the Central Graben on the Norwegian sector targeting the Skagerrak Fm have been placed in an interpod setting, on top of salt structures or very close to salt structures. Most wells have shown that the Triassic is very thin or absent. However, there are dramatic changes in thickness, and the Triassic is much thicker further away from the salt structures (Figure 3). The thickness changes are most likely related to salt movement, and are indicating that salt may have played an important role in controlling the depositional system and the distribution of sandstone and shale.

A seismic section and the corresponding geo-section are given in Figure 3. The wells shown are located in a typical interpod setting, from the Ula field, where the trap is a fault-bound dip closure and from the Oda field, placed on the flank of a diapir, where the Triassic pinches out onto the piercing diapir. Note also how the Triassic varies dramatically in thickness along the section, from the interpods where it is thin or absent to several hundred meters in the adjacent mini-basins. The Skagerrak Fm is thicker and more constant in thickness on the Ula field, compared to the Oda field where it is thinning towards the salt diapir. There were no indications of hydrocarbons in the thin Skagerrak interval in the Oda well 8/10-4 S, but in the Ula well 7/12-6 hydrocarbons were proven (NPD fact pages) (Figure 3).

Fisher and Mudge (1998) stated that the limited success obtained in the Triassic of the Central North Sea reflects lack of confidence in predicting a good reservoir, rather than lack of competent trapping and sourcing mechanisms. Thus, it is important to focus on research and studies on the reservoir distribution.

1.2 Objectives

The objective of this thesis is to improve the understanding of the lateral distribution of the sandstones of the Skagerrak Fm within the study area, by using 3D seismic data and wells in the greater Oda and Ula field area. The interaction between salt tectonics and Triassic sedimentation is investigate in order to understand how salt related subsidence or uplift acted as depocenters for sedimentation, and impacted the deposition of sand and clay in the Triassic. To further build a conceptual model for sandstone fairways. This will provide the basis for better predict the presence of the reservoir in this formation and set up the study area into the regional context for future more detailed studies.

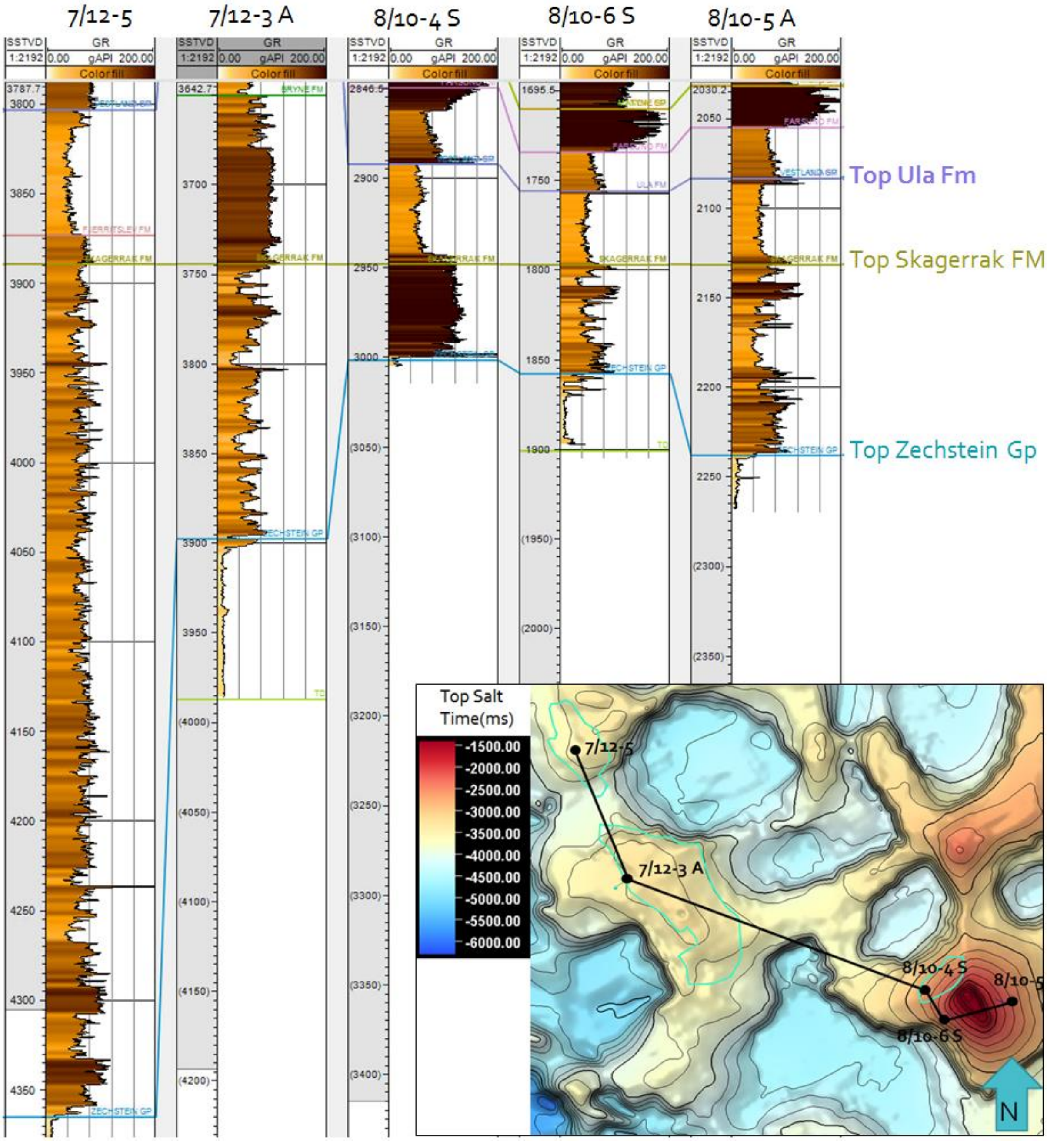


Figure 2: Lithostratigraphic correlation of the Skagerrak Fm, showing its heterogeneity and thicknesses.

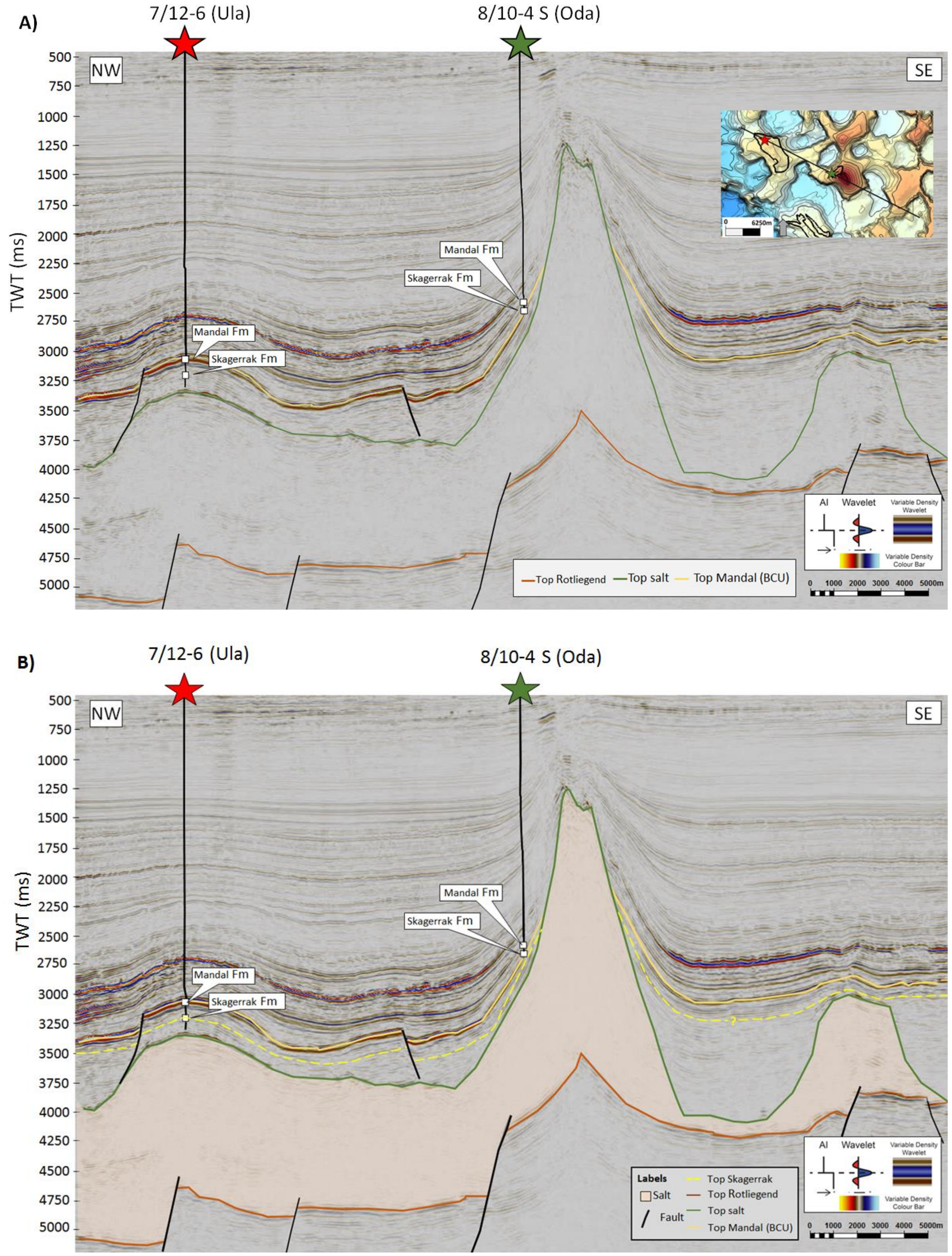


Figure 3: A) Seismic line from seismic cube FP17M02 going through well 7/12-6 on the Ula field and 8/10-4 S on the Oda field, showing salt structures and pods. B) Same seismic line with the salt filled with color and interpretation of Top Skagerrak Fm.
Note that it is not the real Top Rotliegend under the salt diapir, but a seismic velocity pull-up effect.

2. Previous work

2.1 Geological setting of the Ula and Oda field area

The tectonic framework of north-western Europe was developed in pre-Devonian. In Silurian, Baltica collided with Laurentia, and major low-angle thrusts formed the Scottish and Norwegian Caledonides, resulting in closure of the northern Iapetus Ocean (Evans et al., 2003). This was followed by rifting in the latest Devonian time to Middle Carboniferous times (Brekke et al., 2001). The crustal lineaments from pre-Permian time have acted as zones of crustal weaknesses, affecting the North Sea rift system (Evans et al., 2003).

The Pangea supercontinent was completely broken up in the period from the Late Permian to the Early Triassic. This period was the first rift phase, and it is likely that the Central Graben in the North Sea was formed at this time (Bell et al., 2014). The direction of the crustal extension is assumed to have been east west, resulting in faults trending north-south to northeast southwest (Figure 4a) (Færseth, 1996). The rifting period was followed by a period of thermal relaxation and differential subsidence of the graben floor in Late Triassic to Early Jurassic. Triassic sediments have accumulated in these subsiding areas with thickness of up to 4000 m. (Brekke et al., 2001; Lippmann, 2012; Ziegler, 1975) (Figure 4b).

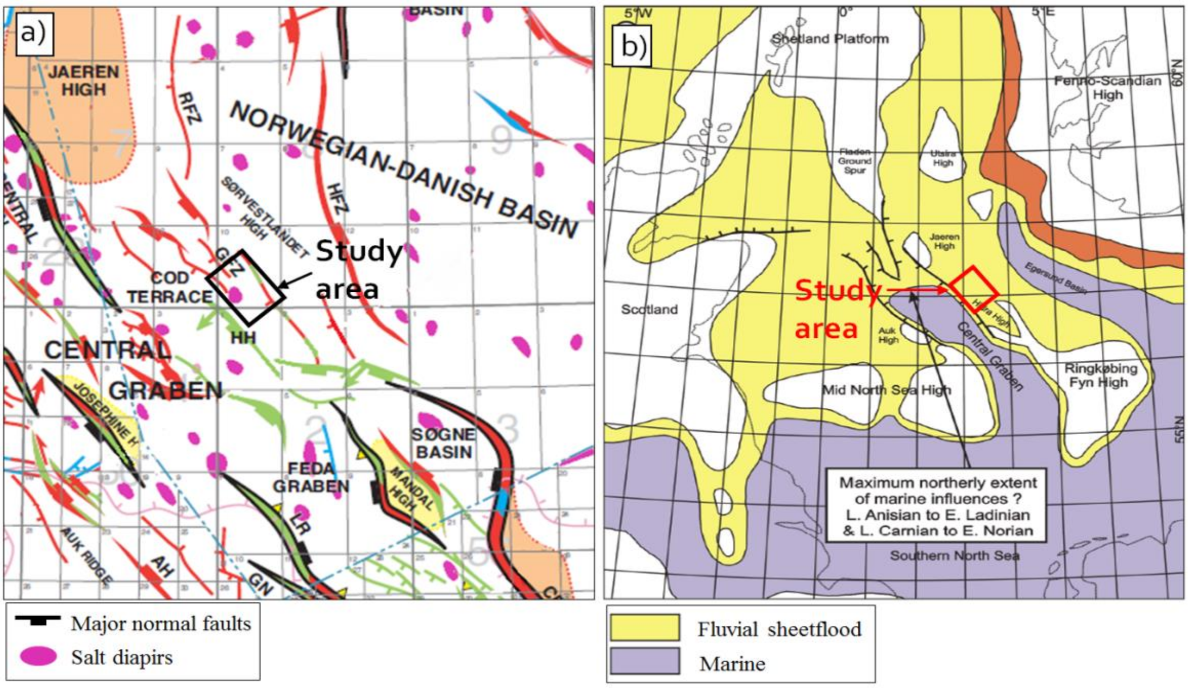


Figure 4: a) Structural map modified after Evans et al., (2003) b) Map of the distribution of the Triassic red beds, modified after Lippmann (2012)

A later rifting event took place from the Middle Jurassic to Early Cretaceous. This rift event is proposed to be related to rise and collapse of a thermal dome in the Forties region, caused by volcanism (Bell et al., 2014) (Figure 5). The faults created and/or reactivated during this rift period have the same strike as the earlier rift phase; north-south and northeast-southwest (Bell et al., 2014). The rifting caused uplift and erosion of footwalls, resulting in removal of large parts of the Triassic sediments (Evans et al., 2003) and decrease in the Triassic thickness.

The period from the Cretaceous to the Cenozoic was characterized by thermal subsidence and pulses of tectonic inversion. Another important event in the Cenozoic is the regional uplift of the basin margins, which lead to widespread erosion of the Triassic and Jurassic strata (Evans et al., 2003).

2.2 Depositional environment

2.2.1 Lithostratigraphy

The general lithostratigraphic column for the Sørvestlandet High and the Cod Terrace in the southern Central Graben is shown in Figure 5. The Triassic succession in the study area is composed of the fluvial to lacustrine Smith Bank Fm mudstones, followed by the heterolithic fluvial dominated Skagerrak Fm. This formation consists of interbedded conglomerates, sandstones, siltstones and shales (Figure 5) (Deegan and Scull, 1977).

The boundary between the two formations is considered to be diachronous, meaning that the Skagerrak Fm in some areas represents the lateral facies equivalent of the Smith Bank Fm and in other areas the Smith Bank does not exist and the Skagerrak Fm directly overlies the Zechstein Group (Fisher and Mudge, 1990). However, the fine-grained Smith Bank is the dominating formation in the early Triassic (Induan-Olenekian) (Evans et al., 2003).

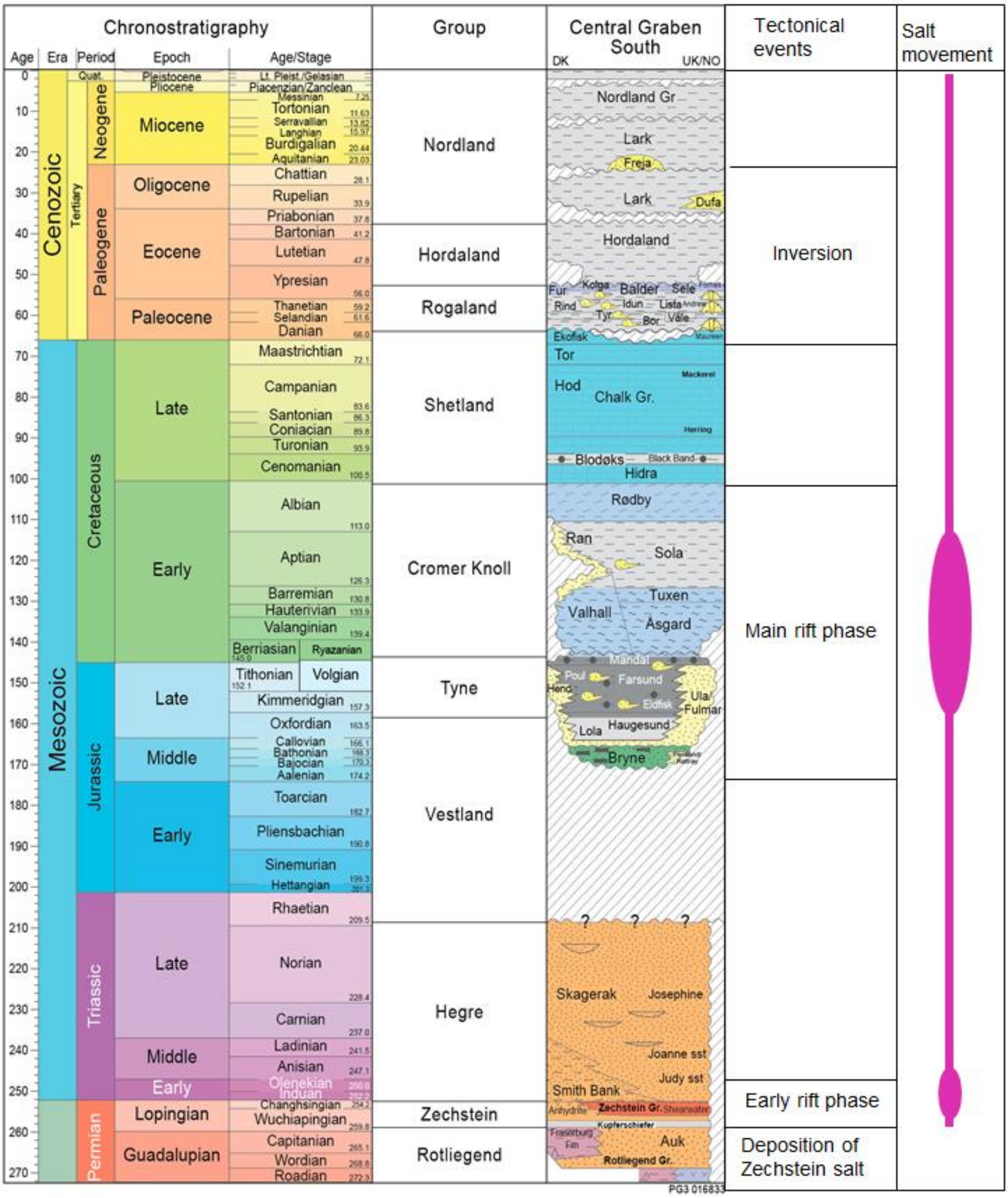


Figure 5: Lithostratigraphic column and main tectonic events for the study area, modified after (Volleset and Dorè, 1984) and Evans et al., (2003).

2.2.3 Climate and paleogeography

The climate in the Triassic was arid to semi-arid (Weibel et al., 2017). Due to northwards continental drifting, there was a gradual cooling of the climate and the humidity was in general increasing between Late Permian and Early Jurassic times (Evans et al., 2003). These climate changes together with changes in the base level had large impact on the regional depositional environments and lithologies.

According to Evans et.al, (2003) the Early Triassic Smith Bank Fm was deposited in a widespread lacustrine/floodplain environment under continental playa conditions (Figure 6). The playa muds are widespread representing the Early Triassic. The mud-prone deposits represent low-energy deposition, and the period is generally dominated by high water tables and low sand supply (McKie, 2014) (Figure 7).

Larger grain sizes in the Skagerrak Fm indicate that this formation was deposited in a higher energy system compared to the shaly Smith Bank Fm. The Skagerrak Fm was deposited as sheet flood and braided-stream sands on an extensive alluvial plain (Figure 6) (Evans et al., 2003). Coarse fluvial material was deposited along the rift margins, grading into finer fluvial- and lake deposits into the center of the basins (NPD, 2014). The fluvial sands were able to expand across the basin during periods of pluvial events with reduced aridity, and reached its maximum basinward extent in the Central North Sea during the Ladinian (Figure 7) (McKie, 2014, McKie and Williams, 2009).

The transport direction of the Skagerrak Fm fluvial and sheet flood sandstones is shown in Figure 8. The system interacted with both axial and transverse systems draining off the Scottish highlands and the Fennoscandia Shield hinterland. From here the eroded material flowed southward, past the study area, into the northern margin of the Southern Permian basin (McKie, 2014)

In the late Triassic the fluvial environment was replaced by vegetated floodplains (Figure 7) (McKie and Williams, 2009). There was a notable change from deposition of continental sandstones and mudstones to shallow- to deep-marine mudstones (Figure 6) (Evans et al., 2003).

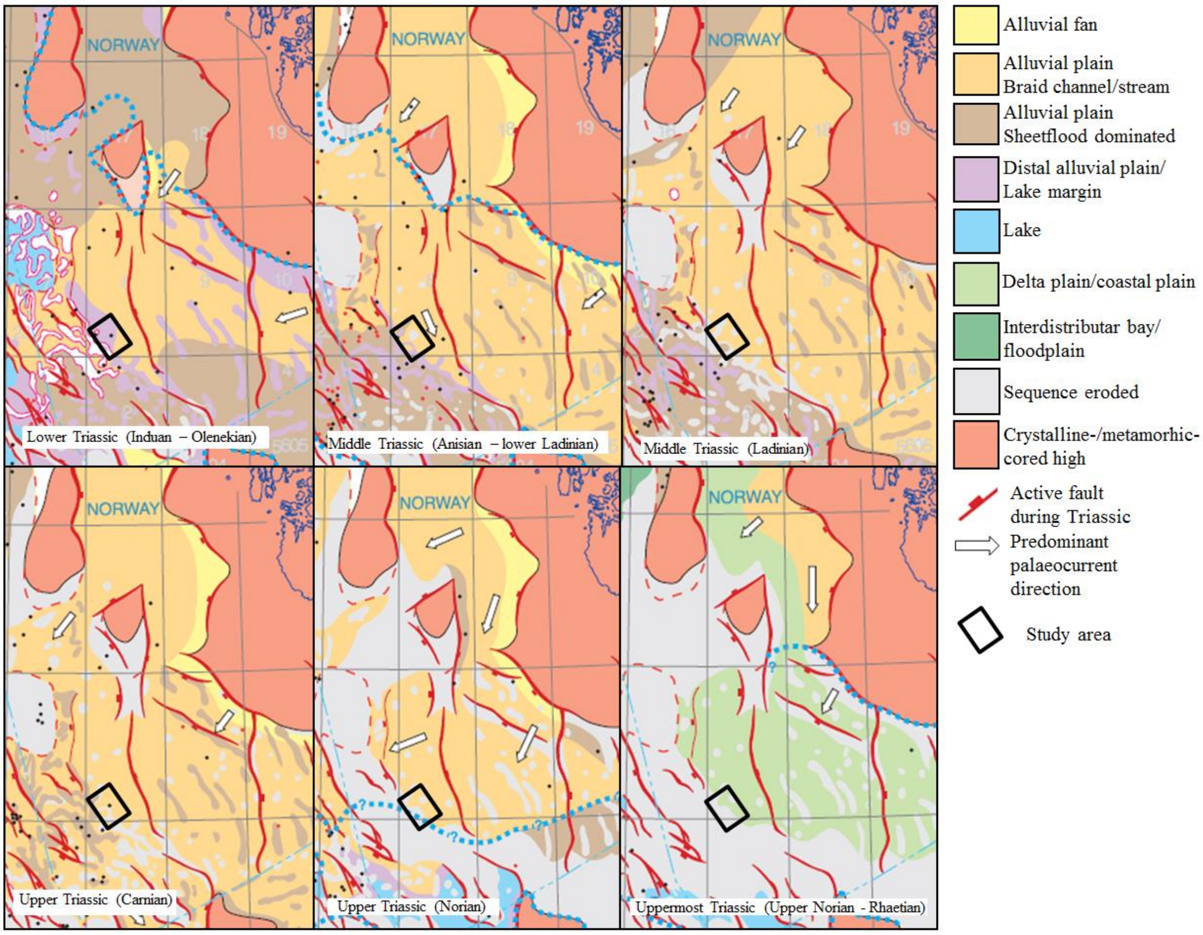


Figure 6: Depositional environment maps for North Sea Triassic, divided into six time sequences. The white arrows show how the sediments were sourced from the basement highs. The sediment transport direction was influenced by the active extensional faults (Evans et al., 2003).

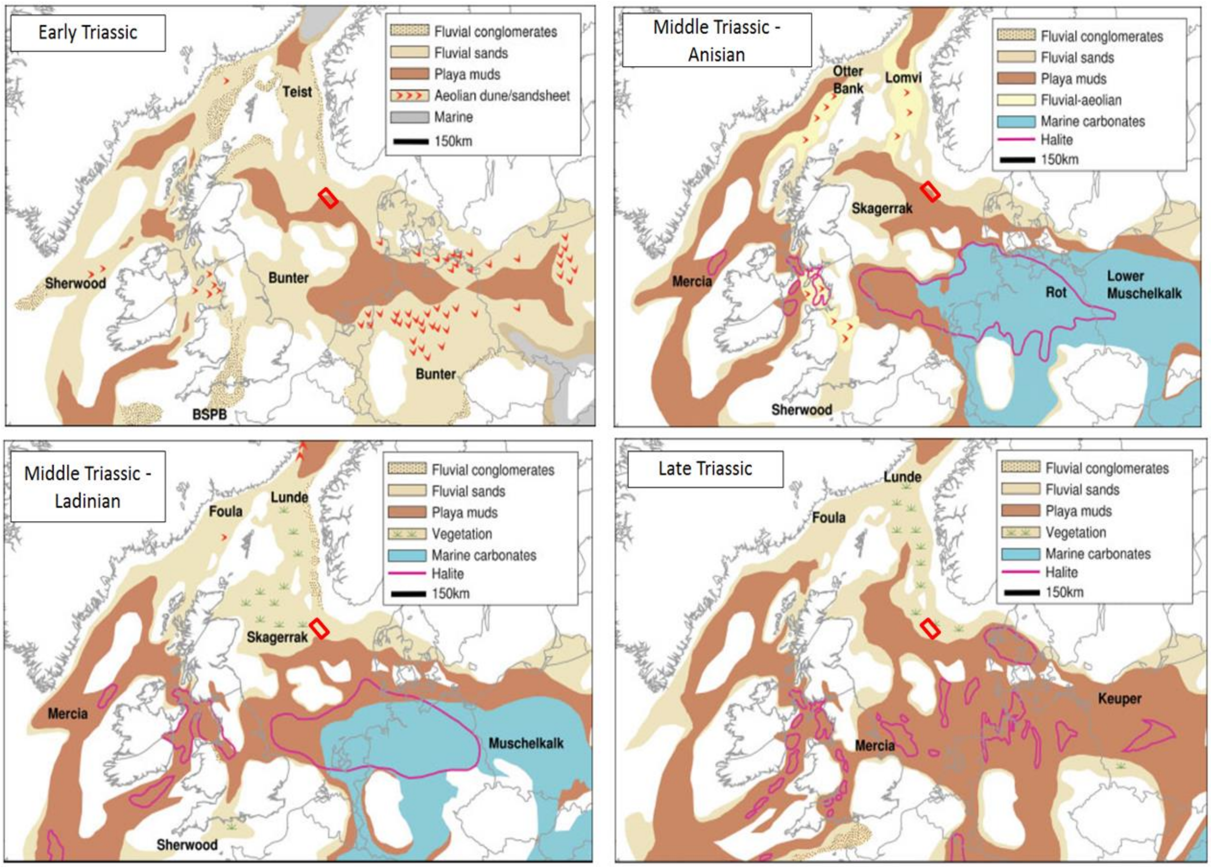


Figure 7: Triassic paleogeography (McKie and Williams, 2009). Approximate boundary of study area within red polygon.

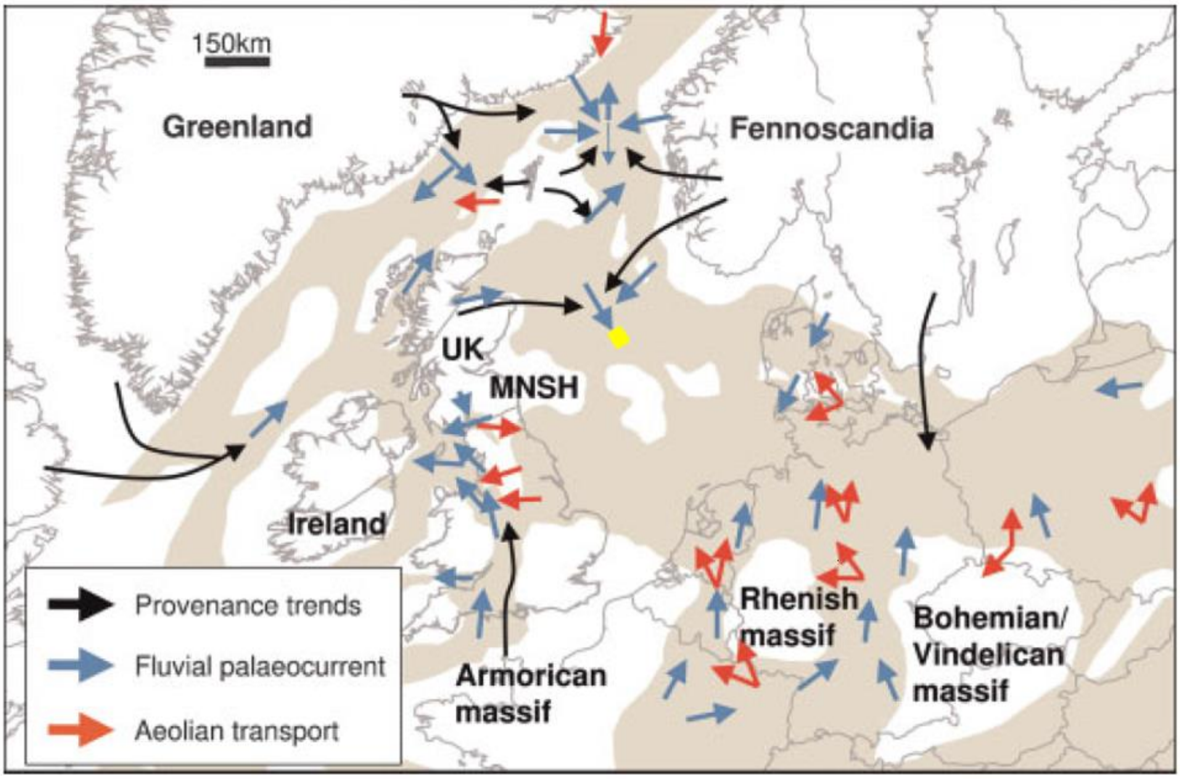


Figure 8: Regional Triassic drainage pathways (McKie and Williams, 2009). Approximate location of study area within yellow rectangle.

Cores

Well 7/12-6

Cores from well 7/12-6 show that the Triassic reservoir is of good quality (NPD fact pages). The reservoir consists of various types of micaceous sandstones that were deposited in a braided stream environment as a product of ephemeral streams. This interpretation is based on the high net to gross ratio, and it is therefore more likely that the environment is braided channel than an alluvial plain (Tveiten 1982). Irregular interbedding of various sedimentary structures is underpinning an environment with ephemeral streams (Tveiten. 1982).

The planar lamination observed indicates deposition in an upper-flow regime in fine grained sediments, and is interpreted to be flood-stage sedimentation (Figure 9) (Tveiten, 1982). On the other hand the cross laminated structures suggest transverse bars or reworking of sand waves, which is typical of braided rivers, and supports the facies interpretation (Figure 9) (Tveiten, 1982). In general for the whole core-section it is less common with structureless rocks, but they do occur, and an example of this is also highlighted in Figure 9.

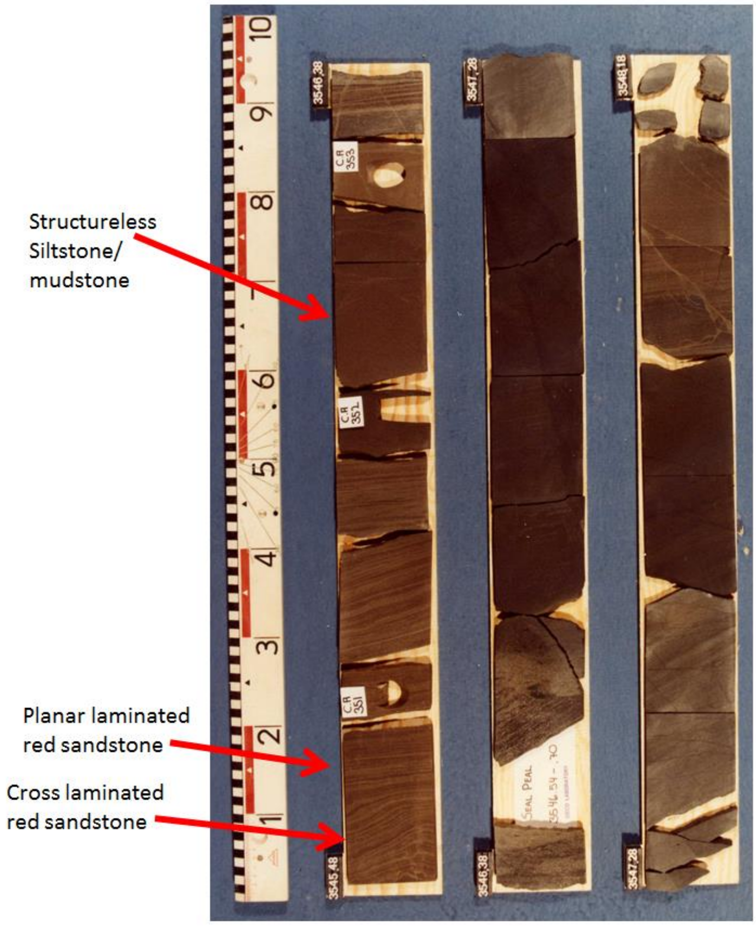


Figure 9: Core from well 7/12-6 from the Skagerrak Fm in the depth interval 3545-3538 (NPDfactpages).

Robertson, which is a part of CGG's Geoscience division, has published a core description of the same well, summarized in Table 1. This interpretation disagrees with Tveiten (1982) to some degree. The interval is interpreted to be deposited in an alluvial plain (Robertson, 1991). However, the sandstones are interpreted to be ephemeral fluvial channel fills, similarly to the interpretation by Tveiten (1982). The mudstones that are interbedded in the sandstones are interpreted to be overbank deposits or lacustrine muds.

Table 1: Table summarizing core chart from well 7/12-6 (Robertson, 1991)

Drilling depth in metres	Lithology description	Interpretation
3517-3532	Sandstone.Very fine to fine grain size. Upward fining units dominated by high to low angle cross bedding. Local horizontal lamination.	Alluvial plain. Ephemeral fluvial channel fill with calcretes.
3532-3541	Sandstone.Very fine to fine grain size.	Alluvial plain. Sand deposits by distal sheet floods. Minor wave reworking of sediment in shallow ephemeral lakes
3541-3555	Sandstone. Very fine to medium grain size. Common cross bedding. Current ripple lamination and parallel lamination. Interbedded with mudstone.	Alluvial plain. Fluvial channel fill sands and inter channel or overbank muds with possible calcretes
3555-3584	Sandstone. Very fine to fine grain size with very coarse and granule grade lags. Some upward fining units. Commonly with wavy indistinct horizontal lamination and slumps. Local horizontal lamination and low angle cross bedding. Interbedded with mudstone.	Alluvial plain. Stacked distal or infrequent sheet floods and minor ephemeral fluvial channel fill sands. Associated with minor inter channel or overbank muds.
3584-3611	Sandstone. Very fine to fine grain size with very coarse to granules sized lags. Some upward fining units. Common horizontal lamination. Local cross bedding, current ripple lamination and indistinct wavy horizontal	Alluvial plain. Stacked ephemeral fluvial channel fill sands and minor overbank or inter channel muds with possible calcretes.

	lamination. Interbedded with minor units of mudstones	
3611-3633	Sandstone. Local concentrations of intraformational mudstone clasts. Grain size is very fine to fine with local very coarse to granule grade lags. Predominantly horizontally laminated with local current ripple lamination, cross bedding and rare wavy horizontal lamination.	Alluvial plain. Ephemeral fluvial channel fill and stacked sheet flood sands with inter channel or overbank muds and possible calcretes.
3633-3665	Sandstone. With mudstone clasts occurring locally. Grain size is very fine to fine. Some upward fining units with common indistinct wavy lamination. Local horizontal lamination, current ripple lamination and minor low angle cross bedding.	Alluvial plain. Probable distal sandflat and, minor ephemeral fluvial channel fill sands. Associated with interchannel or overbank muds and possible calcretes.
3665-3685	Sandstone. Upward fining grain size profiles. Interbedded with mudstone.	Alluvial plain. Probable stacked sheet flood sands, ephemeral fluvial channel fill sands and overbank, inter channel or lacustrine muds.

Well 7/12-11

Cores from well 7/12-11 show conglomerates with matrix similar to sandstone (Figure 10), with a sharp erosional top. There is also a large degree of sandstones, siltstones with lamination and mudstone (Figure 10). The sediments are interpreted to be deposited in an unconfined sheet flood type fluvial setting (Vagle and Fjerstad, 1992). The mudstones are believed to be the result of lacustrine conditions, between floods (Vagle & Fjerstad, 1992).

According to the core description by Robertson (1991), the rocks in the core-interval are alluvial plain deposits. The interpretation agrees with Vagle & Fjerstad (1992) and suggests that the depositional process has been dominated by sheet floods with possible small scale ephemeral channels and shallow lakes.

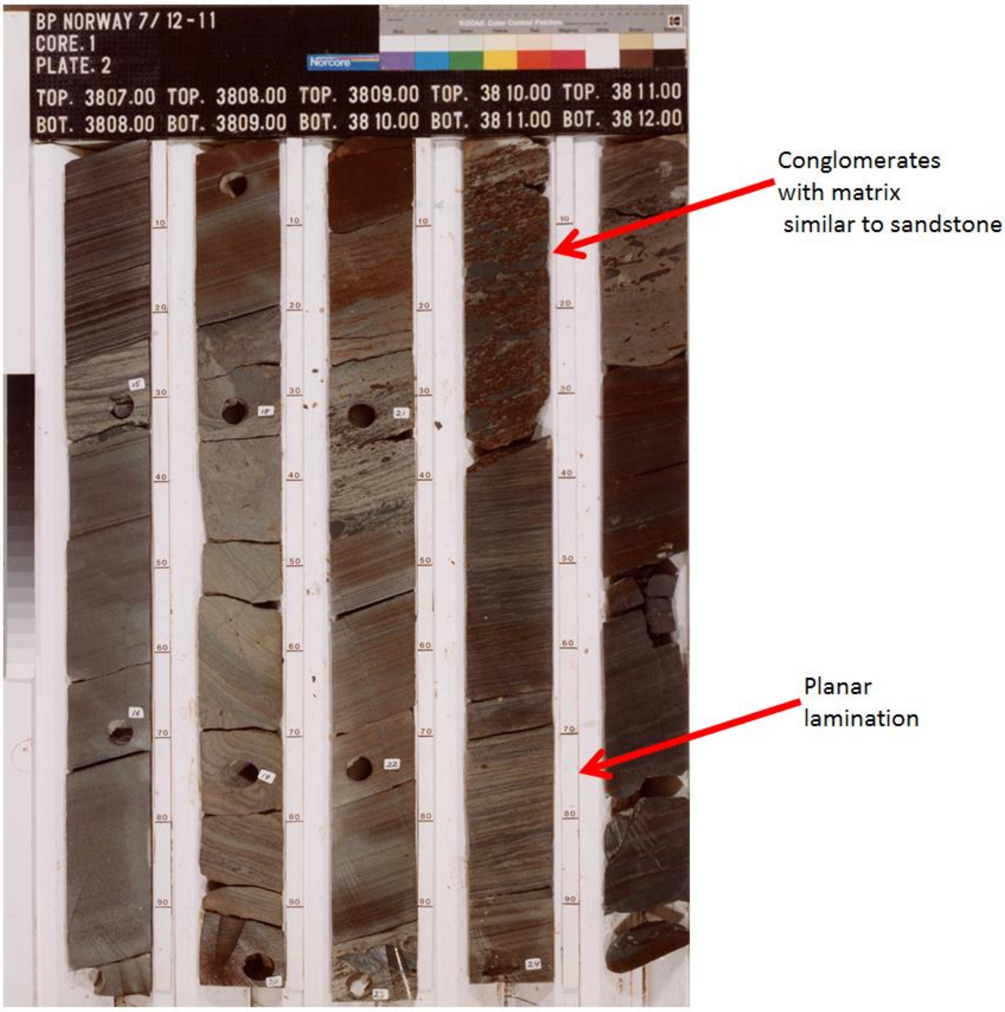


Figure 10: Core from well 7/12-11 from the Skagerrak Fm in the depth interval 3807-3812 (NPDfactpages).

2.3 Salt evolution and composition

2.3.2 Evolution of salt structures and pods

The Zechstein Group is a prominent and extensive salt giant, which covered much of NW Europe during the Late Permian (Bachmann et al., 2010). The salt deposition and movement significantly influenced the patterns of tectonics and sedimentation on the Cod Terrace and Sørvestlandet High, resulting in a large degree of lateral discontinuity of the Triassic strata (Fraser et al., 1993).

The salt movements were activated by sediment loading and fault activity (Smith et al., 1993). Pods started to subside during early extension in the early Triassic, and salt walls started to grow adjacent to the pods (Figure 11) (F. Karlo et al., 2014). When the salt growth stopped salt welds were formed. The subsidence in the pods then also ceased and the Triassic pods grounded on the base of the salt. This led to salt wall collapse and creation of synforms over collapsing salt walls that were infilled by sediments from Triassic, Jurassic and Cretaceous (Smith et al., 1993).

Triassic sediments were reworked as they were transported into the mini-basins (or pods) in between the salt structures (Figure 12), resulting in depocenters where thick Triassic sediments have accumulated (Christensen and Korstgard, 1994; Hodgson et al., 1992). Over the salt structures on the other hand, the Triassic strata is very thin or absent (Figure 11).

The thickness of the salt structure depends on the initial salt thickness compared to sediment supply. A higher sedimentation rate than diapir growth produces a narrowing upward diapir, and a higher diapir growth than sedimentation rate creates a widening upward diapir (Giles and Lawton, 2002).

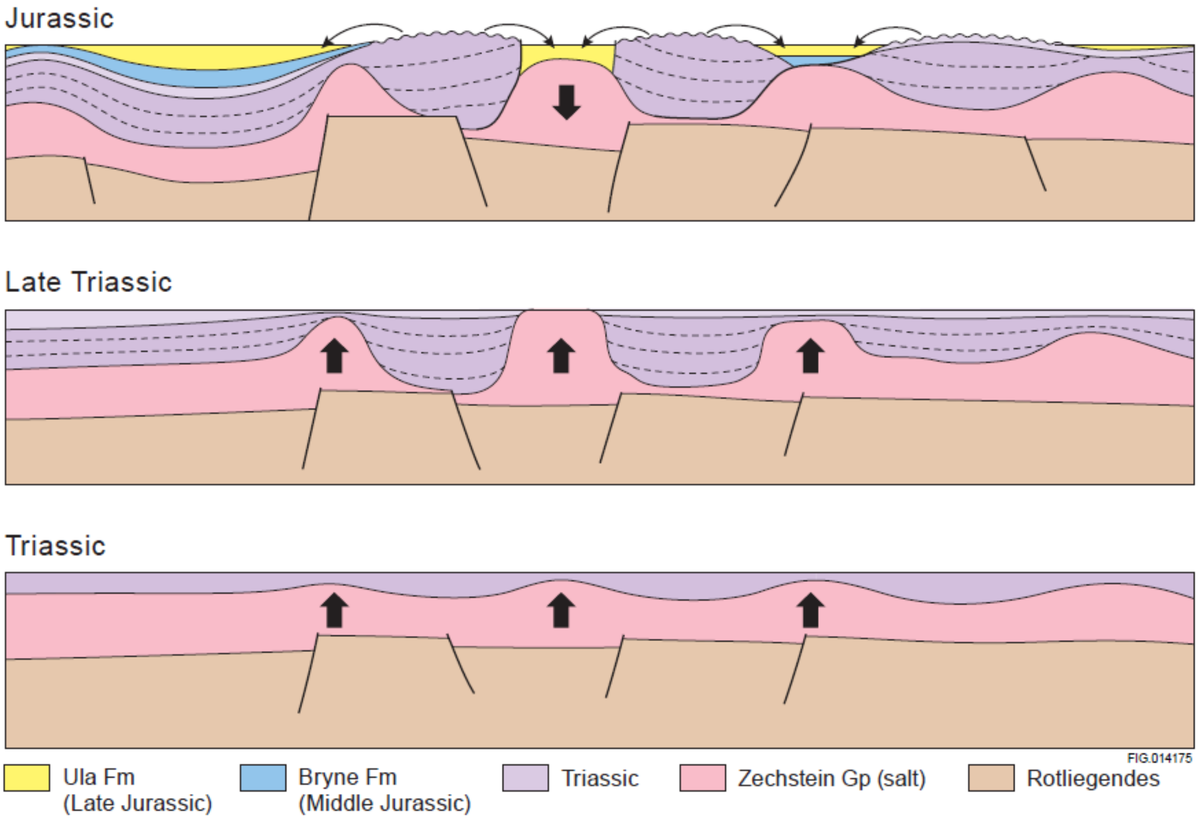


Figure 11: Model explaining structural development, sediment deposition and generation of accommodation space for Triassic and Jurassic sediments by salt withdrawal, deflation and dissolution. Modified from (Bjørnseth and Gluyas, 1995).

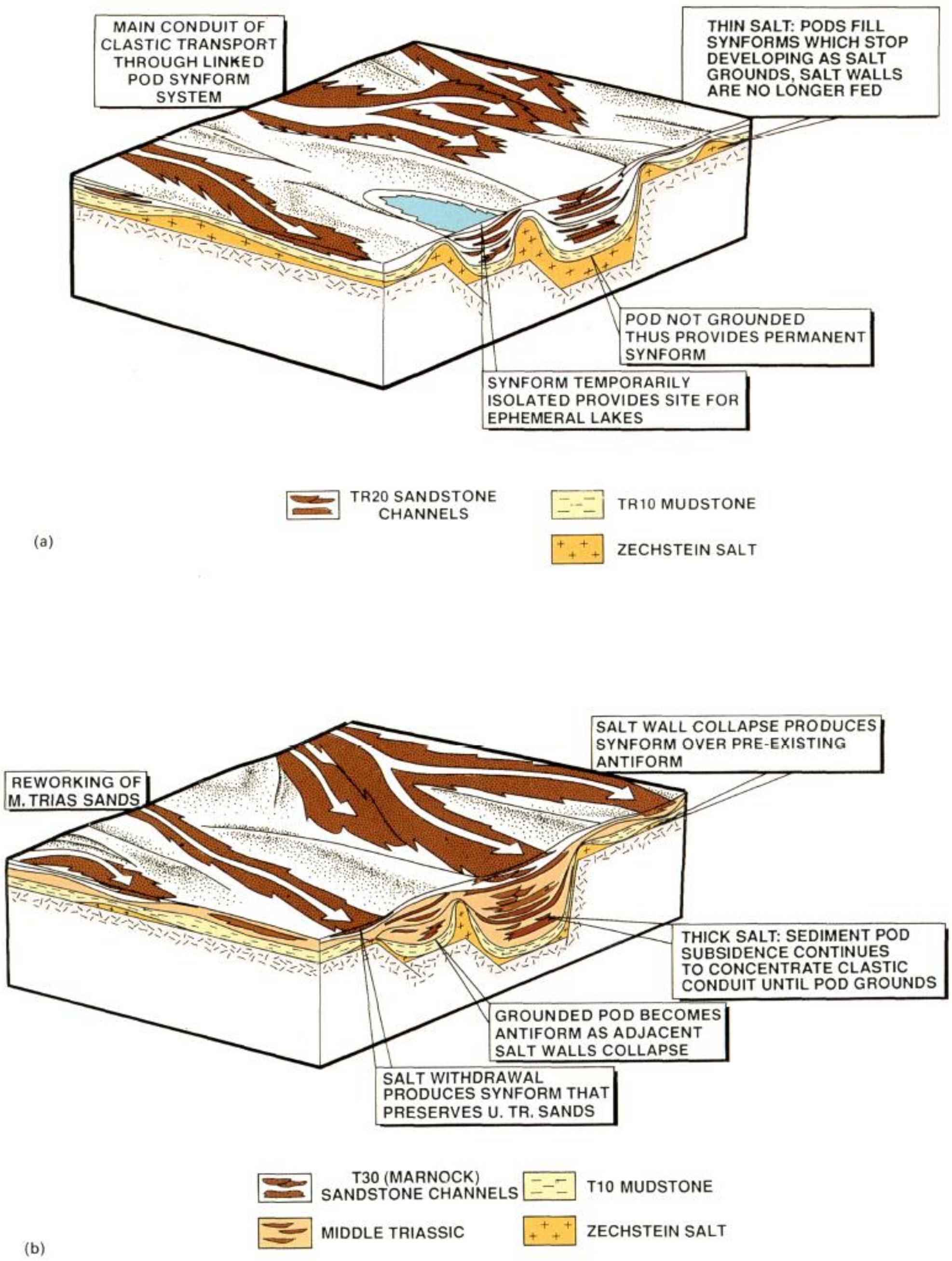


Figure 12: Model of the evolution of Triassic pods (Smith et al., 1993).

2.3.1 Different salt regimes

Salt giants are usually halite-dominated rocks. However, due to cycles of evaporation and freshening of the water, most of salt-related basins do not exclusively consist of halite (Hudec & Jackson, 2017). They also consist of layered evaporate sequences (LES), interbedded with other lithologies such as carbonates and fine siliciclastics (Hudec & Jackson, 2017). This is also observed within the Zechstein Supergroup (ZSG) (Figure 13). During relative high sea level, carbonates and anhydrite were deposited, while in periods of relative low sea level halite is more likely to be deposited (Jackson and Stewart, 2017).

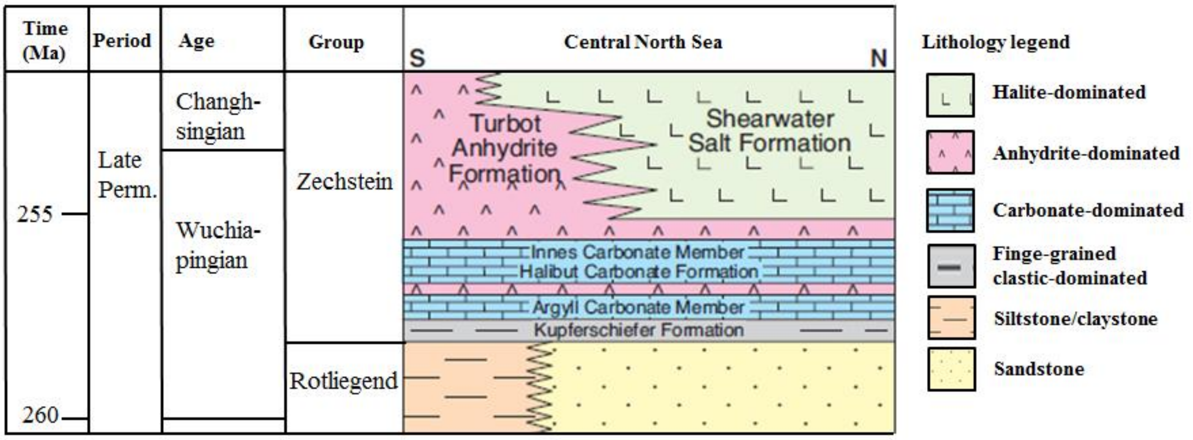


Figure 13: Zechstein Supergroup lithostratigraphic framework of the Central North Sea, modified from Evans et al., 2003 and Jackson and Stewart (2017).

The lithology of the salt controls its ability to flow or fracture, and consequently the rheological variation strongly influences the supra-salt structural style. Halite-dominated rocks and carbonate-dominated rocks have different styles of deformation when buried and stressed. Non-evaporate lithologies such as carbonates and anhydrite are brittle and resistant to flow, and make the salt layer very viscous. A salt layer dominated by these lithologies will therefore be faulted during stress, whilst a halite-dominated layer will be deformed in a ductile manner (Jackson et al., 2019).

In carbonate-dominated area a basement-involved normal fault is therefore able to cut through the unit and extend up into the Mesozoic and sometimes even, Cenozoic succession. In contrast, where the salt layer is thick and halite rich the subsalt faults and supra salt faults will not be connected, and the supra-salt fault will detach to the salt-layer (Jackson et al., 2019). The structural style in the carbonate-dominated area is therefore likely to be characterized by hard-linked faults, whereas areas mostly composed of halite will be dominated by soft-linked faults (Jackson and A Stewart, 2016). Figure 14 illustrates these two different fault linkages.

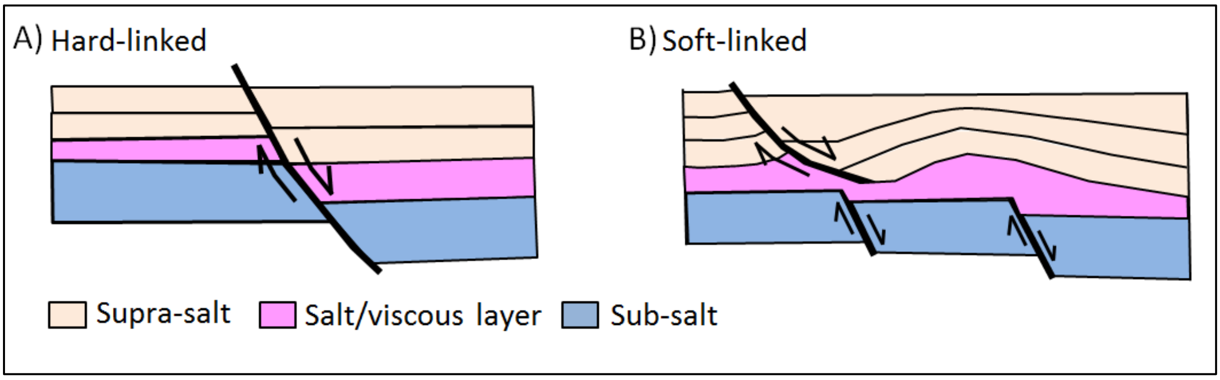


Figure 14: Illustration of two different fault linkages which is associated with two different salt regimes. The hard-linked fault is a continuous planer fault from sub-salt layer to supra-salt layer, and the soft-linked fault is detached onto the salt layer. Modified from (Gabrielsen et al., 2016).

Variations in salt composition also influence the distribution and size of the salt structures, which further makes an impact on the Triassic thickness (Jackson and A Stewart, 2016). Classic salt-tectonic with diaprism and mini-basin development dominates in areas where the salt is thick and halite-rich (Figure 15). Large salt pillows and diapirs, and salt withdrawal mini-basins filled with Triassic strata will occur in these areas (Jackson and A Stewart, 2016). Above the salt structure the strata will be very thin or absent, and there will be a thinning and onlap of the Triassic succession towards it, if the salt moved during deposition.

In areas where the salt is thin or halite-poor large diapiric structures cannot develop, and only very minor diapirism occur in these areas (Jackson et al., 2019). There is very little relief at the top of the salt-layer, and the Triassic strata has minor thickness variations, creating a stable Triassic platform (Figure 15). In the light of this it is important to differentiate between the less mobile salt unit and the mobile unit. This is in order to know in which areas the salt might have controlled the Triassic sedimentation; by creating depocenters and also possible barriers for the drainage system.

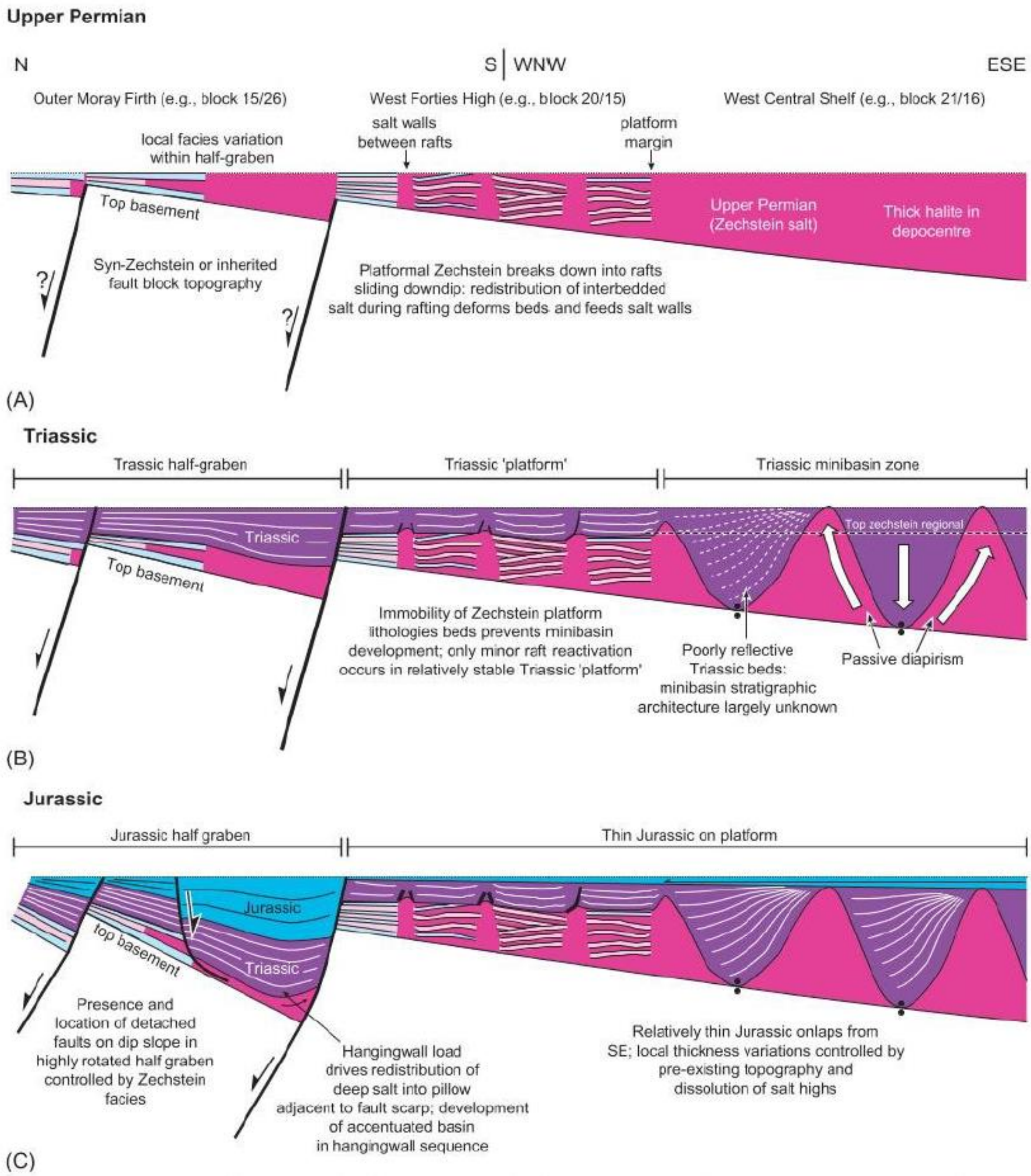


Figure 15: Different structural styles and difference in Triassic thickness, as a result of variations in lithology within the salt layer (Jackson and A Stewart, 2016).

3. Data and Methods

3.1 Dataset – Seismic and Well Data

The dataset used during this project includes checkshots, logs and tops from wells listed in Table 2, and a seismic cube (FP17M02) (Figure 16). The cube is approximately 32x40 km and consists of 2599 in lines and 3277 crosslines. Both the crossline and inline interval is 12,5m. The coordinate reference system used is ED50-UTM31.

Spirit Energy Norway AS, Aker BP ASA and DNO North Sea (Norge) AS have provided the 3D seismic data. The well data is from Diskos and is publicly available.

Table 2: Summary of the different well information (NPD)

Well	Type	Year	TD (MD)m	Oldest rocks penetrated	Field
7/12-11	Exploration	1991	3868	Late Triassic	
7/12-6	Exploration	1981	3700	Triassic	Ula
7/12-3 A	Exploration	1977		Late Permian	Ula
7/12-8	Exploration	1988	3900	Late Triassic	Ula
7/12-9	Exploration	1990	3820	Triassic	Ula
8/10-1	Exploration	1969	3089	Late Permian	
8/10-4S	Exploration	2011	3071	Late Permian	Oda
8/10-6 S	Exploration	2014	2256	Permian	
8/10-5 S	Exploration	2014	2925	Permian	
8/10-3	Exploration	2010	5738	Early Permian	
2/1-10	Exploration	1991	4525	Triassic	
2/1-2	Exploration		3555	Late Permian	
2/1-4	Exploration	1982	4525	Late Permian	Gyda
2/1-3	Exploration	1979	4297	Late Permian	Gyda

2/1-8	Exploration	1985	4151	Triassic	

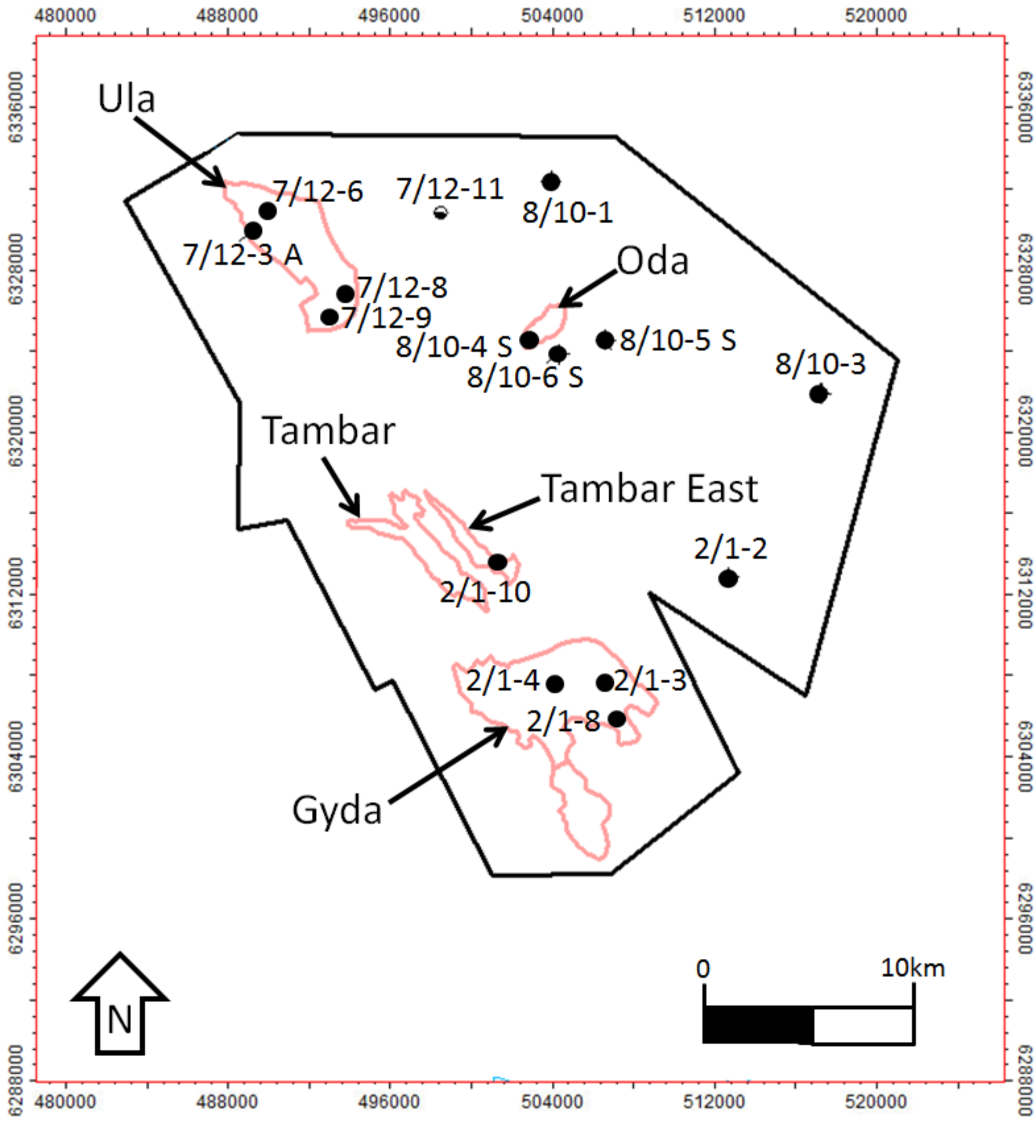


Figure 16: Outline of FP17M02, which also defines the study area. Location of wells used and fields within the study area are also shown.

3.1.1 Quality of the seismic data

The quality of the seismic data is expressed in means of horizontal and vertical resolution, which measures the level of detail that can be resolved in a reflection seismic profile. The vertical resolution has been calculated by dividing the velocity by the dominant frequency ($\lambda = v/f$), to get the wavelength. The vertical resolution is then ¼ times the wavelength; $VR = ¼ * v/f$ (Kearey et al., 2002).

The results of the calculation of the vertical resolution and the wavelength at three different depths in the Triassic interval are listed in Table 3.

Table 3: Calculated results of the wavelength and vertical resolution at different depths within the Triassic interval.

Depth (MD)	Frequency	Average velocity	Wavelength	Vertical resolution
3414m	25Hz	3504m/s	140,16m	35,04m
3473m	25Hz	4135m/s	165,4m	41,35m
3524m	25Hz	4218m/s	168,72m	42,18m

3.2 Methods

- Regional compilation of existing literature regarding structural evolution of the pods, depositional environment of the Skagerrak Fm and paleogeographic maps of the Triassic.
- Petrophysical analysis and stratigraphic correlation of the wells.
- Seismic well tie. The well tie will be used to identify key seismic reflectors such as the Base Cretaceous Unconformity (BCU), Top Zechstein Gp and Top Skagerrak Fm.
- Seismic interpretation; tracking of key horizons, faults and salt structures. In order to provide a better understanding of the stratigraphy in the pods/interpods.
- Seismic facies character analysis
- Structural and thickness maps, to gain an understanding of the structural configuration of the study area and to illustrate depocenters and variations in accommodation space
- The regional and the interpreted data will be used together to analyze the interaction between tectonics and sedimentation in order to establish a model for sandstone fairways and depocenters.

3.2.1 Seismic to well tie

A seismic well tie was done in two steps. The first step was to calibrate the sonic log with the checkshots; secondly a synthetic seismogram was generated. The synthetic seismogram was generated by convolving the sonic and density log with either a wavelet deterministically derived from the seismic in the neighborhood of the well, or by using a 25 Hz Ricker wavelet. This process was applied to all the wells listed in table 1.

The main objective of generating a synthetic seismogram was to tie seismic data to borehole geology, to better interpret and correlate the different reflectors. The quality of the well ties to the main reflectors is considered to be good (Figure 17 and Figure 18). The polarity of the FP17M02 survey is zero phase normal polarity, an increase in acoustic impedance is a red reflector (Table 4 and Figure 18). The polarity of the seabed is opposite of the Base Cretaceous reflector (Mandal Fm).

Table 4: List of mapped seismic horizons with their response in acoustic impedance.

Horizon	Acoustic Impedance	Seismic response	Pick confidence
Mandal Fm	Decrease	Through (Blue)	High
Skagerrak Fm	Decrease	Through (Blue)	Medium
Zechstein Gp	Increase	Peak (red)	Medium

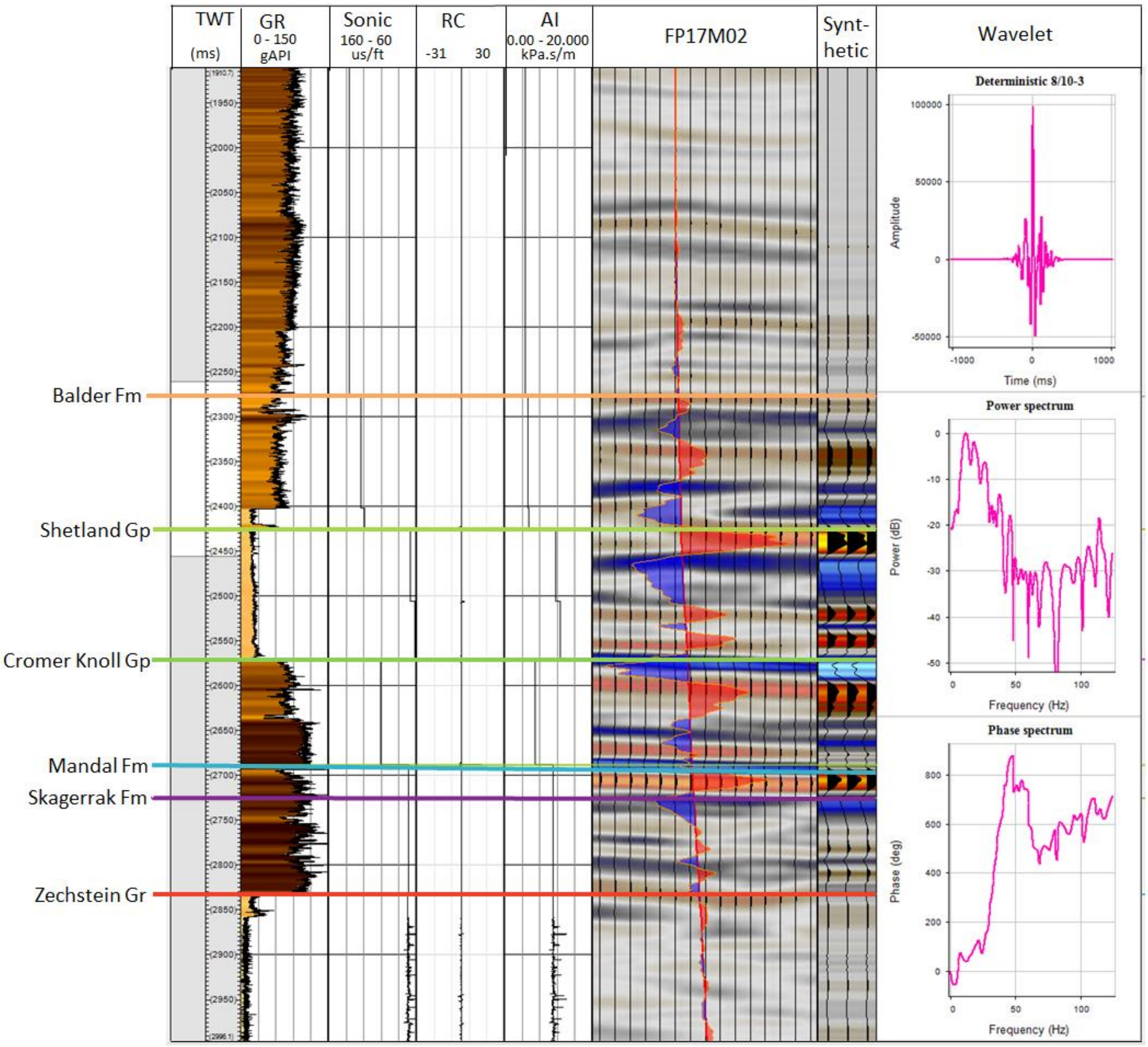


Figure 17: Well 8/10-3 Synthetic Seismogram. The 8/10-3 well is tied to the FP17M02 survey.

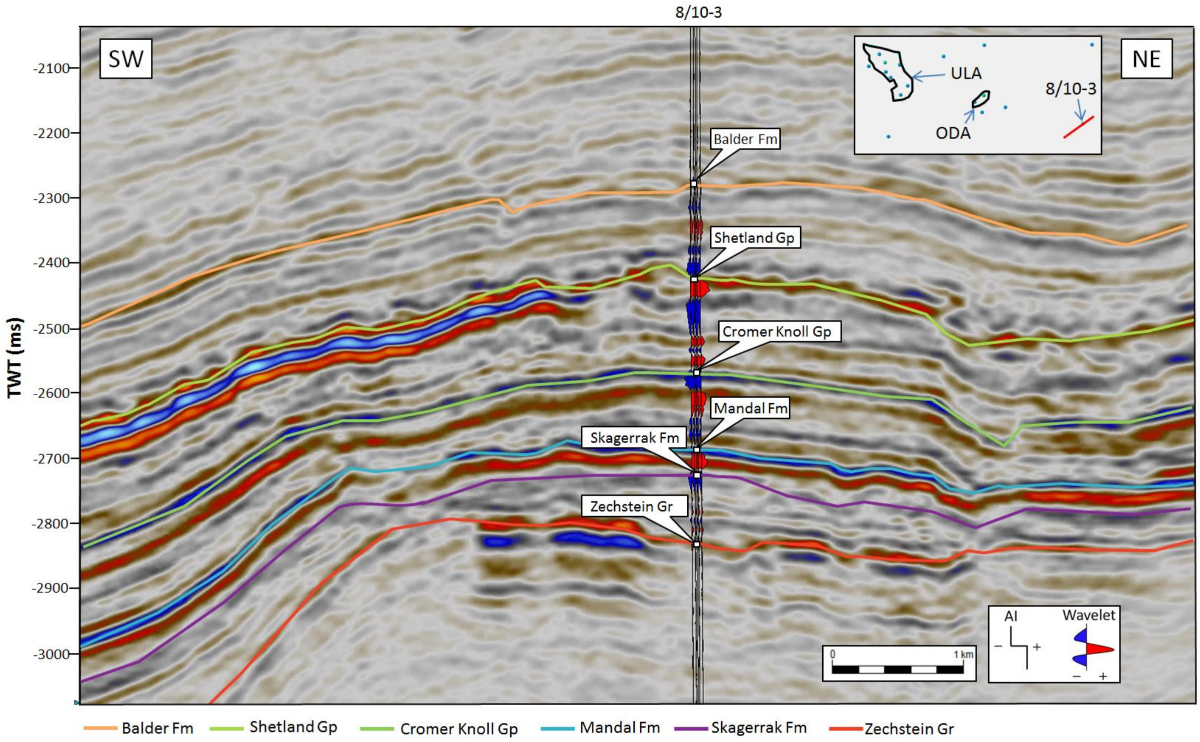


Figure 18: Well to Seismic Tie, Well 8/10-3. Good tie to all reflections and no shift applied.

3.2.2 Seismic interpretation

There are a few challenges when interpreting in this area. Well control of the pod stratigraphy is lacking, and there are several multiples in the pre-BCU section. The base of chalk (Ekofisk Fm) and base of Cretaceous (Mandal Fm) generate strong multiples. These are most visible within the Triassic pods, and sometimes they can hide the real dips of the Triassic strata. Additionally, there is a small acoustic impedance contrast between the Zechstein salt and the Triassic sediments, making interpretation of the geometries and onlap relationships on the flanks of the salt structures difficult (Figure 19).

To enhance the seismic resolution during seismic interpretation a few seismic attributes have been applied. For seismic horizon interpretation the attribute structural smoothing has been used, which reduces noise and enhances edges, making the reflectors more continuous. Cosine of phase also helps to better visualize continuity of seismic horizons, and this attribute has been especially useful to interpret onlap relationships on the flanks of salt structures (Rojo, 2015) (Figure 19). For fault detection the variance attribute helped to enhance the visibility of the discontinuity trends in the seismic volume, especially on time slices (Figure 20). It calculates the amplitude difference between neighboring seismic traces.

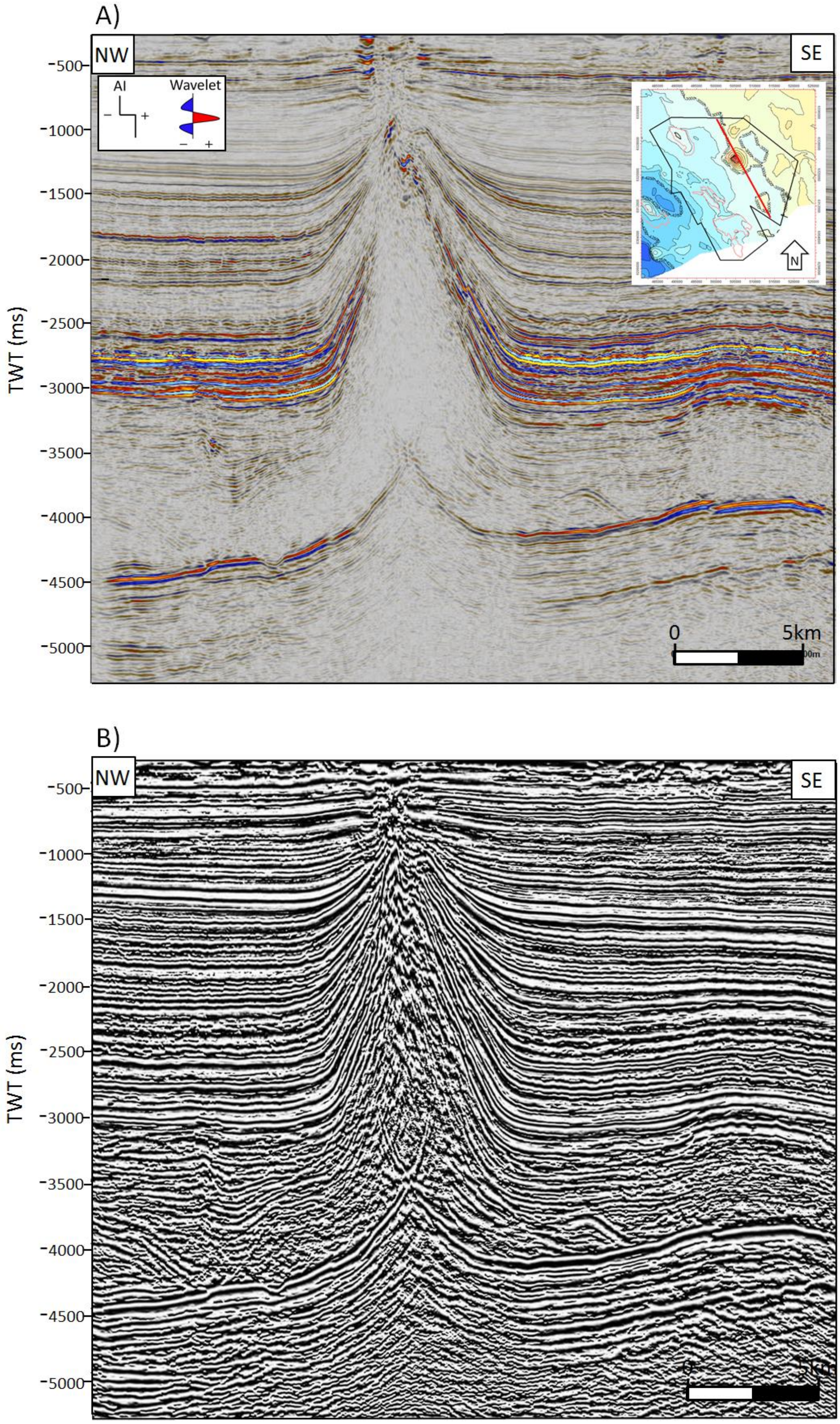


Figure 19 A) Seismic section through the salt diapir at the Oda field B) The same seismic section with the amplitude cosine of phase applied, which enhances the continuity of the reflectors and strata terminations. Location of line is shown on map.

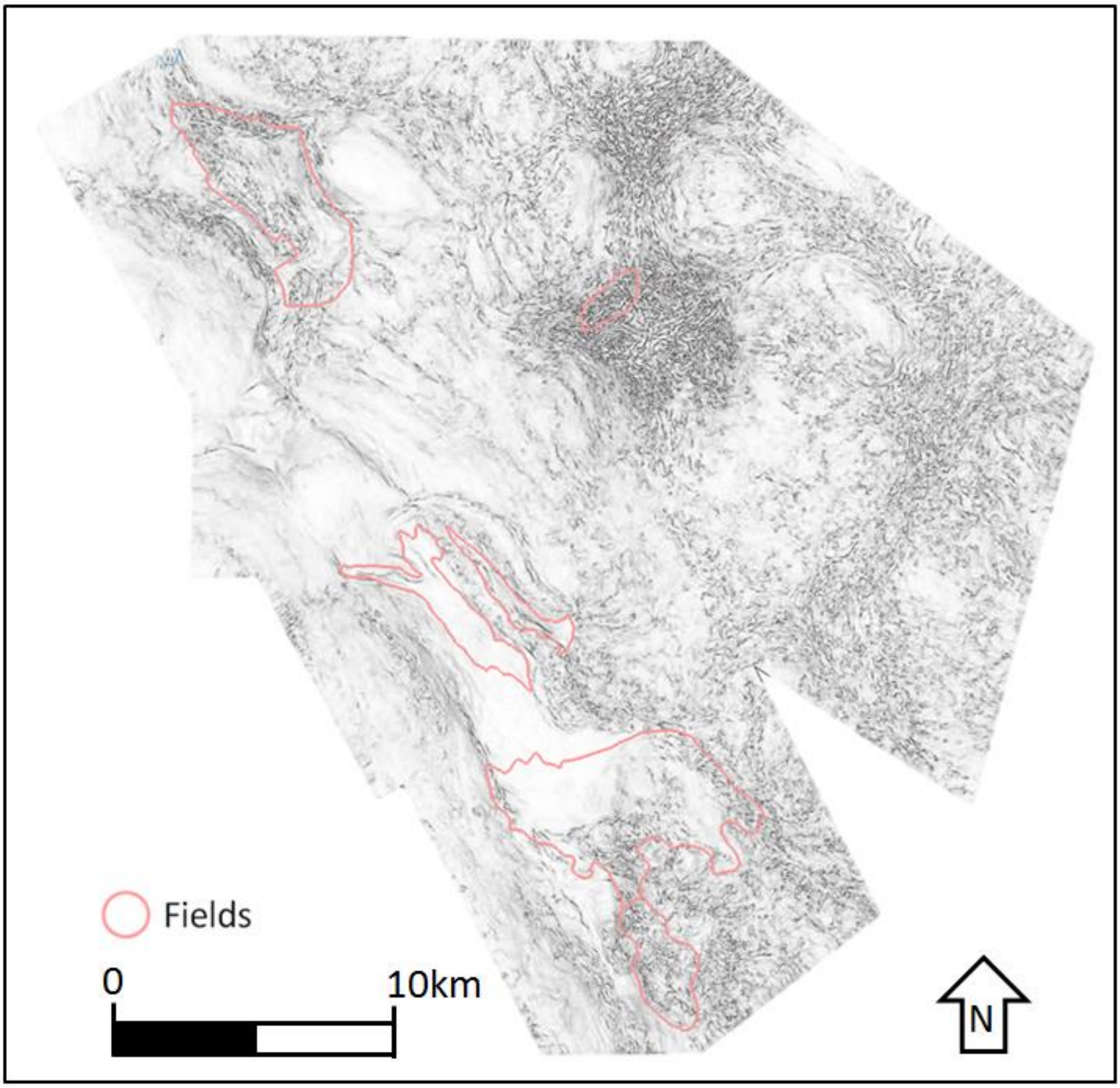


Figure 20: Time slice showing how the variance attribute can visualize discontinuitiy trends in the seismic volume

3.2.3 Depth conversion

The depth conversion method was carried out using the First Geo hiQbe regional average velocity model. The velocity model is based on released seismic stacking velocities and checkshots, and is calibrated against released exploration wells. The depth map fitted well with the well tops, and no bulk shift was applied. A QC of the TWT and depth maps has verified that structures have not been created in depth that were absent in TWT.

3.2.4 Well log analysis and correlation

The well log signatures have been interpreted and correlated, using the well tops provided by NPD. The gamma-ray log, which is the result of the naturally occurring gamma radiation in the rock, has been used to identify stacking patterns and log patterns that can give indications of the depositional environment. However, the GR-logs in the wells used are not normalized, and since we know that sandstone can also contain gamma radiation, particularly in continental environments close to the provenance area, one should always be careful to use the GR-log to differentiate between sand and shale. For this reason a neutron-density cross plot have been used in addition to the GR log when analyzing and correlating. A large separation between the density-neutron log indicates shale, while low density and neutron values indicate a more porous rock type (Figure 29).

4. Observations and interpretations

4.1 Structural framework

The faults within the study area can be divided into two groups, the sub-salt faults and the supra-salt faults. However, in some cases the sub-salt and supra-salt faults are connected, and are therefore called hard-linked faults (Figure 14). Yet, most of the supra-salt faults are soft-linked to the sub-faults, via salt detachment, or they are not connected at all. The supra-salt faults are the main focus of this thesis, and have been mapped and divided in to two fault families based on similar strike, timing and fault style (Figure 21).

Fault family 1 (FF1) is a part of the main supra-salt fault system, which is of Triassic/Jurassic age, and its strike is NW-SE. These are high-angle normal faults, forming half- graben structures (Figure 22). In some areas they are dipping toward each other, forming fault-controlled graben systems. This fault family also consists of some hard-linked faults, marked in purple in Figure 21.

Fault family 2 (FF2) strikes E-W. Besides that, the dip angle is similar to FF1 and the faults form half graben structures. Most of the faults terminate at the BCU level, but there are a few that also offset the entire Cretaceous sequence (Figure 23)

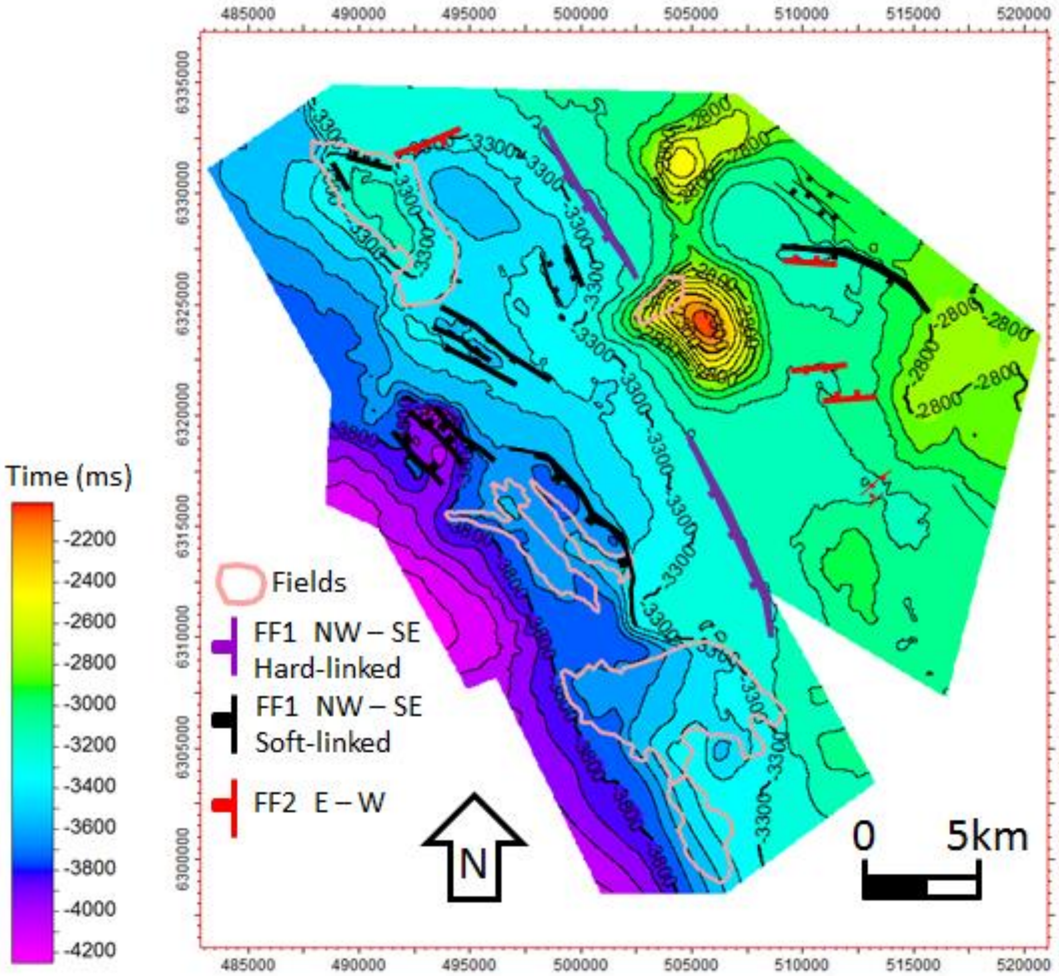


Figure 21: TWT structural map of the Skagerrak Fm and the two different fault families identified (FF1 and FF2).

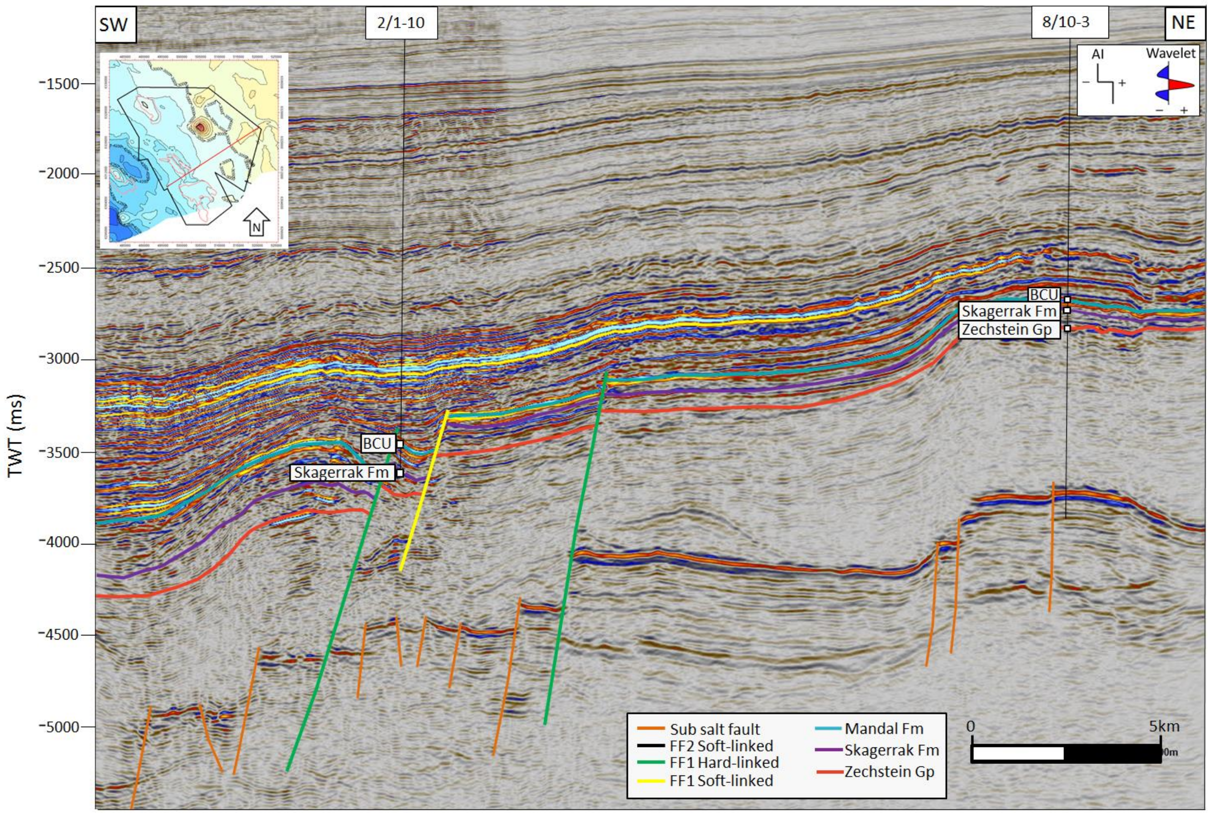


Figure 22: Interpreted SW-NE seismic line through well 2/1-10 and well 8/10-3, showing examples of fault family 1 faults.

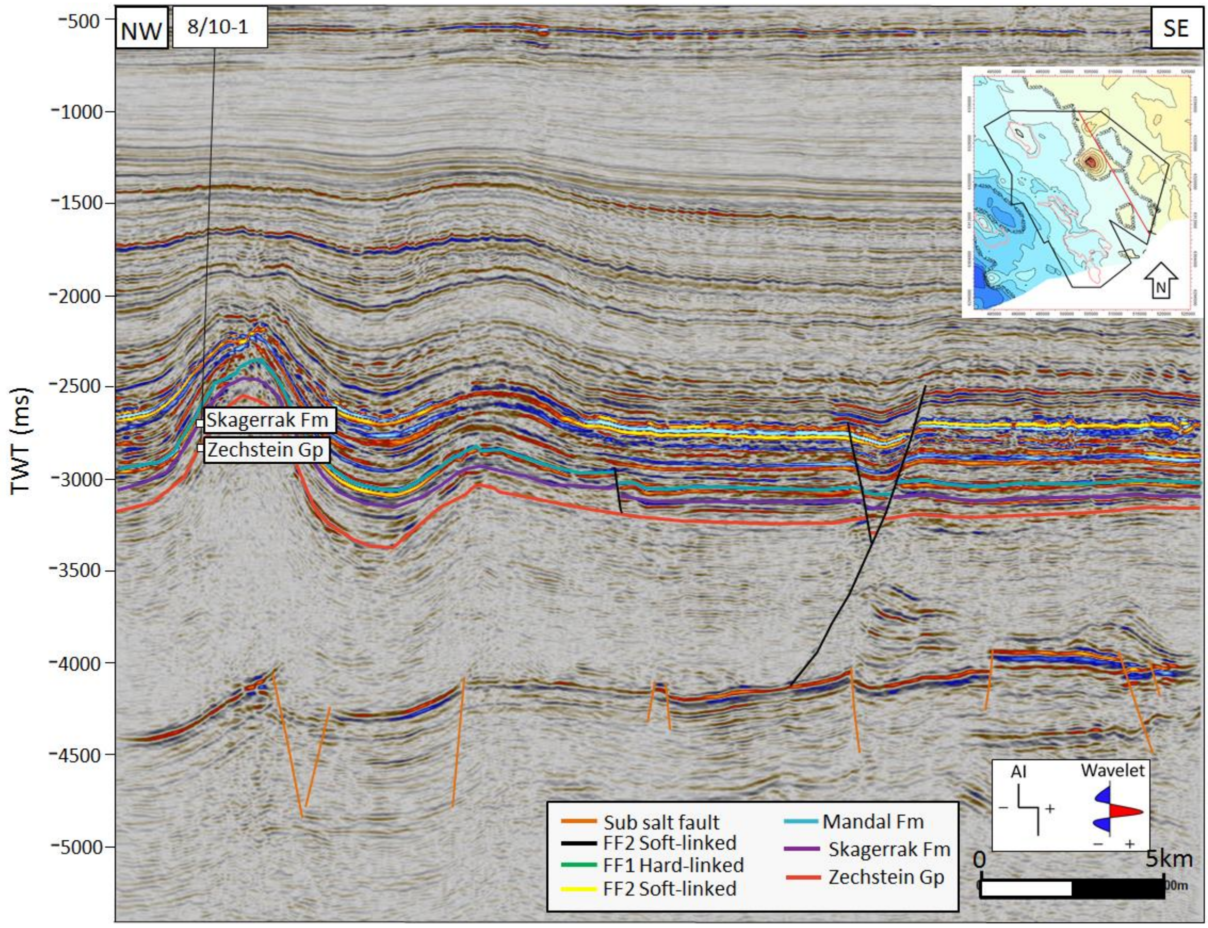
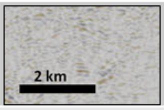
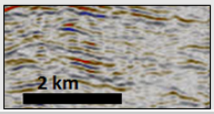
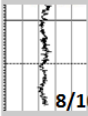
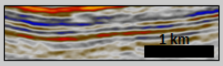
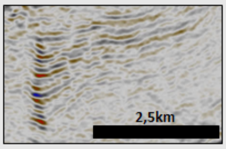
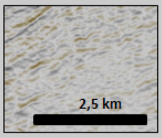
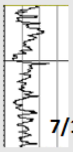
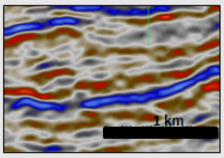


Figure 23: Interpreted NW-SE seismic line going through well 8/10-1, showing examples from fault family 2.

4.2 Seismic facies

Six different seismic facies have been identified. They are characterized by different reflection geometries and amplitude characteristics. Table 5 shows a summary of these characteristics, the spatial distribution and possible interpretations. The facies are correlated with GR-logs where there is well control, however most of the seismic facies have not been tested by wells and the interpretation is therefore uncertain.

Table 5: Summary of the characteristics and interpretation of the seismic facies identified, with one example of each facies.

Seismic facies	Refletcion geometry	Amplitude characteristics	Spatial distribution/ Interpretation	(GR) log pattern example	GR description	Example of seismic facies in the study area
SF 1	Chaotic	Low amplitude	Dominating in the NW in the study area. Halite-dominating salt layer.	Lack of well data		
SF 2	Subparallel and discontinous	Medium amplitude	Dominating in the SE in the study area. Halite interbedded with carbonates and anhydrite.	Lack of well data		
SF 3	Parallel, continuous	Medium to high amplitude	Occurs mainly where the formation is thin. Shale, braidplain	 8/10-4A	Aggrading. Overall high GR value	
SF 4	Wedge shape, semi-continous	Medium amplitude	Occurs in minibasins/high thickness. Stacked braided channels/ delta/lacustrine	Lack of well data		
SF 5	Discontinous and chaotic	Low amplitude to transparent	Dominant in minibasins. Shale, lacustrine. Could be Smith Bank Fm	Lack of well data		
SF 6	Sub-parallel	Medium amplitude	Occurs all over the study area. Braid plain + ephemeral lakes	 7/12-3 A	Blocky to erratic. Increasing upward.	

The seismic facies distribution is shown in Figure 24. The facies nearby most of the wells are dominated by seismic facies 6 in the interval between the Skagerrak Fm and Zechstein Gp, whereas facies 4 and 5 are dominating within the pods where there is no well control. Seismic facies 1 and 2 is found within the Zechstein group, where there is also no well control.

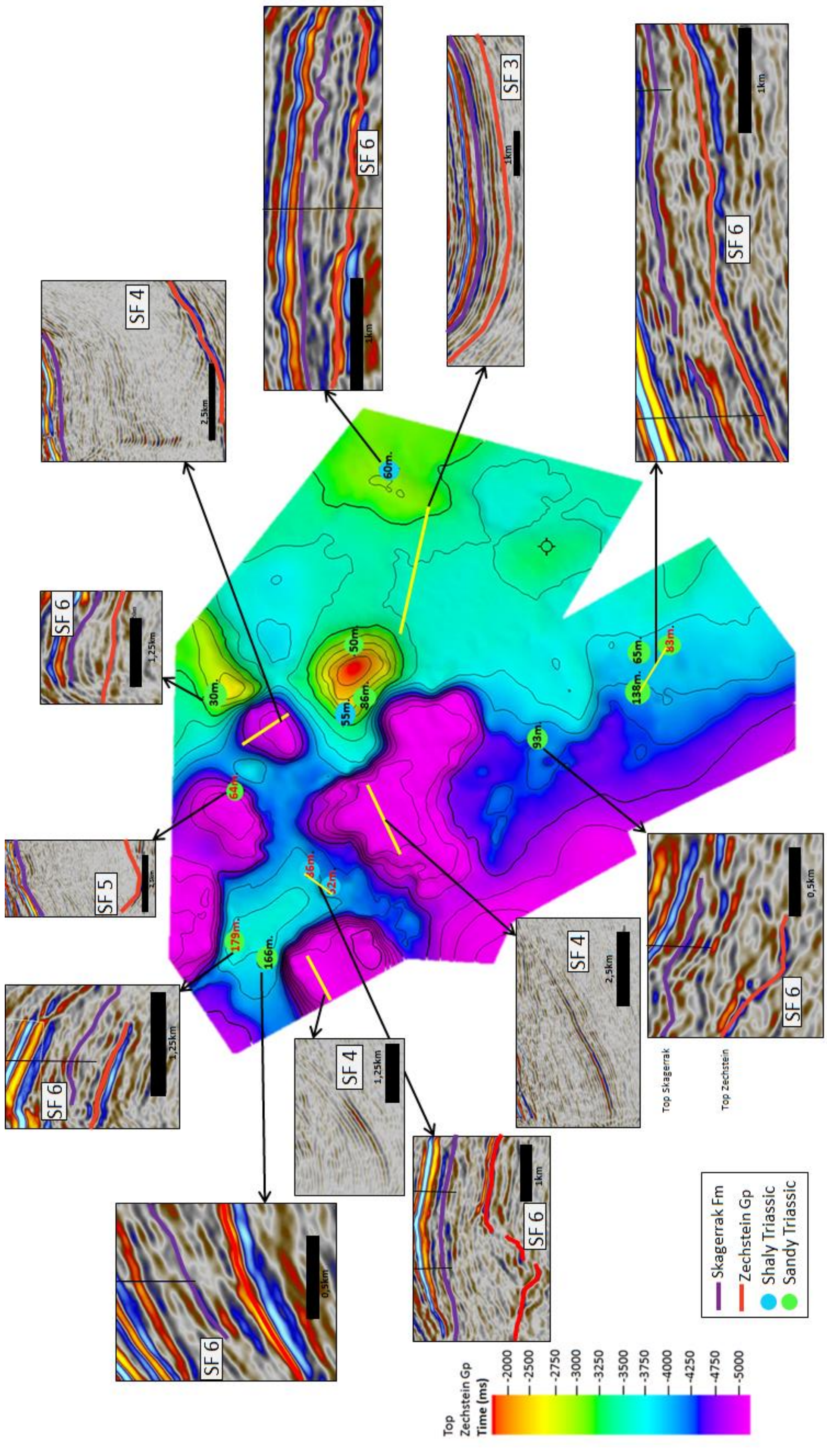


Figure 24: Distribution of the seismic facies

4.3 Late Permian

4.3.1 Seismic observations

Two main seismic facies have been identified within Zechstein Group of Late Permian age. SF1 is characterized by a chaotic seismic response with low amplitude, and SF2 has a more subparallel seismic response with medium amplitude (Figure 25 A).

There is a notable difference in structural style associated with these two different seismic facies. Seismic facies 1 (SF1) dominates where the faults are soft-linked, while seismic facies 2 (SF2) dominates in areas with hard-linked faults. Above SF2 there is minor thickness variation in the Triassic compared to the large variation in Triassic thickness seen above SF1 (Figure 25 B). In some areas, the Triassic strata are thinning toward SF1, and in other places, depocenters are forming above it where the Triassic sequence is at its thickest. Areas dominated by SF2 are characterized by rollers and small salt pillows whereas larger diapirs are more characteristic for SF1.

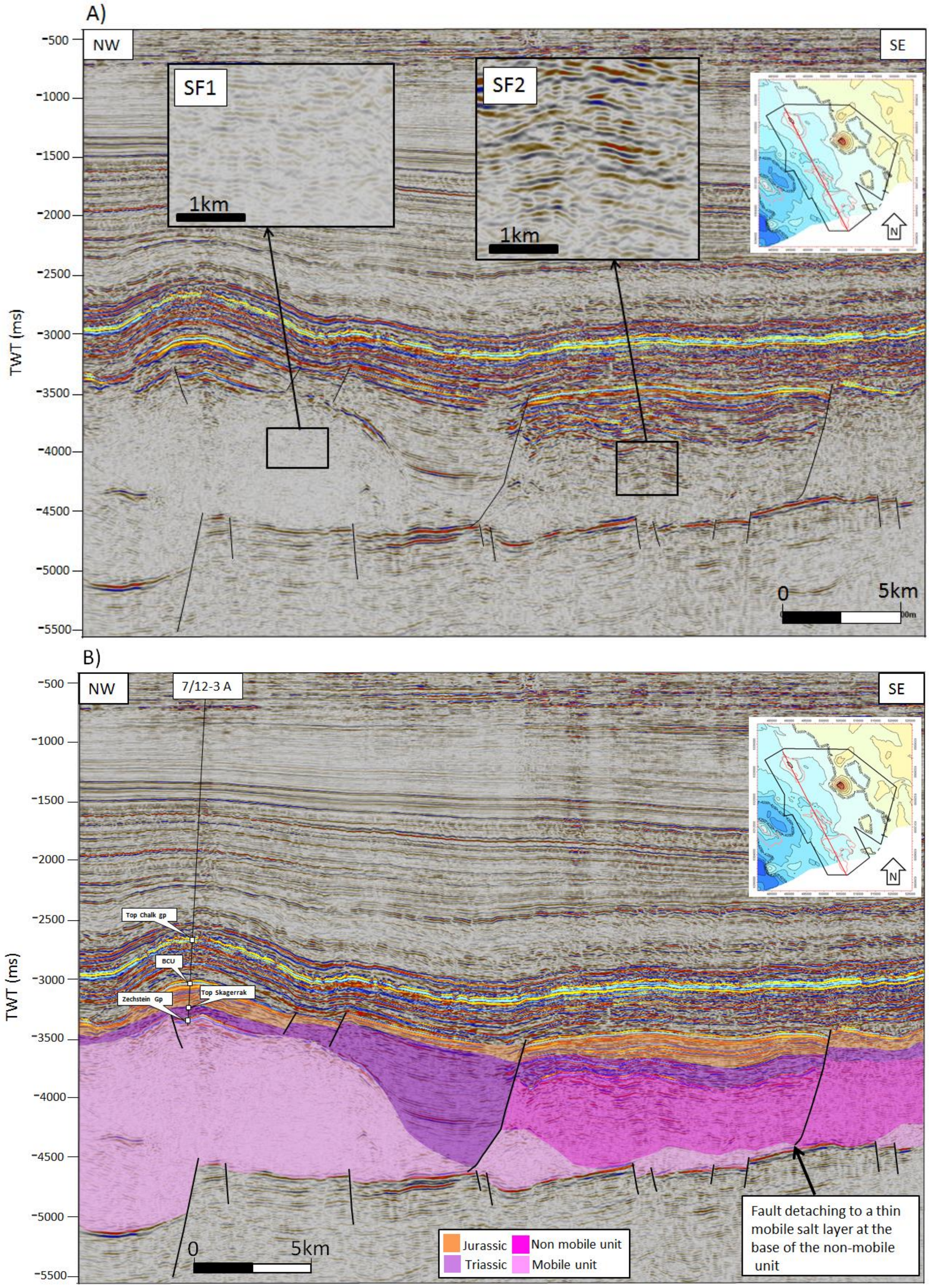


Figure 25 A) Seismic line going through well 7/12-13 A highlighting the two different seismic facies observed within the Zechstein group. b) Interpreted seismic line going through well 7/12-13 A

4.3.2 Maps

Figure 26 A shows a depth structure map of the Top Zechstein Gp. The deepest areas are located in the NW, and this is also where the highest salt structures are also placed, next to the deepest areas (Figure 26 B). The highest salt structure is clearly the salt structure at the Oda field, which can be identified on the depth map by the red color, and highlighted in figure 26 B. The area in the SE is less deformed than in the NW, and the topography is much gentler (Figure 26).

SF1 and SF2 have been mapped out, and Figure 27 shows that SF1 is dominating in NW, where the pods are separated by a polygonal pattern of salt structures. In contrast, SF2 is dominating in SE, which is an inter-pod area. This area can be compared to what Jackson and Stewart (2017) called Triassic “platform” area, since it has not been deformed and has a relatively low relief.

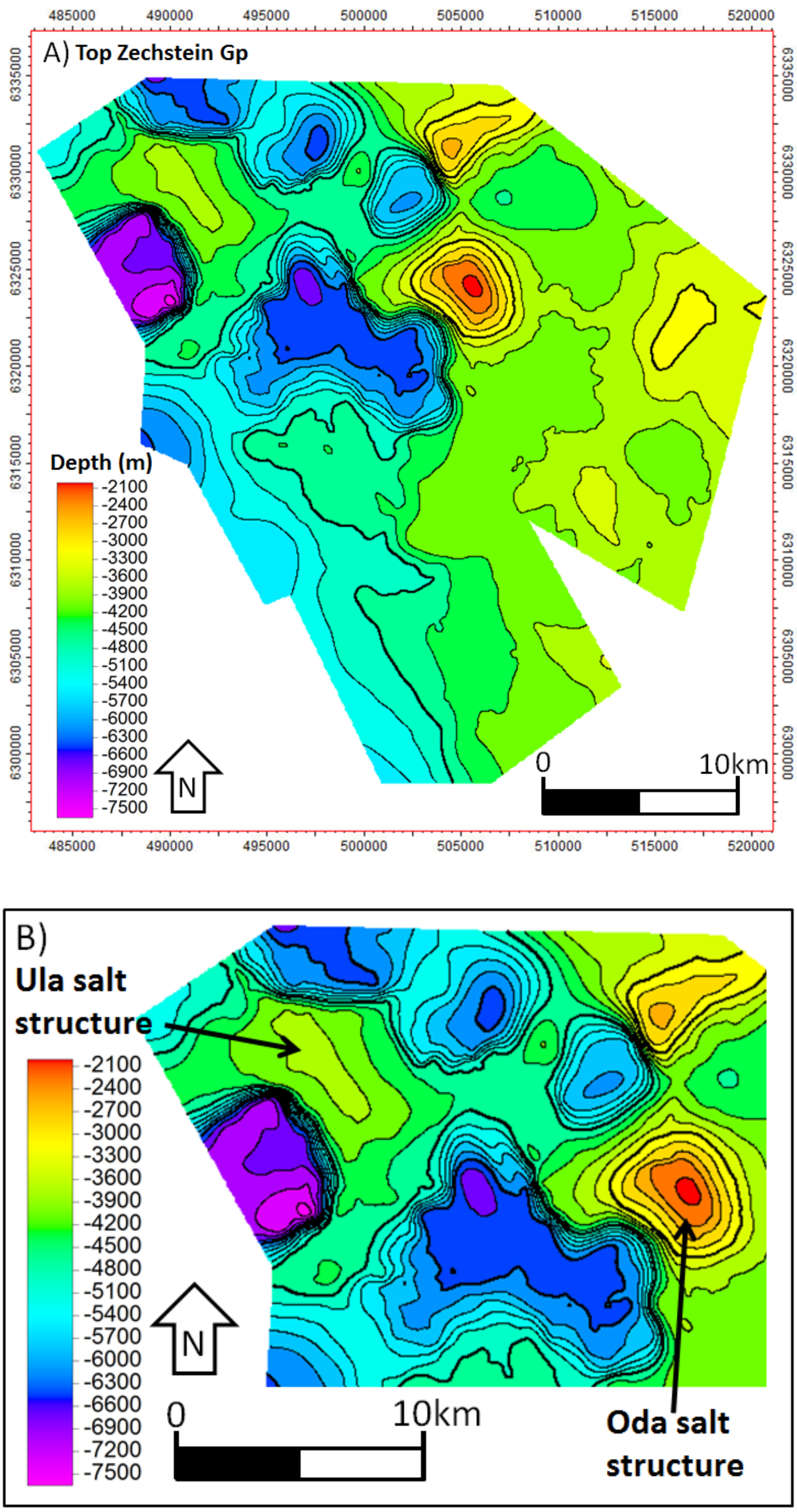


Figure 26: A) Depth map of the Zechstein group B) Highlighting the area in the NW where the pods are separated by a polygonal pattern of salt structures

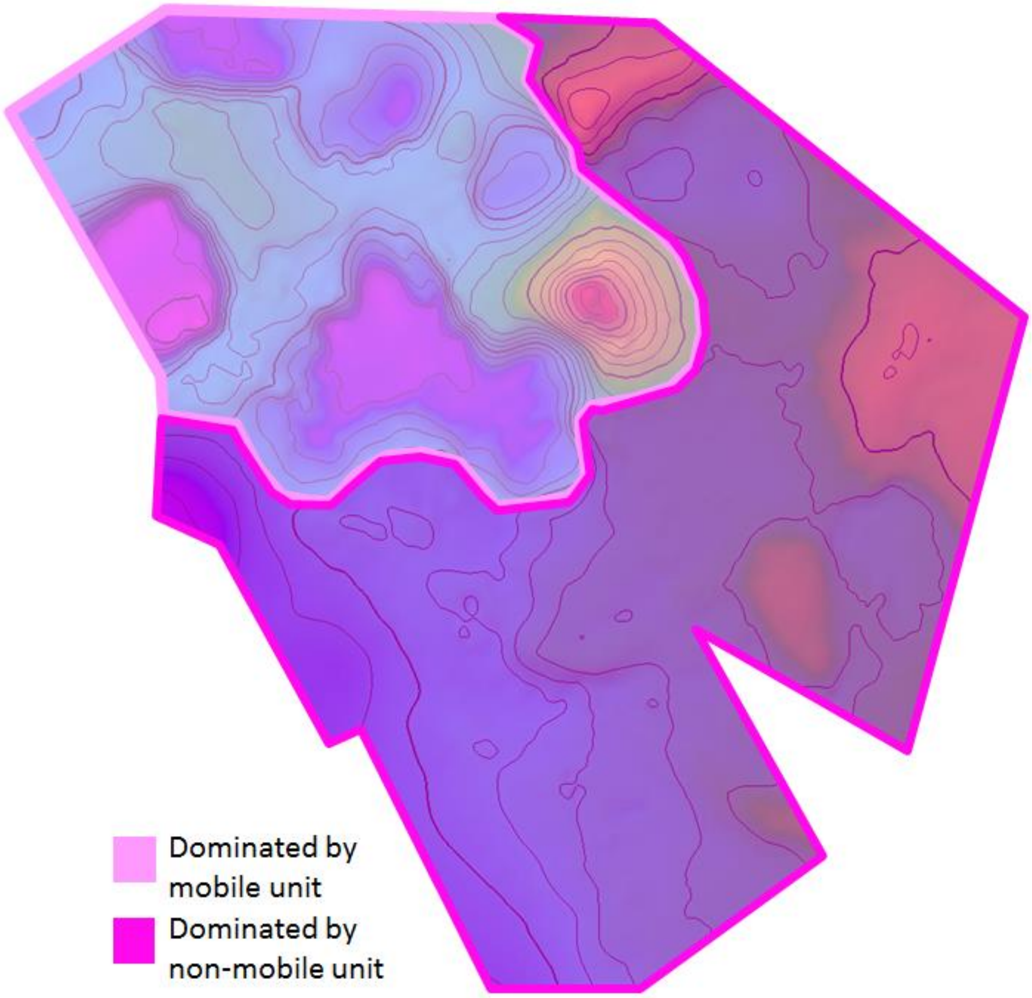


Figure 27 Map of the Zechstein group showing area dominated by mobile unit and area dominated by non-mobile unit

4.3.3 Interpretation

Based on the seismic observations, SF1 is interpreted to be a unit mostly composed of halite. The presence of diapirs and salt withdrawal mini-basins nearby suggests that it is a less viscous and mobile unit. In contrast, SF2 creates minor suprasalt deformation, which indicates that it is a viscous and non-mobile unit. It is therefore interpreted to represent layered evaporates sequences of carbonates, anhydrite and siliciclastic. These lithologies are brittle, and the faults are prone to be hard-linked when they go through this unit. However, there is often a thin layer of the mobile unit at the base of the brittle salt unit, and the faults detach to this layer and become soft-linked (Figure 25).

4.4 Triassic

4.4.1 Well Data Character and well correlation

General observations from the wells

The thickness of the Skagerrak Fm in the wells ranges from 50 to 248m.; however some of the wells did not penetrate the Zechstein Group or the Smith Bank Fm, so the depth of the base of the Skagerrak Fm is not confirmed. Figure 28 shows the thickness of the Skagerrak in the different wells, the GR-log signature of the formation and the location of the different well correlations are shown in figure 28-31.

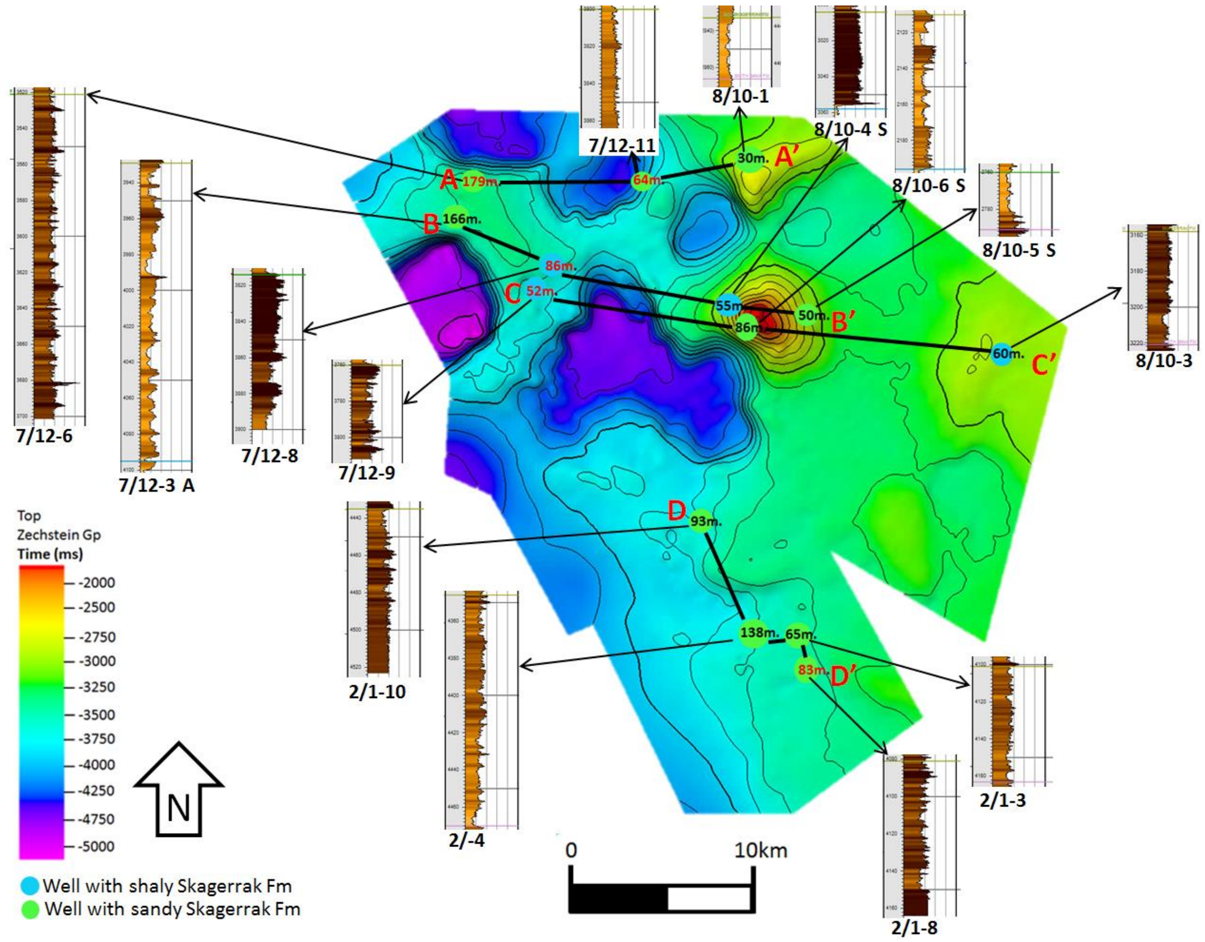


Figure 28: Thickness of the Skagerrak Fm in the wells and location of the four well correlations. The thickness written in red is where the base is not defined, making the thickness uncertain.

There are a few wells that show a similar log-response. The GR-log response in wells 7/12-8, 7/12-9, 8/10-4S and 8/10-3 are generally high, with a few fining upward sequences. In contrast, well 7/12-3 A, 8/10-1, 8/10-6 and 8/10-5 S show much lower GR-log responses, with many fining upward sequences. The GR-log response of well 7/12-11 varies very little, and is showing an aggrading trend. The rest of the wells, 7/12-6, 2/1-4, 2/1-3 and 2/1-8 are also showing an overall aggrading trend but with many thin fining upward sequences that makes the log look erratic in some intervals.

Well correlations

Four stratigraphic well correlations have been carried out flattened on the Top Skagerrak Fm, which includes the GR-log and a cross-plot of the neutron and density logs. Well correlation A-A’ (Figure 29) is a correlation trending E-W, including wells 7/12-6, 7/12-11 and 8/10-1. The GR response of well 7/12-6 shows a spiky to erratic well log signature with some thin fining upward sequences. The neutron and density logs are shifting between a wide and narrow response with lower values. Moving eastward well 7/12-11 is showing a blocky sequence with a stable GR-trend followed by a coarsening upward trend. The GR-log values are lower than in well 7/12-6, however the neutron and density logs are showing an overall large separation. Well 8/10-1 also shows a blocky and coarsening upward trend. No neutron and density logs were available for this well.

Well correlation B-B’ (Figure 30) is a correlation trending NW-SE, including well 7/12-3, 7/12-8 and 8/10-4 S. This correlation is showing a change from fining upward sequences in well 7/12-3 A and partly in well 7/12-8 to a more monotonous high GR-log response in well 8/10-4. The Skagerrak Fm interval in well 8/10-5 S is coarsening upwards.

Well correlation C-C’ (Figure 31) is similar to correlation B-B’ trending NW-SE, including well 7/12-9, 8/10-6 S and 8/10-3. Well 7/12-9 and 8/10-3 are showing relatively high GR-values. Well 8/10-6 S on the other side shows some packages with lower GR-values, and the neutron and density cross-plot is also shows some intervals that have relatively low values.

The last well correlation is trending more or less N-S and includes well 2/1-10, 2/1-4, 2/1-3 and 2/1-8 (Figure 32). The log responses of these 4 wells are all showing an aggrading trend, but there are some gentle upward fining sequences. No very low or high values. All of these wells in correlation D-D’ show a similar log response that differs a little from the rest of the wells. Other than that, the correlations show that there are no obvious changes in direction or patterns to notice in any specific direction.

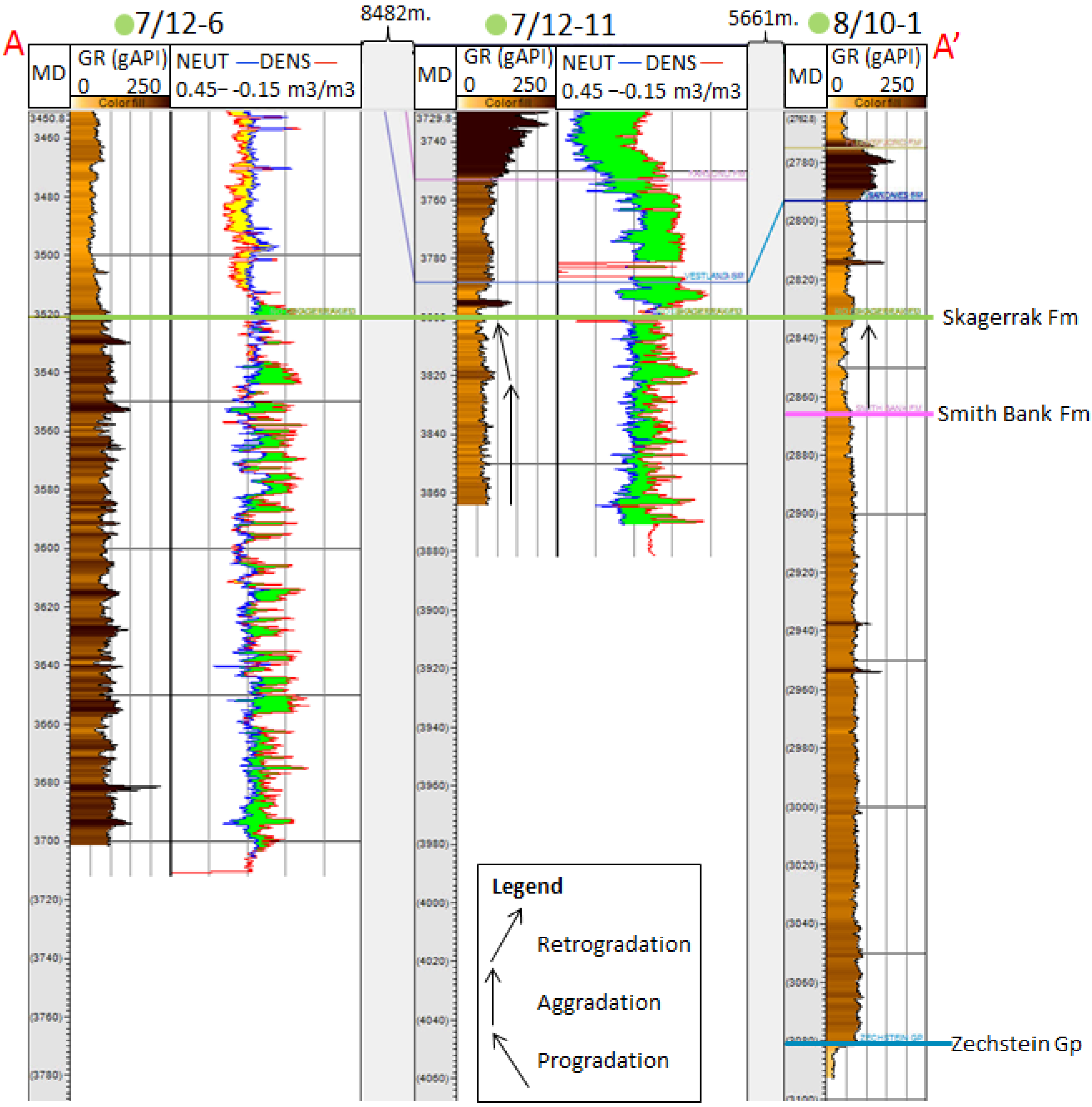


Figure 29: Well correlation including well 7/12-6, 7/12-11 and 8/10-1

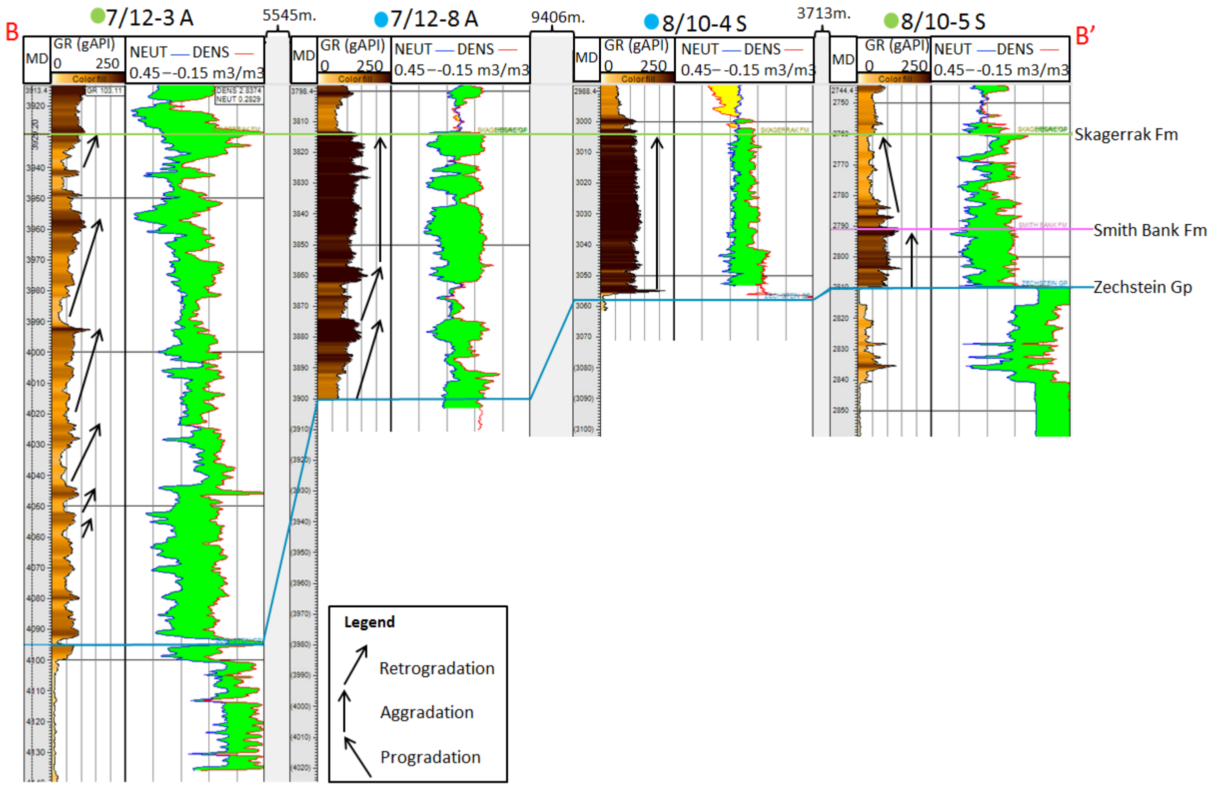


Figure 30: Well correlation including well 7/12-3 A, 7/12-8, 8/10-4 S, 8/10-5 S.

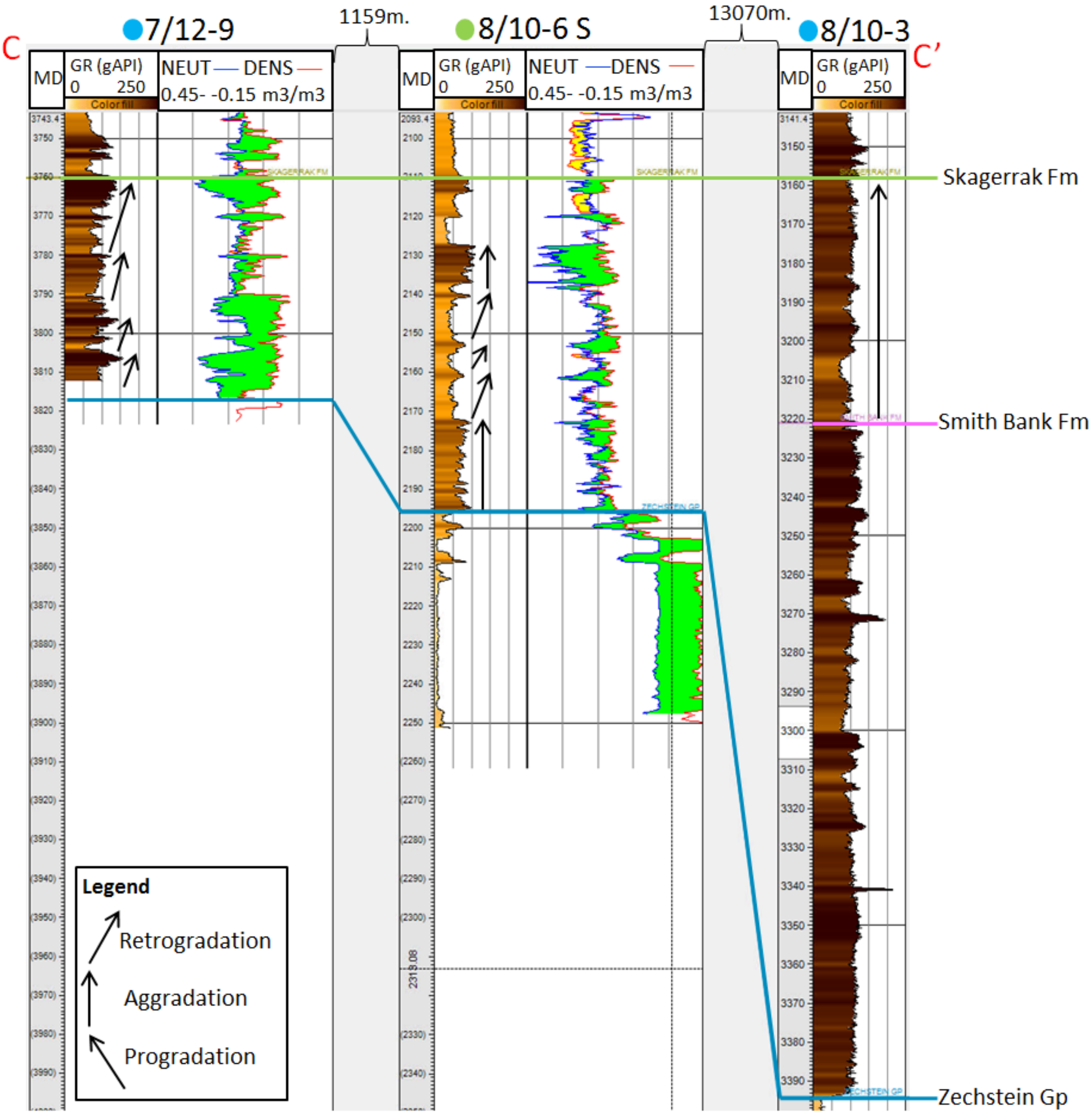


Figure 31: Well correlation including well 7/12-9, 8/10-6 and 8/10-3.

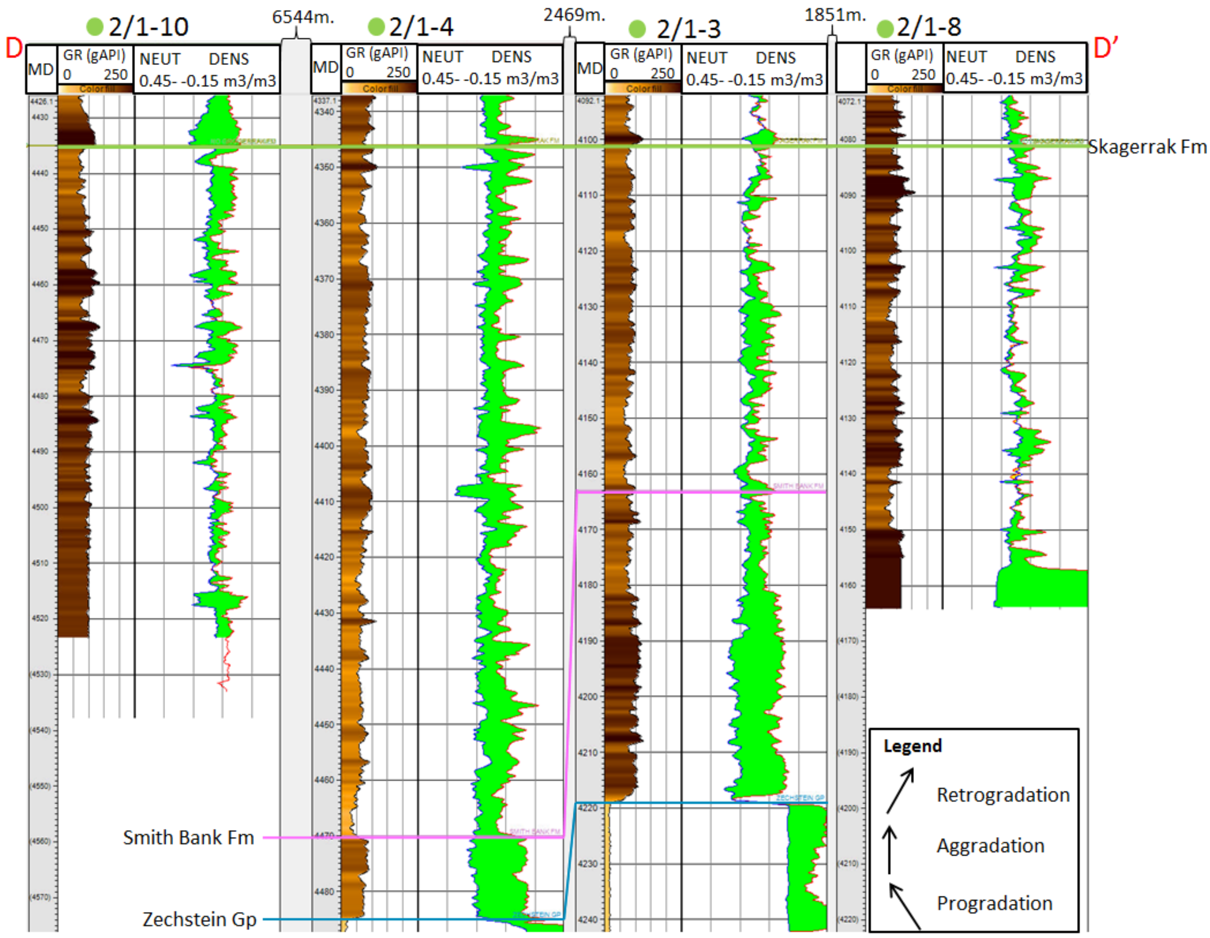


Figure 32: Well correlation including well 2/1-10, 2/1-4, 2/1-3 and 2/1-8.

4.4.2 Seismic character

General observations from seismic

The pick of the top Triassic has a medium to high confidence; it is interpreted on a continuous trough, and there is well control in most of the fault blocks. However, there is no well control in the pods where the Triassic is at its thickest.

The lateral variation in thickness in the Triassic sequence is very apparent on seismic. A good example of these variations is shown in Figure 33. Note how the Triassic layer is getting thinner toward the salt structure, and getting thicker where the salt layer is getting thinner.

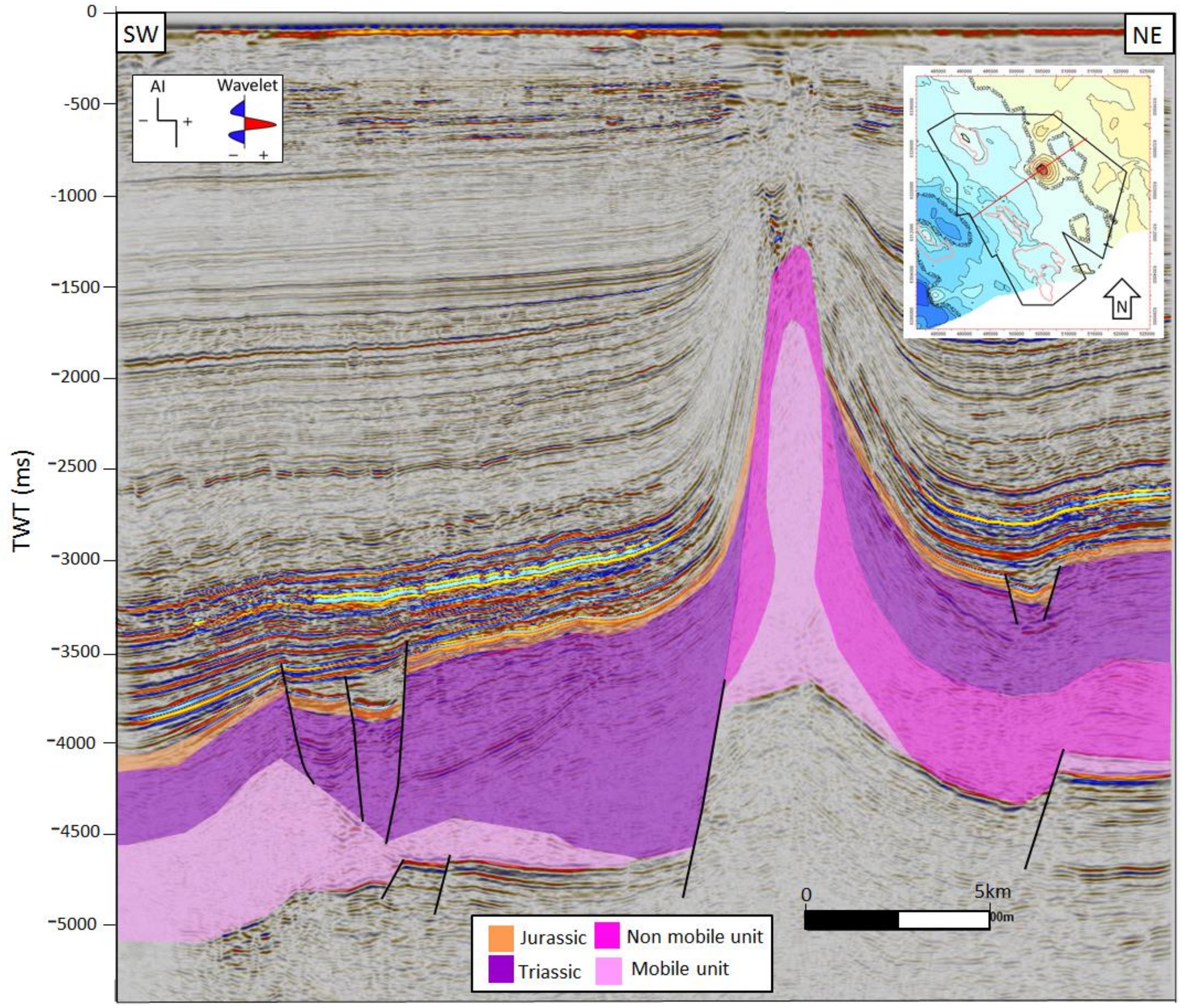


Figure 33: Interpreted seismic line going through the salt structure at the Oda field

Seismic facies

The analysis of the seismic facies has been challenging because of the seismic quality in the Triassic sequence. The reflectors within the Triassic are not continuous enough to be able to divide into different sequences, and attribute maps are not giving any useful results that show any recognizable patterns of a facies distribution. However it is noted that seismic facies 6 and 3 are the most widespread facies, while facies 4 and 5 are most common within the pods.

Seismic facies 4 has been mapped out, because it is within three wedges that have been found in three different pods (Figure 34). It appears as medium to high amplitude reflectors that are dipping, the shape of it varies a little bit from tabular to more wedge shaped in one of the pods. It is very easily recognized, as it differs a lot from the facies below and above (Figure 35). Facies 5, which often appears below facies 4 in the pods, has much lower amplitude and is almost transparent.

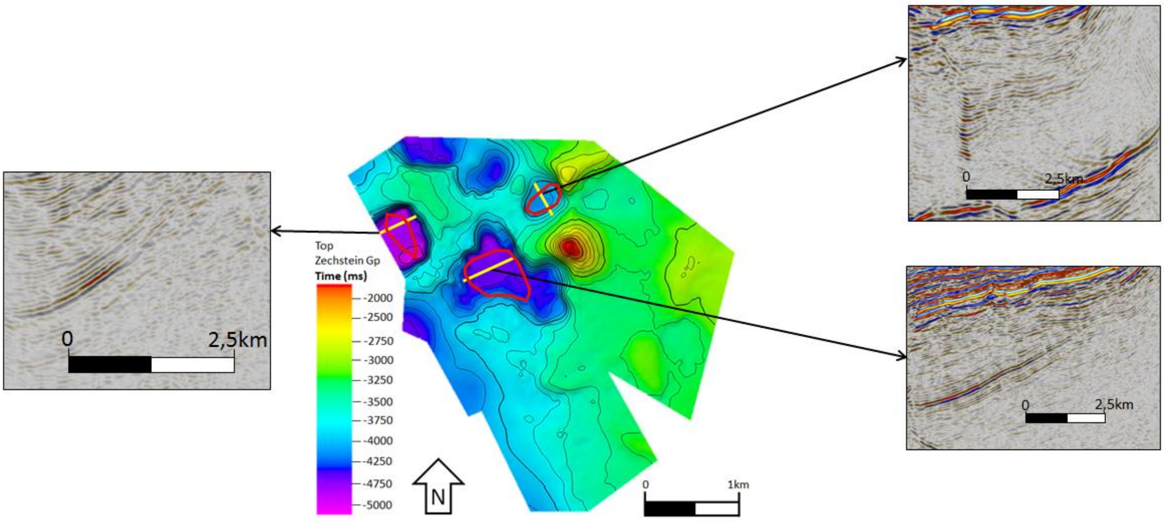


Figure 34: Shows the mapped wedges within the red polygons on a time structural map of the Zechstein group and examples of each of the wedges.

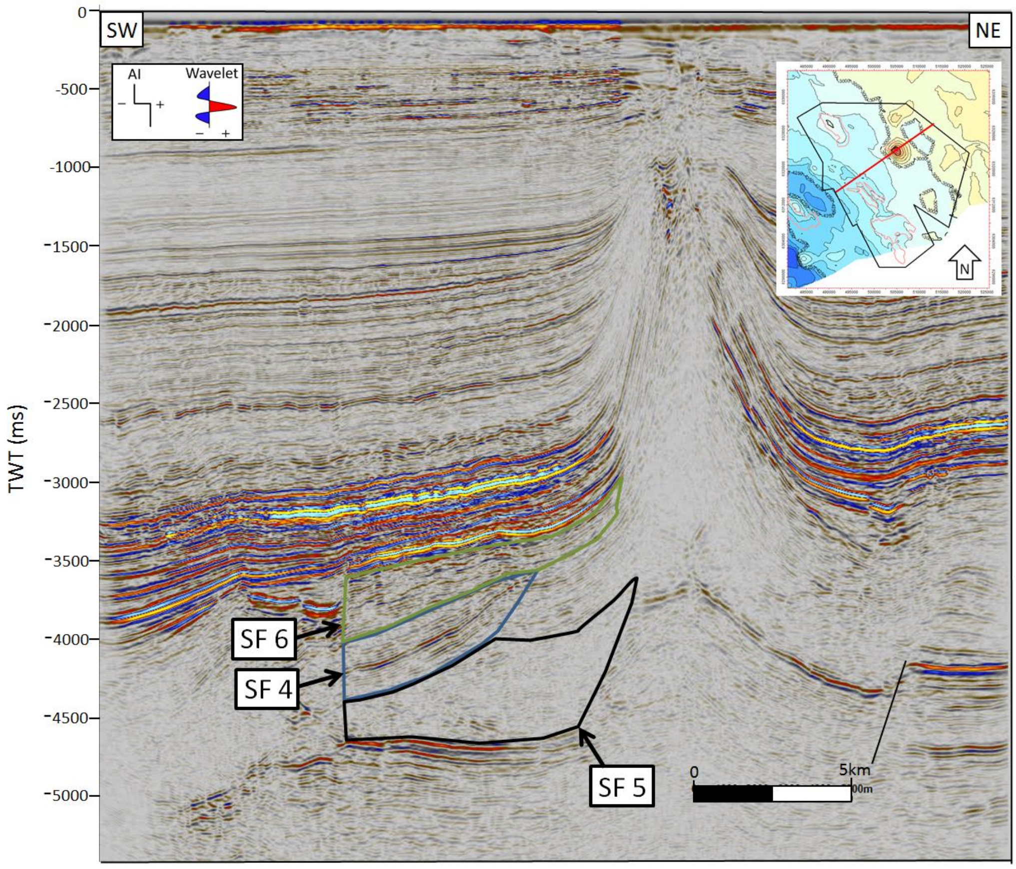


Figure 35: Uninterpreted seismic line going through the salt structure at the Oda field, highlighting seismic facies variations within the Triassic.

There is an example from the UK sector where a reflective wedge within the pod has been interpreted as sandy Skagerrak formation, whereas the less reflective sequence is interpreted as the shale-dominated Smith Bank Fm (Figure 36). However this pod has not been drilled through. Another analogue to seismic facies 5 is found in the public mega merge cube, where there are wells that have drilled trough the facies is on the Sleipner field (Figure 37). Note how the low amplitude to transparent seismic response corresponds to the Smith Bank Fm.

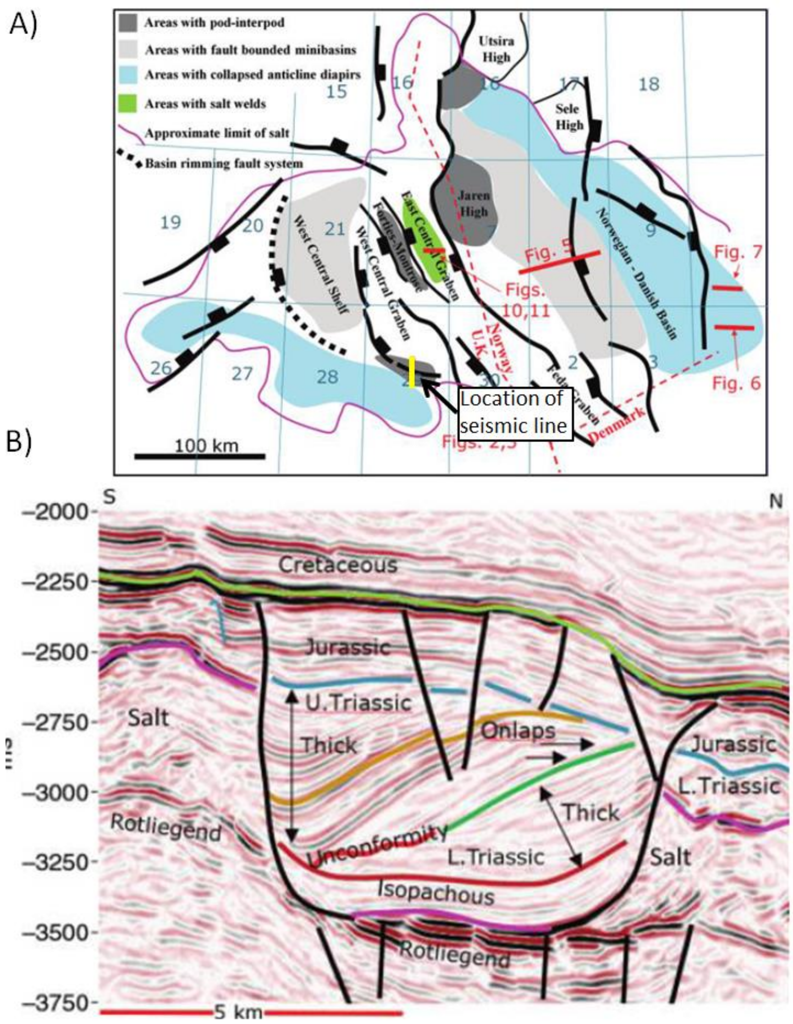


Figure 36: A) Location of seismic B) Example of internal geometry within a pod on the UK Sector. (Karlo et.al., 2014)

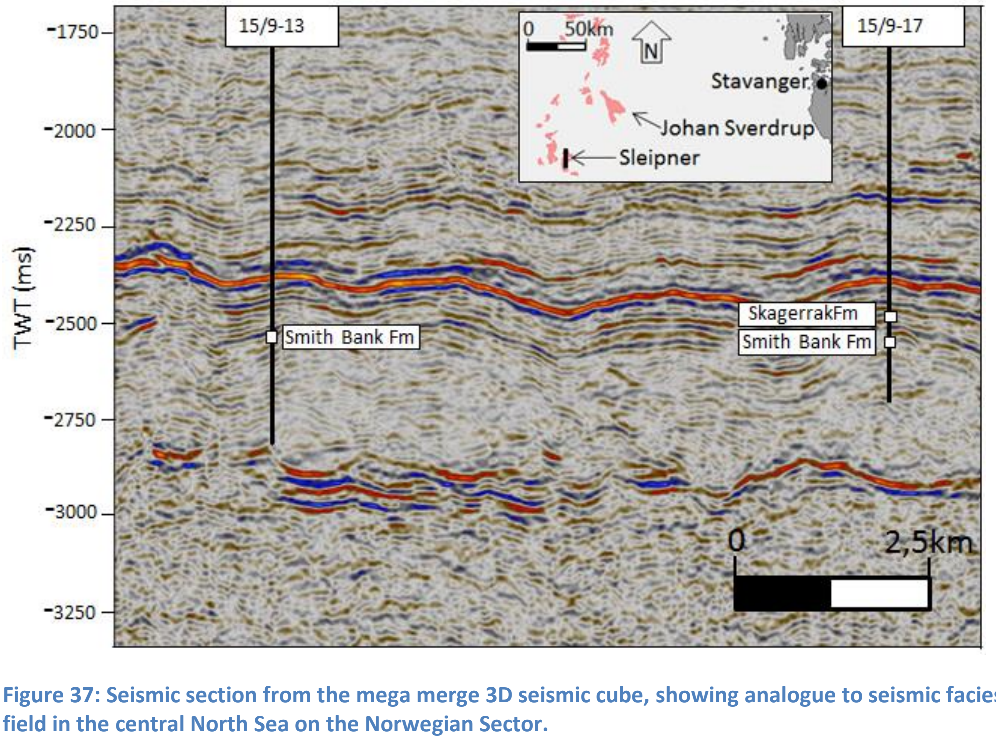


Figure 37: Seismic section from the mega merge 3D seismic cube, showing analogue to seismic facies 5 from the Sleipner field in the central North Sea on the Norwegian Sector.

4.4.3 Structural depth map and thickness map

The structural depth map of the Top Skagerrak Fm, interpreted as the top Triassic, (Figure 38) shows that the shallowest point of the Skagerrak Fm is at -2200 m below sea level and the deepest point is at approximately -5400 m. The highest areas of the formation is around the salt structure on the Oda field, and in general the formation deepens from east to west.

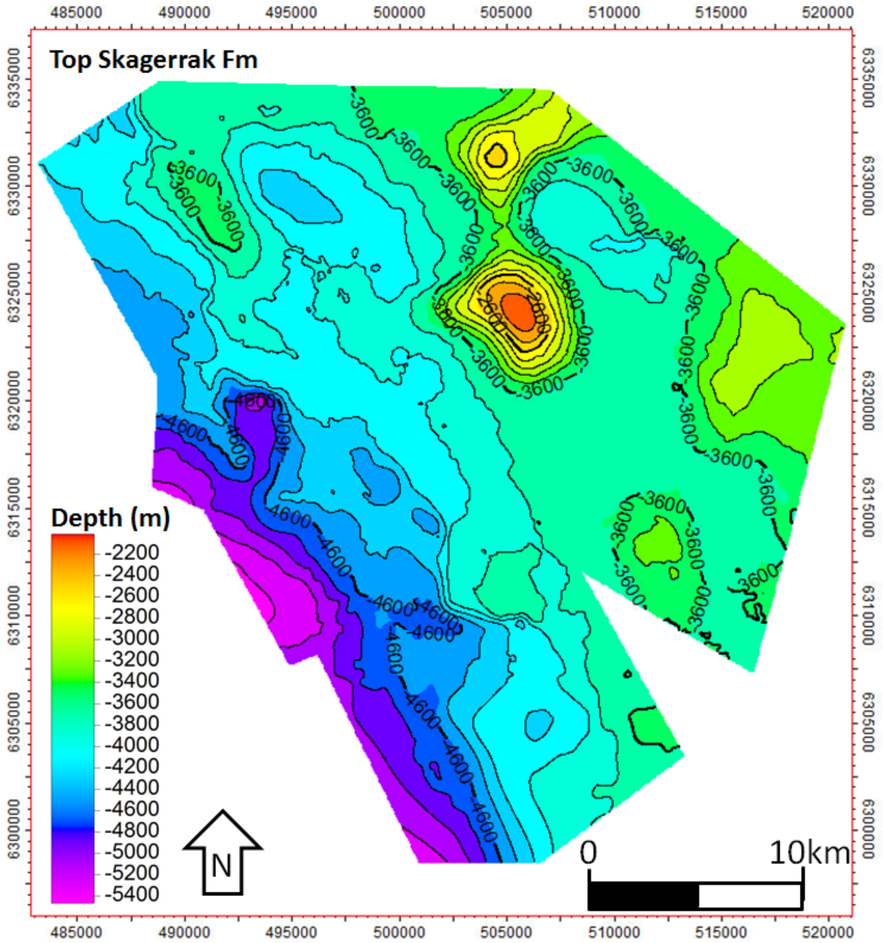


Figure 38: Time structural map of top Skagerrak Fm

The Triassic thickness map shows in Figure 39 that there is one area where Triassic is absent. This is where the highest salt structure is, the Oda salt structure (Figure 39). Next to this area of zero thickness there is a large and thick depocenter, where the Triassic reaches thicknesses of up to 2500 and in some areas up to 3000m. There are also four other depocenters of variable size located in the NW in the map. These depocenters are located close to the topographic highs observed in the NW in Figure 38. In contrast to this area in the NW, the area to the SE in the map has a relatively constant thickness (Figure 39).

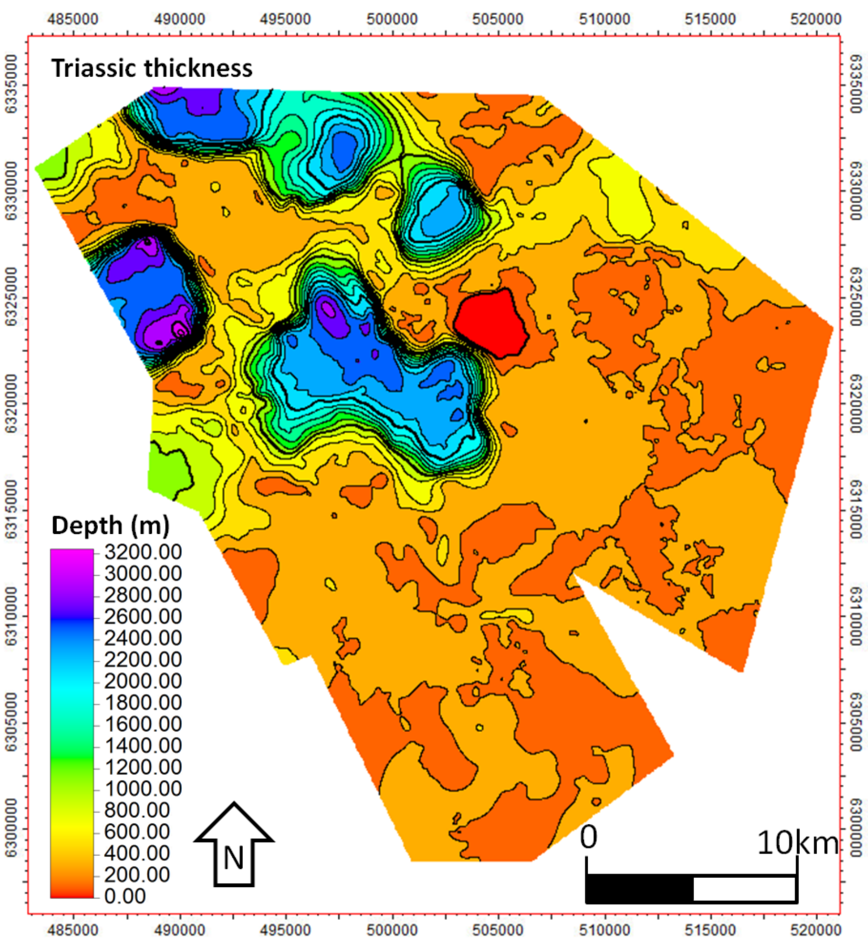


Figure 39: Thickness map between Top Skagerrak Fm and Top Zechstein Group

4.4.4 Interpretation

Wells

The spiky to erratic GR well log signature of well 7/12-6, with some thin fining upward sequences, together with a rapidly shifting neutron density cross-plot is pointing towards a heterogeneous sand and shale sedimentation (Figure 29). The thin sand packages in between the shale could be channel deposits from laterally migrating ephemeral braided channels, and as the channels are shifting shale from the flood plain is deposited. This interpretation is supported by the core observations carried out by Tveiten (1982) for this well, which is described in detailed in the previous work chapter.

Cores from well 7/12-11 suggest a sheet flood plain fluvial setting with some lacustrine influence in between the floods (Vagle & Fjerstad). This fits well with the aggrading to slightly coarsening upward trend seen on the well logs, which also suggests sheet flood deposits (Figure 29). Well 7/12-3 A, 8/10-6 S and 8/10 5 S is also dominated by sandy channel deposits, but with smaller packages that are interpreted as stacked braided channels.

Well 8/10-6 S also shows intervals with higher GR values that look less sand-dominated, and is possibly influenced by some flooding events that have happened in lacustrine conditions. Wells 7/12-8, 8/10-4 S, and 8/10-3 show a more monotonous high GR-log response, which is likely to represent longer periods of lacustrine environment or a flood plain setting.

Blocky and aggrading GR-log responses with medium high values in the southern wells 2/1-10, 2/1-4, 2/1-3 and 2/1-8 implies a heterogeneous sedimentation of sand and shale (Figure 32). There are no well-developed sand packages in these wells, which indicate that this part of the study area is distal to the channel feeder system.

Seismic

Parallel and continuous seismic events together with high GR-value characterize seismic facies 3, and are interpreted as shale deposits. This facies occur in the area where the Triassic thickness is thin and constant, implying a quiet and continual stable fluvial plain, with possibly flood plain, alluvial plain or lacustrine environment.

Seismic facies 4 has inclined reflection geometry with medium to high amplitude response. There is no well control in the pods where this facies occur, and the interpretation is therefore uncertain. In the structural maps, it is interpreted that accommodation space increased within the pods; therefore the drainage system may have transported heterogeneous sediments into this pod. It is suggested that the pods could have been filled with lacustrine deposits, channel deposits or deltaic deposits. The deltas could have developed where the rivers met the lakes during high subsidence periods related to salt movement. However since some of the wells around the pods show indications of fluvial sands, it is possible that the tabular wedge structure could be composed of stacked braided channels.

Seismic facies 5 has discontinuous and chaotic reflection geometry with very low amplitude reflections. This facies is present in pods and often at the base of the Triassic sequence; it is therefore possible that this facies represents the shale-dominated Smith Bank Fm or possibly lacustrine shales within the Skagerrak Fm.

A sub-parallel reflection geometry and medium amplitude reflections together with a blocky to erratic and upward increasing GR-log signature is associated with seismic facies 6. This is the most widespread facies in the study area, it suggests a heterogeneous fluvial sedimentation of sand and shale. The heterogeneous deposition is likely to be a product of the widespread ephemeral braided streams, in addition to periods in between that were more dominated by lacustrine conditions.

5. Discussion

5.1 Timing of salt mobilization influences Triassic pod development

Regionally the onset of the salt movement was in Early Triassic (Karlo, et al. 2014), triggered by sediment loading and extension. The lateral thickness variations observed in the Triassic are underpinning ongoing subsidence and diapirism during the Triassic. The Jurassic thickness is more constant thickness, and in general the strata above the Triassic do not show major thickness changes towards the salt structure, suggesting that most of the salt movements in the area ceased at the end of Triassic.

There was a significant period of extension between the Upper Jurassic to Lower Cretaceous, so why did the salt movement cease during the Triassic? One possible explanation is that there was not enough mobile salt left at this time and the Triassic roof was too thick to break through, similar to stage 3 in figure 40. Accordingly the extension between the Upper Jurassic and Lower Cretaceous occurred above buried Triassic salt diapirs and ridges (Figure 43).

There is one example of a diapir that breached the overburden and pierced through the Jurassic and Cretaceous, as well as the Triassic; the salt structure at the Oda Field (Figure 33). This dome must have been reactivated during the inversion period in the Cenozoic (Evans et al.,2013), because there was more mobile salt present that could flow, in addition to faults in the overburden that made the roof thin enough to break through (Figure 41).

In the large interpod area in the SE of the study area, the Triassic thickness is relatively constant (Figure 42). Figure 42 shows how salt welds are formed in this area, indicating that the mobile salt layer has been depleted and there was not enough mobile salt to be mobilized. This occurs where the salt layer is dominated by anhydrite and non-evaporitic lithologies such as claystone, carbonate and siltstone. The immobility of these lithologies prevents pod development and creates little deformation in the Triassic (Jackson and A Stewart, 2016) (Figure 43), and results in a top Triassic surface with gentle topography.

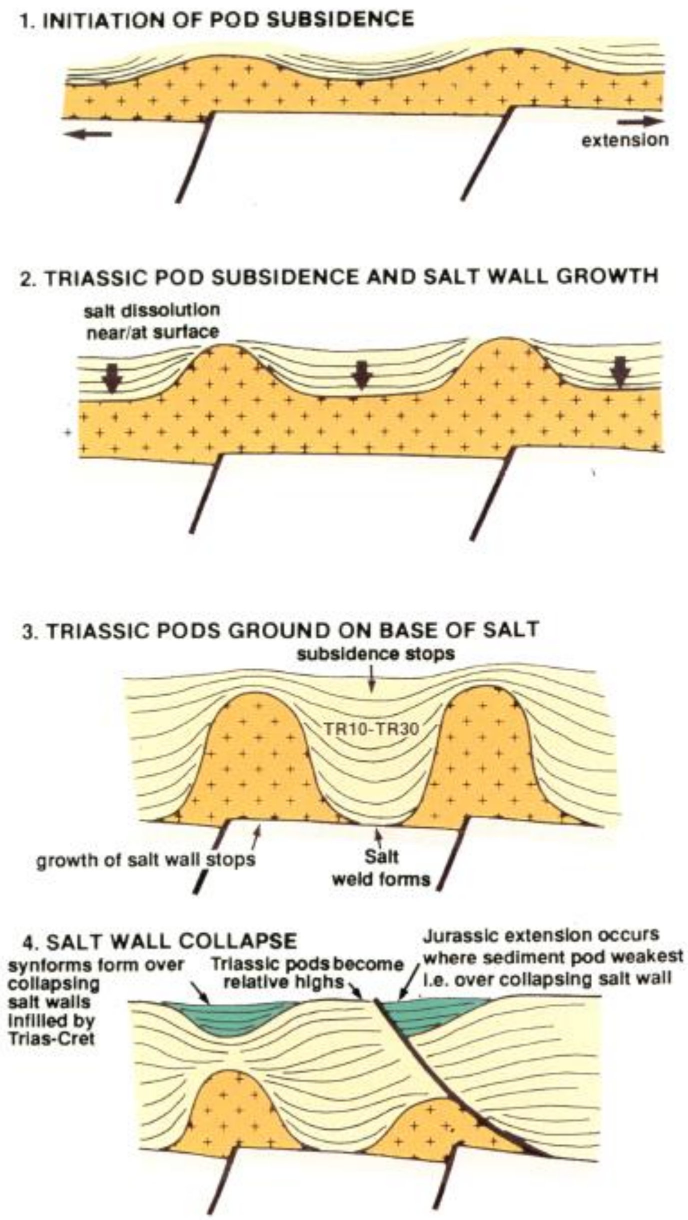


Figure 40: Model of the evolution of the Triassic pods (Smith et. al., 1993)

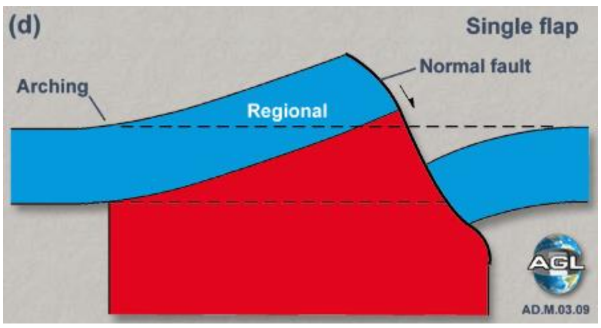


Figure 41: Single flap active diapirism (Schultz-Ela et al., 1993)

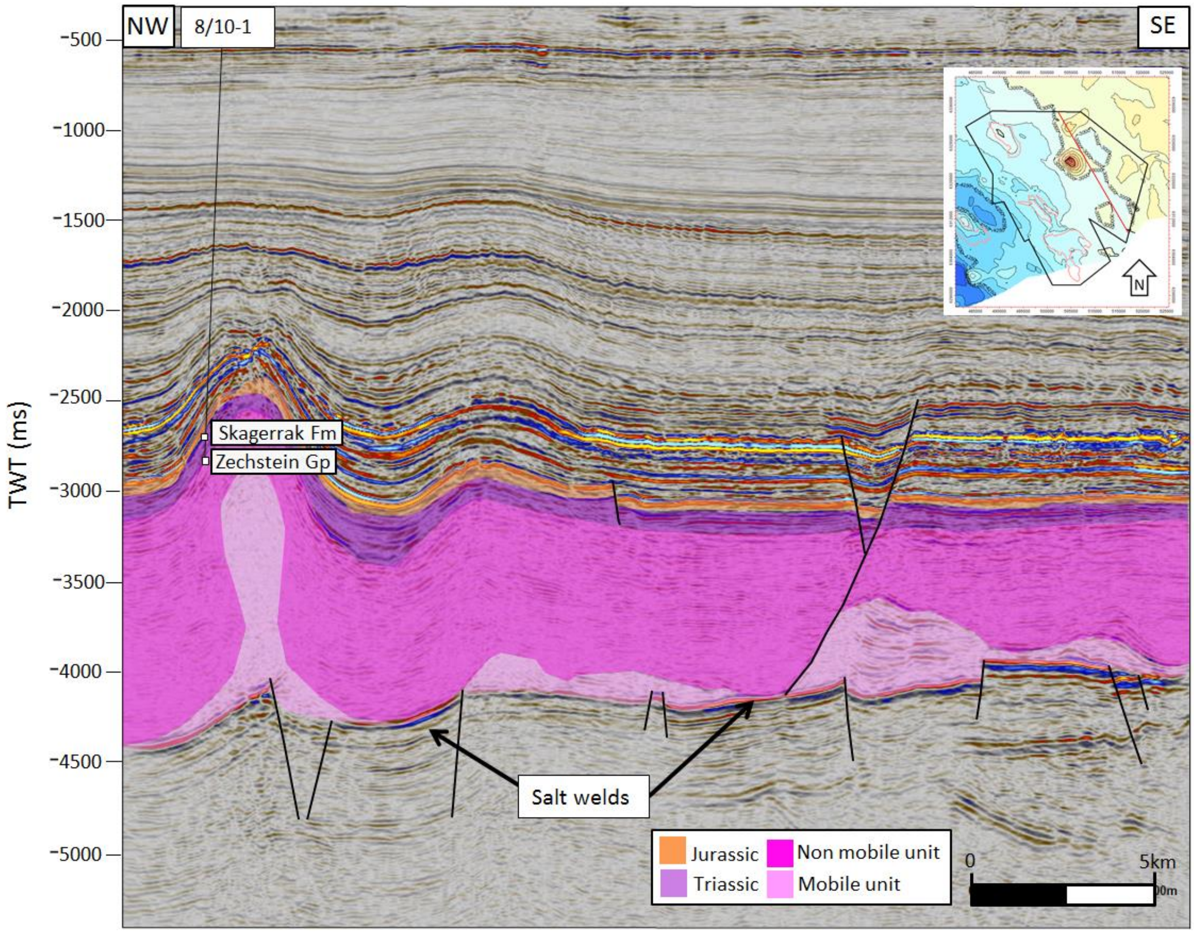


Figure 42: Seismic line highlighting areas where the mobile salt layer has depleted and salt welds have been formed.

5.2 Controls on variations in facies and thickness in the Skagerrak Fm

There is a large variation in facies within the Skagerrak Fm. Facies is a key factor when determining reservoir quality (Smith et al., 1993). Some wells have penetrated shale only, suggesting a lacustrine or floodplain environment. Other wells have proven promising sandstone packages, suggesting braided channel deposits. This indicates that the regional drainage system is an important control on the facies variations, and is crucial to understand in order to predict the location of the different depositional elements. Important controlling factors of the drainage system are the salt tectonics and fault trends.

Salt control

Triassic thickness variations are directly related to the rheology of the "salt layer" underneath (Jackson and A Stewart, 2016). This relationship is illustrated in Figure 43, which is comparing a seismic line within the study area to the model proposed by Jackson and Stewart (2016). No salt mobilization during deposition results in a constant thickness, so where the salt is immobile a constant Triassic thickness and a relatively gentle Top Triassic surface occurs. Jackson and Stewart (2016) has named this the “Triassic platform”, and is where the salt layer is dominated by anhydrite, carbonates and clastics.

In contrast, where the salt-layer is halite dominated, the salt has moved and pods with accommodation space are formed. Sediments have been directed into these pods resulting in depocenters where thick Triassic sediments have accumulated. Whereas above the large salt structures formed, the Triassic layer is very thin or absent (Figure 42, Figure 11 and Figure 12). This is the area that Jackson and Stewart (2016) named “Triassic mini-basin zone”, and is characterized by large variations in Triassic thickness.

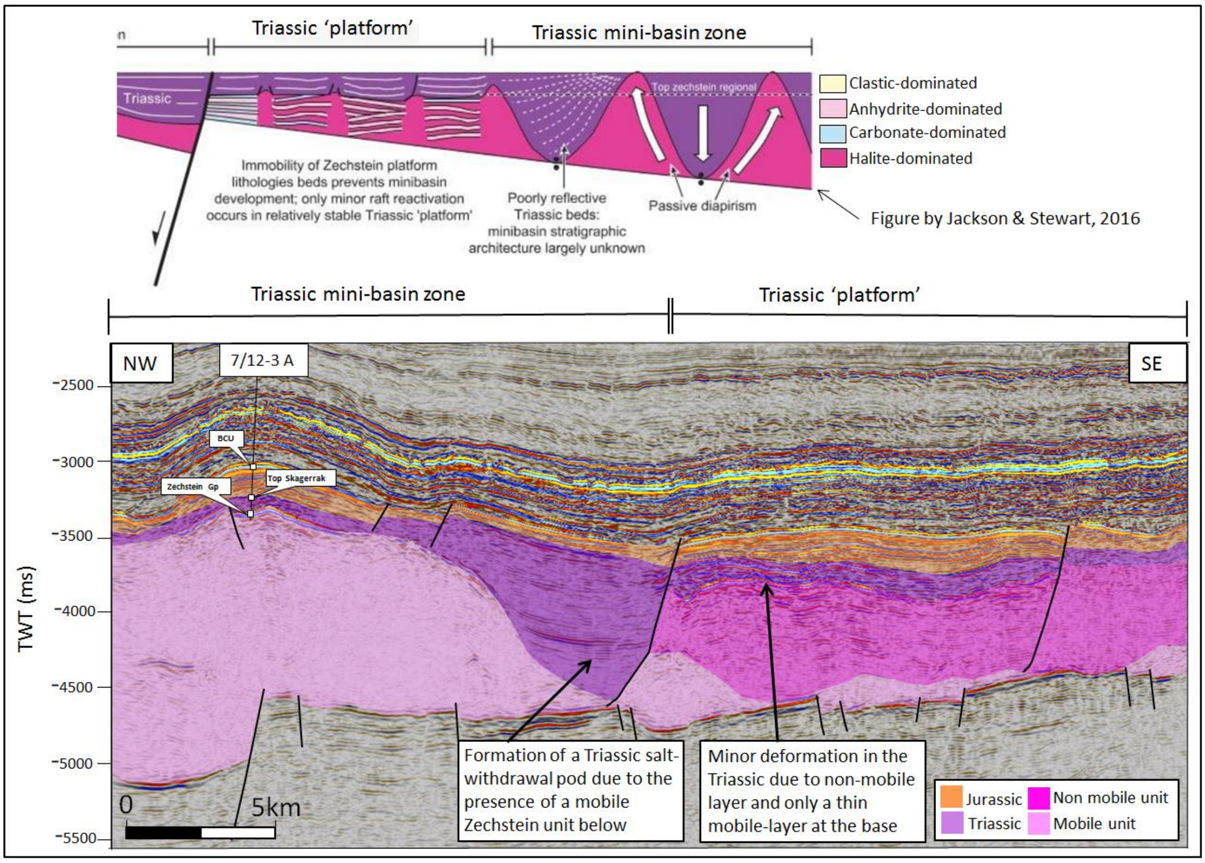


Figure 43: Seismic line highlighting the lateral thickness observations in the Triassic, indicating salt movement during deposition in Triassic.

In the area where the immobile salt is present, the top salt surface has a low relief, and the salt layer probably played little or no role in the sediment pathways. How did the landscape look at the Triassic time in the area of the mobile unit? Did the salt structures create a lot of relief and act like barriers for the river systems during salt movement? Or was the landscape flat with a low relief, enabling the river systems to cover the entire study area?

It is likely that the salt movement has limited the sediment distribution. However, well logs in wells 7/12-6, 7/12-3, 8/10-1, 8/10-6 S and 8/10-5 S, which are placed on top of salt structures suggest fluvial sand packages. For well 7/12-6 this is also supported by cores that are interpreted to be braided channel deposits of good reservoir quality (Tveiten, 1982). Therefore, the river channels must have been able to flow across the salt structures during, at least, some periods of the Triassic. Either the river had enough energy and eroded its way through a landscape with some relief, or there were periods with quiescence in between the salt movement where the rivers were more widespread, because the salt growth and hence the building of relief at surface was slower than sedimentation rates.

Fault control

The Triassic thickness map does not show any apparent thickness differences between hangingwalls and footwalls (Figure 39). Depocenters are located close to the salt structure and are not clearly related to the faults. However, the faults may have been a controlling factor for the facies variations. The faults do create an offset in the Triassic (Figure 22), and the uplifted footwalls may have limited the sediment contribution. The rotation and uplift of the footwall blocks have probably acted as a barrier for the drainage system, and directed the rivers to flow along the faults.

5.3 Conceptual models for sandstone fairways

Based on the observations from the wells and seismic, time thickness maps created and regional information, two different conceptual models are proposed (Figures 35 and 36). These models do not represent any specific time periods in the Triassic, since dating Triassic fluvial and alluvial sediments are difficult due to barren flora and fauna for biostratigraphy dating. Hence the models represent possible scenarios depending on salt movement. These scenarios may have happened multiple times during the Triassic, as the well logs and cores indicate stacked fluvial systems with lacustrine or flood plain deposits in between (Table 5).

Figure 35 illustrates a period of underfill. In this model salt movements lead to subsidence and generation of accommodation space. This means that the rate of accommodation space creation is larger than the sedimentation rate. The depocenters created are separated and surrounded by salt walls and could potentially become an area for lakes and lacustrine conditions (Smith et. al., 1993). The lacustrine conditions dominated in the mini-basins, where the lakes were at its largest.

The salt movement created barriers for the river systems, and the river channels must have had a lot of energy to flow across the salt structures. It is therefore suggested that the pod zone was an area of a high energy fluvial system at this time. The landscape in the interpod zone had a much lower relief, and is likely to be a more stable fluvial plain with a lower energy fluvial system.

The rivers transported significant amounts of sediments, and deltas were generated where the rivers entered the lakes. The cores from wells 7/12-6 and 7/12-11 suggest sheet flood deposits (Tveiten 1982; Robertson, 1991; Vagle & Fjerstad, 1992). When these sheet floods entered the lakes it is possible that minor fans were created, which quickly reworked the deposits (Smith et.al.,1993). In addition, since the salt was moving at this time, it is possible that there were alluvial fans deposited that were locally sourced by erosion of uplifted diapirs. An example of this kind of diapir-related alluvial fan is observed in the Great Kavir diapirs located in Central Iran (Rojo, 2015, p.89)

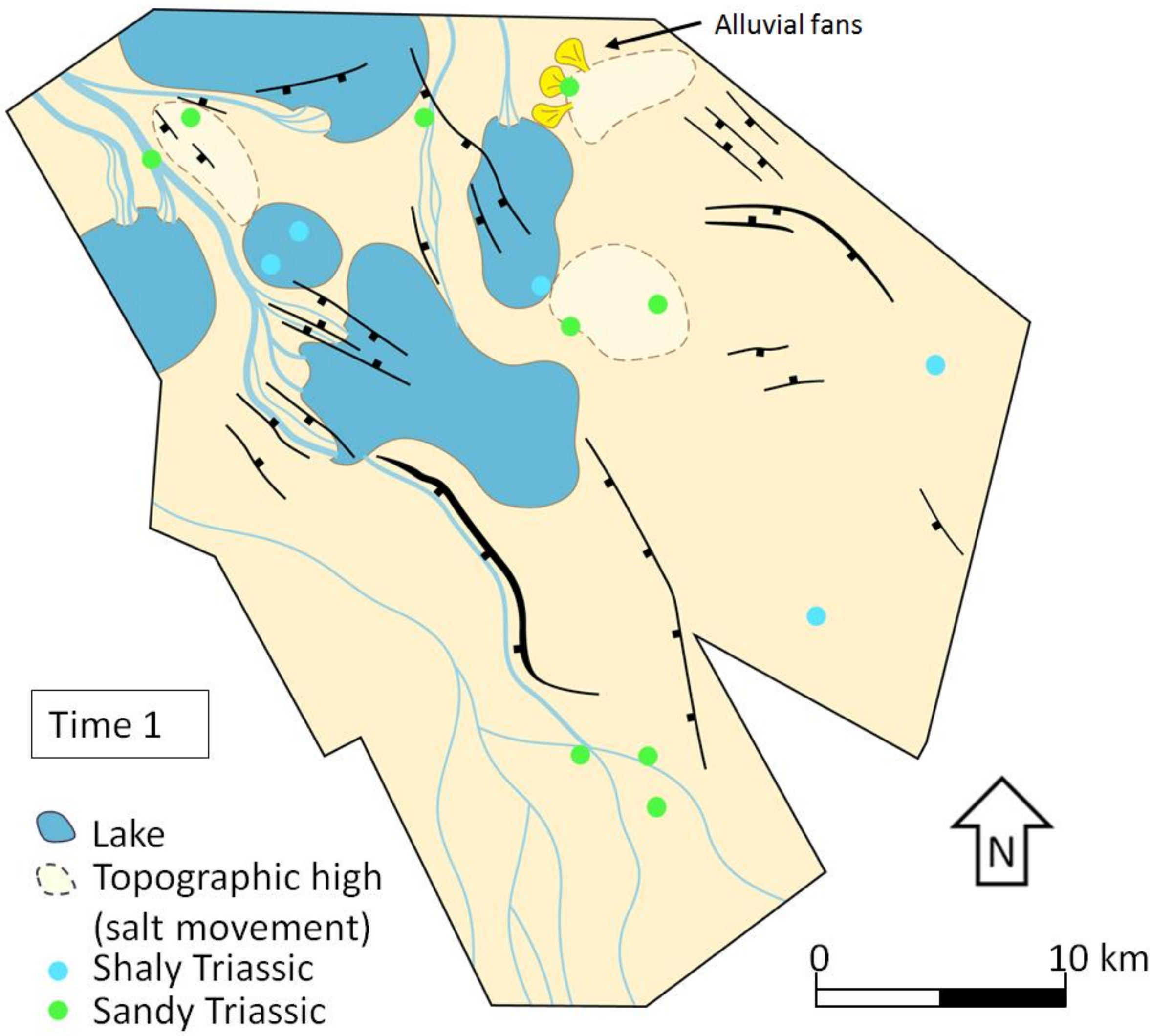


Figure 44: Proposed depositional environment and possible sandstone fairway in a period with underfill.

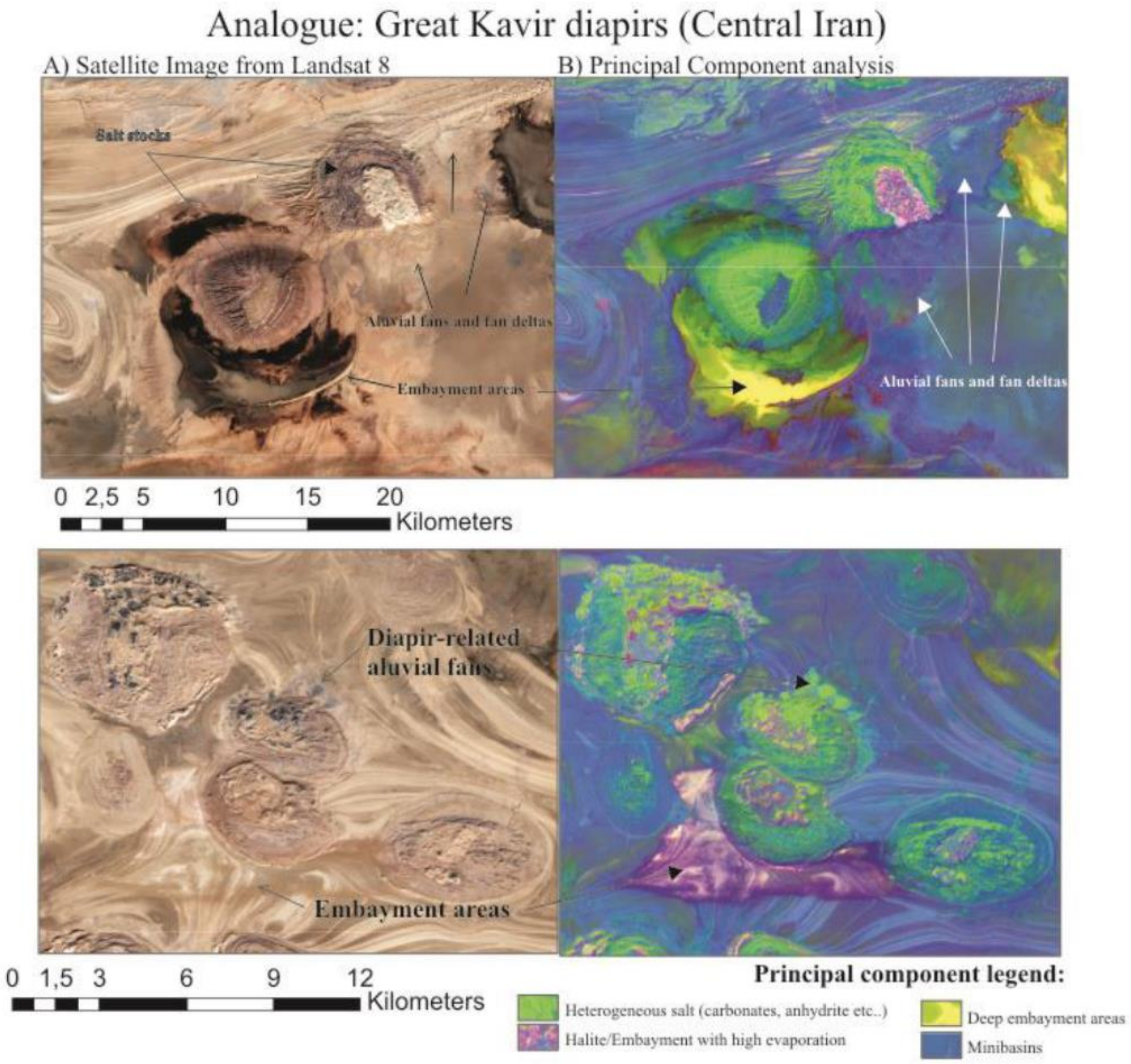


Figure 45: Satellite pictures of an analogue of a diapir-related alluvial fan from Central Iran (Rojo,2015,p.90).

Another scenario (Figure 46) occurred when the accommodation space was filled up by sediment loading, and the lakes have disappeared due to sediment deposition. The pods represent localized depocenters but were probably not significant topographical lows at this time (Akpokodje et. al., 2019). The salt tectonics were not active and the braided system was more widespread in these periods. The fluvial system was possibly less confined by the salt structures at this time, and sand deposits were less channelized and more sheetflood dominated.

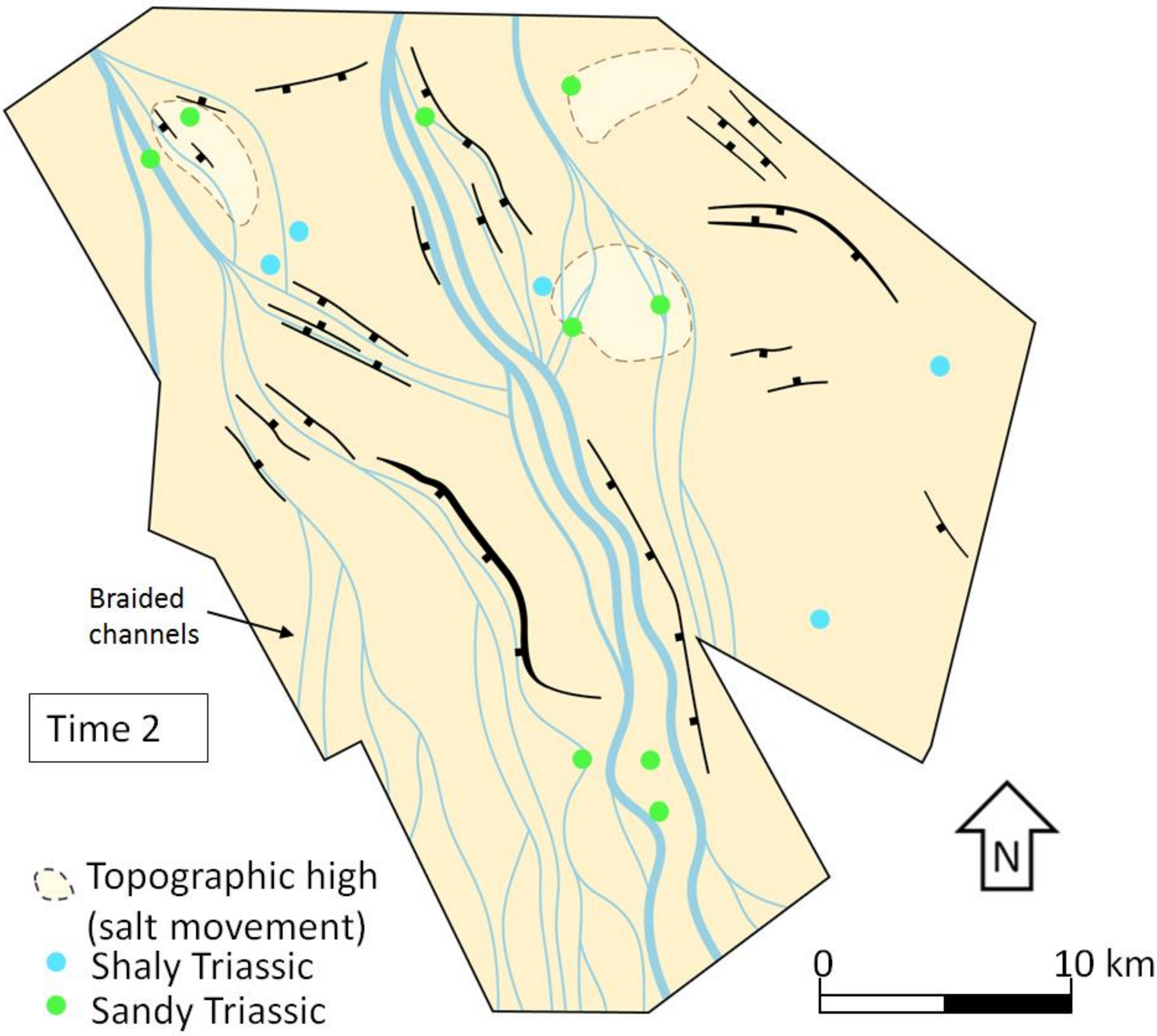


Figure 46: Proposed depositional environment and possible sandstone fairway with the position of the wells.

Figure 47 shows how the conceptual model fits into the regional context. The regional map shows that the depositional environment within the study area is dominated by distal alluvial plain/lake margin and alluvial plain sheetfloods. The conceptual model fits better with the alluvial plain braid channel/stream depositional environment interpreted further north on the regional map (Figure 6).

The sources of sediments in the models are proposed to be from the NW, with some input from the west. However, regionally the Skagerrak Fm was transported southwards from the Fennoscandia in the east and from the Scottish mainland in the west (McKie & Williams 2009) (Figure 8), hence the sediments could have been sourced from the NE as well (Figure 47). Some studies suggest that the Skagerrak Formation sandstones mainly were sourced by erosion of the Fennoscandia Shield hinterland in the east (Figure 47) (Evans et.al, 2003).

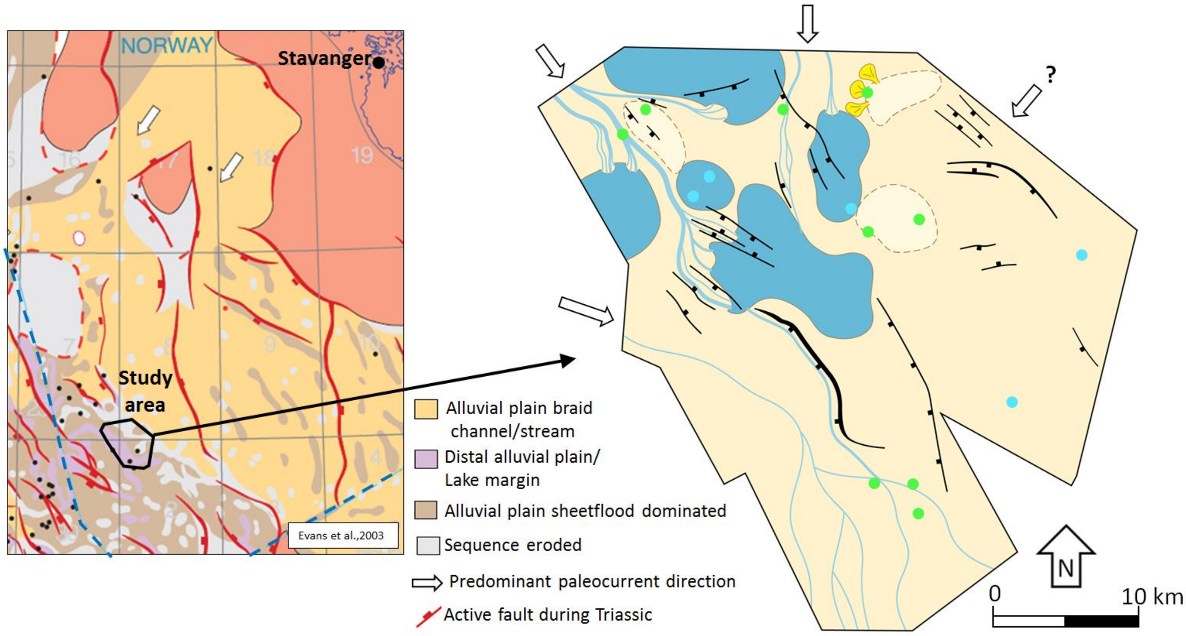


Figure 47: Regional depositional environment map to a local conceptual model. The arrows show possible source directions. Regional map by (Evans et.al, 2003).

5.4 Insights into reservoir potential

Understanding the timing of the salt movement and salt composition is crucial for the Triassic reservoir potential. A setting where the salt has moved during deposition and pierced through the Triassic succession will make the strata pinch out and possibly decrease the reservoir potential towards the diapirs. A thicker Triassic layer with a more constant thickness was deposited above a salt structure that has not moved during deposition, and will probably have better reservoir potential. However, within the pods the Triassic sequence is even thicker, and could have even more reservoir potential.

A study on the UK-sector has divided the Triassic stratigraphy into three sequences, TR10, TR20 and TR30 (Figure 48). TR10 is the non-reservoir rock unit equivalent to the Smith Bank Fm, TR20 is a middle Triassic fluvial sheetflood deposits and TR30 is proposed as the unit with the best reservoir quality (Smith et al., 1993). This unit is composed of channel and sheetflood deposits of Late Triassic age. It is suggested that this unit was deposited in the axes of the pods in between the salt walls (Figure 49), and that depocenters within the pods are capable of trapping and preserving the sands here (Smith et al., 1993). This has been proven by several wells, for instance well 30/1C-6 (Figure 50) where the reservoir is in an isolated pod that contains highquality Upper Triassic sandstones (Smith et al., 1993).

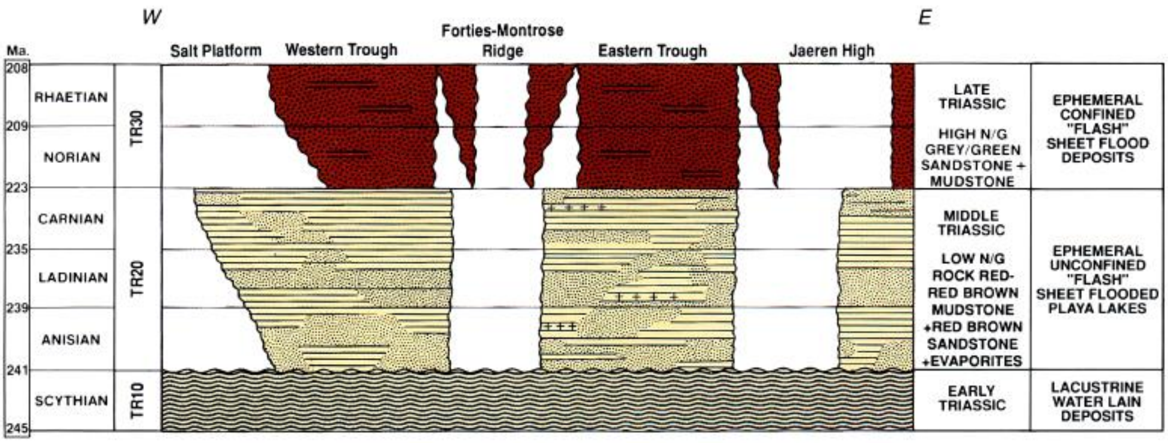


Figure 48: Triassic sequence stratigraphy on the UK Sector (Smith et al., 1993).

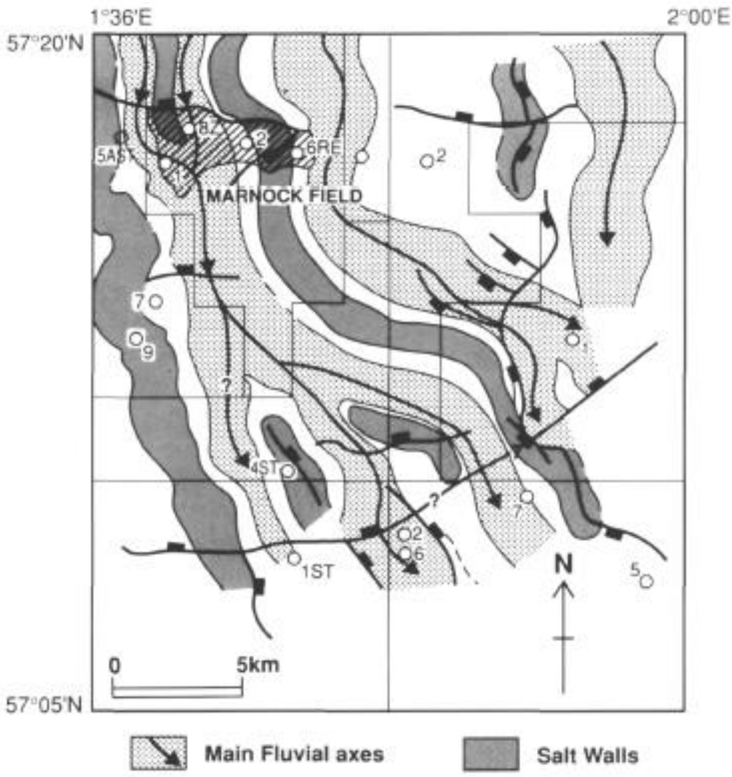
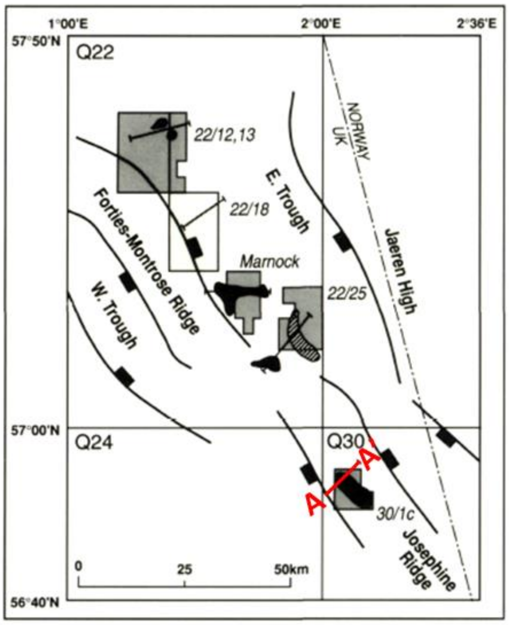


Figure 49: Proposed areal distribution of high quality Skagerrak sandstone (TR30) reservoir in the axial part of the fluvial tract in between the salt walls, in the Marnock Field area, UK (Smith et al., 1993).

A)



B)

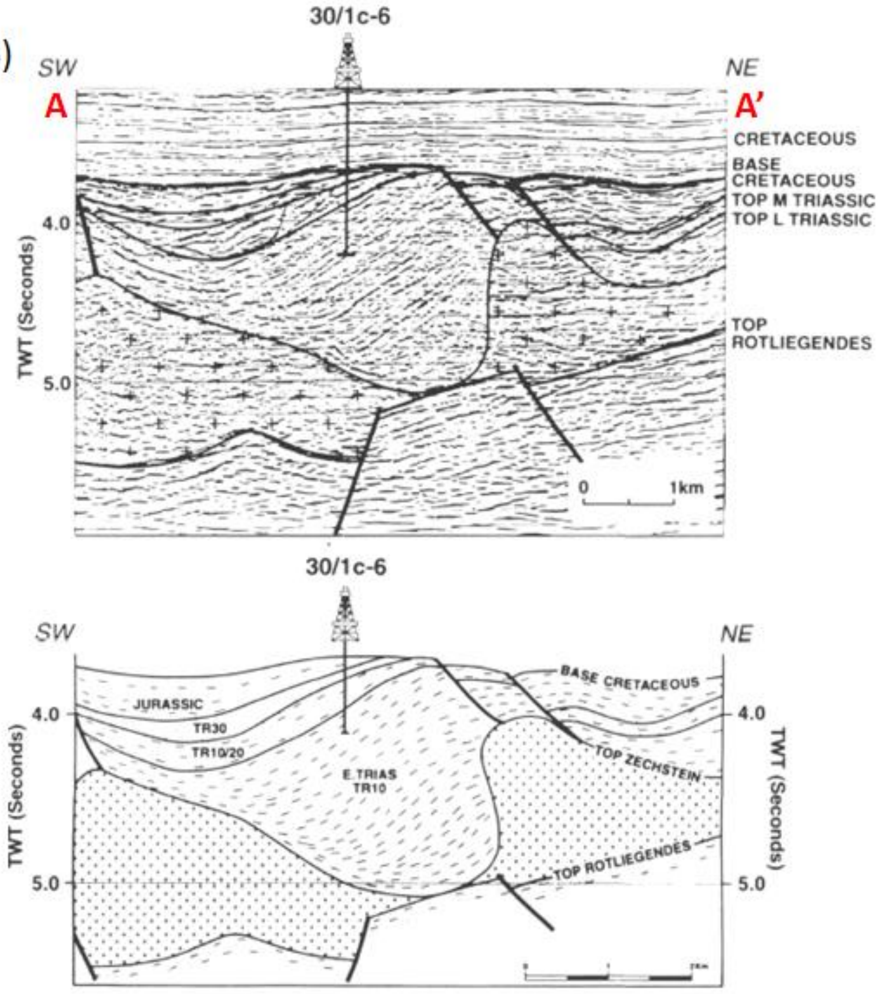


Figure 50: A) Location of seismic line B) Example of well that has drilled high quality reservoir sandstone of the Skagerrak Fm in a pod on the UK sector (Smith et al., 1993).

The Skagerrak Fm sandstones have been reworked as they have been transported a long distance in between the salt structures (Smith et.al., 1993) (Figure 12), and the fluvial channel elements within this system are expected to be clean, coarse-grained sandstones of good reservoir quality (Akpokodje et al., 2018). In the study area the Skagerrak sandstones have been observed in wells on the flank of the salt structures, and according to the findings on the UK sector it is likely that there are even more sandstones to find within the pods. If the river channels have been directed into the pods, the high amplitude reflectors (SF 4) might represent a sandy Skagerrak Fm.

However, the reservoir quality in the Triassic sandstones in the central graben is highly variable (Smith et. al., 1993). It is difficult to make accurate reservoir predictions of the formation, in such a heterogeneous environment. There are large variations between wells that are relatively close. For instance wells 8/10-4 S and 8/10-6 S are separated by a distance of 1.6 km and show very different log motifs. 8/10-4 S suggests only lacustrine or floodplain deposits while well 8/10-6 S show indications of nice sandy channel deposits. These large variations between wells that are so close to each other and in a similar structural setting, makes it difficult to find a consistent pattern of the reservoir distribution.

5.5 Recommendations for further work

One of the main challenges when trying to understand the lateral distribution of the sandstones of the Skagerrak Fm is to differentiate between shale and sand by using seismic where there is lack of well control. Another challenge is that the Triassic section seems to be quite transparent on the seismic without a lot of internal reflections. Additionally, the Triassic section is characterized with a lot of multiple in the seismic data, making it difficult to see and interpret the real reflections in the Triassic. Focusing on optimal imaging of the Triassic strata in the processing may result in improved data quality and better imaging. Broadband data has been acquired over the study area, but these data have not been available for this work.

Improved imaging of the Triassic will enable sequence stratigraphic analysis, facies definition and seismically differentiate between Triassic sandstones and shales. The latter would require detailed rock physics analysis of the wells and seismic offset stacks. This will improve the understanding of the Triassic depositional systems further and the impact salt has on Triassic sedimentation.

A detailed sequence stratigraphic analysis is required in order to obtain better age control, and to subdivide the formation into different lithological units. Better age control would also open opportunities to connect the conceptual models to different time periods within the Triassic. At this time, too few wells have been drilled through thick sequences of the formation, to be able to correlate units within the formation at this time. It might therefore be necessary to drill the Triassic pod, in order to get a better picture of the lateral lithological variations. However, it is difficult to get good biostratigraphic dating of the Triassic units because typically the North Sea Triassic is barren of bugs, though there might be some potential for chemostratigraphy.

A recommendation would also be to perform more studies on the lateral rheological variations within the Zechstein Group. Very little is known about the compositional variations within the Zechstein Group on the Norwegian sector compared to the UK (Jackson and A Stewart, 2016). Investigation of these variations would be important to get a better understanding of the sub-salt structural style (Jackson et al., 2019), which again has a large impact on the Triassic reservoir distribution.

6. Conclusion

- The salt thickness and composition has a large impact on the sub-salt structural style, and furthermore the lateral distribution of the sandstones of the Skagerrak Fm.
- Two salt regimes have been identified based on seismic; one that is dominated by halite and one where the salt layer is interbedded with carbonates and anhydrite. The halite-dominated unit is mobile and creates accommodation space for the Skagerrak Fm sandstone to accumulate. This unit is dominating in the northwestern part of the study area in the "pod zone" where thick Triassic depocenters have been created next to the salt structures. The other salt unit is non-mobile, and has created an area in the SE with relatively constant Triassic thickness together with a Top Triassic surface with gentle topography.
- Regionally the Skagerrak Fm is part of a large fluvial alluvial system. Within the study area it has been interpreted to be deposited in a braided stream environment with ephemeral lakes, based on primarily cores and log-responses.
- Two conceptual models for sandstone fairways representing different scenarios depending on salt movement has been proposed. The first model represents underfill where accommodation space is created by salt withdrawal in the interpod area. The second model represents an overfill period, with salt tectonic quiescence when the accommodation space is filled up, and the braided system is more widespread
- The pods (Triassic mini-basins) are suggested to be areas characterized by accumulation of large amounts of sediments throughout the Triassic from both low energy fluvial plain systems and high energy fluvial systems. In the scenario of underfill, the pods are suggested to be areas characterized by high energy fluvial system where stacked braided systems accumulated. Less accommodation space and a more stable and fluvial plain where lower energy fluvial system or flood plain deposited characterize the interpods, which have a much lower relief.
- It is suggested that the braided rivers have been directed into the pods, where there has been accommodation space for sediments to be deposited, creating a Triassic reservoir potential. The interpods area dominated by the non-mobile salt unit is further from the channel feeder, the wells show less developed sand packages and therefore likely has a lower reservoir potential.

7. References

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