NTNU – Trondheim
Norwegian University of
Science and Technology

Depositional trends of the Statfjord Group from the Stord Basin to the Utsira High

Carina Høie Østebø

Petroleum Geoscience and Engineering
Submission date: July 2014
Supervisor: Egil Tjåland, IPT
Co-supervisor: Evy Glørstad-Clark, Det norske oljeselskap ASA

Norwegian University of Science and Technology
Department of Petroleum Engineering and Applied Geophysics

Depositional trends of the Statfjord Group from the Stord Basin to the Utsira High

Document last updated 02-07-2014 21:28 CEST

Depositional trends of the Statfjord Group from the Stord Basin to the Utsira High

Preface

Summary

List of figures

List of tables

Preface

This report was made during the spring of 2013 in TGB4900 Petroleum Geology, and is my master thesis at the Norwegian University of Science and Technology (NTNU). The report is written in cooperation with Det norske oljeselskap ASA (Det norske). Parts of chapter 2 - 4 are edited from my project thesis "Seismic mapping of the Early Jurassic succession in the Stord Basin". This project formed the basis for my master thesis.

First, I would like to give a special thanks to my supervisor, Egil Tjåland, for giving advice in order to give proficient knowledge during this semester.
Secondly, I would like to give a special thanks to my co-supervisor, Dr. Evy Glørstad-Clark at Det norske, for her guidance and valuable scientific input throughout the semester.

The project has been conducted in collaboration with Det norske oljeselskap ASA (Det norske). I thank Det norske for permission to publish these results. I would also like to thank Det norske for providing access to all the required data in order to take on and complete this thesis and for allocation of a desk at their office.
Last but not least, I would like to thank my fellow students and colleagues at Det norske for interesting and helpful discussion throughout the semester.

Carina Høie Østebø
July, 2014

Summary

This study aimed to understand the lateral distribution of the Early Jurassic Statfjord Group in the Stord Basin and upon the Utsira High. The Stord Basin in the northern North Sea is located approximately 50 km south of the Troll Field. The tectonostratigraphic framework of the Early Jurassic succession in the Stord Basin has been investigated to better understand the sub-regional distribution of depositional facies of the Statfjord Group.

The Stord Basin was formed due to extension pre-Jurassic times, with a major phase in Permian-Triassic. Very few wells have been drilled in the Stord Basin, and the stratigraphic succession and depositional facies distribution across the basin is somewhat speculative. Based on all public data, including 2D and 3D seismic, wells surrounding this area and core photos, an interpretation of the gross depositional environment in Early Jurassic was made.

The study method includes seismic-well tie, seismic mapping, literature study, well correlation and interpretation of depositional facies from well logs and core photos.

Seismic mapping indicate that the Utsira High likely represented a paleo-topographic high during deposition relative to the Stord Basin, reflected also in the depositional maps.

The extensional breakup and forming of The Stord Basin was formed mainly due to extension in Permian - Triassic time, and continued into the Middle and Late Jurassic time. In this study two seismic horizons have been interpreted in the basin. Seismic interpretation has been carried out aiming to understand the distribution and thickness of the Early Jurassic succession in the Stord Basin and evaluate the seismic signature of this interval. Seismic mapping of the Top Hegre and Top Statfjord horizons give a framework of the Early Jurassic Statfjord Group. A literature study of previous work considering the Stord Basin has been done to gain knowledge of the structural and lithostratigraphic framework of the basin.

Facies distribution within the Statfjord Group was predicted based on the results of seismic mapping and resulting isochor maps. No gross depositional facies maps are published in the area, whereas prevalent detailed core analysis and core descriptions of wells in the area are well documented. This study aims to test if seismic mapping of accommodation space can help predict gross sedimentary facies in this region.

Sammendrag

Målet med denne masteroppgaven var å forstå den laterale fordelingen av den tidlig jurassiske Statfjord Gruppen i fra Stordbassenget og opp på Utsira Høyden. Stordbassenget er lokalisert i den nordlige Nordsjø og ligger ca 50 km sør for Troll feltet. Det tektonostratigrafiske rammeverket av den tidlig jurassiske Statfjord Gruppen i Stordbassenget har blitt undersøkt for å bedre forstå den sub-regionale fordelingen av avsetningsfacies i Statfjord Gruppen.

Stordbassenget ble dannet på grunn av ekstensjon i pre-jurassiske tider, med en stor fase i perm-trias. Svært få brønner har blitt boret i Stordbassenget, og den stratigrafiske suksesjonen og avsetnings-facies distribusjonen på tvers av bassenget er noe spekulativ. Basert på alle offentlige data, inkludert 2D og 3D seismikk, brønner rundt dette området og kjernebilder, ble en tolkning av brutto avsetningsmiljø i tidlig jura gjort.

Studiemetoden i denne oppgaven omfatter seismisk-brønn-tie, seismisk kartlegging, litteraturstudie, brønn korrelasjon og tolkning av avsetningsfacies bra brønnlogger og kjernebilder.

Seismisk kartlegging viser at Utsira Høyden trolig representerte en paleotopografisk høyde i forhold til Stordbassenget under avsetning, noe som også er reflektert i avsetningskartene.

Den ekstensjonale oppsprekking og dannelsen av Stordbassenget ble hovedsaklig dannet på grunn av ekstensjon i perm-trias, og fortsatte inn i midt- og senjura. I denne studien har to seismiske horisonter blitt tolket i bassenget. Seismisk tolkning har blitt utført med formål å forstå fordelingen og tykkelsen av den tidlig jurassiske suksesjonen i Stord bassenget og å evaluere den seismiske signaturen av dette intervallet. Seismisk kartlegging av horisontene Top Hegre og Top Statfjord gir et rammeverk av den tidlig jurassiske Statfjord Gruppen. En litteraturstudie av tidligere arbeid med tanke på Stod bassenget har blitt gjort for å få kunnskap om den strukturelle og lithostratigrafiske rammen av bassenget.

Facies distribusjon innen Statfjord Gruppen ble forutsagt basert på resultatene av seismisk kartlegging og resulterende tykkelseskart. Ingen brutto avsetnings facies kart er publisert i området, mens utbredt detaljert kjerneanalyse og kjerne beskrivelse av brønner i området er godt dokumentert. Denne studien tar sikte på å teste om seismisk kartlegging av avsetningsrom kan bidra til å forutsi brutto sedimentære facies i denne regionen.

1 Introduction

The study area of this project is located within the Stord Basin in the northern North Sea, 50 km south of the Troll Field. The Early Jurassic succession in the Stord Basin and Utsira High is relatively poorly understood. Multiple publications of the Statfjord Group exist (i.e. Ryseth & Ramm, 1996; Ramm & Ryseth, 1996; Ryseth 2001), but most studies are concentrated around the Tampen Spur and Horda Platform. The main purpose of this master thesis is to create a tectonostratigraphic framework of the Early Jurassic succession in the Stord Basin in order to understand the available accommodation space of the Statfjord Group. This is mainly done by mapping 2D and 3D seismic data in the area.

The main goal of this master thesis is to understand the sub-regional distribution of depositional facies of the Statfjord Group based on the seismic mapping of accommodation space, and on available well data and core photos.

The interpretation was done by using available 2D and 3D seismic data, and also based on available well data in the basin. Seismic interpretation establishes a framework to understand the regional thickness distributions of the Statfjord Group, and seismic facies analysis and isochron maps indicate that the Utsira High likely was a paleo-topographic high during deposition in Early Jurassic relative to the Stord Basin. Core photos of key wells has also been included as a part of this study. One of the deliverables is a gross depositional environment (GDE) map.

This thesis includes four deliverables:

1. Sub-regional seismic mapping of two seismic markers in the Lower Jurassic succession from the Stord Basin onto the Utsira High. A seismic reflector tied to the Top Statfjord Group was interpreted. Additionally, Top Hegre Group was interpreted, representing the base of the Statfjord Group.
2. Time-thickness maps of the Early Jurassic succession to understand the available accommodation space, indicating areas where the Statfjord Group potentially is missing in the Stord Basin.

3. Wireline log correlation of the Statfjord Group in the study area.
4. Gross Depositional Enviroment (GDE) maps for selected intervals in Early Jurassic (Hettangian/Early Sinemurian and Late Sinemurian).

In addition to the deliverables mentioned above, the thesis intends to address several questions:

1. What was the role of Utsira High during Early Jurassic? Was it a topographic high during deposition or not?
2. Where does the Statfjord Group pinch out in the Stord Basin?
3. Are there any signs of syn-depositional tectonic activity during deposition of the Statfjord Group in the study area?
4. Are there any paleo-topographic highs in the Stord Basin during Early Jurassic?

This thesis is the result of work performed using all available public data followed by a detailed and refined seismic interpretation of the area. Seismic mapping for this project was further used to evaluate the source rock potential - within the Statfjord Group in the Stord Basin. Analysis of the source rock potential is summarized in the Appendix.

2 Database and Data Utilisation

The understanding of the petroleum system in the Stord Basin could not have been developed without a regional evaluation of the area. This thesis is the result from a regional appraisal of the Stord Basin. All public data for the study area has been utilized to compile a seismic interpretation of the acreage.

All of the data used in this thesis is public data. Published core photos are gathered from NPD (Norwegian Petroleum Directorate).

2.1 Seismic Database

The regional mapping of the Stord Basin was undertaken using a combination of 3D cubes and a number of 2D lines of different quality and vintage (Fig. 2.1).

The acreage is covered by 2D public seismic data acquired between 1980 and 2006; the seismic dataset used to interpret the study area is detailed in Fig. 2.2 and Table 2.1.

Table 2.1 Seismic database list.

Survey name	Survey type		Public	Vintage
	3D	2D		
EN0101	x		x	2001
I08	x		x	2008
J09	x		x	2009
HRT91		x	x	1991
HRT93		x	x	1993
HT91		x	x	1991
NSR06		x	x	2006
SBD95		x	x	1995
SBDE96		x	x	1996
ST8125		x	x	1981
ST8201		x	x	1982
ST8516		x	x	1985
TLGS80		x	x	1980
TT98		x	x	1998

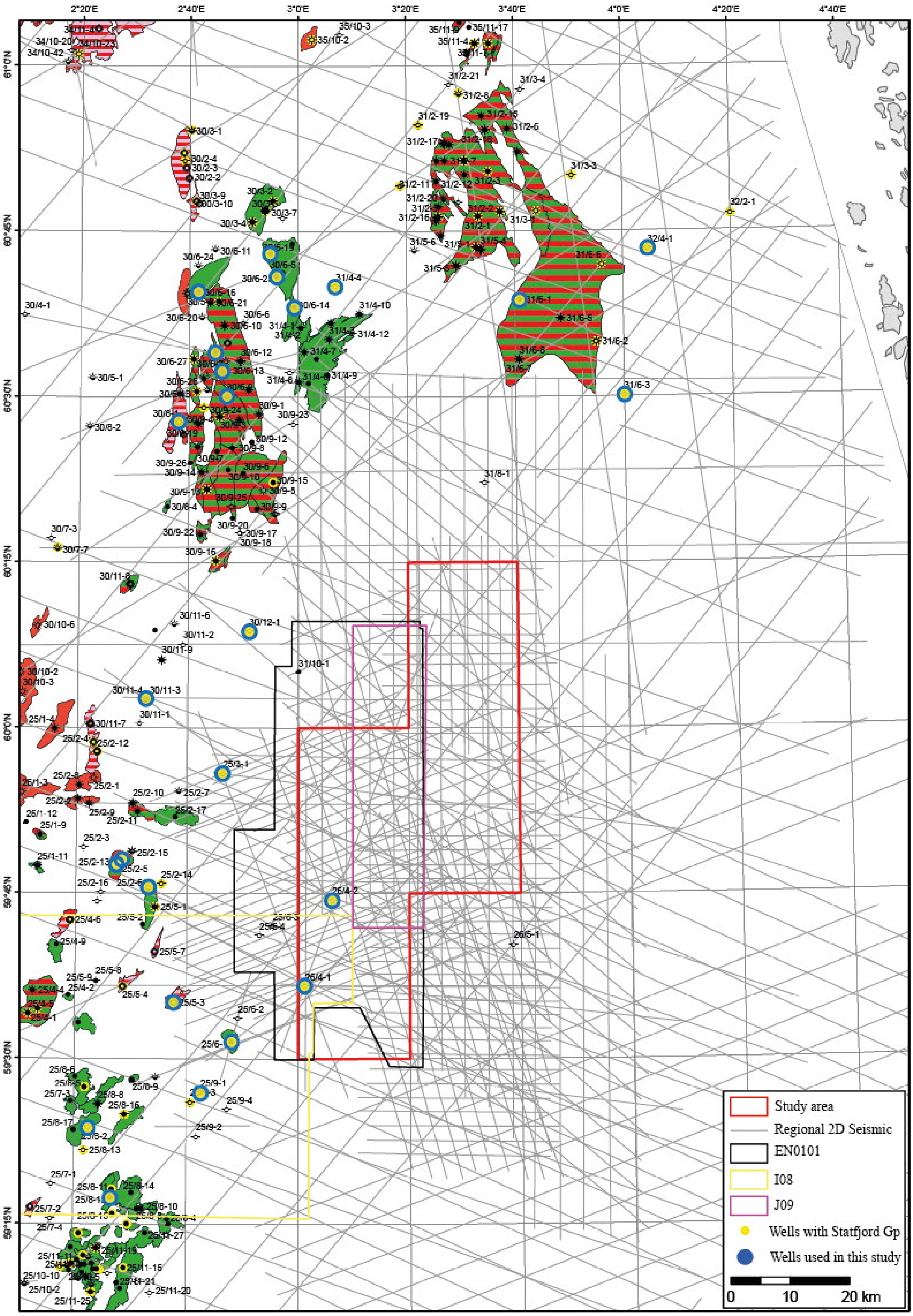


Fig. 2.1 Regional database: Seismic and well data used in this study.

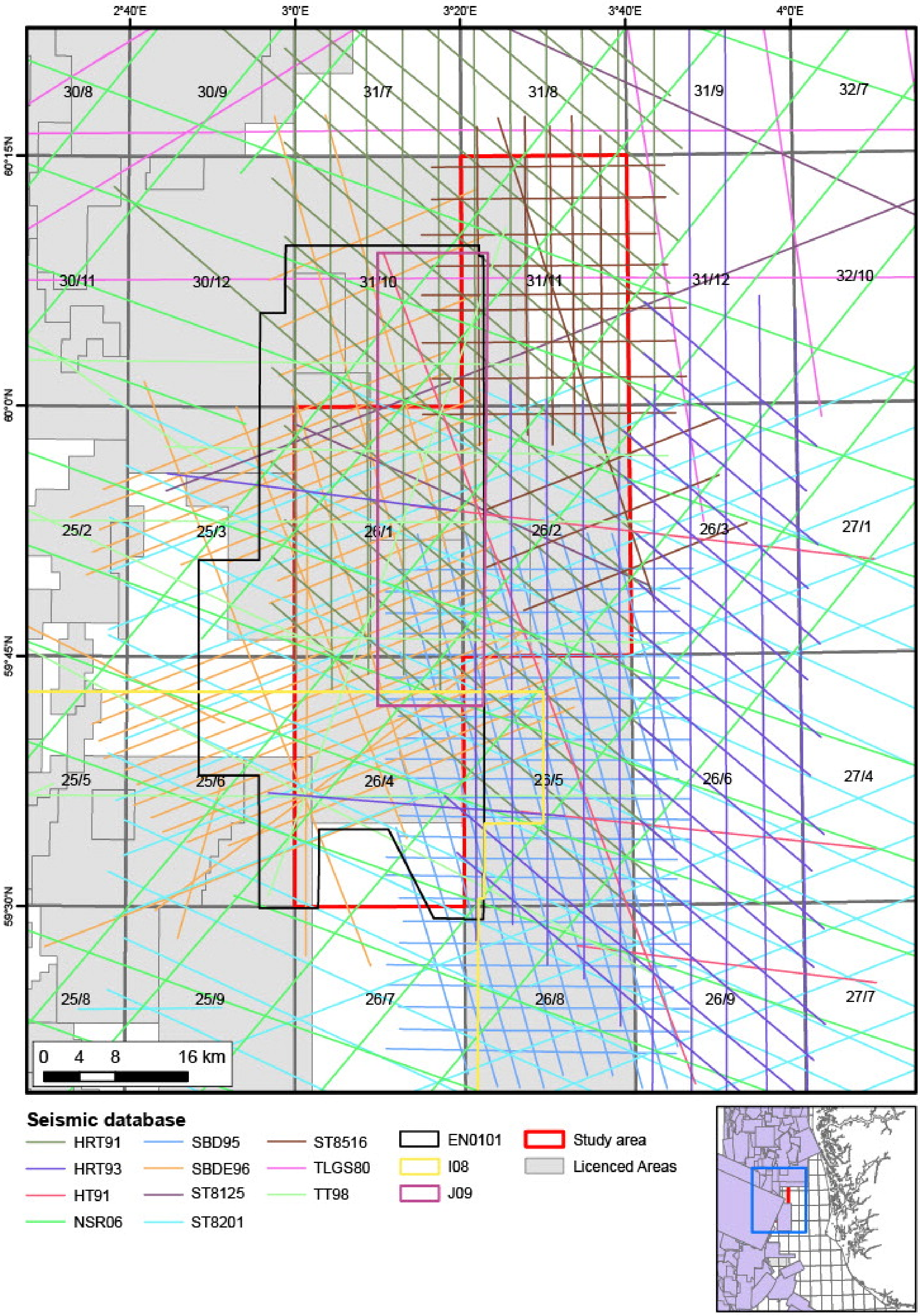


Fig. 2.2 Study acreage: Seismic database.

2.2 Well Database

The Stord Basin is one of the most underexplored areas in the Norwegian North Sea. Well 26/4-2 provides useful information about the thickness and quality of the shallow horizons of the Nordland Group and the Rogaland Group. The well, however, did not penetrate the Lower Jurassic and Upper Triassic sequence.

A seismic to well tie was performed for 26/4-1 on the edge of the Stord Basin. Well 26/4-1 was drilled as a wildcat exploration well by BP (operator) in 1987. The coordinates of the well is 59° 36' 37.84" N, 3° 1' 13.26" E. This point is intersected by several of the seismic lines. The primary of the well was to test a Paleocene mound and sandstones of Jurassic age within a footwall closure, as well as gain information on reservoir quality and hydrocarbon source (NPD 2014). Total depth of the well is 3690 m. The well penetrates the Nordland Group (Quatemary), Hordaland Group (Upper Paleogene to Upper Neogene), Rogaland Group (Lower Paleogene), Shetland Group (Upper Cretaceous), Cromer Knoll Group (Lower Cretaceous), Viking Group (Upper Jurassic), Vestland Group (Middle Jurassic), Dunlin Group (Lower Jurassic) and the Statfjord Group (Lower Jurassic).

Well 25/6-1 is located northwest of the main study area in block 25/6. In this thesis the well 25/6-1 was used for a well-tie at the location of Utsira High. Well 25/6-1 was drilled as a wildcat exploration well by Saga Petroleum ASA (operator) in production licence 117. Coordinates of the well is 59° 31' 32.04" N, 2° 48' 2.07"E. This point is intersected by some of the available seismic lines of this study. Total depth of the well is 2881 m. The oldest penetrated age in the well is the Pre-Devonian and the well is drilled through the whole Statfjord Group succession (NPD 2014).

Wells that penetrate the Statfjord Group in areas surrounding the study area have been used in completion logs for well correlations. Well tops from nearby areas have been used for seismic interpretation. Well 26/4-1 was also used to provide a geochemical calibration for the source rock potential of the Statfjord Group.

A total of 25 wells located around the study area have been included in the regional database and are listed in Table 2.2. They are all displayed in Fig. 2.1.

Table 2.2 Well database.

Well	Status	Year	TD (MD) [m]	TD Stratigraphy	Cores studied
25/2-5	Oil/Gas	1976	4000	Triassic	
25/2-6	Oil shows	1977	3750	Triassic	
25/2-13	Oil/Gas	1990	3908	Late Triassic	Yes
25/3-1	Dry	1989	3922	Late Triassic	
25/5-3	Gas/Condensate	1990	2900	Triassic	
25/6-1	Oil	1986	2881	Pre-Devonian	
25/8-2	Dry	1975	2578	Late Triassic	
25/8-12 S	Oil	1999	2096	Late Triassic	Yes
25/9-1	Dry	1995	2525	Late Triassic	
26/4-1	Dry	1987	3690	Triassic	Yes
26/4-2	Dry	2004	2302	Late Cretaceous	
30/6-9	Oil/Gas	1982	3476	Late Triassic	
30/6-14	Oil	1984	2900	Early Jurassic	
30/6-15	Oil/Gas	1984	3972	Late Triassic	Yes
30/6-16	Oil/Gas	1985	3300	Triassic	
30/6-19	Oil	1986	3301	Early Jurassic	
30/6-23	Oil	1990	3209.5	Early Jurassic	
30/6-28 S	Oil	2012	4064	Late Triassic	
30/8-1 SR	Gas/Condensate	1996	5149	Early Jurassic	
30/11-4	Oil shows	1984	5255	Late Triassic	Yes
30/12-1	Dry	1994	3641	Early Jurassic	
31/4-4	Dry	1981	3150	Early Jurassic	
31/6-1	Oil/Gas	1983	4070	Pre-Devonian	
31/6-3	Dry	1983	2250	Triassic	
32/4-1	Dry	1996	3186	Pre-Devonian	

2.3 Core Database

Wells with cores at Statfjord level were used in the stratigraphic evaluation of the group. Core data from four wells located in quadrant 25, 26 and 30 in the northern North Sea were used to assess the lithology of the Statfjord Group. These wells are listed in Table 2.3.

Table 2.3 Core database. Well information and cored intervals for well 25/2-13, 25/8-12 S, 26/4-1 and 30/6-15.

Well 25/2-13			
Core no	Cored intervals [m]	Age	Formation
11	3709.0 - 3726.3	Early Jurassic	Statfjord Group
12	3727.0 - 3744.7	Early Jurassic	Statfjord Group
13	3745.0 - 3763.0	Early Jurassic	Statfjord Group
14	3763.0 - 3781.5	Early Jurassic	Statfjord Group
15	3781.5 - 3792.0	Early Jurassic	Statfjord Group
16	3792.0 - 3810.6	Early Jurassic	Statfjord Group
17	3810.5 - 3828.8	Early Jurassic	Statfjord Group
18	3829.0 - 3847.0	Early Jurassic	Statfjord Group
19	3847.0 - 3854.2	Early Jurassic	Statfjord Group

Well 25/8-12 S			
Core no	Cored intervals [m]	Age	Formation
1	1905.0 - 1938.8	Early Jurassic	Stafjord Group

Well 26/4-1			
Core no	Cored intervals [m]	Age	Formation
4	3308.0 - 3316.9	Early Jurassic	Statfjord Group

Well 30/6-15			
Core no	Cored intervals [m]	Age	Formation
1	3254.0 - 3272.1	Early Jurassic	Nansen Formation
2	3272.0 - 3291.5	Early Jurassic	Eiriksson Formation
3	3294.0 - 3321.0	Early Jurassic	Eiriksson Formation
4	3321.0 - 3348.0	Early Jurassic	Eiriksson Formation
5	3349.0 - 3363.6	Early Jurassic	Eiriksson Formation
6	3365.0 - 3376.0	Early Jurassic	Eiriksson Formation
7	3377.0 - 3388.1	Early Jurassic	Eiriksson Formation
8	3390.0 - 3398.5	Early Jurassic	Eiriksson Formation

3 Seismic Mapping

3.1 Phase and Polarity

Before starting to interpret seismic horizons, the issue of polarity needs to be addressed. The Society of Exploration Geophysicists (SEG) has adopted two polarity standards for the display of zero-phase seismic data; SEG normal and SEG reverse. The zero phase wavelet reaches its maximum density at time zero and in case of SEG normal polarity, an increase in acoustic impedance corresponds to a peak (Fig. 3.1.B). In case of SEG reverse polarity, an acoustic impedance increase corresponds to a trough at time zero (Fig. 3.1.C).

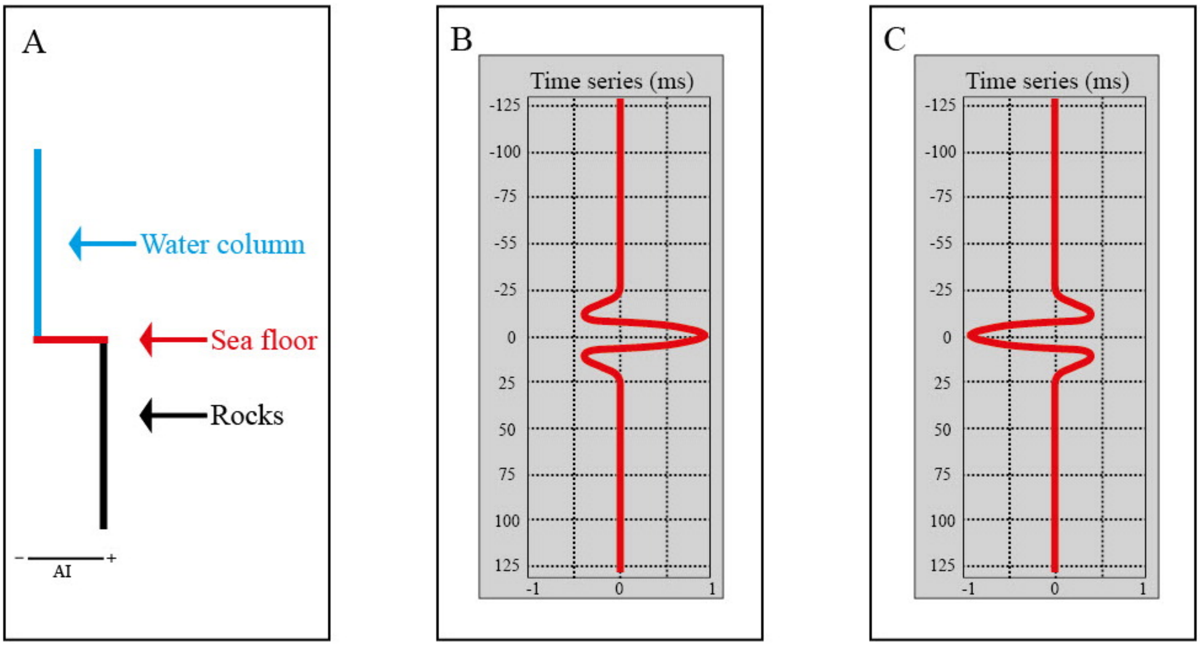


Fig. 3.1 Reflection at time zero. *A: Acoustic impedance (AI) at the sea floor provides a confident increase. B: In case of SEG normal polarity, sea floor would be represented by a peak. C: In case of SEG reverse polarity, sea floor would be represented by a trough.*

The sea-floor reflector dictates the choice of polarity. The seismic wave is propagating from water with a velocity of 1480 m/s to higher velocity stratas and thus the sea floor reflector represents a secure increase in acoustic impedance (Fig. 3.1.A). The wiggle trace shown in Fig. 3.2 implies a zero phase dataset. The positive reflection in the wiggle trace correlate to the red colour in the colour display. This positive red reflection represents the main peak and the two blue negative reflections are interpreted as side lobes. The seismic reflection in Fig. 3.2

indicates that the seismic database applied in this thesis is displayed with a SEG normal polarity.

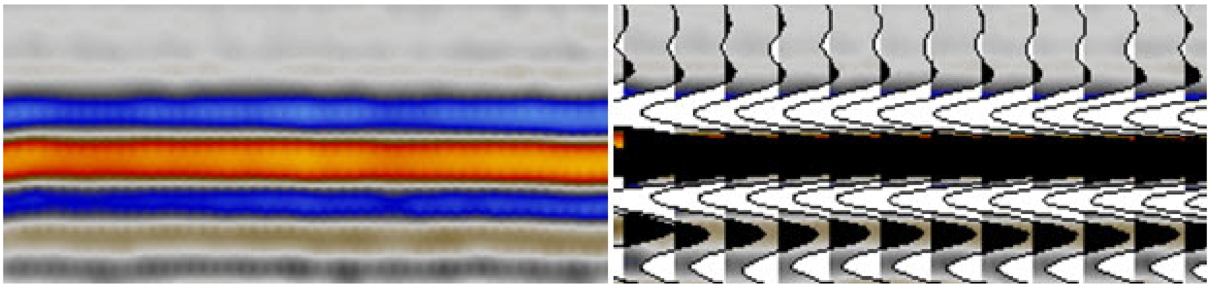


Fig. 3.2 Sea bottom reflection from the seismic line TT98-106. *Left: Colour display. Right: Wiggle trace.*

3.2 Interpretation Method

The interpretation performed in this thesis has been done using Schlumberger's computer software Petrel 2013.2.

The first step in seismic interpretation is to observe the imported seismic data. By observation of geological features and correlation with the available wells, the issue of which horizons to track is determined. The question of polarity is also answered in this step. With answers from the observation phase, the second step begins. This is the interpretation phase where horizons are tracked.

Adobe Illustrator CS5 is the second main program used in this thesis. This is a drawing program. After the observations and interpretations are done in Petrel, the work is carried out and exported to Adobe Illustrator. By using this program, a graphical design of the interpretation can be given. The result is high resolution figures.

The third program used to provide this thesis is the Oildfield Data Manager (ODM) 3.8. ODM is a powerful integration and interrogation workspace used to organize all well data available. This workspace is used to visualize well data and to build well correlation panels.

3.3 Seismic Interpretation

Two seismic horizons have been regionally mapped throughout 256 km^2 in the Stord Basin area: Top Statfjord Group and Top Hegre Group. These surfaces have been used as input for giving the structural framework of the basin.

The criteria used to pick the seismic events are listed in Table 3.1 and discussed in the paragraphs below.

Table 3.1 Interpreted seismic horizons.

Horizon	Peak	Trough	Color
Top Statfjord Gp	x		🟦
Top Hegre Gp	x		🟥

The seismic database is a zero phase dataset where an increase in Acoustic Impedance (AI) is displayed as a peak (SEG normal, see 3.1 Phase and Polarity). The seismic colour scale adopted for the figures in this thesis is such that a red-yellow colour in the colour display represents a "hard" event whereas the black-blueish indicates a "soft" event.

Seismic waves normally migrate slower in open marine mudrocks (Lower Dunlin Group) than in marginal marine sediments (Upper Statfjord Group). (For details on the lithology, see 5.1 Lithostratigraphy of The Statfjord Group). This provides the reflection from the interface between the Dunlin Group and the underlying Statfjord Group. The Top Statfjord reflector is interpreted as a peak. Seismic waves normally also migrate slower in fluvial sandstones (Lower Statfjord Group) than in alluvial beds (Upper Hegre Group). This provides the reflection from the interface between the Statfjord Group and the Hegre Group. The Top Hegre reflector is interpreted as a peak.

The seismic interpretation has been carried out on 2D seismic lines and 3D seismic cubes of the surveys listed in Table 2.1 (2.1 Seismic Database).

3.4 Well Ties

The Stord Basin is one of the most underexplored areas in the Norwegian North Sea. Only a few wells provide control on the Lower Jurassic and Triassic horizons. There is only one drilled well (26/4-1) with available sample data for the Statfjord Group in the Stord basin. Well 26/4-1 is located on the flank of the basin and represents the key well in this thesis. The well has been tied to the seismic data and a seismic well-tie is documented in Fig. 3.3.

A composite seismic line in Fig. 3.5 illustrates the seismic well tie to the seismic reflector Top Statfjord and Top Hegre. Fig. 3.4 shows the location of the composite line. The line has been extended towards the centre of the basin where a structural horst is observed. The Top Hegre and Top Statfjord reflectors are represented by a peak in this dataset. The well 26/4-1 penetrates the entire Statfjord Group succession. Younger horizons in the well tie are used as a guideline for mapping the Statfjord Group.

The Top Statfjord and Top Hegre reflectors are proved to be relatively difficult to map over larger distances of the basin.

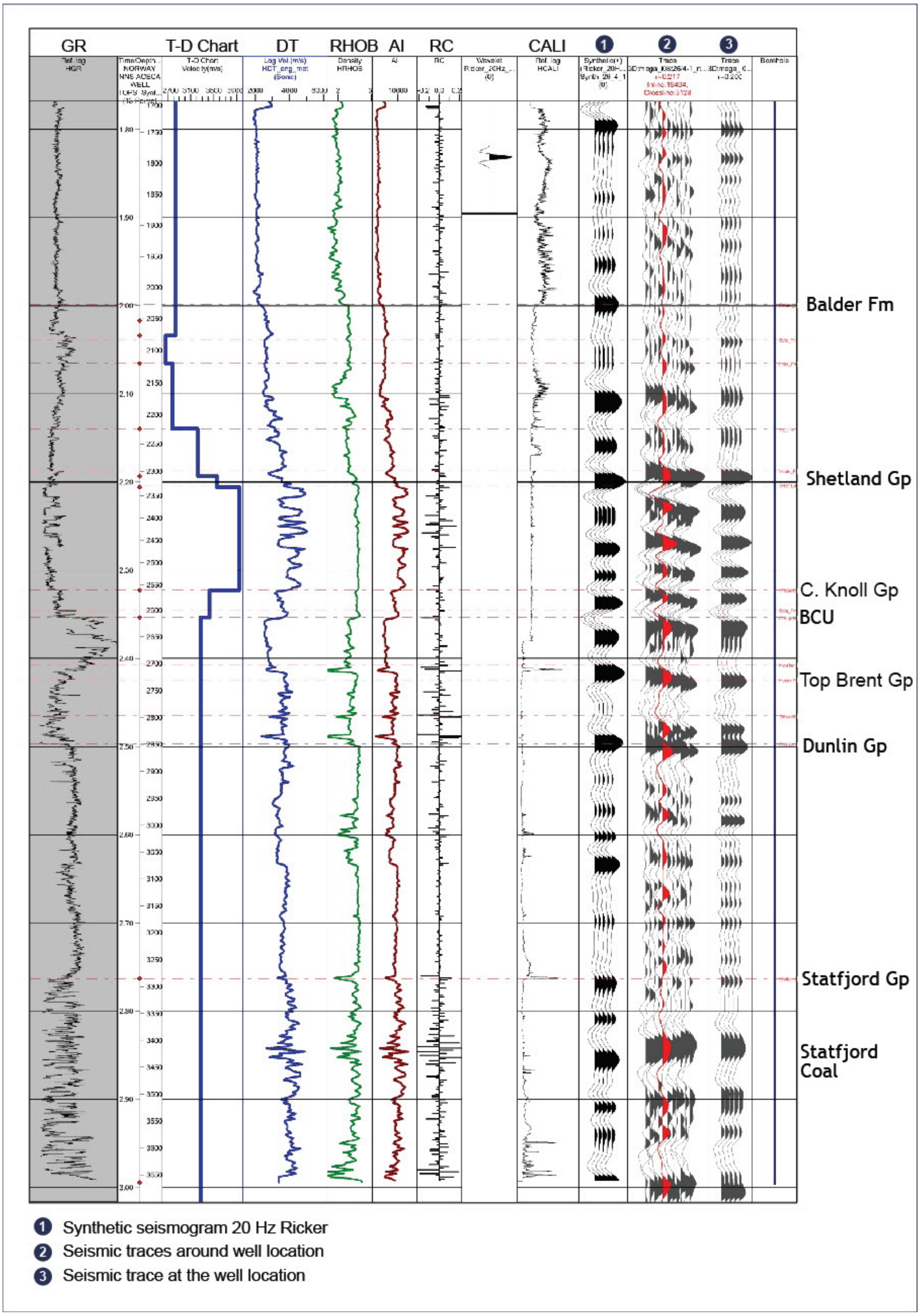


Fig. 3.3 Synthetic seismogram for well 26/4-1.

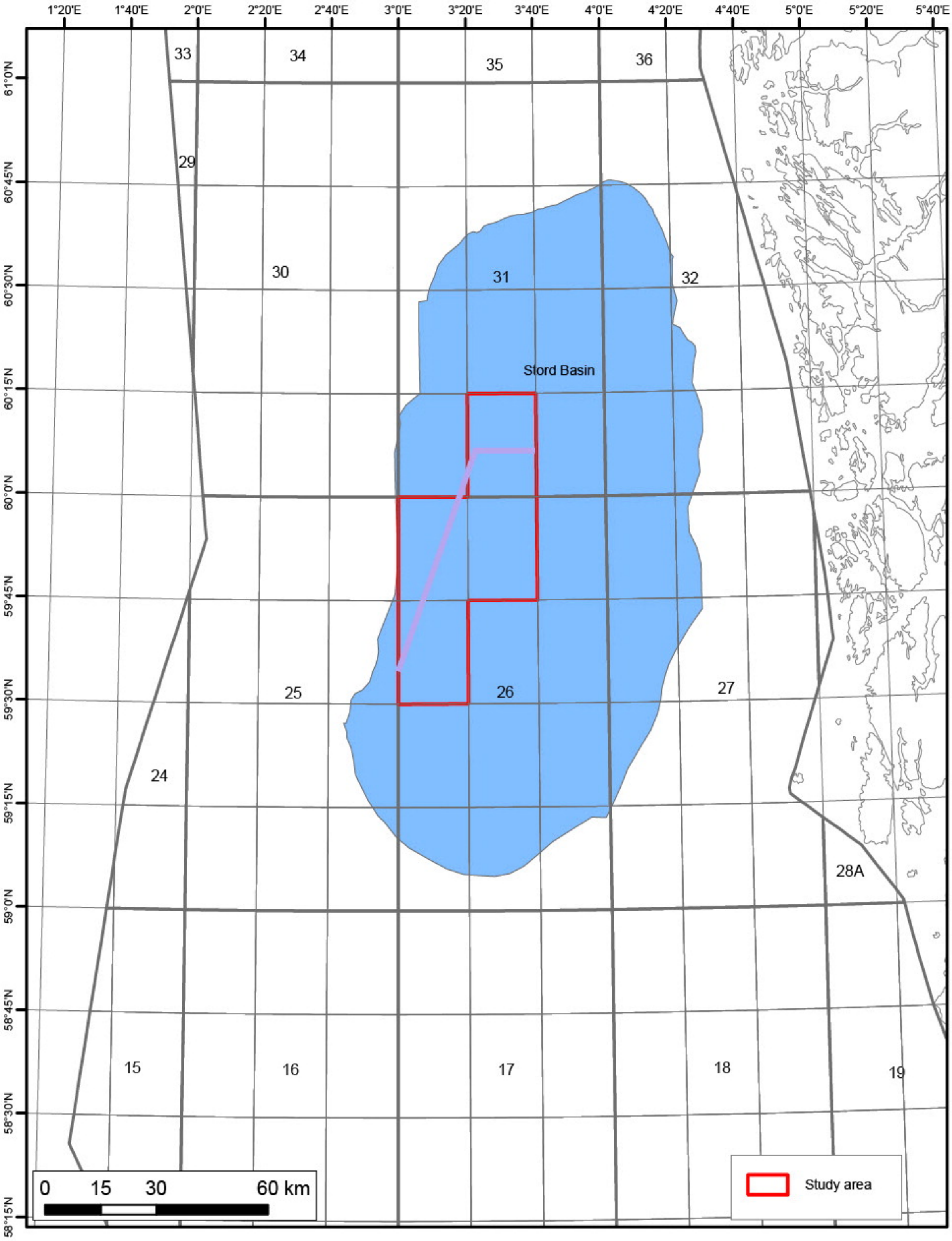


Fig. 3.4 Location map of the regional well-tie line indicated by the purple line.

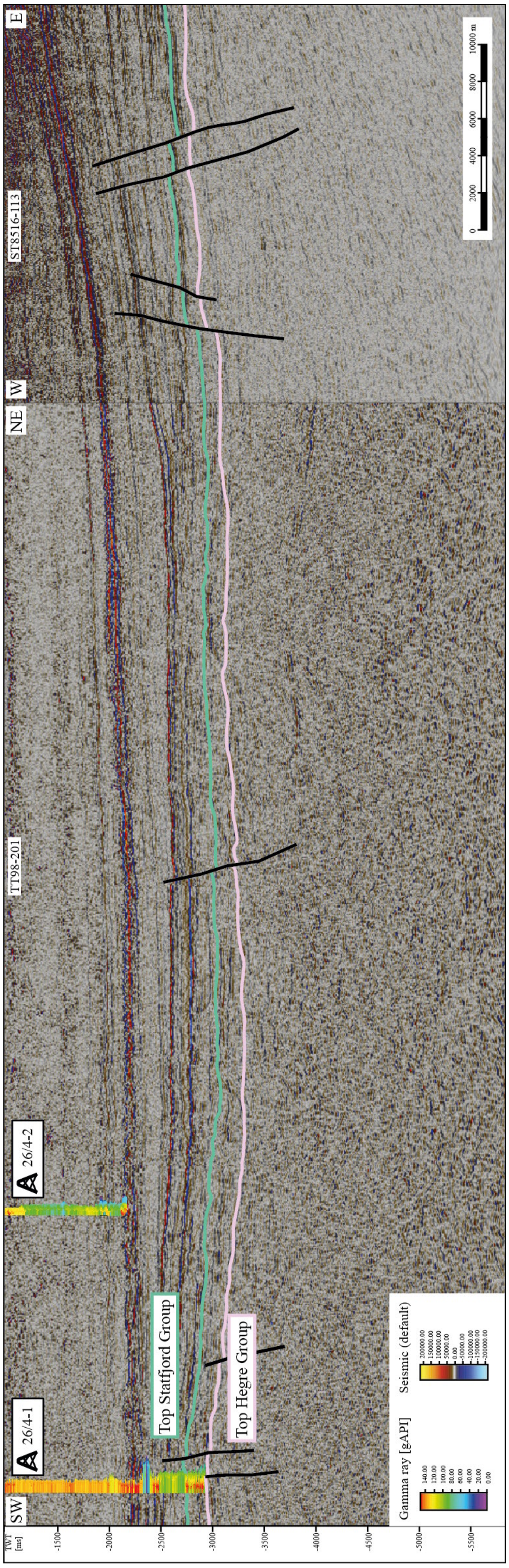


Fig. 3.5 Regional composite seismic line calibrated to well 26/4-1. *The location of the seismic line is shown in Fig. 3.4.*

4 Geological Setting

The Stord Basin is located east of the Viking Graben in the northern North Sea between 59° and 60°N, and 3° and 4°E. The Stord Basin is approximately trending north to south and is bordered by the Utsira High to the west and by the Øygarden Fault Complex to the east (Fig. 4.1). The axis of the basin plunges to the north-west. To the south the basin is bounded by the Ling Depression. The Øygarden fault Complex displaces the basement vertically by 3-5 km across normal faults and extends more than 300 km (Færseth et al. 1995). The Utsira High to the west is a horst and has a shallow basement which is dipping to the north.

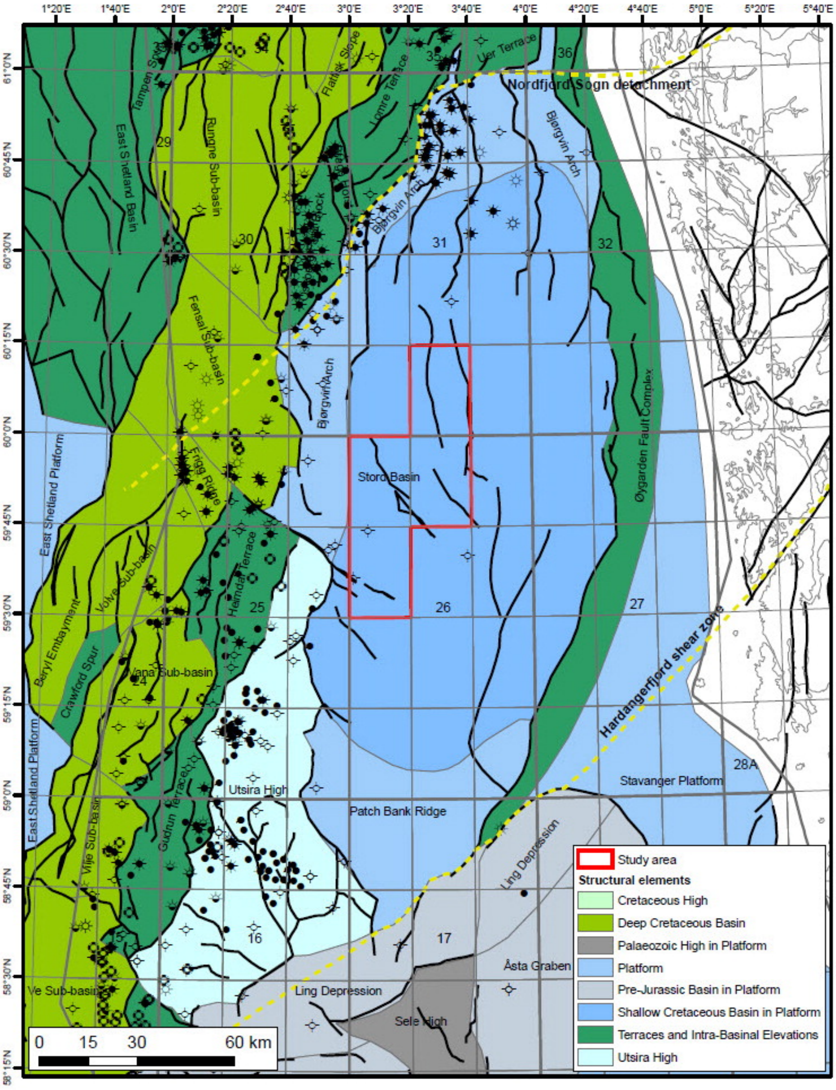


Fig. 4.1 Structural element map. *Yellow dashed lines show the approximate position of the large shear zones described by Færseth (1996). Main structural elements slightly modified from NPD. The study area is outlined in red.*

Fig. 4.1 also comprises wells drilled in the area. Notably there are no boreholes drilled through the entire sedimentary succession in the Stord Basin. This introduces uncertainty to the deep stratigraphic succession.

Multiple articles of the tectonic evolution of the northern North sea exists (e.g., Badley et al. 1988; Fraser et al. 2002; Gabrielsen et al. 1990; Ziegler 1990; Underhill &Partington 1993). Only few publications have focused on the evolution of the Stord Basin. Fig. 4.2 summarizes the tectono-stratigraphic evolution of the area. Applicable chrono- and lithostratigraphy is combined and shown in the figure. The Statfjord Group is of Rhaetian (Late Triassic) to Sinemurian age (Early Jurassic). The underlying group is the Hegre Group. For details see "The Geological Time scale 2004" by Gradstein et al..

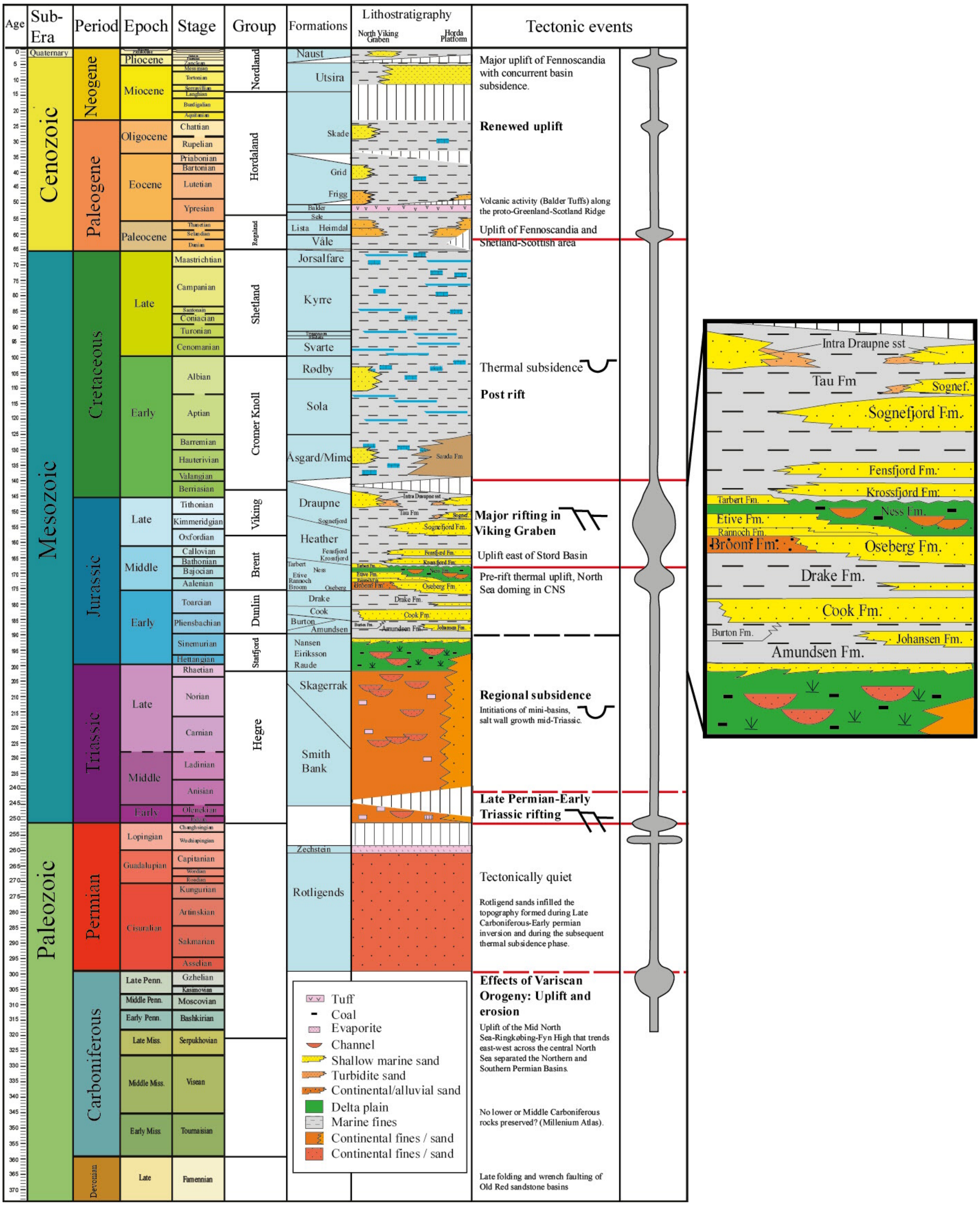
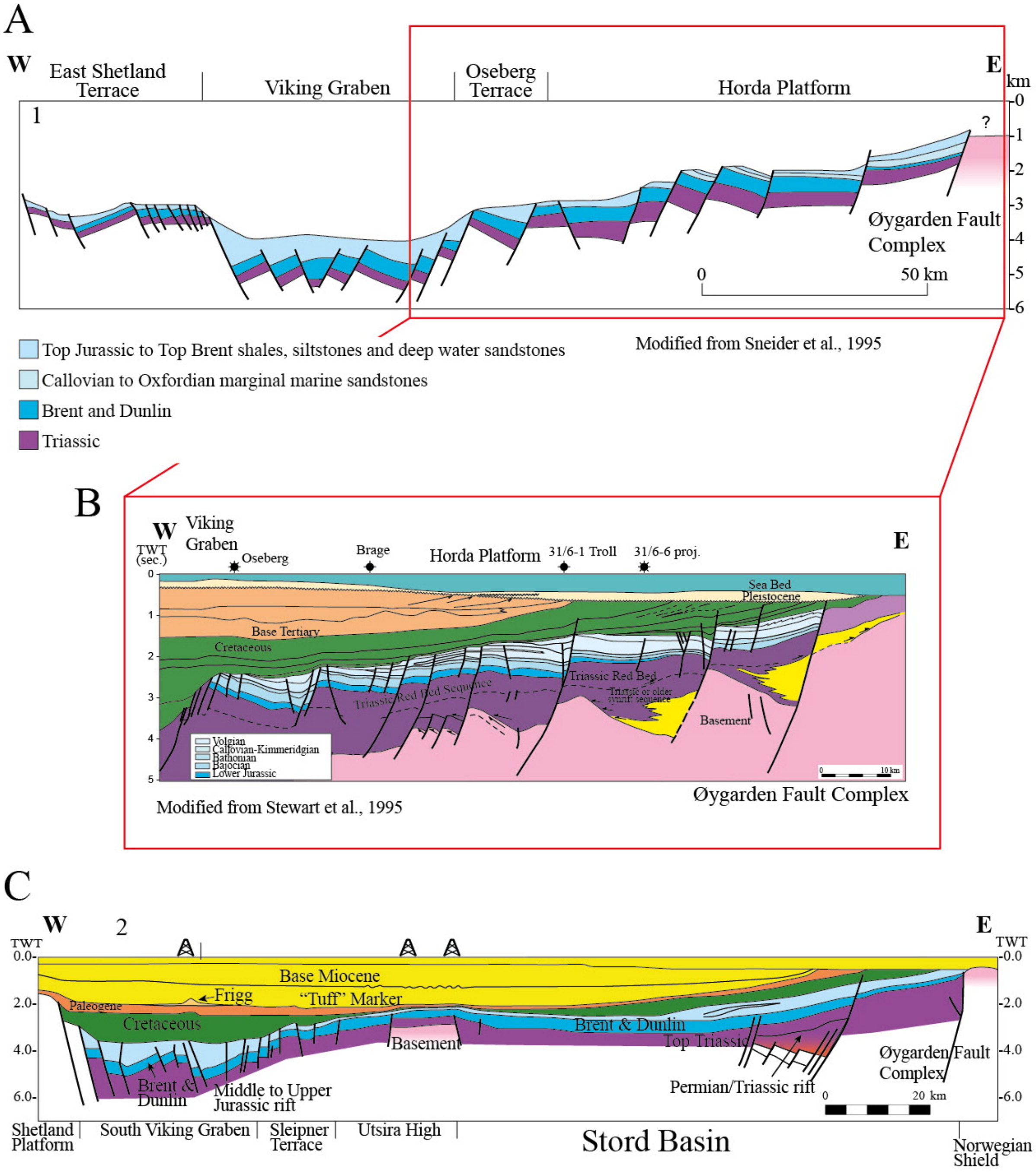


Fig. 4.2 Tectono-stratigraphic summary. *Main tectonic events and lithostratigraphy for the northern North Sea close to the Stord Basin are summarized. Focus in this thesis is within the Lower Jurassic/Upper Triassic succession. Chronostratigraphy from Gradstein et al. (2004). Chronostratigraphy modified from Deegan and Scull (1977).*

4.1 Structural Framework

Fig. 4.3 illustrates three published geoseismic sections. The figure comprises different geometries across the Stord Basin compared to the Horda Platform to the North and the Viking Graben to the west (Steward et al.1995; Sneider et al. 1995).



Modified from Sneider et al., 1995

Modified from Stewart et al., 1995

Modified from Sneider et al., 1995

Fig. 4.3 Regional cross-sections. *A: Regional cross-section across the Viking Graben north of the Stord Basin. B: Schematic section across the Oseberg field and to the east. C: Schematic section across the Viking Graben and the Stord Basin. Location of these lines is shown in Fig 4-4.*

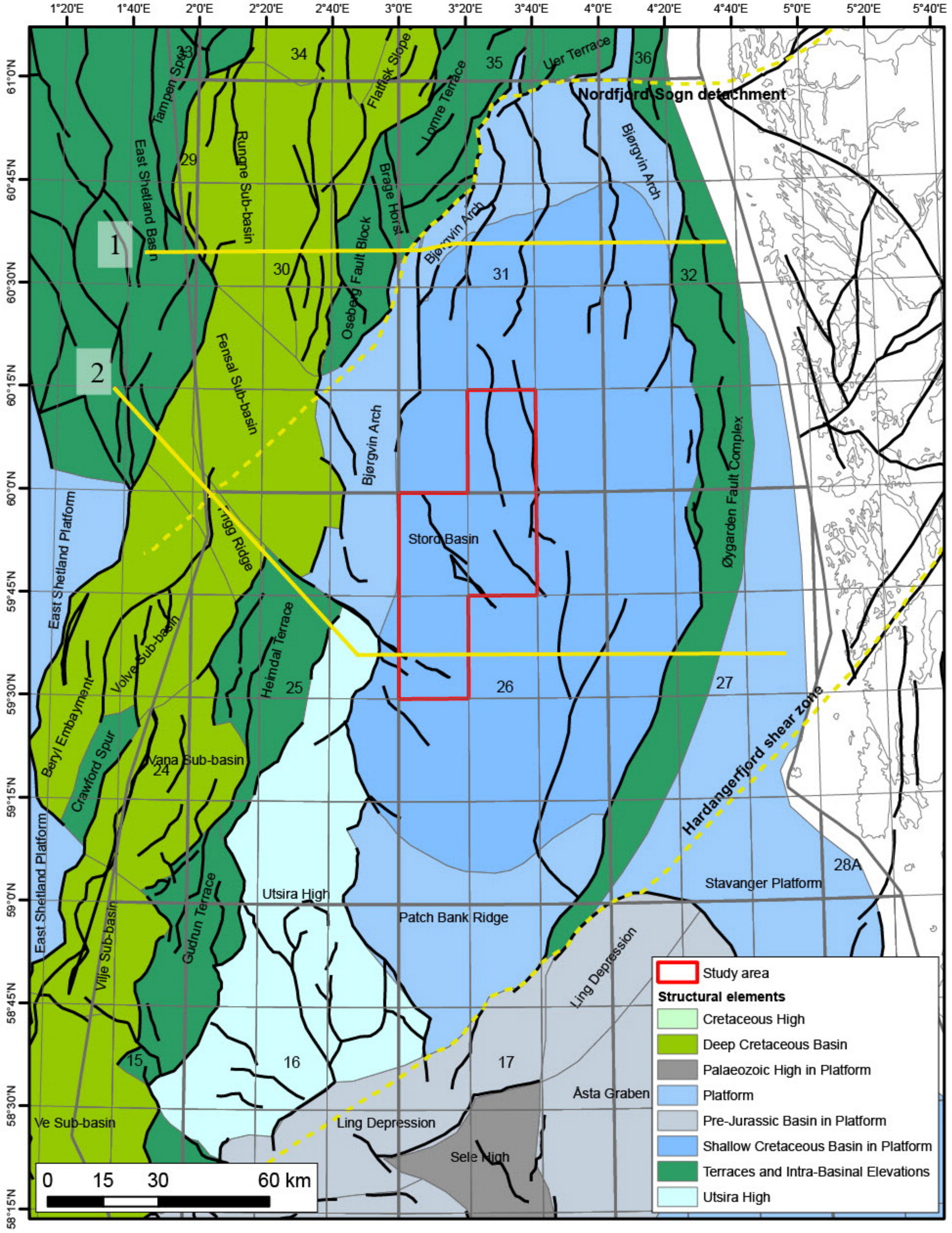


Fig. 4.4 Location map. *Yellow lines indicate position of seismic lines in Figure 4-3. Main structural elements slightly modified from NPD.*

Due to the repeated rifting in the area, the tectonic complexity of the Viking Graben is greater, whereas the rifting of the Stord Basin appears to be characterized of older episodes. The rifting of the Stord Basin appears to be less dominated by activity from Triassic and onward.

In the location map, Fig. 4.4, a basement discontinuity called the Nordfjord-Sogn detachment is shown as the upper yellow dashed line. This discontinuity was associated with the WNW Devonian extensional movements (Færseth 1996). Structural elements are separated by the fault zone which is oriented NE-SW across the basin. It was probably during the early Paleozoic Caledonian orogeny that the basement of the Stord Basin was consolidated, with a maximum depth reaching 8-10 km (Færseth 1996).

The dating of the main rift phase of the Stord Basin is poor, but it is considered to have occurred from the Late Permian into Early Triassic (Færseth 1996; Lippard 1996). Due to the uncertainties with the oldest part of the stratigraphic succession, the deformation of earlier stratigraphy is difficult to document. On the flanks of Utsira High, upper parts of Paleozoic rocks have been penetrated. A structural study by Biddle & Rudolph (1988) includes seismic data indicating a thickening of the Paleozoic succession into the Stord Basin.

The entire part of the northern North Sea is affected by the Permo-Triassic extension, resulting in an extended crust, a N-S trending sedimentary basin some 170-200 km wide (Færseth et al. 1995, Færseth 1996).

Strata from Middle Triassic to Lower-Middle Jurassic in the North Sea basin have been presented as strata from a post-rift event. These strata have been interpreted to represent a response to thermal subsidence following the main Permo-Triassic rifting. The subsidence rate was not uniform and differential subsidence is observed across a number of faults (Færseth 1996; Ryseth 2001).

The Triassic and Lower Jurassic sediments are separated from the Middle Jurassic succession with a significant hiatus. This separation is related to the Mid North Sea Dome associated with uplift at the triple junction between the Central, Viking and Witch Ground grabens (Underhill & Partington 1993). A broad mantle plume represents this dome. Early Jurassic sediments were uplifted and eroded as a result of the dome.

The second major extensional phase is well dated from Bathonian to Late Volgian (Ziegler 1990). During the Middle Jurassic phase of rifting, up to six discrete episodes of extensional block faulting took place. Jurassic extension was concentrated to the Viking Graben to the west, south of 60°N (Fig. 4.3). In the Stord Basin the stretching and faulting was negligible (Færseth 1996). The second major extensional phase reactivated many of the Triassic normal faults, and probably also created some new ones (Biddle & Rudolph 1988). Extension caused fault-driven subsidence. This resulted in deepening of the Viking graben and marine shales were deposited. By this time the Stord Basin was part of a platform system/area with relatively uniform thickness of the succession. The area east of the Stord Basin was subject to uplift. This area of uplift resulted in multiple prograding units from east to west. On seismic data this can be observed as seismic clinoforms (Fig. 4.5). These successions are correlated to the lithostratigraphic Johansen, Krossfjord, Fensfjord and Sognefjord formations (Fig. 4.2) (Vollset and Doré 1984).

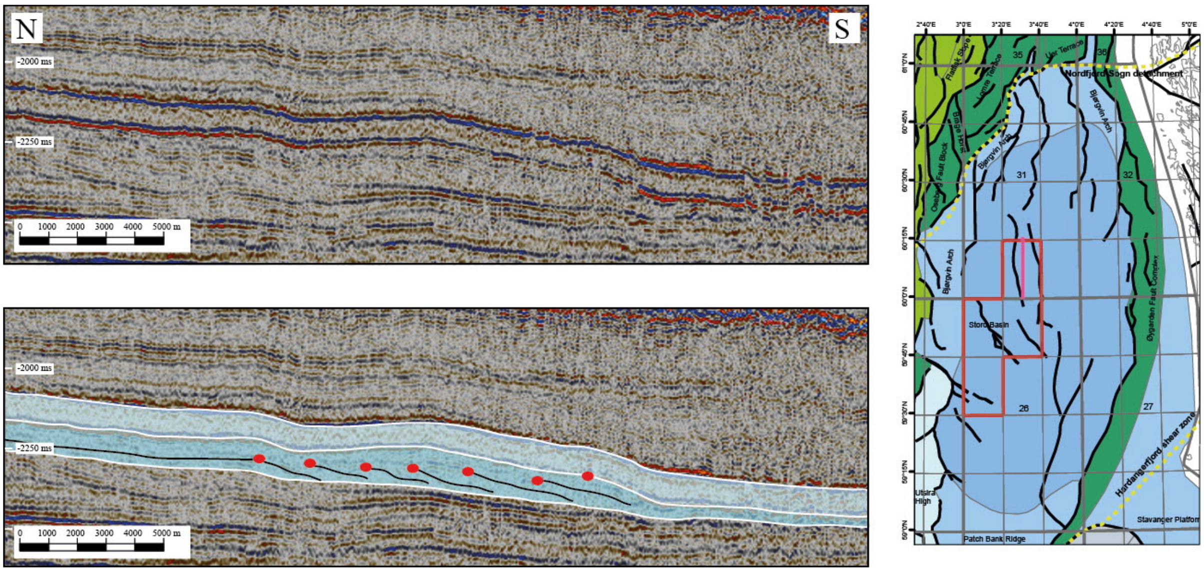


Fig. 4.5 Seismic line (HRT91-208) indicating prograding clinoforms from north. *Red dots illustrate clinoform breaks.*

The transgression of the Viking Graben is diachronous and becomes younger from north to south. The Jurrassic rifting, dated from Bathonian (Middle Jurassic) to Late Volgian (Upper Jurassic) is associated with faulting and followed subsidence. This rifting episode led to a high influence of the sediment routing facies distributions and gross thickness within the Jurassic sequence (i.e. Rattey & Hayward 1993). In the later stages, Kimmeridgian to Volgian, the extension led to major faulted block on both sides of the North Viking Graben. The result was large scale tilted blocks bounded by major master faults and eroded footwall crests. During

Ryazanian (Lower Cretaceous), the rifting ended clearly by the widespread development of anoxic shales, sealing the top of major structural highs. These events are not obvious in the Stord Basin, which during the Late Jurassic started to subside. During the Late Jurassic the Stord Basin subsided as a result of thermal cooling associated with Middle Jurassic extension decay (Coward et al. 2003; Færseth 1996). Reinforced with sediment loading, the subsidence continued throughout the Cretaceous and most of Cenozoic time. Throughout Jurassic and Cretaceous there has been a continuous deposition of sediments, resulting in conformable strata.

In the Early Cenozoic reverse displacement of older faults occurred. During Late Cretaceous to Early Paleocene a period of inversion occurred (Biddle & Rudolph 1988). The inversion was obtained by reversal of some of the pre-existing faults. Each inverted structure represents a small amount of basin shortening. The inversion and basin shortening is a result of an interaction of stress fields set up in NW Europe. Timing of the Early Tertiary inversion structures in the Stord Basin corresponds well with important tectonic events in the Alps and in the northern Atlantic Ocean (Biddle & Rudolph 1988).

In late Cenozoic parts of the Norwegian shelf was subject to several episodes of uplift. Significant erosion took place, particularly in Late Palocene, Late Oligocene and Middle Miocene. The uplift and following erosion resulted in deposition of westward prograding sedimentary wedges in the Stord basin. In the Stord Basin the Paleocene sediment sequence is uniform in thickness except for a thicker wedge on the eastern flank. During Eocene and most of Oligocene the tectonic activity was quiscent. Lack of tectonic activity resulted in deposition of fine-grained clastics and basinal shales. The deposition thickness of the Eocene and Oligocene sequence is locally constant across the basin. Away from the centre of the basin and eastwards the sequence of Eocene and Oligocene is thinning out. In the Late Oligocene new tectonic activity took place. The Pleistocene deposits are characterised by large westward prograding clinoforms downlapping on the Utsira Formation. During the Late Pleistocene events of glacial erosion occurred, resulting in removal of Tertiary sediments. It is estimated that 400-600 m of Tertiary sediments have been removed from central parts of the basin (Kjennerud et al. 2011).

4.2 Stratigraphic Framework

The Triassic succession in the study area is represented by the Smith Bank and Skagerrak formation (Fig. 4.2). The Skagerrak Formation represents alluvial fan and fluvial deposits and belongs to the upper sandy section of the Triassic succession (Deegan & Scull 1977; Lervik 2006). Extensive development of lithologically monotonous red beds is remarkable for the Triassic succession. A range from coarse conglomerates to basin filling fluvial sandstones and lacustrine deposits are notable for these non-marine sediments of Triassic age (Lervik 2006).

A post depositional uplift has over large areas resulted in removal of the Triassic-Early Jurassic Statfjord Group. Sedimentation took place in a shallow epicontinental basin. The basin experienced broad patterns of subsidence following the earlier Permian-Triassic rift events. (Hermanrud et. al 1991; Husmo et al. 2002; Ryseth 2001).

Deposition of the Statfjord Group took place in the Late Triassic Rhaetian stage through the Early Jurassic Sinemurian stage. This time of deposition is spanning a period of approximately 13 Ma. Sediments of the Statfjord Group are mainly continental with a thinner marginal marine succession at the top (Deegan and Scull 1977).

A comparison of the Tampen Spur, Horda Platform and Utsira High indicates an Early Jurassic drainage system with a southerly dipping continental paleoslope that terminated in shallow marine enciroments to the south (Ryseth 2001). This will be duscussed in detail in chapter 5 Stratigraphy of The Statfjord Group.

Sediments derived from the Mid North Sea Dome formed a large delta during the Middle Jurassic. The delta prograded northwards along the Viking Graben. The Mid North Sea dome collapsed and initiation of Middle Jurassic extension occurred. This caused retreat of the large delta by flooding of the Viking Graben. Fluvial and paralic deposits (Ness/Sleipner Formations) was capped by shallow marine deposits (Tarbert/Hugin Formations) as a result of the flooding of the delta. Subsidence in the Stord Basin continued throughout the Jurassic and Cretaceous, resulting in deposition of conformable sediments, with flooding of the shallow marine Upper Jurassic sediments in Volgian/Tithonian and deposition of the Draupne Formation (Vollset & Dore 1984).

Relative tectonic quiescence throughout the Cretaceous characterizes the sedimentation of this period. The east-west prograding wedge correlated to the Lower Cretaceous Sauda Formation may however indicate a minor uplift of the area to the east in Early Cretaceous (Vollset & Dore 1984). The Cretaceous and Cenozoic successions were briefly described under 4.1 Structural Framework.

5 Stratigraphy of The Statfjord Group

The Early Jurassic succession is moderately well documented in parts of the North Sea, particularly by core descriptions in the Tampen Spur and Horda Platform areas. Very regional depositional trends are published, but no depositional facies maps are well documented. Following is a brief summary of published work on the Statfjord Group.

Ryseth and Ramm (1996) investigated the alluvial architecture and differential subsidence in the Statfjord Group [1] in the North Sea. The aim of this study was to give a prediction of the reservoir potential of the Statfjord Group. The Statfjord Group was and still is an important potential reservoir unit in the evaluation of open acreage in the North Sea. Late Triassic/Early Jurassic sandstones from the Statfjord Group form one of the main reservoir intervals in several Norwegian hydrocarbon fields located in the Viking Graben.

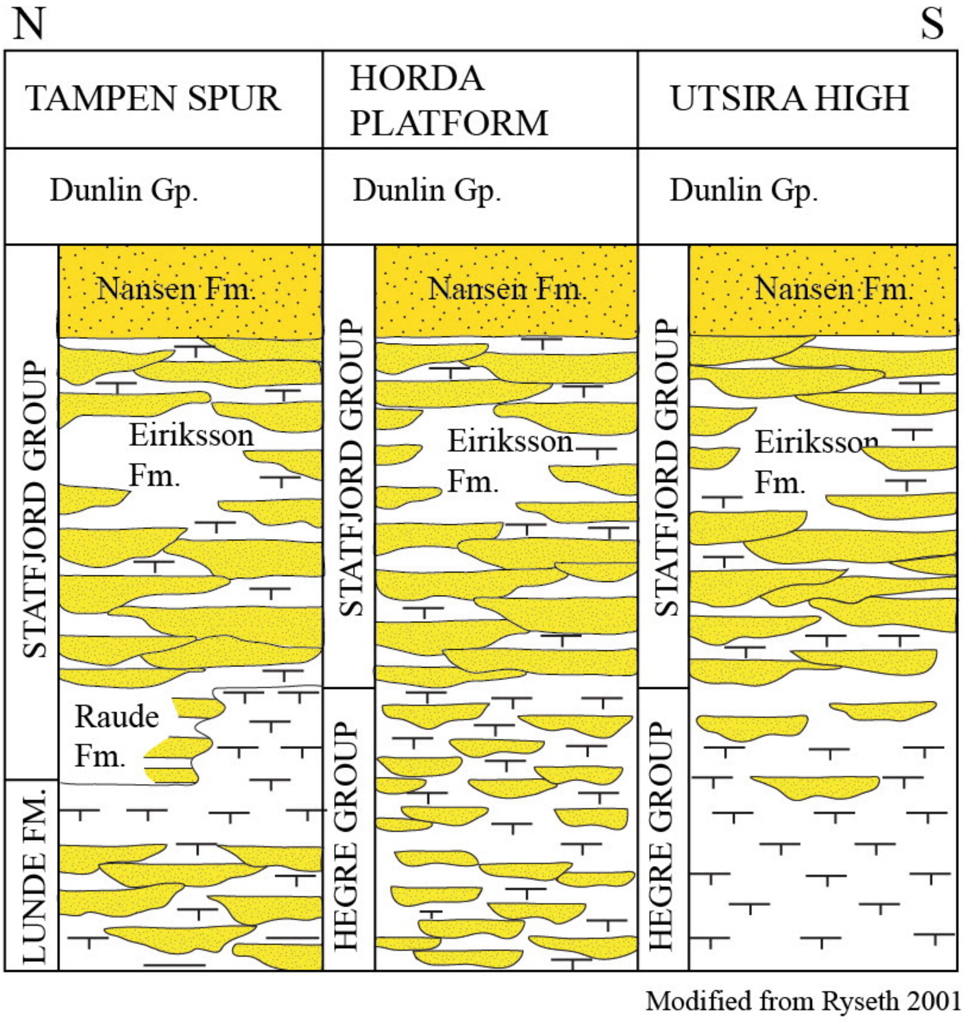
Another study by Ramm and Ryseth (1996) examined the reservoir quality and burial diagnesis in the Statfjord Group. Burial depth of the Statfjord Formation varies from 2 km at the flanks of the Viking Graben and exceeds 6 km in the central of the Graben. Sandstones of the Statfjord Group have undergone diagenetic effects caused by compaction, quartz cementation and formation of fibrous illite. Diagenetic effects make the reservoir quality of the Statfjord Group various at depth below 3000 to 3500 m. This is due to reduction of porosity and permeability. Chlorite coatings and high pressure may limit the reduction of porosity at greater depths and these effects may also preserve a good permeability where limited potassium supply hinders the illitization (Ramm & Ryseth 1996). The proportion of sandstone in the Statfjord Group varies from less than 40% to more than 80% (Ryseth & Ramm 1996). In areas where the Statfjord Group is deeply buried, the unit may be unprospective due to diagenetic effects despite the high content of initial sand (Ramm &Ryseth 1996).

The tectonic evolution of the northern North Sea has been described in numerous articles (e.g. Badley et al. 1988; Fraser et al. 2002; Gabrielsen et al. 1990; Ziegler 1990; Underhill & Partington 1993; Færseth 1996; Steel & Ryseth 1990). Only a few publications have focused on the evolution of the Stord Basin. Environmental interpretations of the Statfjord Group have been done in several studies (Røe & Steel 1985; Ryseth 2001). The tectonic and environmental evolution of the northern North Sea was discussed in chapter 4 Geological Setting.

[1] In 2006 Lervik proposed an upgrade of the previous Statfjord Formation. In 2013 the elevation of the group was verified by NPD.The Statfjord Formation was assigned a group status and the previous members (Raude, Eiriksson and Nansen) were assigned a formation status. Recent studies, including this thesis, refer to the Statfjord Group. Previous studies name the unit Statfjord Formation.

5.1 Lithostratigraphy of The Statfjord Group

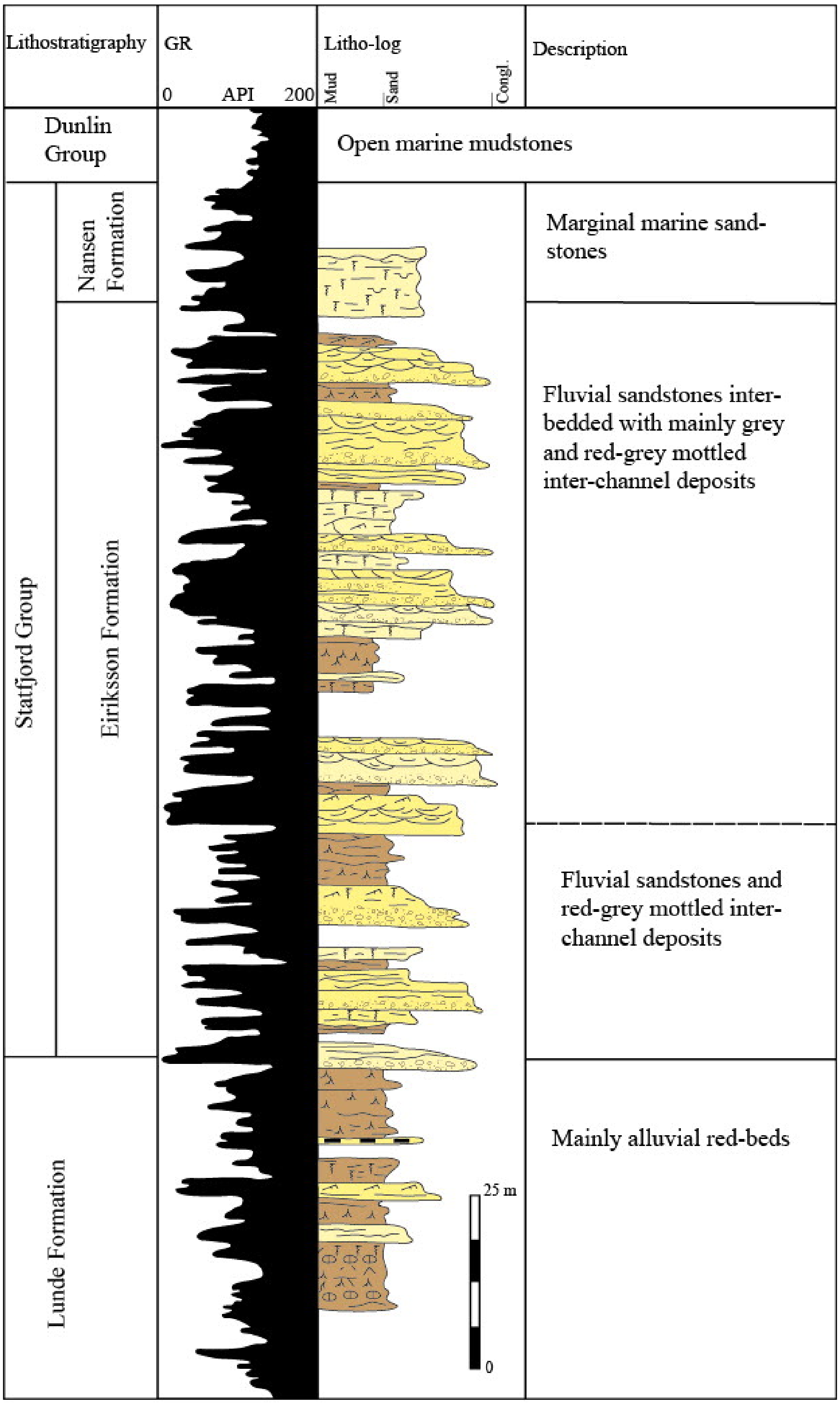
The lithostratigtaphic nomenclature for the Statfjord Group was defined by Deegan and Scull in 1977. The Statfjord Group was subdivided into continental deposits of the Raude and Eiriksson formations, capped by the marginal marine Nansen Formation. In 1984, Vollset and Dore supported the definition of the Statfjord Group but emphasized that the subdivision could only be applied west of the Viking Graben. The lithostratigraphic nomenclature by Vollset and Doré are comprised in Fig. 5.1.



Modified from Ryseth 2001

Fig. 5.1 Lithostratigraphic nomenclature for Late Triassic and Early Jurassic deposits in the Viking Graben area. The nomenclature is defined by Vollset and Doré (1984).

In the Tampen Spur area the Raude Formation is commonly correlated to the uppermost part of the Lunde Formation (Ryseth 2001). A schematic type log of the Statfjord Group in the Horda Platform and Stord Basin is illustrated in Fig. 5.2, and briefly summarized in the paragraph below.

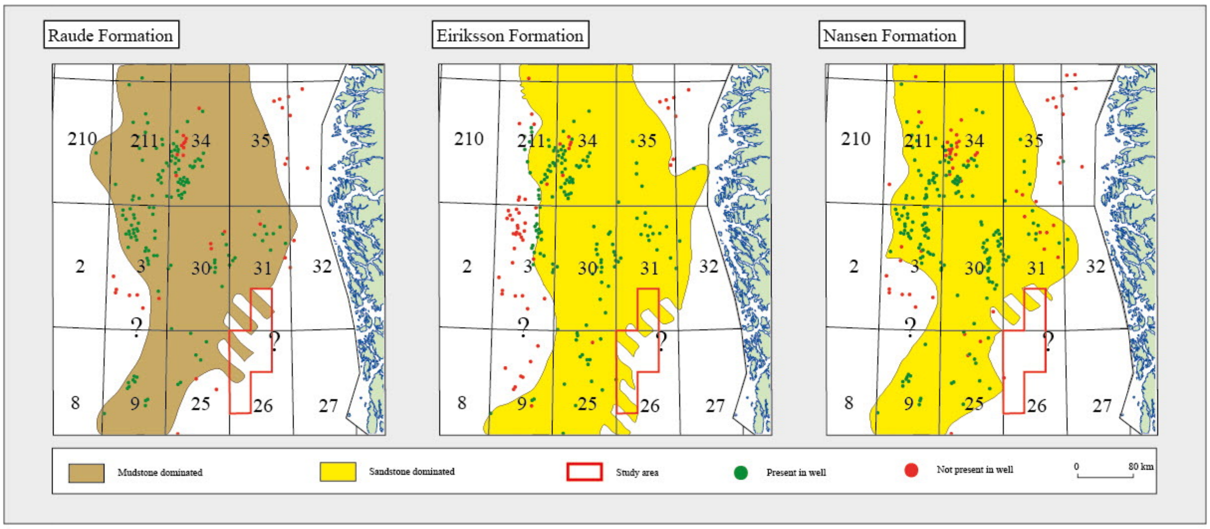


Modified from Ryseth and Ramm, 1996

Fig. 5.2 Type log of the Statfjord Group in the Horda Platform and Stord Basin.

The generalized Statfjord Group comprises numerous coarse-grained sandstones ranging in thickness from 3 to 25 m separated by mottled red and grey silty mudstones and thin layers of very fine to fine-grained sandstones (Fig. 5.2).

The Raude-, Eiriksson- and Nansen Formations are deposited over large areas in the northern North Sea (Goldsmith et al. 2003). Fig. 5.3 shows the distribution of the Statfjord Group.



Modified from Goldsmith et al. (2003)

Fig. 5.3 Distributions of the Raude-, Eiriksson- and Nansen Formation. *Green dots illustrate wells where the formations are present. Red dots illustrate wells where the formations not are present, but here it is assumed that the formations have been removed by later erosion.*

The Statfjord Group is of Rhaetian-Sinemurian (Upper Triassic-Lower Jurassic) age. A rapid increase of the sandstone content compared to the underlying Triassic units represents the lithostratigraphic base of the Statfjord Formation. The base of the Statfjord Group in the Viking Graben and Horda Platform areas are suggested to be chosen below the lowest massive sandstone unit prior to crossings into dominantly red-brown shales of the Upper Hegre Group (Vollset and Dore 1984). A rapid transition from sandstones to marine mudrocks from the overlying Dunlin Group defines the lithostratigraphic top of the Statfjord Group (Ryseth 2001; Steel and Ryseth 1990). In general the Statfjord Group records a vertical transition from distal, semi-arid continental deposits thorugh shallow marine, transgressive deposits to open marine mudstones of the overlying Dunlin Group (Ryseth 2001; Goldsmith et al. 2003). An overall upward transition of the colors changes from red to grey. The log character of the Statfjord Group becomes more erratic upwards (Goldsmith et al. 2003).

A lithological description of the three formations of the Stafjord Group follows:

5.1.1 Raude Formation

The Rhaetian Raude Formation is the lowermost part of the Statfjord Group, but is correlated to the uppermost part of the Lunde Formation in the study area. Continental coarsening upward claystones, mudstones and siltstones are the main content of the Raude formation (Ryseth & Ramm 1996). The formation also provides a minor presence of white sandstones. These vary from very fine to very coarse. Continental calcrete bearing red-beds prevail at the base of the formation (Røe and Steel 1985). Towards the top the continental contents interact between red and grey-green (Goldsmith et al. 2003; Deegan and Scull 1977). Deposition of the upper part is of braided stream origin according to Deegan and Scull (1977) due to presence of large scale cross-bedding and scour and fill.

Røe and Steel (1985) suggests that the sandstones are deposited in a flood basin environment in distal alluvial fans. Palaeosols of the Raude Formation are rich in desiccation cracks, root structures and carbonate nodules. Mottled or red-brown mudstones with paleosols may defend a well drained subaerial floodplain environment (Nystuen and Falt 1995; Goldsmith et al. 2003).

The lower boundary of the Raude Formation is characterized by a transition from shalier deposits of the underlying Lunde Formation. The base is often difficult to regocnize but clearly defined on gamma ray logs (Deegan and Scull 1977).

5.1.2 Eiriksson Formation

The Eiriksson Formation consists of a fluvial sandstone rich interval interbedded with finer-grained interfluvial overbank deposits (Ryseth 2001; Goldsmith et al. 2003). The sandstones are massive and thicker than those of the Raude Formation. Beds of sandstones in the Eiriksson Formation are white to light grey and comprise a grain size from medium to very coarse. The massive sandstone beds are interbedded with grey shales that are silty, micaceous and carbonaceous. The thick sandstones also comprise thin layers of lignite fragments, pebbles and granules, often concentraded along cross bedding foresets and in channels (Deegan & Scull 1977).

The boundary between the Raude Formation and the overlying Eiriksson Formation is commonly defined by a sharp upward transition. The base of the formation is characterized beneath the lowermost massive sandstone unit. This transition indicates a tectonically uplift of the hinterland. The possible hinterland rejuvenation may have occurred due to early Cimmerian tectonics. In addition an alteration to a more humid climate is reflected from the transition which resulted in replacement of the previous formed evaporitic soils and carbonate nodules to carbonaceous- and coal-rich layers. Mudstones and siltstones alter from red to grey/green as a result of the climatic change (Goldsmith et al. 2003).

Compared to underlying older deposits, the Eiriksson and Nansen Formation are formed during a period of a more humid climate. This is suggested by the lack of presence of pedogenic layers with caliche in the two formations. The Nansen- and Eiriksson Formaion were deposited in a terminal-fan setting. Periodical flooding of marine waters reached high onto the plain due to discrete depositional slopes of the terminal-fan depositional setting. Slopes on fan deltas or alluvial fans would be to steep to allow the waters to reach that high (Nystuen and Falt 1991; Goldsmith et at 2003).

The distinct transition into calcareous sandstones of the Nansen Formation represents the upper boundary of the Eiriksson Formation (Deagan & Scull 1977).

5.1.3 Nansen Formation

The Nansen Formation comprises marginal marine sandstones (Ryseth & Ramm 1996; Ryseth 2001).

The base of the Nansen Formation is characterized by a boundary from the underlying noncalcareous sandstones of the Eiriksson Formation into calcareous cleaner sandstones of the Nansen Formation (Deegan and Scull 1977). The Nansen Formation consists of thin shale beds. These beds include presence of marine fossils and are most frequently present in the upper part of the formation. (Goldsmith et al. 2003; Deegan and Scull 1977). The presence of fossils and stacking patterns of facies association suggests that sediments of the upper part were deposited in a marine environment (Goldsmith et al. 2003).

The upper boundary is characterized by an abrupt transition from calcareous sandstones of the Nansen Formation into argillaceous depositions from the Dunlin Group (Deegan & Scull 1977). The transition from marginal marine deposits of the upper Statfjord Group into marine mudrocks of the Dunlin Group indicates that the Nansen Formation belongs to a transgressive and reworking depositional phase (Røe and Steel 1985).

Some parts of the fine-grained units of the Nansen Formation provide traces of roots, calcrete and coals. These units are suggested to be deposited under subaerial conditions. Other parts of fine-grained units of the formation consist of abundant bioturbation, wave ripples, flaser and lenticular lamination. Unlike the former fine-grained units, these latter parts are suggested to be deposited under a condition of standing water (Røe and Steel 1985; Goldsmith et al. 2003). An abrupt transition from the marginal marine Nansen Formation into fine-grained offshore deposits of the Amundsen Formation support that the upper boundary of the Statfjord Group represent a rapid transgressive event (Røe and Steel 1985).

5.2 Facies variations of The Statfjord Group

This chapter comprises observations of the sedimentary facies variations of the Statfjord Group observed from available core photos. The observations are compared to previous published work. The photographs are carried out from the NPD database. The location of the wells used in this chapter is shown in Fig. 5.4.

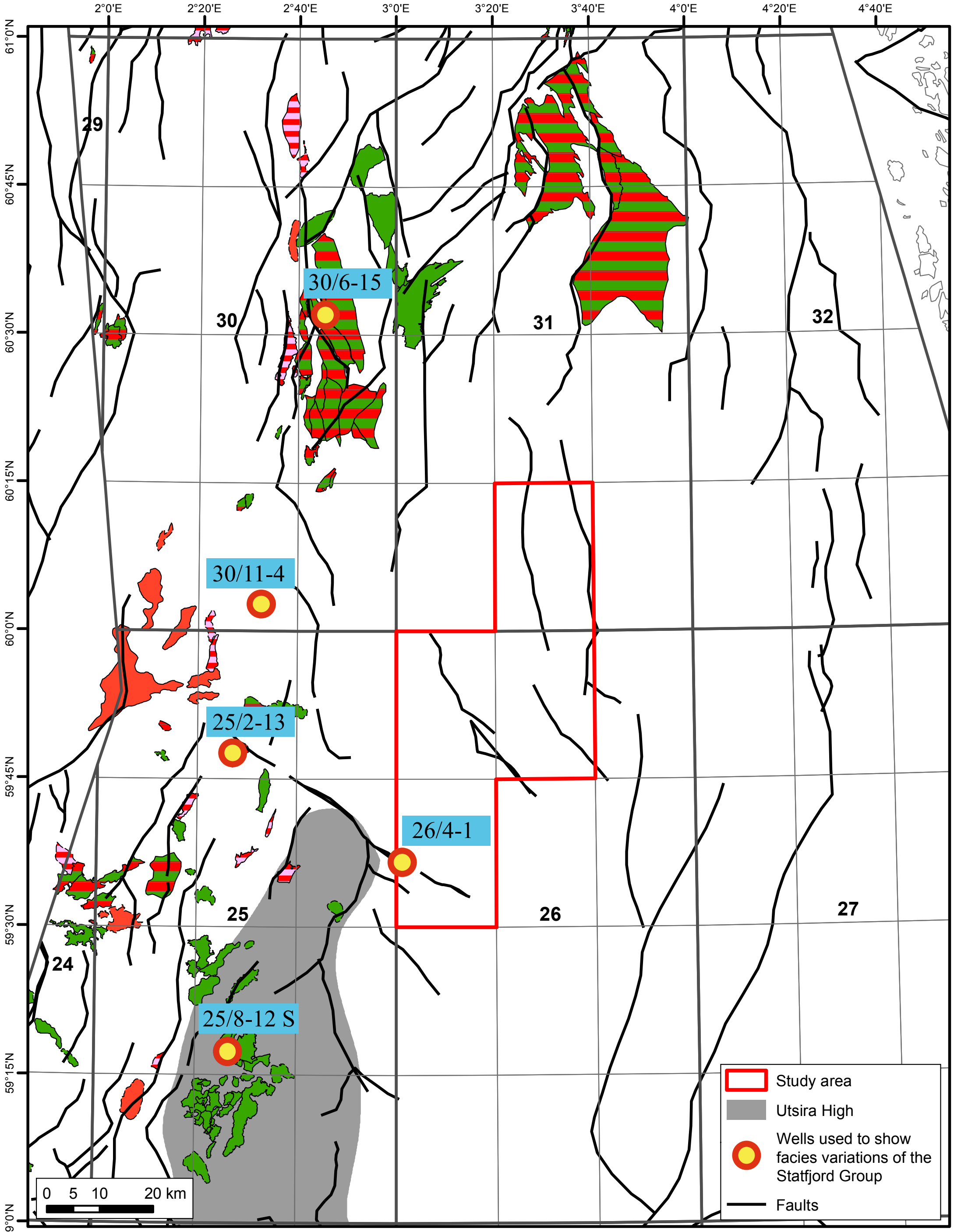
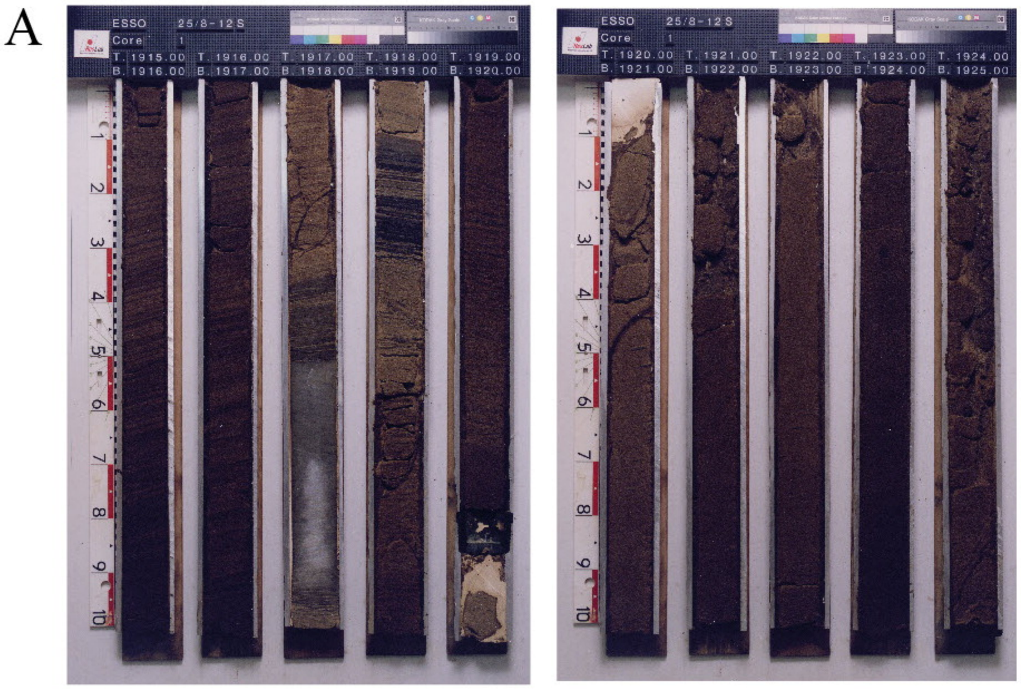


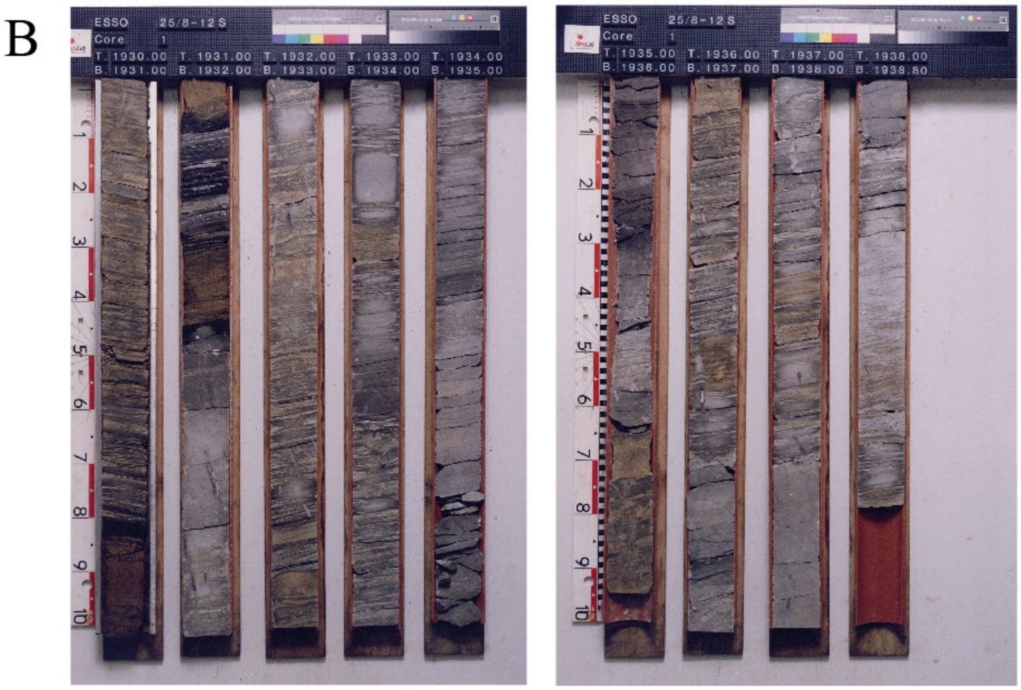
Fig. 5.4 Location of wells with available core photos from NPD. The wells are used to study facies variations of The Statfjord Group.

25/8-12 S

Core photos from the well 25/8-12 S, located on the Utsira High, comprise facies variations within the Statfjord Group. Both fluvial and marginal marine systems dominate the core samples, see Fig. 5.5.



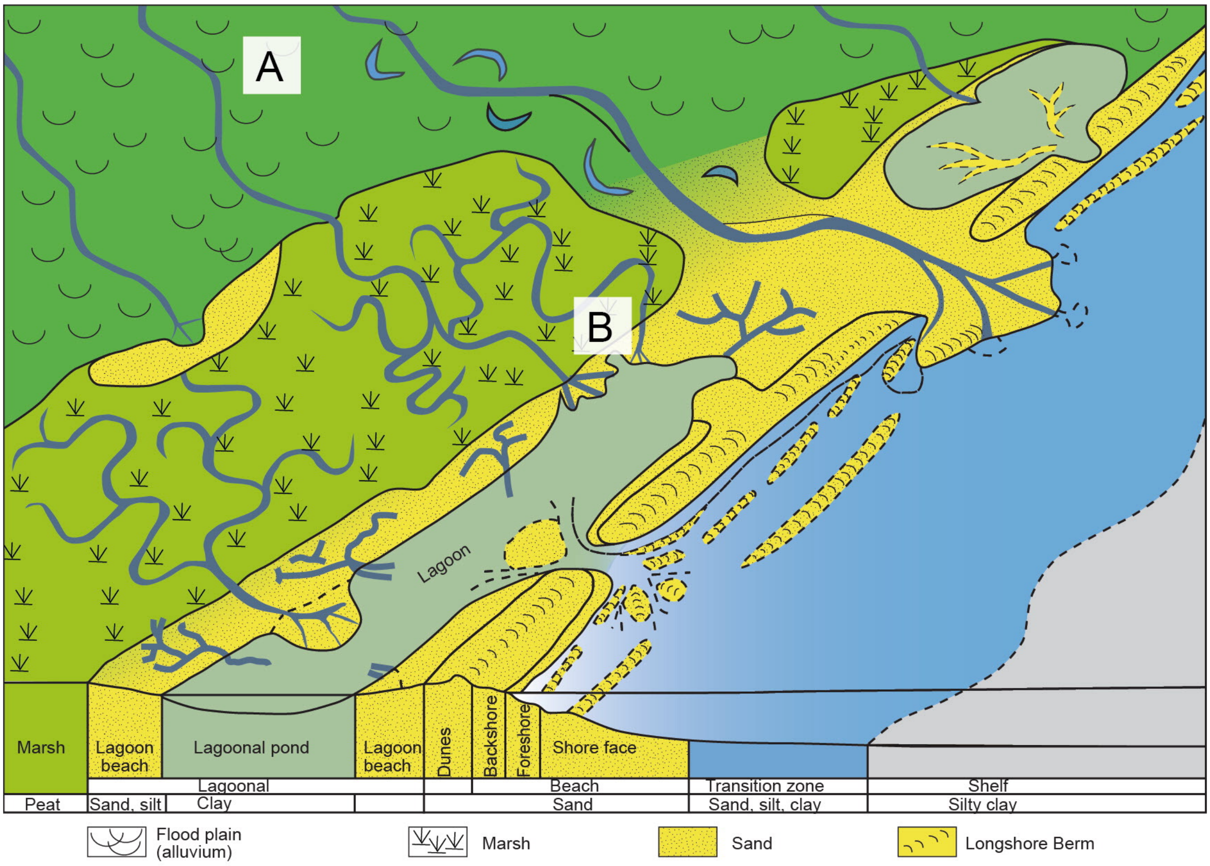
1915-1920m: Fluvial systems 1920-1925m: Fluvial systems



1930-1935m: Marginal marine systems 1930-1939m: Marginal marine systems

Fig. 5.5 A. Corephotos from well 25/8-12 S dominated by fluvial channels. B. Core photos from well 25/8-12 S comprising marginal marine facies. Photos from NPD.

A conceptual sketch shown in Fig. 5.6 illustrates a marginal marine environment. The sketch emphasizes where the core samples of well 25/8-12 S may have been deposited.



Modified from Reineck 1970

Fig. 5.6 Marginal marine environment. *Conceptual sketch.*

25/2-13

Well 25/2-13 is located in the northern Utsira area. Ryseth (2001) made a description and plotted the core data of the well. A modified cored section is shown in Fig. 5.7. The well contains fluvial deposits overlain by shallow marine and open marine deposits. The section confirms a vertical alteration between cross-stratified and massive sandstones on the Utsira High. Cross-stratification is dominated by troughs and the fluvial sandstones are generally finer grained (Ryseth 2001).

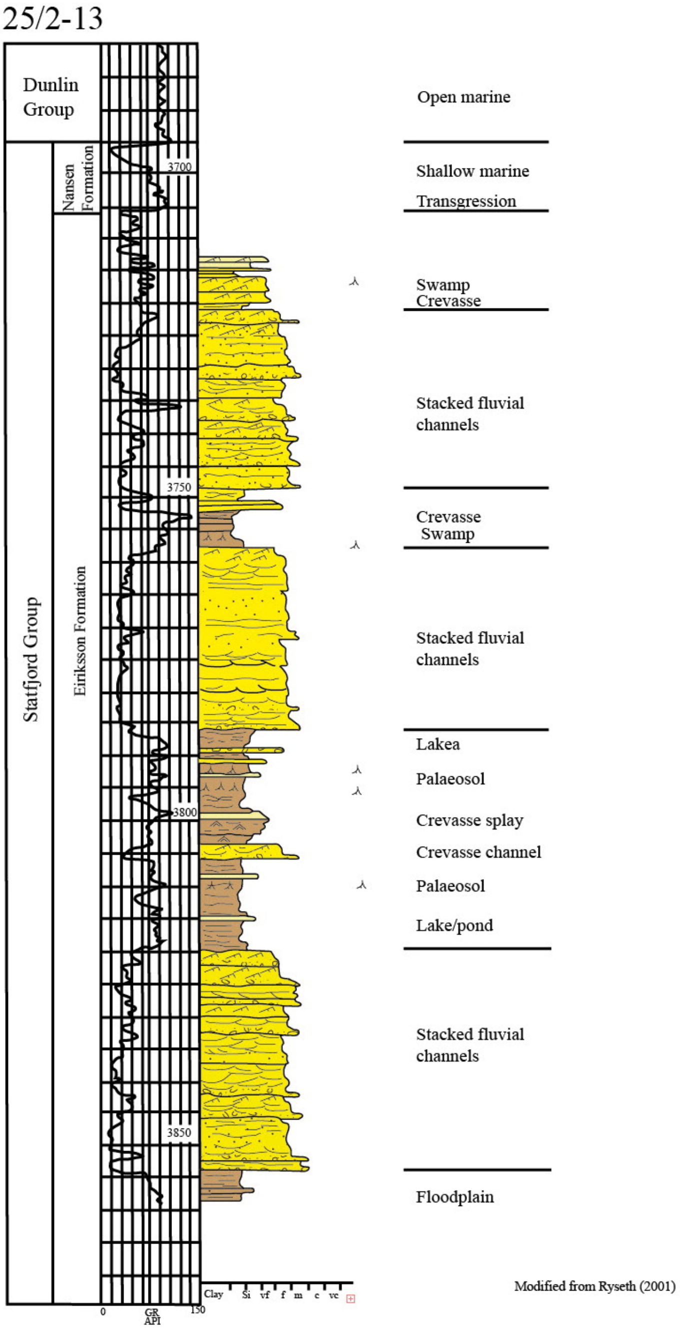


Fig. 5.7 Core description from well 25/2-13

The NPD database for well 25/2-13 comprises 127 m of core photos within the Statfjord Group, extending from 3709 - 3854.2 m. Core photos in Fig. 5.8-Fig. 5.10 confirm facies variation as illustrated by Ryseth (2001) (Fig. 5.7).

Core photos from well 25/2-13 are dominated by massive sandstone beds containing clasts. Colors of the clasts are ranging from grey to black (Fig. 5.8).

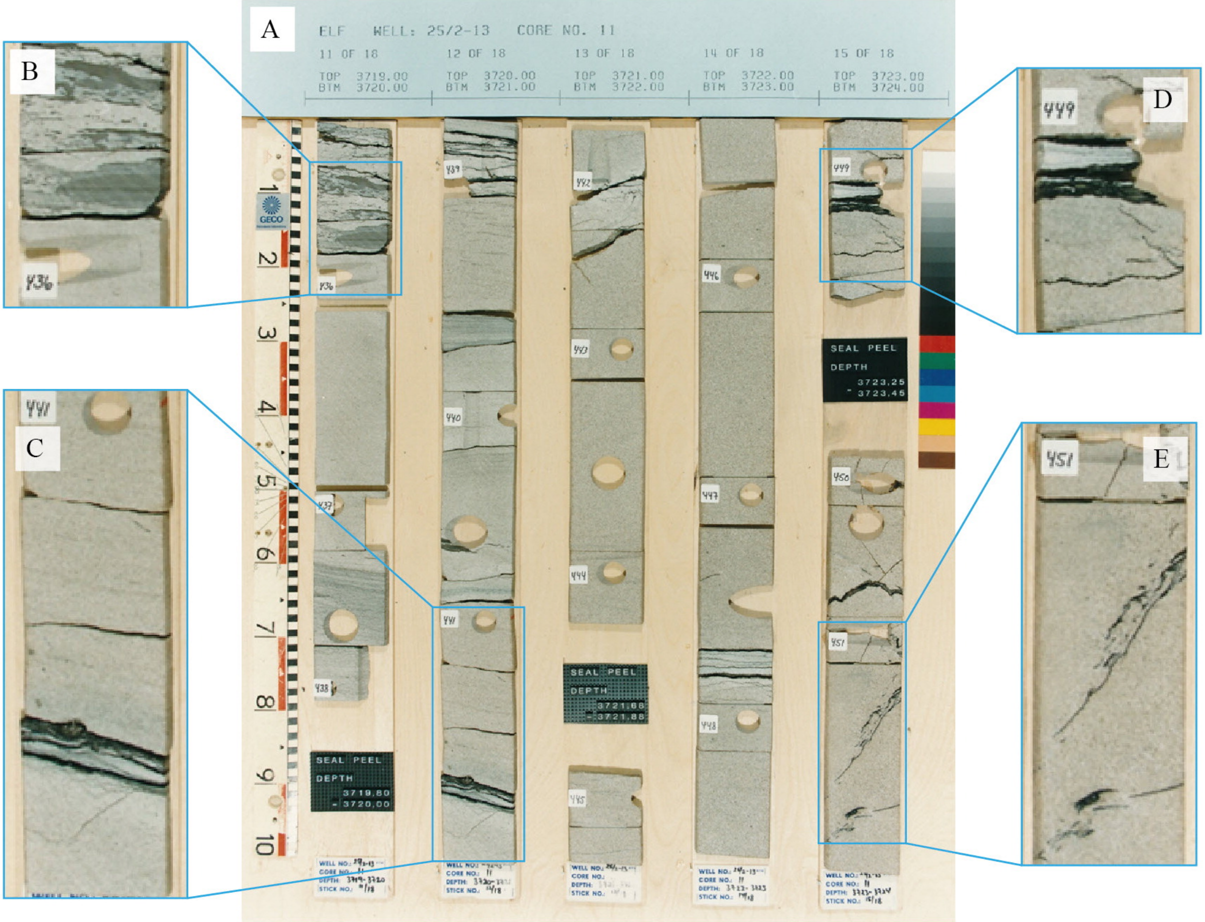


Fig. 5.8 Massive sandstone. *A. NPD photo, well 25/2-13 core no. 11, nr.11-15. B. Large grey clay clasts. C. and D. Coal fragments within massive sand. E. Coal layers within massive sand. Possible slump facies. Note the steep layering of the coal.*

A minor amount of sandstone intervals contain erosive boundaries. Sequences are fining upward above the boundaries and claystone clasts prevail at the base (Fig. 5.9).

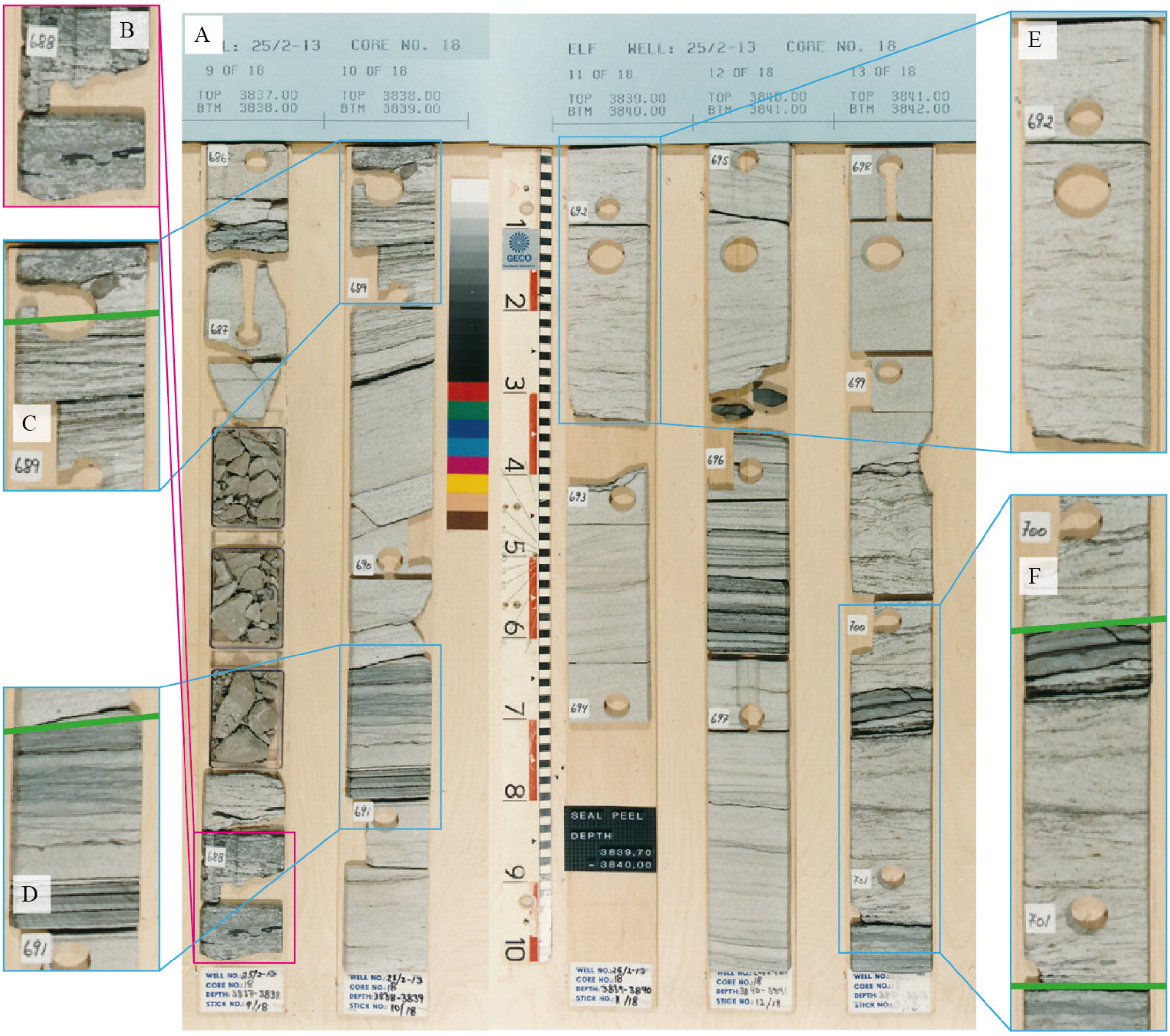


Fig. 5.9 Sandstone intervals with erosive boundaries. *Green lines are interpreted as channel bases. Sequences above each channel base are fining upwards. A. NPD photo, well 25/2-13 core no. 18, nr 9-13. B. Claystone clasts. C. Channel base. D. Channel base and underlying current ripple lamination. E. Current ripple lamination. F. Two nearby channel bases.*

The core photos comprise facies of plant rootles (bioturbation), current ripple lamination, low angle crossbedding, slump and coal. Coal layers are few with measured lengths up to 50 cm (Fig. 5.10).

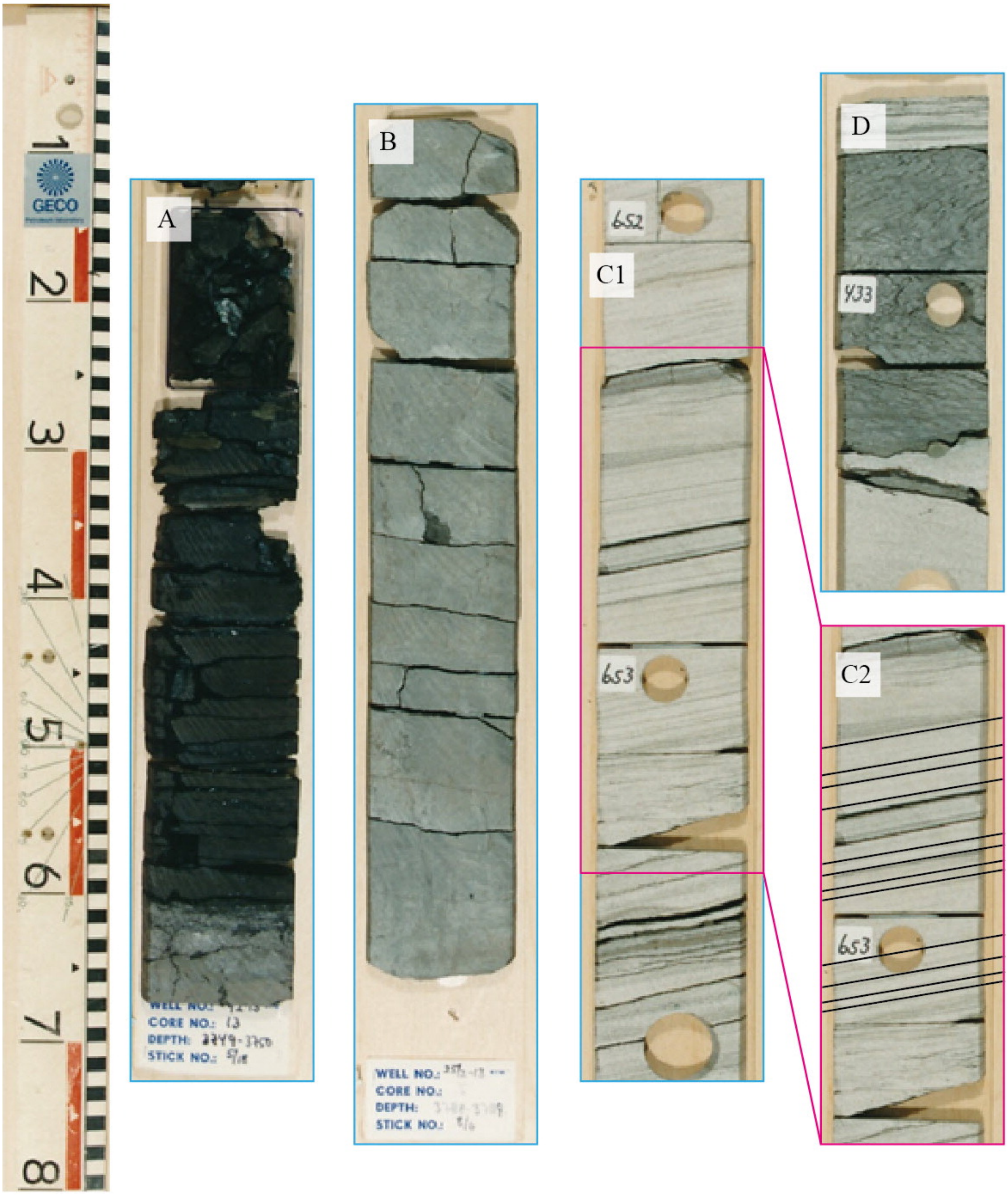


Fig. 5.10 Facies variation. *A. Coal from core no. 13, nr. 5 of 18, at approximately 3749.47-3749.93 m. (The photo extends to 3750.) B. Plant rootles from core no. 15, nr 8 of 11, at approximately 3788.35-3789. C1. Low angle crossbedding from core no. 17, nr.17 of 19, approximately at 3826.05-3826.66. C2. Outcrop of C1 with schematic lines illustrating the crossbedding. D. Slump from core no. 11, nr. 10 of 18, approximately from 3718.15-3718.45. All photos from NPD, well 25/2-13.*

The massive sandstones containing clasts are apparently strucutreless. Sandstones containing grey clasts may represent eroded floodplain clays, whereas those containing black clasts may represent coastal plain deposits. The fining upward sandstone intervals with clasts of claystone at the base indicate channel-deposits. Presence of root structures indicate terrigenous conditions. Low angle crossbedding may represent channel fill deposits. Current ripple lamination indicate overbank deposition.

The facies association represented in the core photos implies a terrigenous setting. Due to lack of marine facies the depositional environment is interpreted to be a coastal plain with fluvial channels (Fig. 5.11).

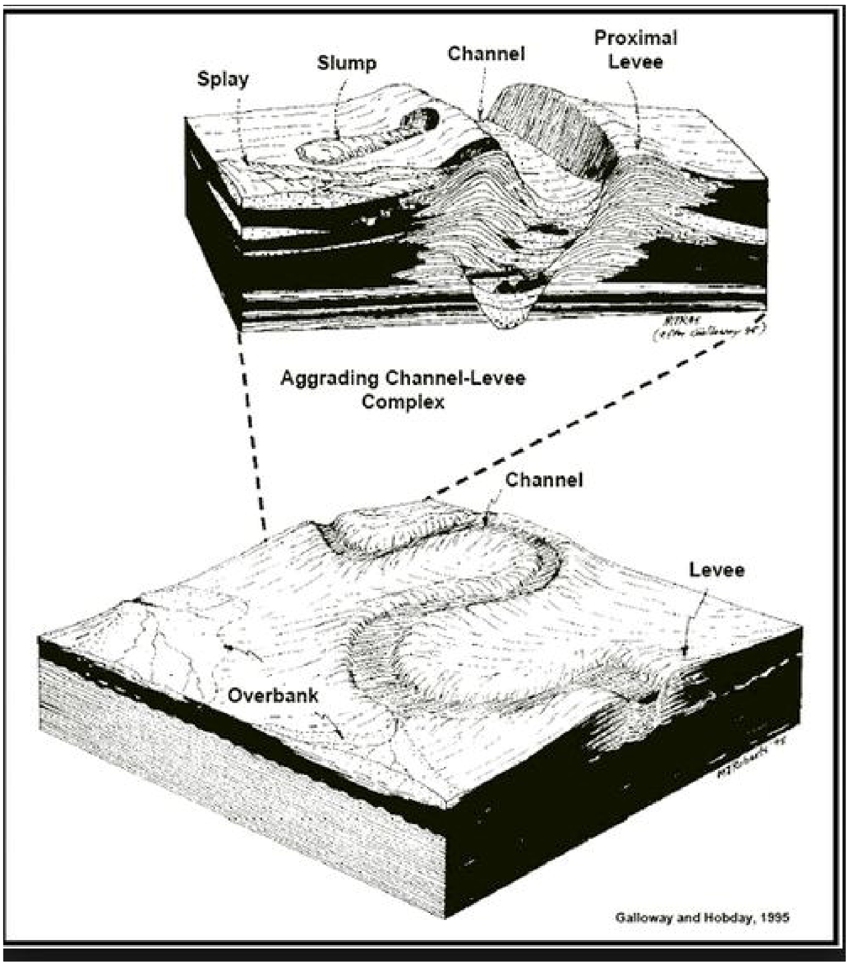
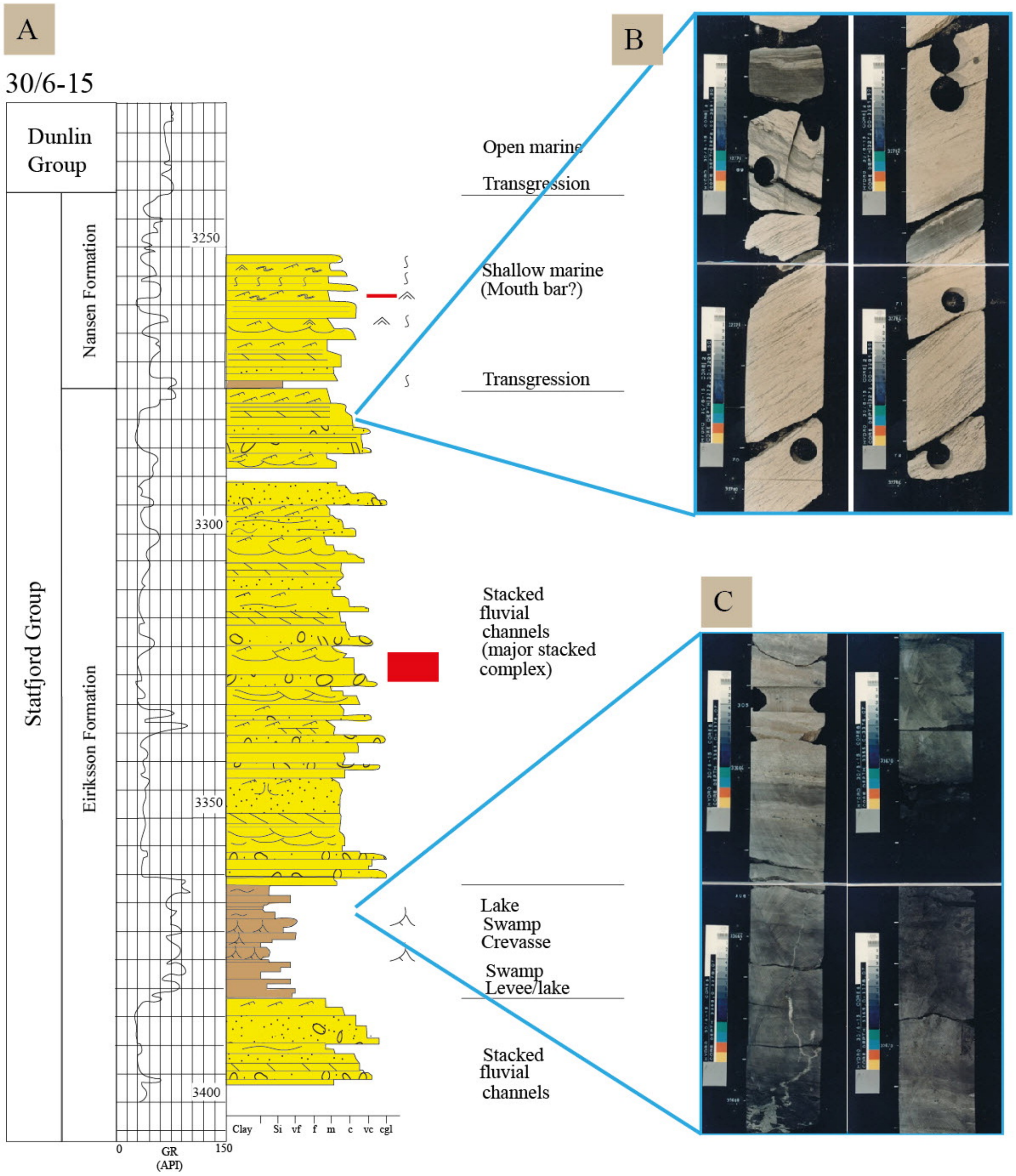


Fig. 5.11 Conseptual sketch: Fluvial channel on a coastal plain. *From Galloway and Hobday, 1995.*

30/6-15

Well 30/6-15 is located on the Horda Platform area. This well also contains fluvial deposits overlain by shallow marine and open marine deposits. As for the well 25/2-13, Ryseth (2001) made a description and a schematic cored section of the well 30/6-15 (Fig. 5.12. For well 30/6-15, the NPD database comprises 144 m of core photos within the Statfjord Group. Core photos in figure Fig. 5.12-Fig. 5.14 confirm facies variation as plotted by Ryseth (2001).



Modified from Ryseth (2001)

Fig. 5.12 Facies variation from well 30/6-15. *A. Core description. B. Core no. 7, 3277.45-3278.6 m. Dominated by ripple lamination. Silty shale and planar cross-bedding are also present. C. Core no. 8, 3366.20-3367.4 m. Plant rootles indicating terrigenous conditions. Red markers indicate location of the next photos.*

Coarse-grained sandstones dominate the section. Planar and trough cross-stratification characterizes the fluvial sandstones in the section. Fluvial sandstones show irregular vertical grain size. Abrupt transitions between the coarse and fine deposits characterize cored sections on the Horda Platform (Ryseth 2001) Fig. 5.12).

The core photos within the Statfjord Group interval of well 30/6-15 comprise an extensive interval of the fluvial Eiriksson Formation capped by a thinner shallow marine Nansen Formation. Samples from the Nansen Formation point out calcrete nodules, wave ripples and thin layers of shale, Fig. 5.13. Facies of the Nansen Formation may indicate mouth bar deposits.

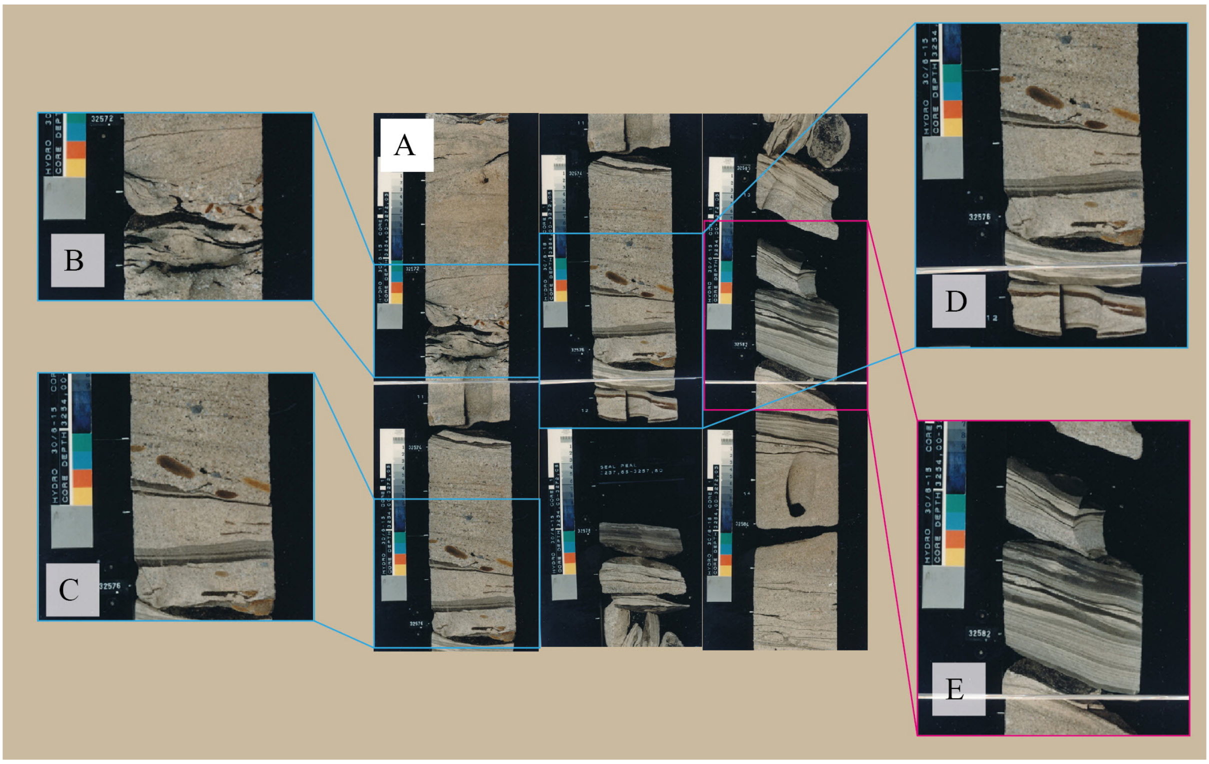
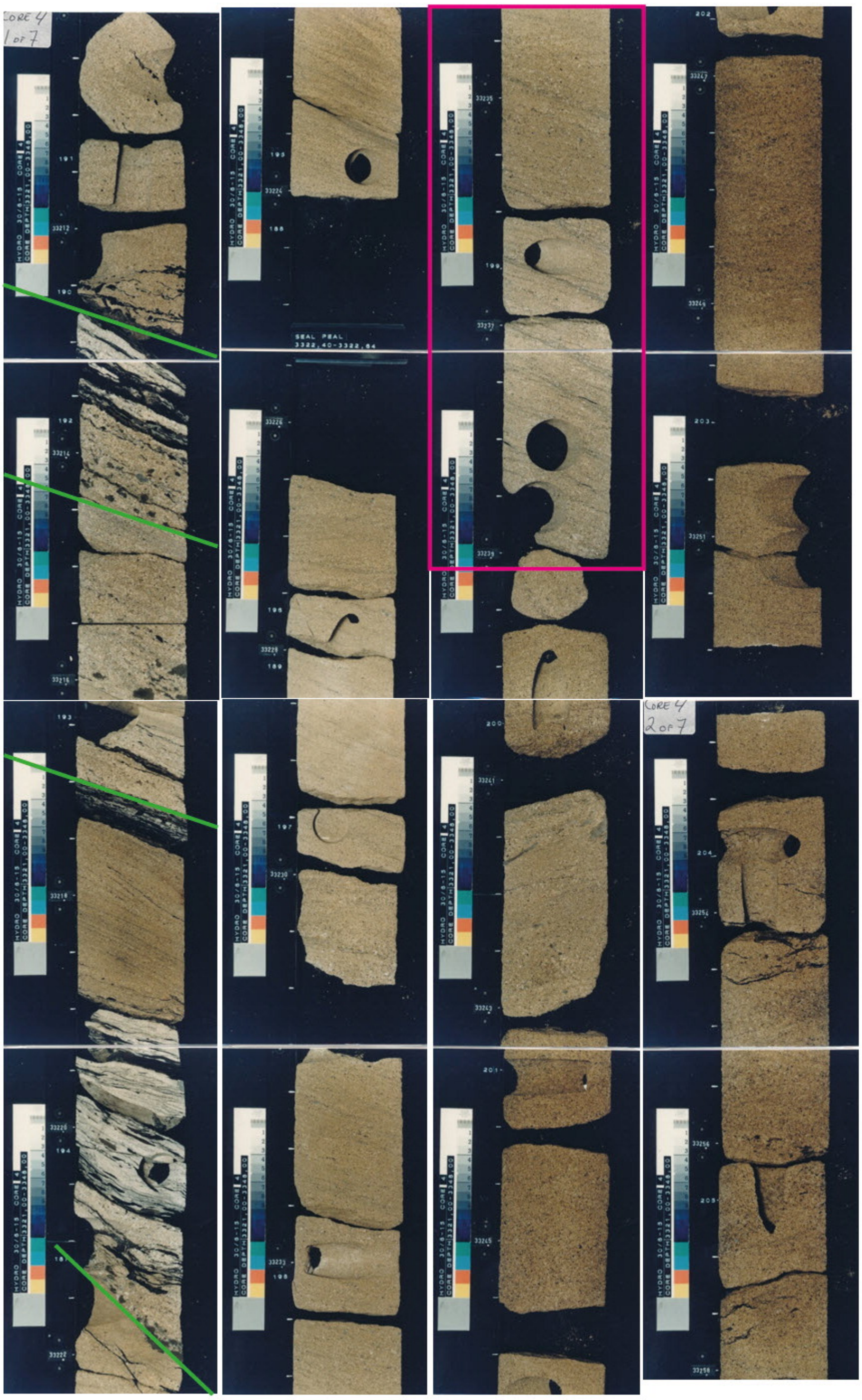


Fig. 5.13 Nansen Formation. *A. NPD photo, well 30/6-15 core no. 1, 3257.05-3258.40 m. B., C. and D. Calcrete nodules. E. Wave ripples and thin layers of shale. Facies of core possibly indicate mouth bar conditions.*

Fig. 5.14 shows a core interval of 4.8 m within the Eiriksson formation. The interval includes sandstones with various grain sizes, from very coarse at the base into fine to medium at the top. Current ripples are outlined in the figure. Erosive bases with clasts at the base indicate channel processes.



3320.00-3325.80 Stacked fluvial channels

Fig. 5.14 Eiriksson Formation. *NPD photos, core no. 4. The interval is dominated by stacked fluvial channels. Green lines indicate erosive bases with clasts at the base. Dark pink box indicates current ripples.*

26/4-1

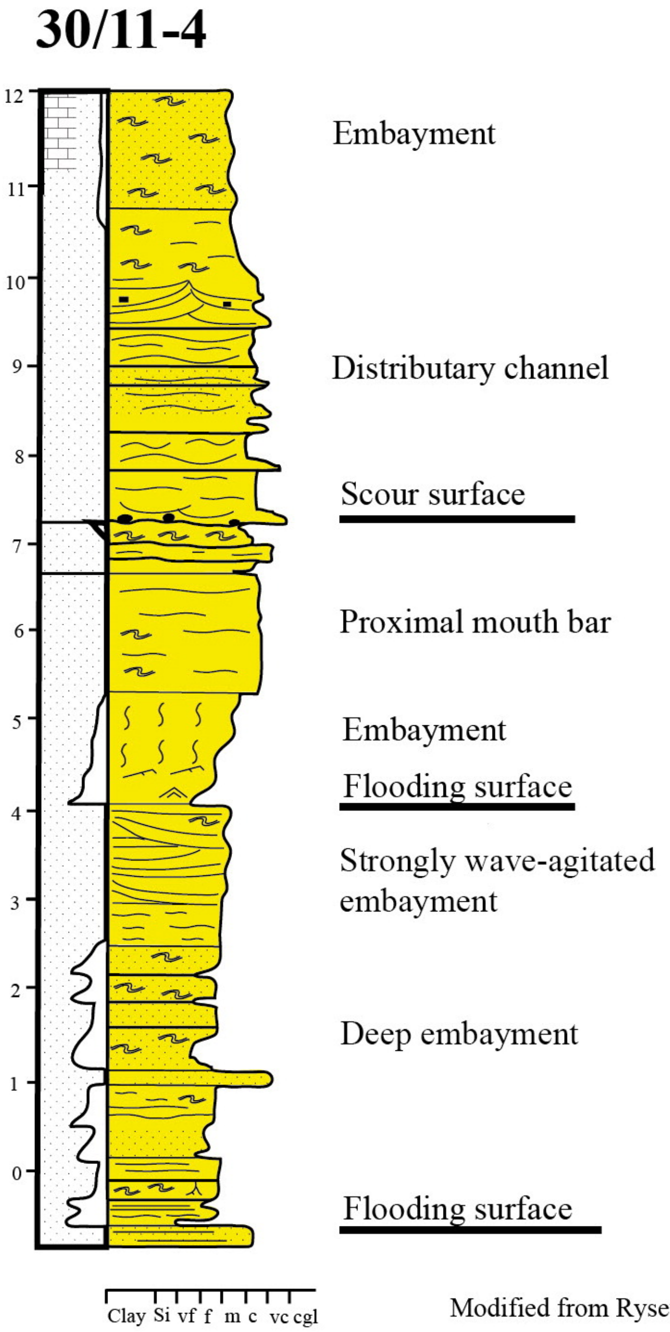
8 meters of core photos within the Statfjord Group are available for the well 26/4-1. This well is located on the flank of the Stord Basin. Core photos for the well comprise continental deposits, see Fig. 5.15.

3308.00-3313.00m: Continental system 3313.00-3316.85m: Continental system

Fig. 5.15 Corephotos from well 26/4-1 dominated by continental deposits

30/11-4

Core photos from the last well studied in this chapter, well 30/11-4 located furher south, is not available in the NPD database. A core description of the Nansen Formation interval of this well, located in the Viking Graben, is illustrated in Fig. 5.16. The schematic cored section shown is related to a shoreface environment. This section is dominated by hummocky/swaley cross-stratification, intense bioturbation and low-angle beds. Ryseth (2001) interpreted the depositional environment to be a marine shoreface affected by strong waves.



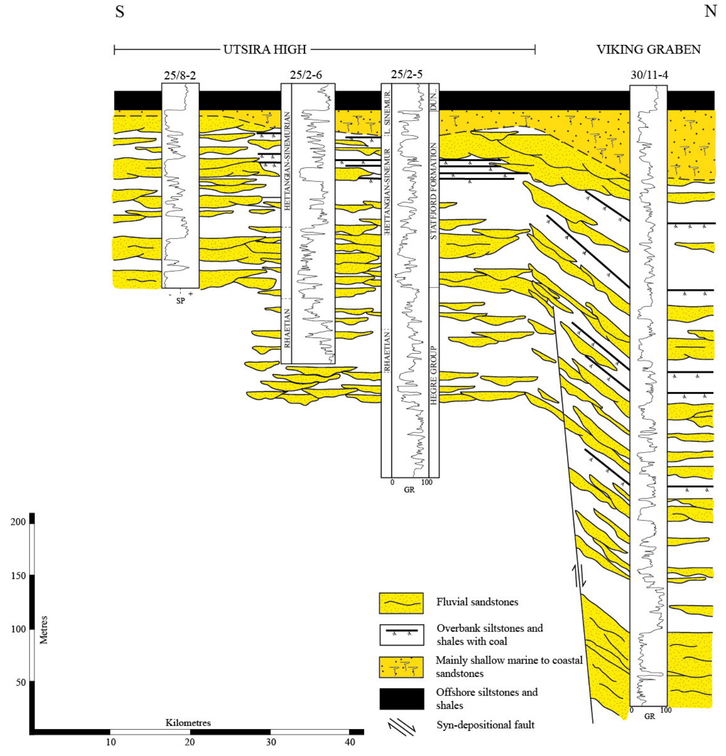
Modified from Ryseth (2001)

Fig. 5.16 Core description from well 30/11-4

5.3 NW-SE Correlation

The thickness of the Statfjord Group varies from 30 meters at the basin margins to more than 500 meters in central parts of the basin. The multiform thickness of the Statfjord Group is indicating a significant differential subsidence (Steel & Ryset 1990; Ryseth & Ramm 1996; Ryseth 2001). Analysis of the effect of this differential subsidence during Early Jurassic suggests that sedimentation kept pace with the generation of accommodation space. Variations in stacking patterns and net to gross of the entire succession are the result (Ryseth & Ramm 1996; Ryseth 2001).

The total thickness of the Statfjord Group is around 150-200 m on the Utsira High, whereas the succession has a thickness of about 600 m in well 30/11-4 in the Viking Graben. The Statfjord Group in well 30/11-4 mainly consists of continental deposits capped by a thinner marginal marine succesion (Fig. 5.17); Ryseth 2001). The proportion of fluvial sandstones within the alluvial succession shows great variations from less than 40% to more than 80% regionally. This proportion reflects available accommodation space (Ryseth & Ramm 1996; Ryseth 2001).



Modified from Ryseth (2001)

Fig. 5.17 Correlation panel for the Utsira High area. *The correlation illustrates the architecture of the Statfjord Group.*

A well correlation panel for the Utsira High are shown in Fig. 5.18. The correlation panel confirms high net-to-gross values at the Utsira High as illustrated by Ryseth (2001).

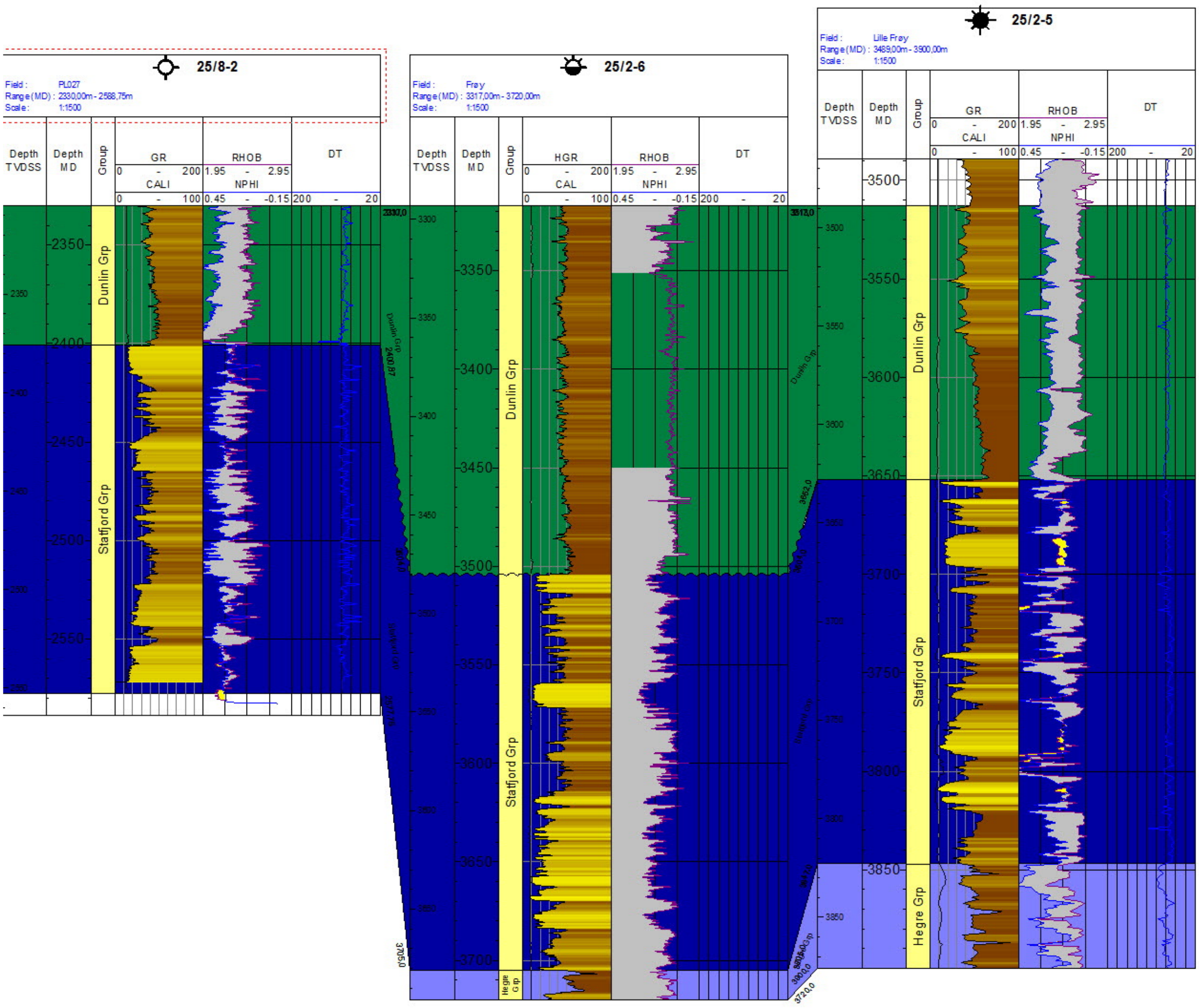


Fig. 5.18 Well correlation for the Utsira High. *N/G for 25/8-2: 0.40, N/G for 25/2-6: 0.50 and N/G for 25/2-5: 0.40.*

The areas Tampen Spur, Horda Platform and Utsira High are studied. A comparison indicates an Early Jurassic drainage system with a southerly dipping continental paleoslope. The slope terminates in a shallow marine environment to the south (Ryseth 2001). Interpretations assign marine incursions from the south with alluvial facies dominating to the north (Ryseth 2001). The dominantly continental Statfjord Group links to age-equivalent coastal and marginal marine deposits on the Utsira High. The Statfjord Group studied on the Tampen Spur and Horda Platform areas illustrate laterally persistent multistory and multilateral sandstone sheets succeeded by laterally extensive mudrock intervals with isolated channel sandstones (Ryseth &Ramm; Ryseth 2001; Røe & Steel 1985).

Fig. 5.19 shows the location of the well correlation panel (Fig. 5.18) and the schematic correlation panel (Fig. 5.17) for the Utsira High area. The figure also illustrates the direction of marine incursions from the south as indicated by Ryseth (2001).

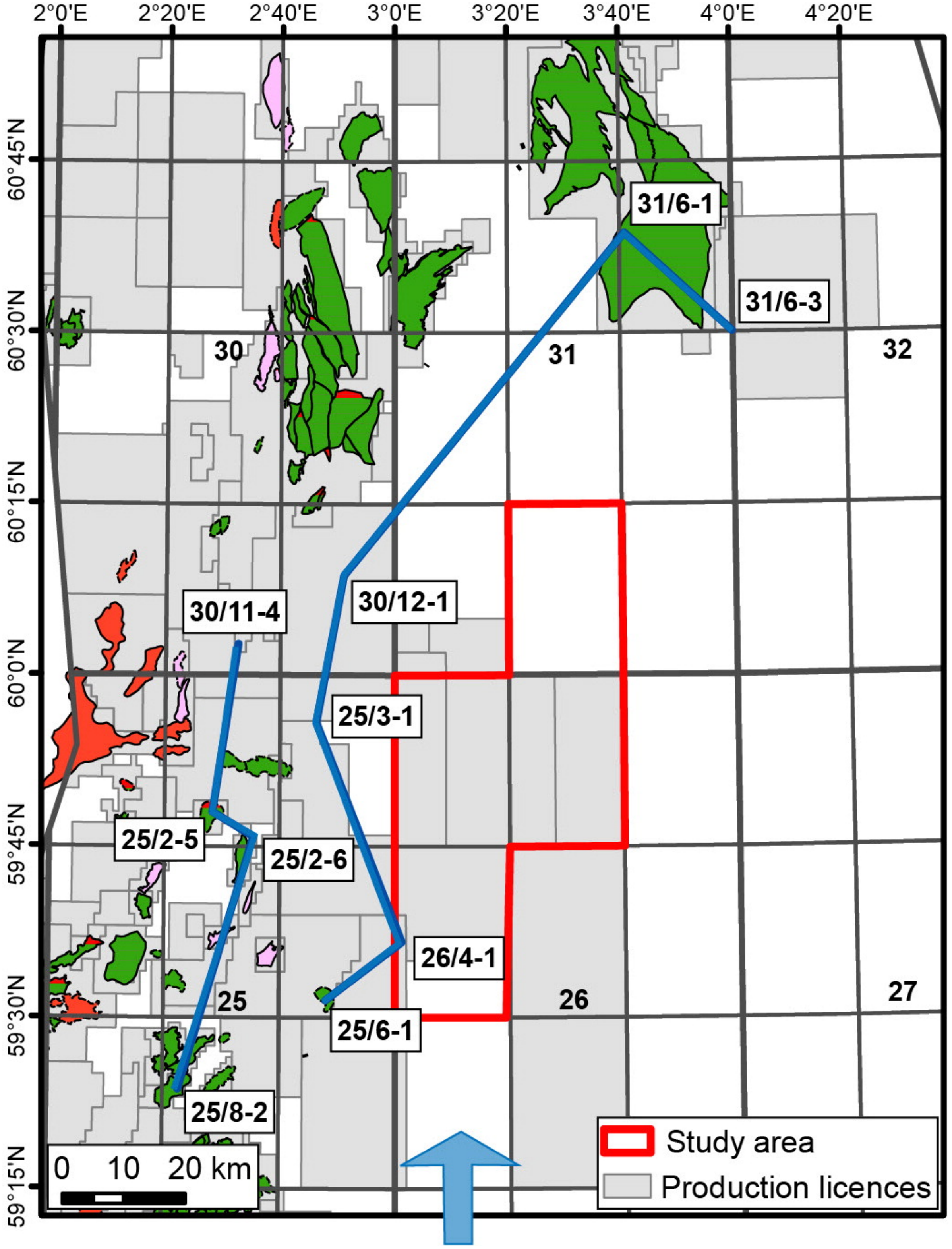


Fig. 5.19 Location of correlation panels for the Utsira High area. *Blue arrow indicate direction of marine incursion.*

The thickness of the Statfjord Group surrounding the studied and interpreted area of this thesis varies from a minimum of 16 meters (well 32/4-1) in the Troll area to a maximum of 615 meters (well 30/11-4) (Fig. 5.20).This variation indicates significant syn-depositional subsidence between the basin margin and the area to the west (Ryseth & Steel 1990). Wells in the Troll area have thickness of the Statfjord Group ranging from 16 to 57 meters and represent the thinnest sedimentary package around the study area.

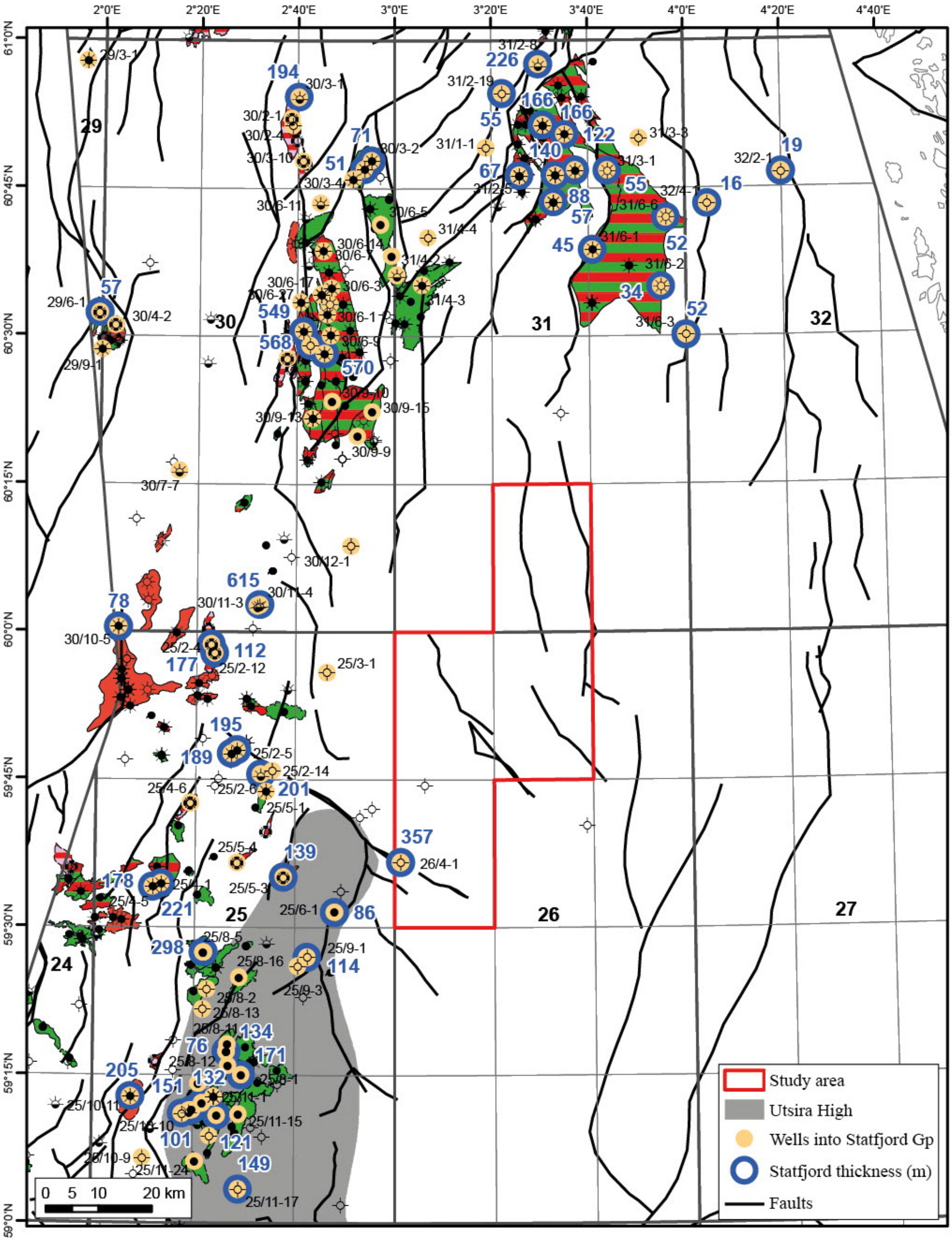


Fig. 5.20 Statfjord Group gross thickness from wells. *All wells penetrating the Statfjord Group is shown in orange; with thickness of the Statfjord Group indicated on wells penetrating the entire succession. The thickness varies considerably by area due to syn-depositional differential subsidence.*

Wells penetrating the Statfjord Group in areas sourrounding the Stord Basin is used in completion logs for well correlations, see Fig. 5.21.

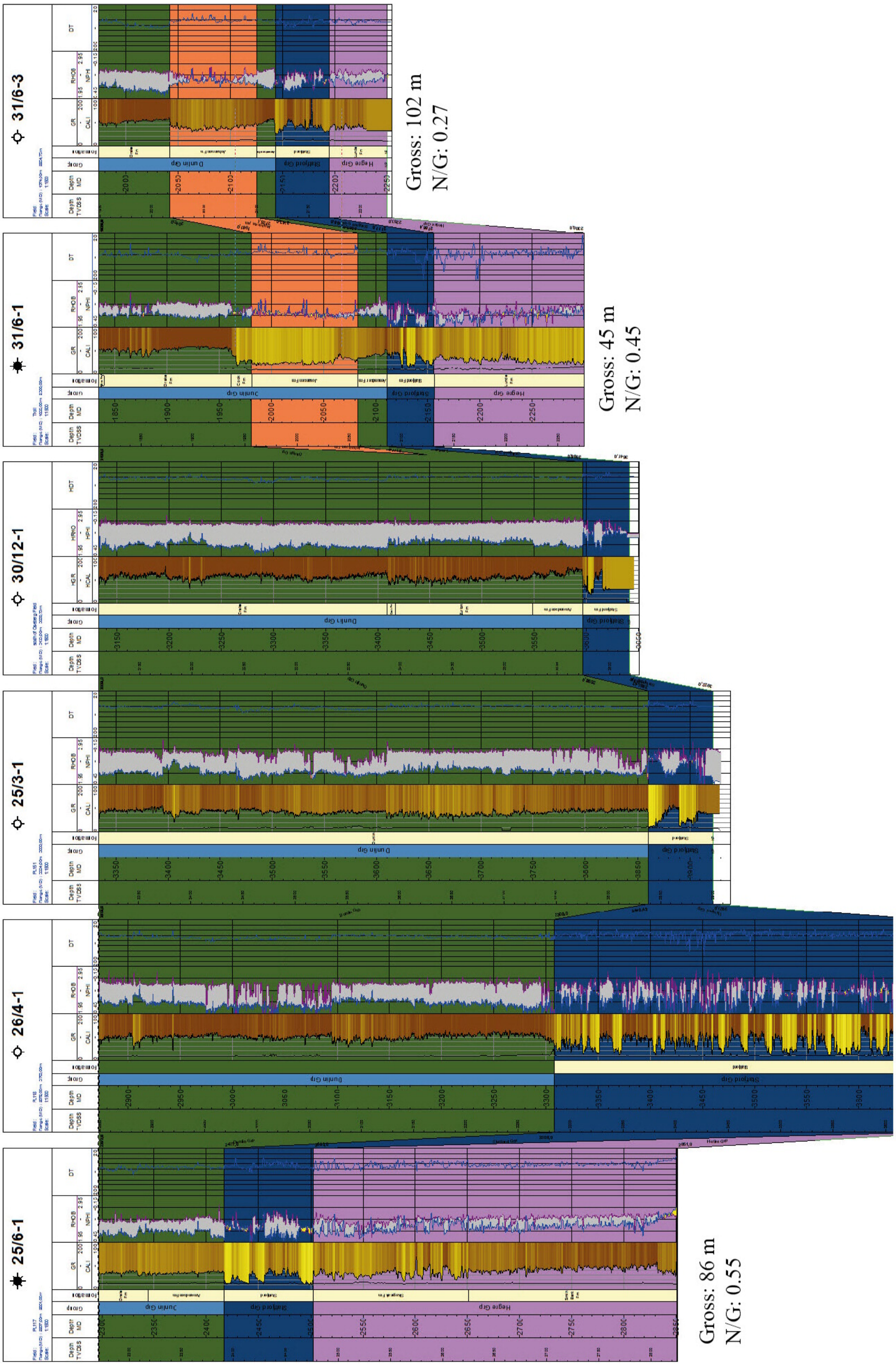


Fig. 5.21 Well correlation panel. *Only 26/4-1 is in the Stord Basin proper. Net-to-gross values are estimated for wells penetrating the entire Statfjord Group succession.*

An estimate of net-to-gross values are calculated for wells with entire successions of the Statfjord Group (Fig. 5.21). This calculation intends to study trends of the net-to-gross in the Stord Basin are thus approximate values. The values are calculated from amounts of sand-intervals in the well-logs divided by gross values. The gross values are fetched from NPD. This will further be discussed in chapter 7 Discussion.

6 Seismic Results

6.1 Introduction

An excerpt of the interpretations is shown in the following subchapters. The observed and interpreted area extends over large distances which makes it difficult to show the results in detail on paper. Fig. 6.1 and Fig. 6.2 show the location of the interpreted lines. Selections of important observations are displayed in this chapter. The selections are described in three steps. First, excerpted lines are observed. In the second step the seismic lines are interpreted and located on a structural map. In chapter 7 the observations and interpretations are further discussed in relation to previous research and interpretations. The observation, interpretation and discussion of the lines are mainly related to the marked horizons, Top Hegre Group and Top Statfjord Group.

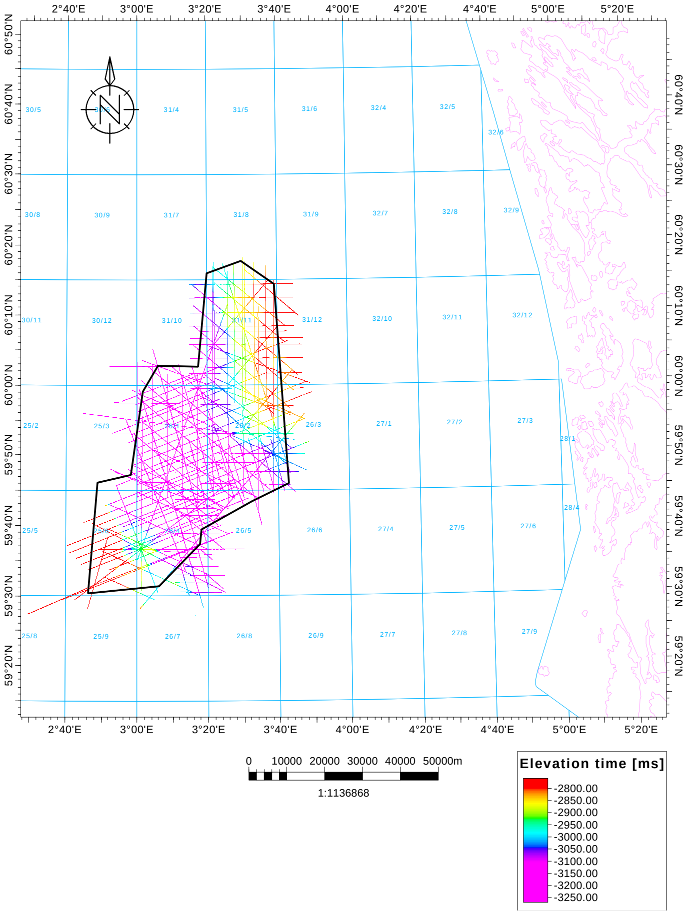


Fig. 6.1 Top Hegre TWT. *Location of interpreted seismic lines. Location of polygon is indicated in black.*

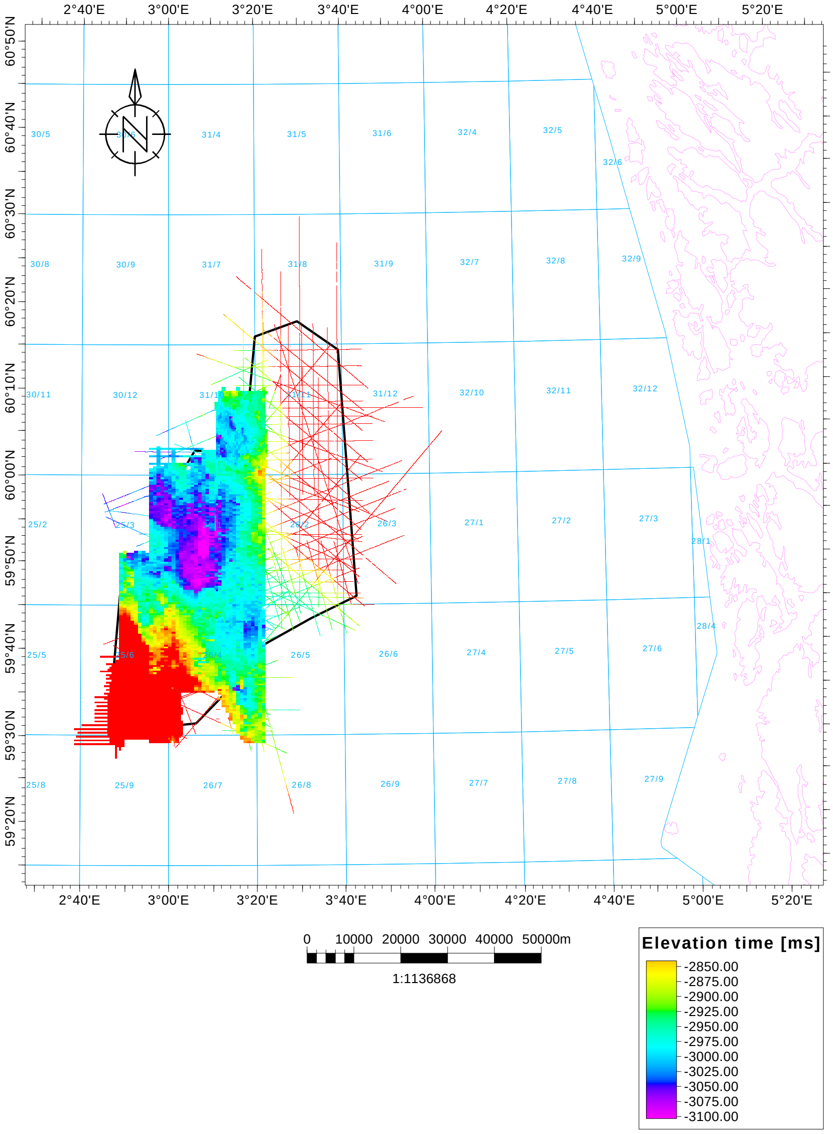


Fig. 6.2 Top Statfjord TWT. *Location of interpreted 2D lines and 3D cubes. Location of polygon is indicated in black.*

The Top Hegre Group and the Top Stafjord Group have been regionally mapped from the Utsira High in block 25/6 to the centre of the Stord basin in block 31/11. The Top Hegre reflector has been mapped on available 2D seismic lines, whereas the Top Statfjord reflector has been mapped on several 2D seismic lines and also some 3D seismic cubes (see 2.1 Seismic Database for location of the seismic database).

Fig. 6.1 and Fig. 6.2 display the polygon used to create surface grids. The polygon covers latitudes from 59°30'N to 60°17'N. Longitudes of the polygon span 2°46'E to 3°43'E.

6.2 Reflection Profile TT98-201

The 2D seismic line TT98-201 has a direction SW-NE, and is located across the Stord Basin. Well 26/4-1 and well 26/4-2 are located within the line. TT98-201 is intersected by several other lines and is used as a reference for interpretation of the other intersected lines. TT98-201 is interpreted in its total length of approximately 75 km.

6.2.1 Observations

TT98-201 is shown in Fig. 6.3.

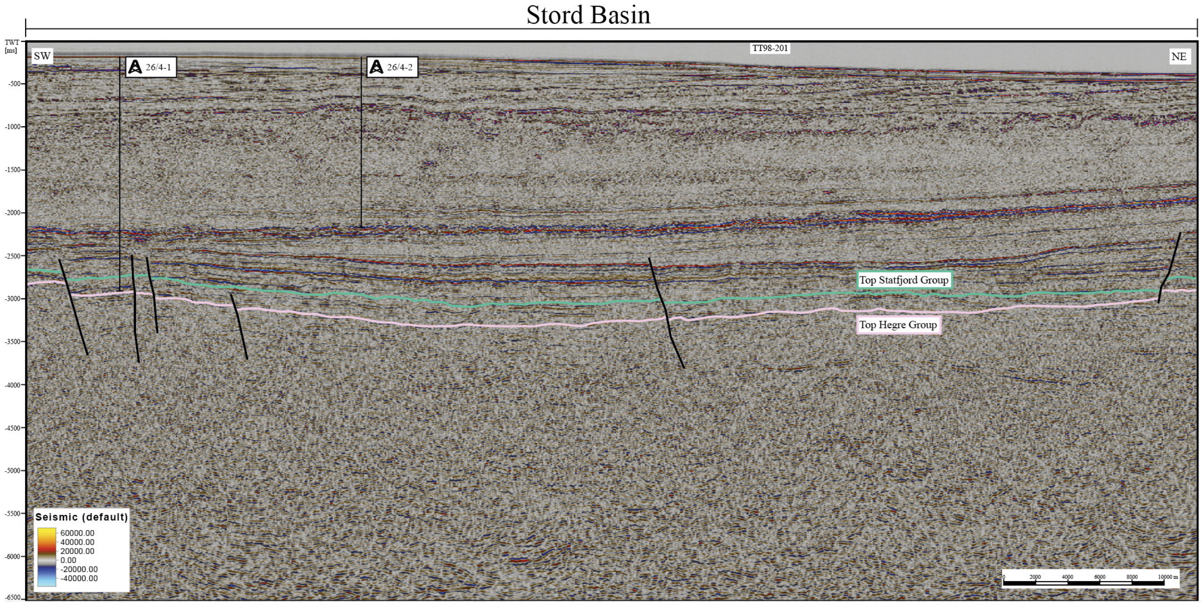


Fig. 6.3 Seismic line TT98-201.

Two wells are located within the line: Well 26/4-1 and well 26/4-2. Well 26/4-1 intersects the green and the pink horizons, whereas well 26/4-2 is not intersecting the horizons. Abrupt terminations of reflectors are shown in the seismic. The seismic displays a lateral change of reflectors at depths greater than 2500 ms. Seismic reflectors at depths shallower than 2750 ms are clearer than the deeper ones. The thickness variation between the pink and green horizon shows significant thinning from the centre of the figure to the SW. A minor thinning is observed from the centre of the figure to the NE.

6.2.2 Interpretations

The location of TT98-201 is presented in Fig. 6.4.

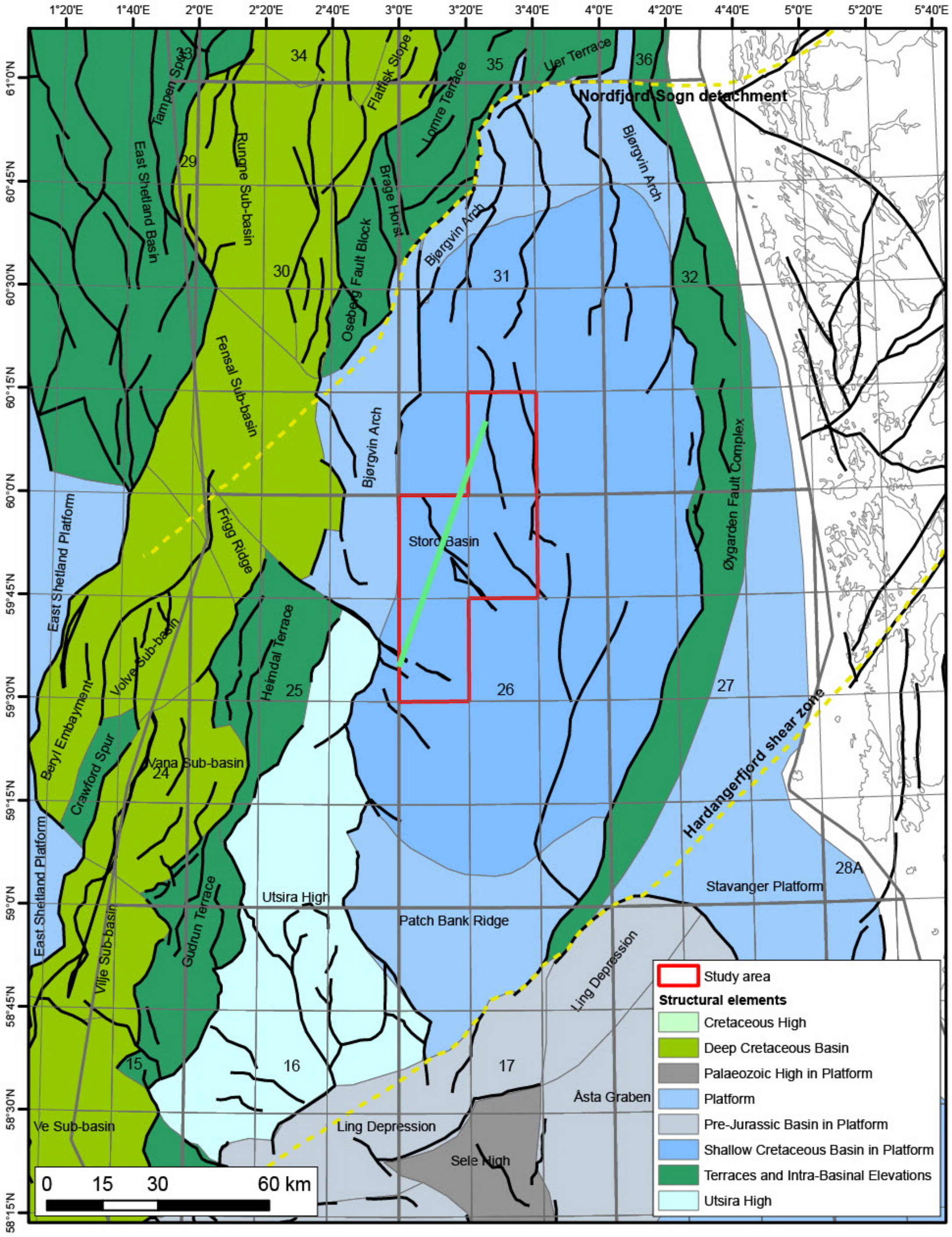


Fig. 6.4 Structural element map. Green line shows the location of the seismic line TT98-201. *Main structural elements slightly modified from NPD.*

The line is located within the Stord Basin, stretching from SW-NE. Block 31/11, 26/1 and 26/4 are the blocks mainly intersected. Abrupt terminations of the reflectors are interpreted as normal faults, where the hanging wall is immersed relatively to the footwall. The oldest penetrated age in well 26/4-2 is Late Cretaceous, and could therefore not confirm the interpretations of reflectors at Triassic/Early Jurassic age. Well 26/4-1 is penetrating the Top Statfjord Group, and also throughout the whole Statfjord Group succession. This well together with young formations was used as a guidance to start the mapping of the Top Statfjord Group and the Top Hegre Group. Top Hegre Group is the equivalent to the base of the Statfjord Group. The pink horizon is interpreted to be the Top Hegre Group, whereas the green horizon is interpreted to be the Top Statfjord Group. Further seismic interpretations were based on the reflections at the location of well 26/4-1 and extended towards the centre of the basin.

6.3 Reflection Profile NSR06-31166

The seismic line NSR06-31155 is located across the block 31/11 with direction NW-SE. NSR06-31166 is located close to the centre of the Stord Basin. It is interpreted in a length of approximately 25 km. The line is intersected by several other lines and thus gives a reference to the depth of interpretations in other lines.

6.3.1 Observations

NSR06-31166 is presented in Fig. 6.5.

At depths greater than 2000 ms, abrupt terminations of several reflectors are shown, stretching from 2000 ms to 4500 ms. The reflections are stronger at depths shallower than 2500 ms.

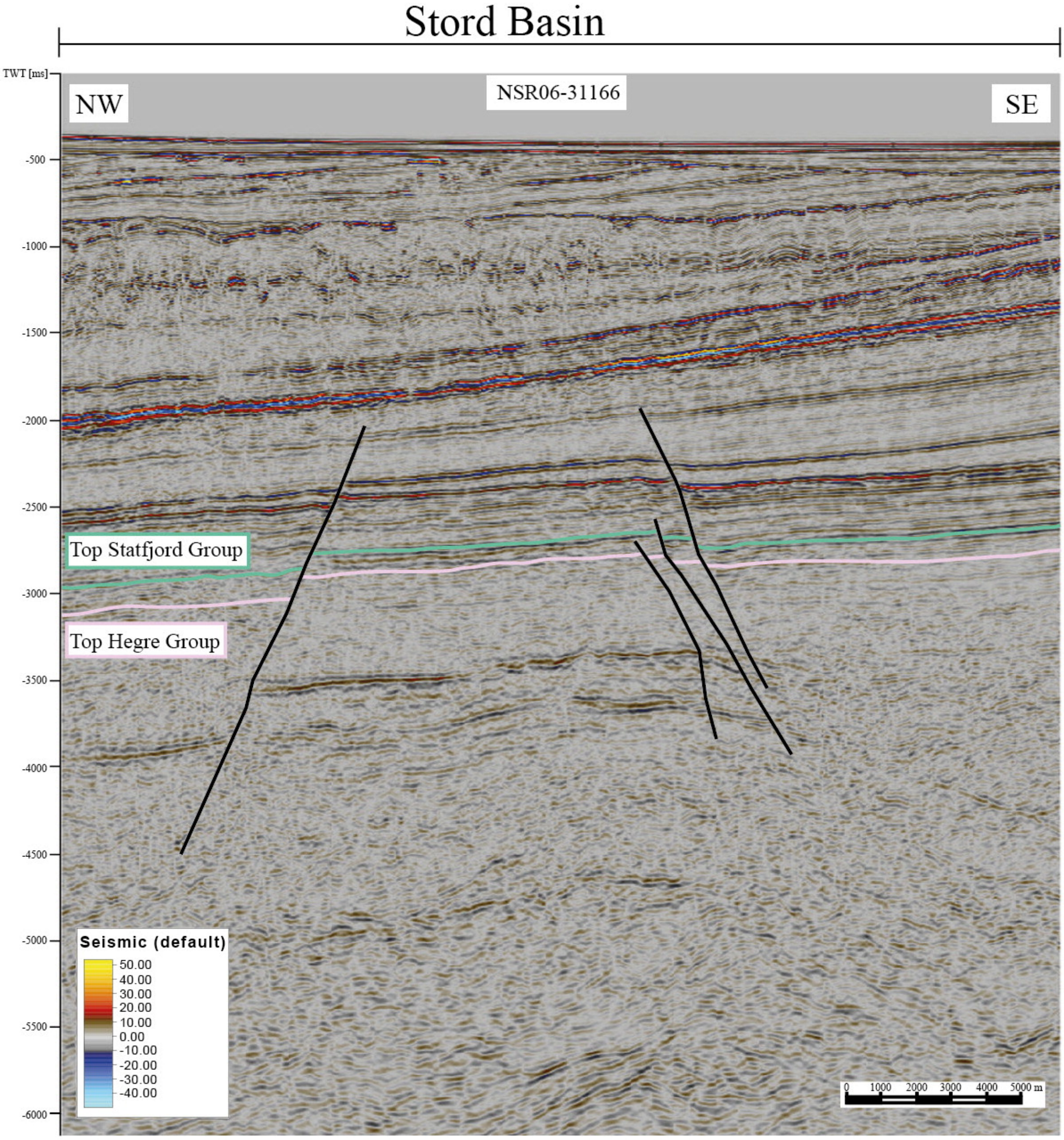


Fig. 6.5 Seismic line NSR06-31166.

6.3.2 Interpretations

The location of NSR06-31155 is shown in Fig. 6.6.

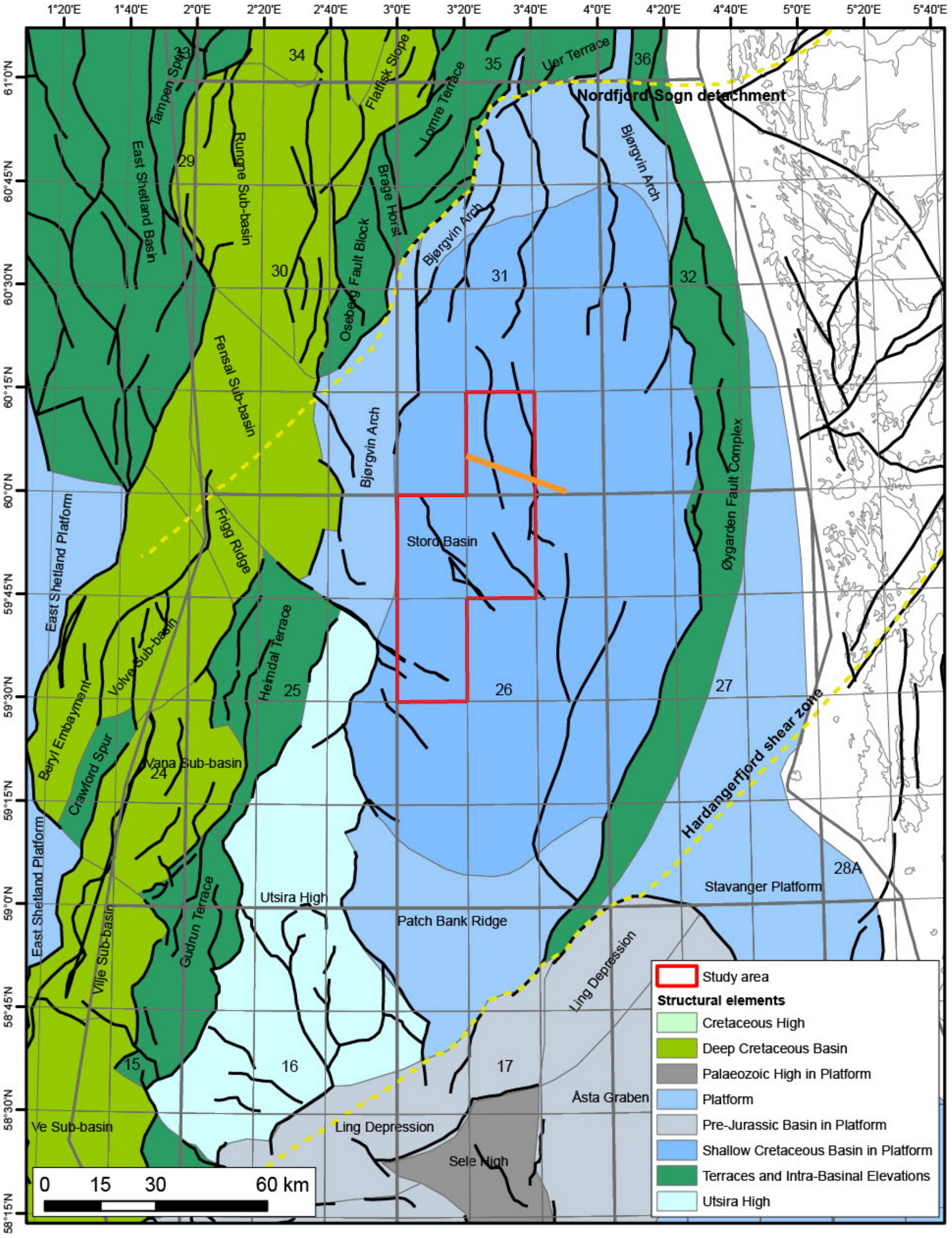


Fig. 6.6 Structural element map. Orange line shows the location of the seismic line NSR06-31166. *Main structural elements slightly modified from NPD.*

The line is mainly located in block 31/11, close to the centre of the Stord Basin, and has a direction from NW to SE. Abrupt terminations are interpreted to be normal faults, affecting both the Top Statfjord and Top Hegre reflector. The lateral changes with terminations are interpreted to be normal faults. Normal faulting results in a raised fault block, a horst, shown in Fig. 6.5.

6.4 Reflection Profile SBDE96-302

The seismic line SBDE96-302 is located in block 25/6, 26/4 and 26/2. SBDE96-302 is stretching from the Utsira High in SW towards the centre of the Stord Basin in NE. Two wells are drilled in the location of this line, well 25/6-1 and well 26/4-1. Well 25/6-1 is penetrating formations of Pre-Devonian age and thus includes the Triassic/Jurassic Statfjord Group. Well logs from this well verify that the Statfjord Group is stretching from 2417 m to 2503 m. The thickness of the Statfjord Group is 86 m at this location. Further northeast, well 26/4-1 verifies a thickness of the Statfjord Group of more than 380 m. SBDE96-302 is interpreted in its full length of 50 km.

6.4.1 Observations

The seismic line SBDE96-302 is shown in Fig. 6.7.

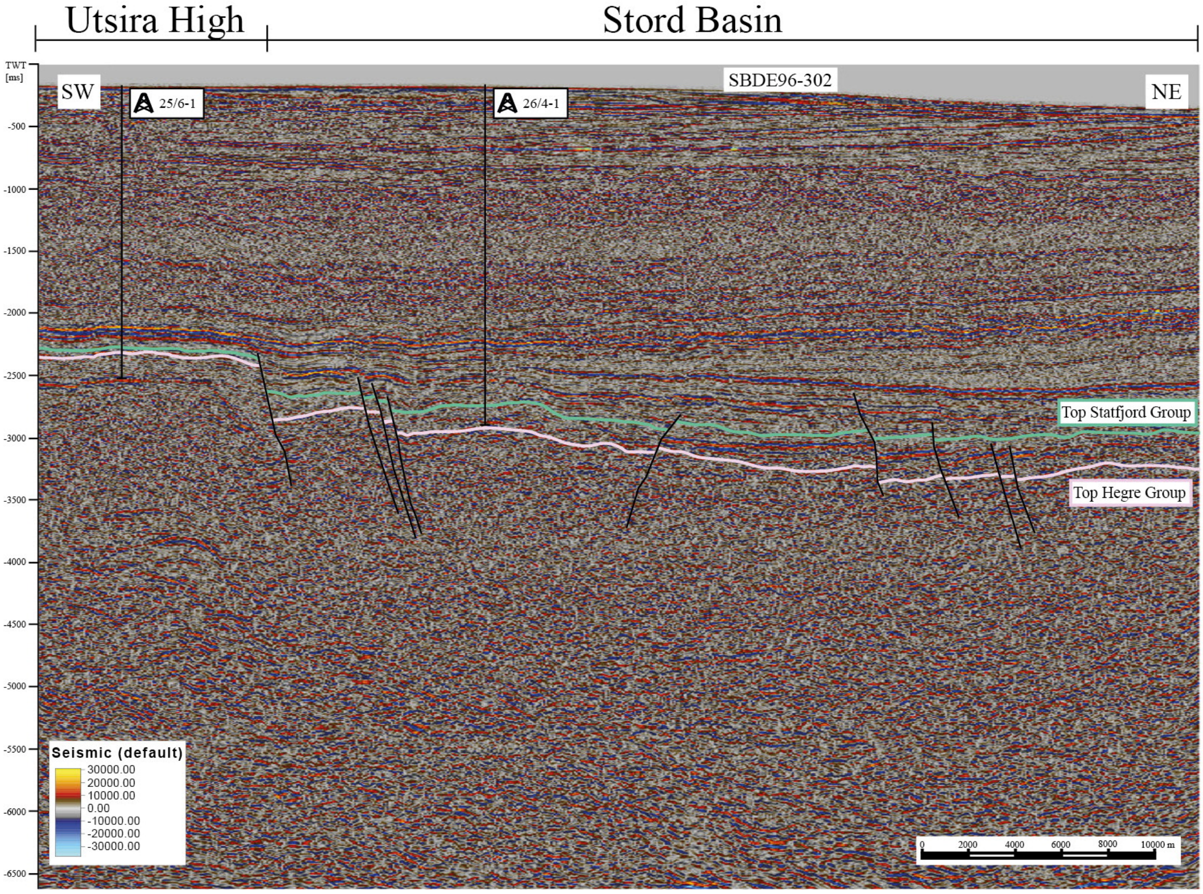


Fig. 6.7 Seismic line SBDE96-302.

Both the Top Hegre and the Top Statfjord reflectors are terminated several times throughout the line. The depths of Top Statfjord vary from 2250 ms to 3000 ms, whereas from 2300 ms at the shallowest down to 3250 ms for Top Hegre. Well 25/6-1 and 26/4-1 are penetrating both of the horizon. A significant thickening of the vertical distance between the horizons is observed from SW to NE.

6.4.2 Interpretations

SBDE96-302 is mainly located in block 25/6 and 26/4 (Fig. 6.8).

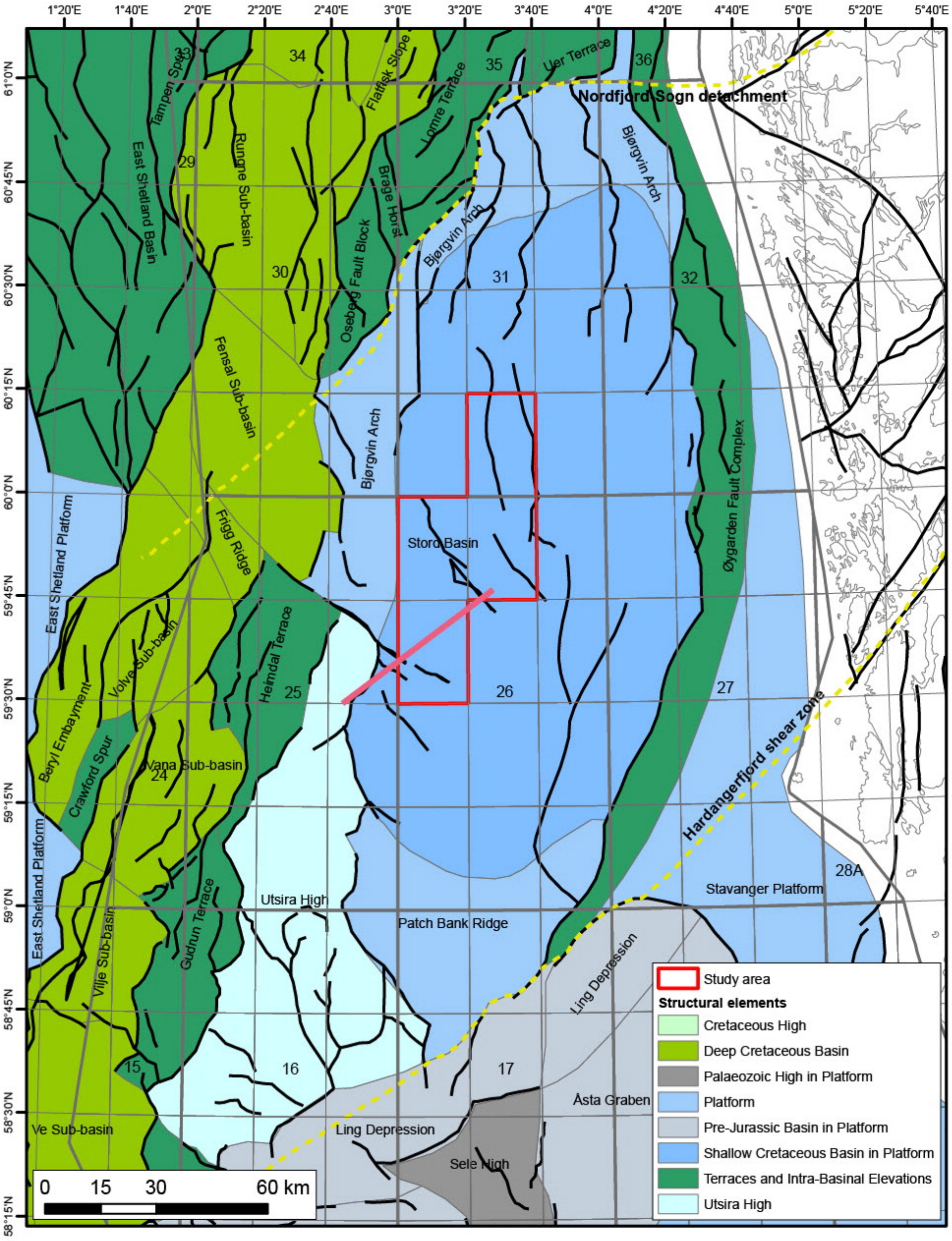


Fig. 6.8 Structural element map. Dark pink line shows the location of the seismic line SBDE96-302. *Main structural elements slightly modified from NPD.*

SBDE96-302 stretches toward the centre of the Stord Basin into block 26/2. Well 25/6-1 and 26/4-1 confirm the interpretations of the Top Hegre Group and Top Statfjord Group at the Utsira High and the flank of the Stord Basin, respectivelly. The latter well gives an estimate of the depth of the horizons in block 26/4. Several abrupt terminations are shown in the line. These are interpreted to be normal faults. The result is deepening of the hanging walls.

6.5 SW-NE Composition Line

A composition line is assembled to illustrate the trend of sedimentation in the Stord Basin. This composition line is located from the Utsira High in block 25/6 and extended towards the centre of the Stord basin through block 26/4 and 26/2. The extension of the composition line is closed in block 31/11. The composition line is interpreted in its full length of 90 km.

6.5.1 Observations

The composition line is shown in Fig. 6.9.

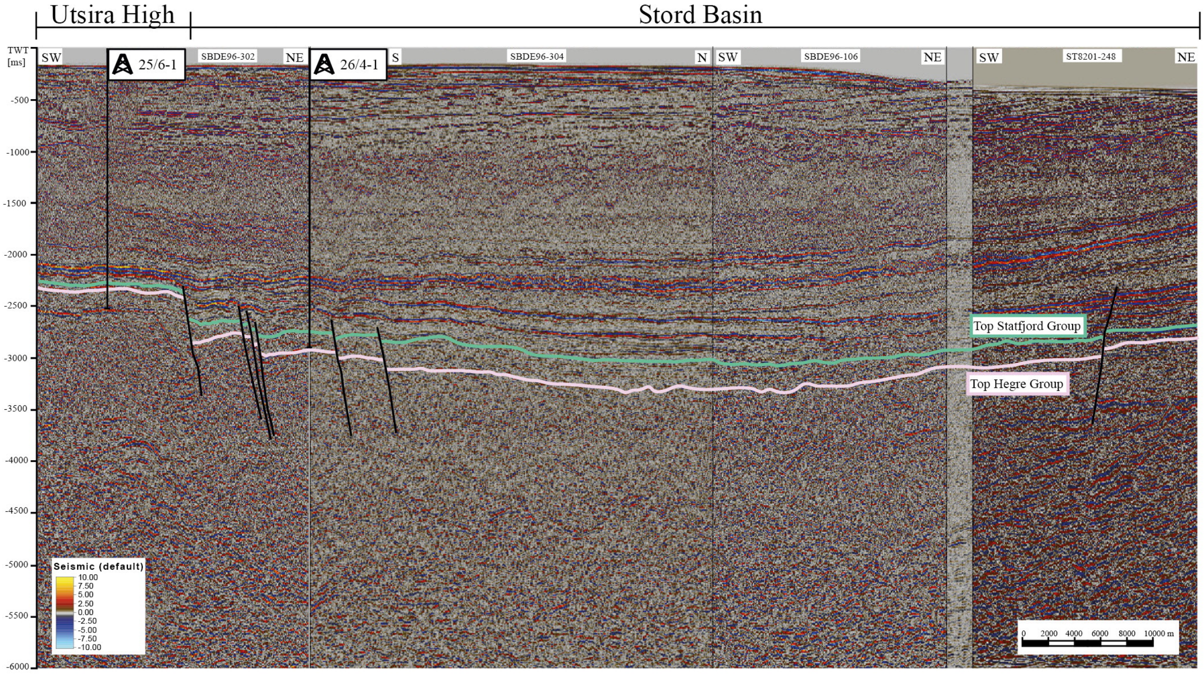


Fig. 6.9 Composition line.

Two wells are located within the line: Well 26/4-1 and well 25/6-1. Well 26/4-1 is almost penetrating the Top Hegre horizon, whereas well 25/6-1 is penetrating it. Several abrupt terminations of the reflector are seen in the seismic. Reflectors above the Top Hegre and Top Statfjord horizons are much clearer than the underlying ones. The shallower horizon seems to be more compacted on the high to the left in the figure. Increased accommodation space above the Top Hegre horizon is indicated in the centre of the figure. Thickness variations between the horizons exhibit a significant thickening from SW to the centre of the line. A slightly minor thinning is observed from the centre of the figure to the NE.

6.5.2 Interpretations

The composition line showed in Fig. 6.9 is extended from block 25/6 at the flanks of the Stord Basin in SW towards block 31/11 at the centre of the basin in NE (Fig. 6.10).

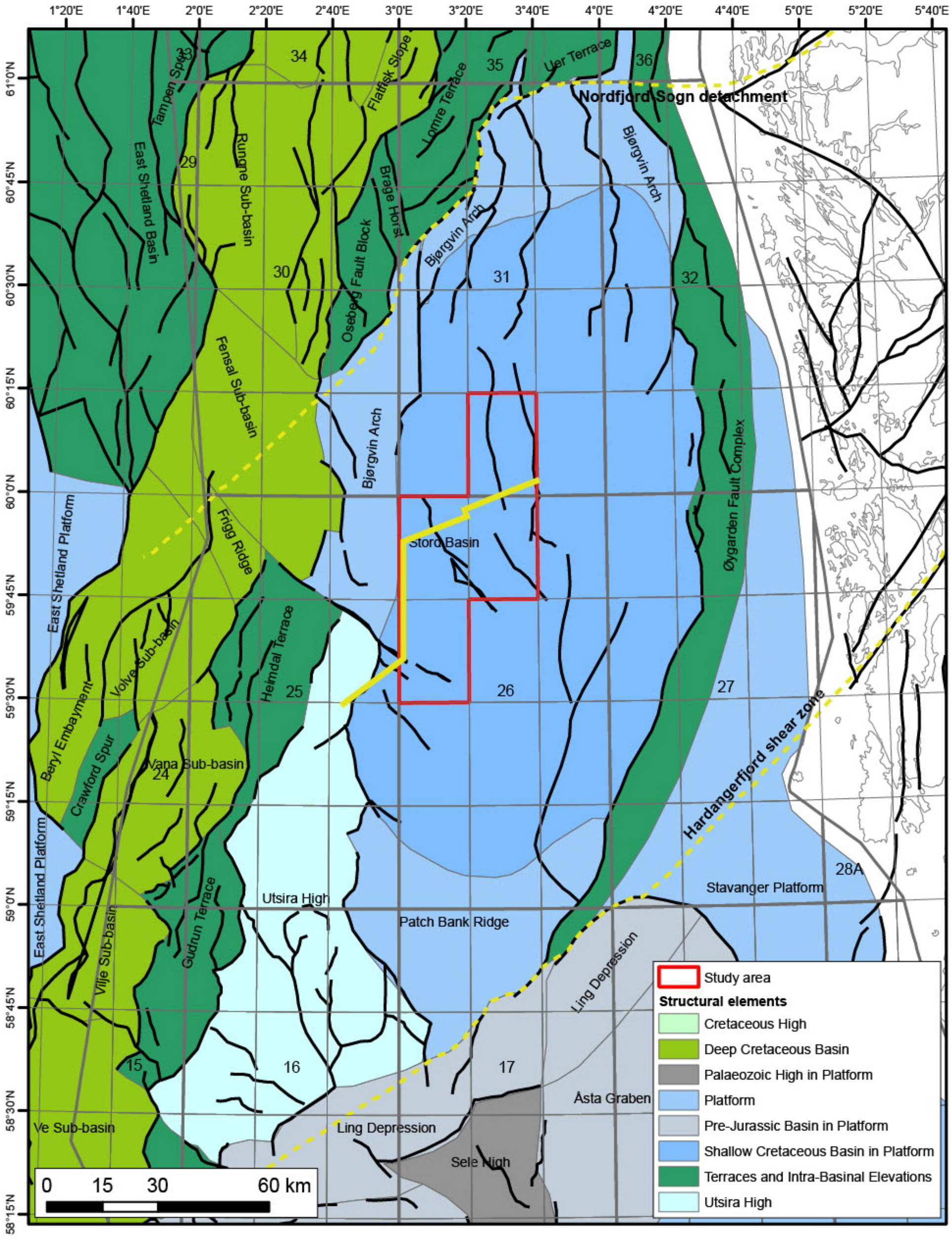


Fig. 6.10 Structural element map. Yellow line shows the location of the composition line in Figure 6-9. *Main structural elements slightly modified from NPD.*

The composition line is located from the Utsira High (SE) to the centre of the Stord Basin (NE). Due to tectonics, the seismic horizons exhibit significant vertical variations. The terminations observed in the line are interpreted to be normal faults.
Well 26/4-1 confirms the interpretation of the Top Statfjord, whereas well 25/6-1 confirms interpretation of both the Top Statfjord and the Top Hegre horizons.

6.6 Isochore Map

To understand the available accommodation space, a time-isochore map of the Statfjord Group succession was made. The isochore map was built by using the Top Hegre and the Top Statfjord surface maps, and is shown in Fig. 6.11.

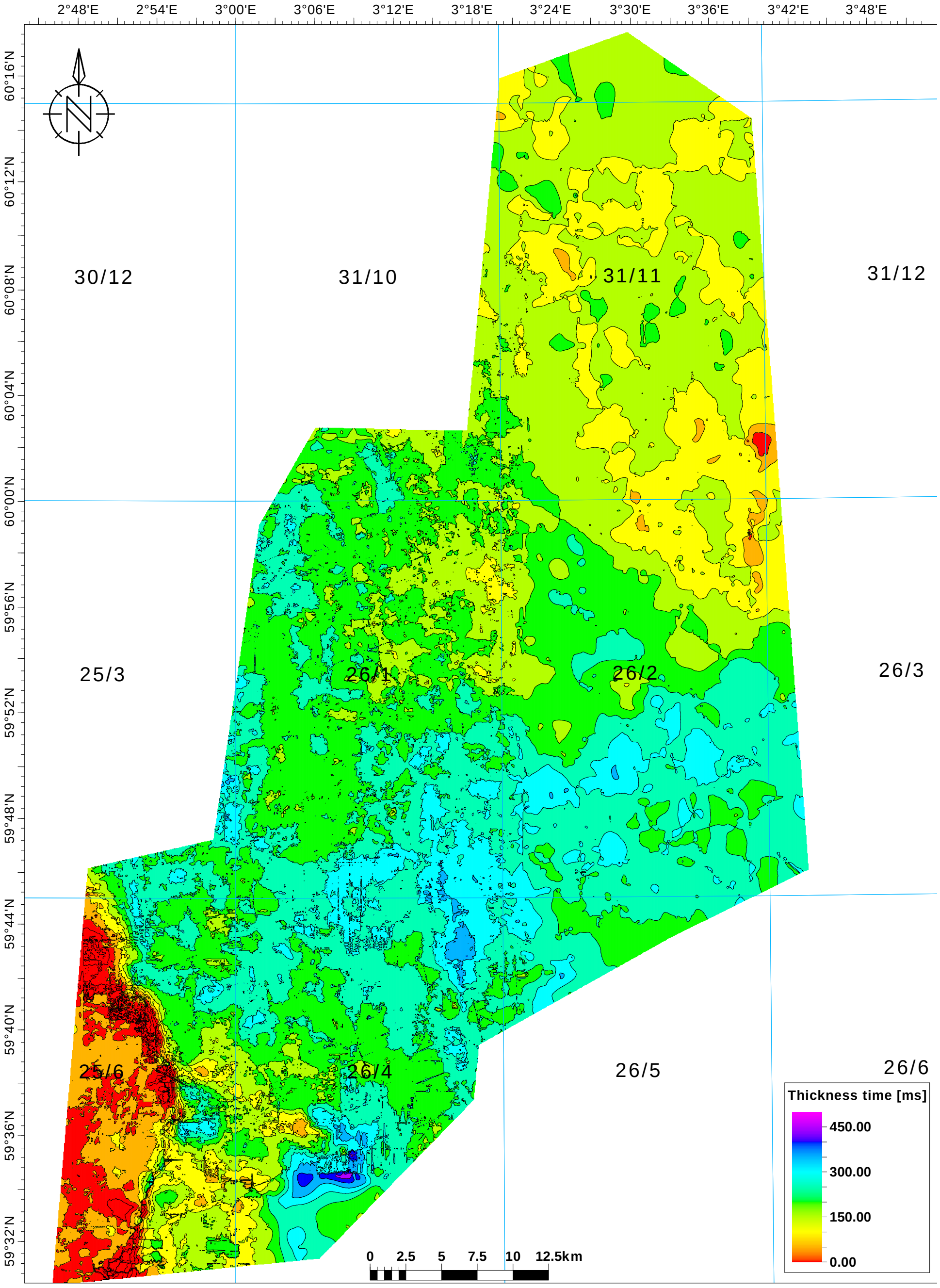


Fig. 6.11 Early Jurassic (Statfjord Gp) isochore map [TWT] illustrating the accommodation space in the Stord Basin. Ci is 50 ms.

A significant thick area is illustrated in dark blue/purple at coordinate 59°34'N, 3°08'E in block 26/4 (Fig. 6.11). This area may represent a sub basin. The isochore map indicates significant thinning onto the Utsira High to the southwest. Towards the northeast the Statfjord Group is thinning out. The area of block 31/11 is an area where the Statfjord Group might have been eroded. This area shows relatively thin thicknesses of the Statfjord Group. In addition, the red contour at coordinate 3°39'E, 60°03'N, indicates an area where the Group potentially is missing in the Stord Basin. This will be further discussed in 7 Discussion.

6.7 Depth Conversion

Depth conversion was performed in Petrel using corrected NS-1210T-DN velocity data delivered by Aker Geo. The regional velocity cube in UTM zone 31, has grid dimensions 3000X3000 m laterally and 100 ms vertically from 0 to 12800 ms, and is calibrated against well 26/4-1.

The two-way time grids of the Top Statfjord and Top Hegre time maps were depth converted with the above described velocity cube. Time and depth maps for the two horizons are shown in Fig. 6.12 and Fig. 6.13. This cube is based on released 2D seismic stacking velocities that are correlated to well check-shot data.

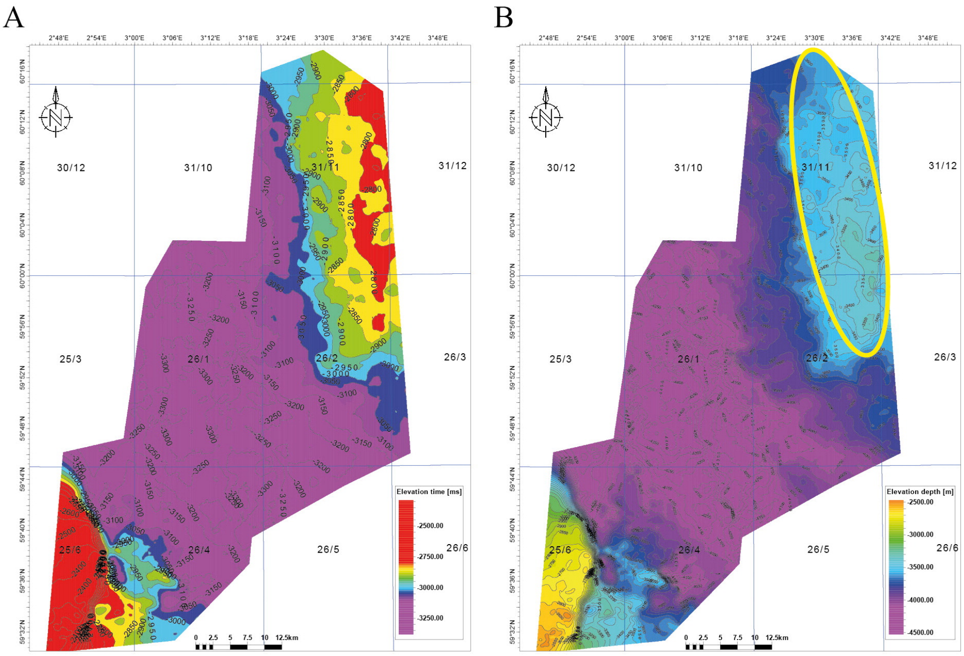


Fig. 6.12 Top Hegre time (TWT) and depth (TVD) maps. *A. Ci= 50 ms. B. Ci=50 m. Note that the depth conversion results in a push-down effect at the Utsira High area in block 25/6. Another push-down effect is illustrated by a yellow ellipse to the northeast.*

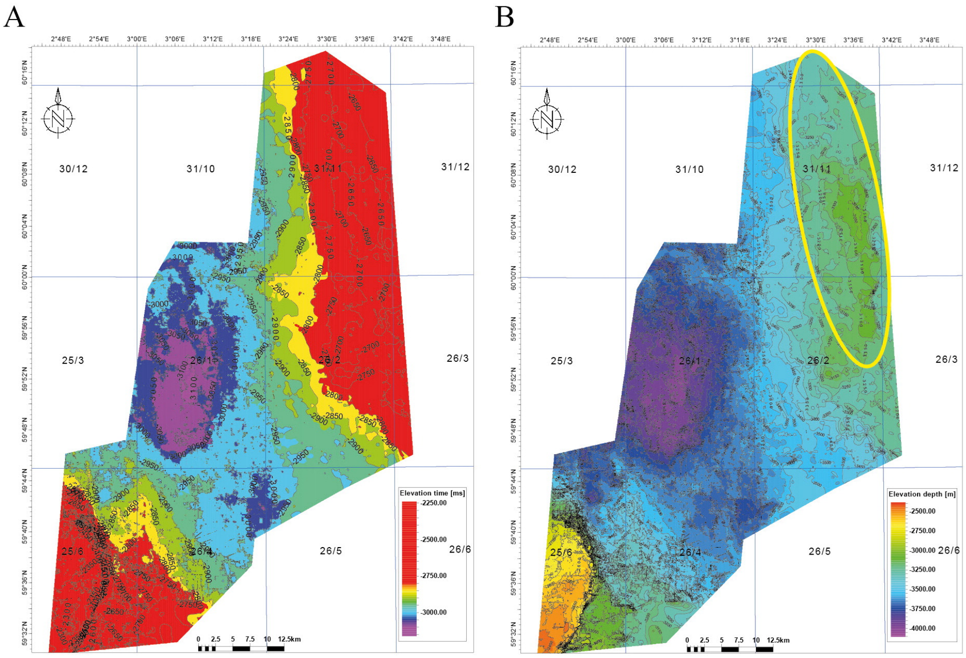


Fig. 6.13 Statfjord time (TWT) and depth (TVD) maps. *A. Contour increment is 50 ms. B. Contour increment is 50 m. Note that the depth conversion results in a push-down effect at the Utsira High area in block 25/6. Another push-down effect is illustrated by a yellow ellipse to the northeast.*

The Top Statfjord and Top Hegre TWT maps (Fig. 6.12.A and Fig. 6.13.A) illustrates the significance of the laterally varying velocity field caused by the tilted and uplifted older strata towards the southwest and northeast. Fig. 6.12.B and Fig. 6.13.B show the resulting depth map.

The most significant effect of the depth conversion is seen at the Utsira High in block 25/6 and along the uplifted norhteastern area. Fig. 6.12. B and Fig. 6.13.B illustrates that this area has been pushed down by the depth conversion.

Fig. 6.14 shows a velocity profile, extracted from the Aker Geo average velocity cube over the study area. The lateral velocity varations are reflected in the general reflector geometries seen in the seismic data. The general increase towards east in the average velocity along a constant time surface can account for the pushdown effect on the north-eastern part of the study area.

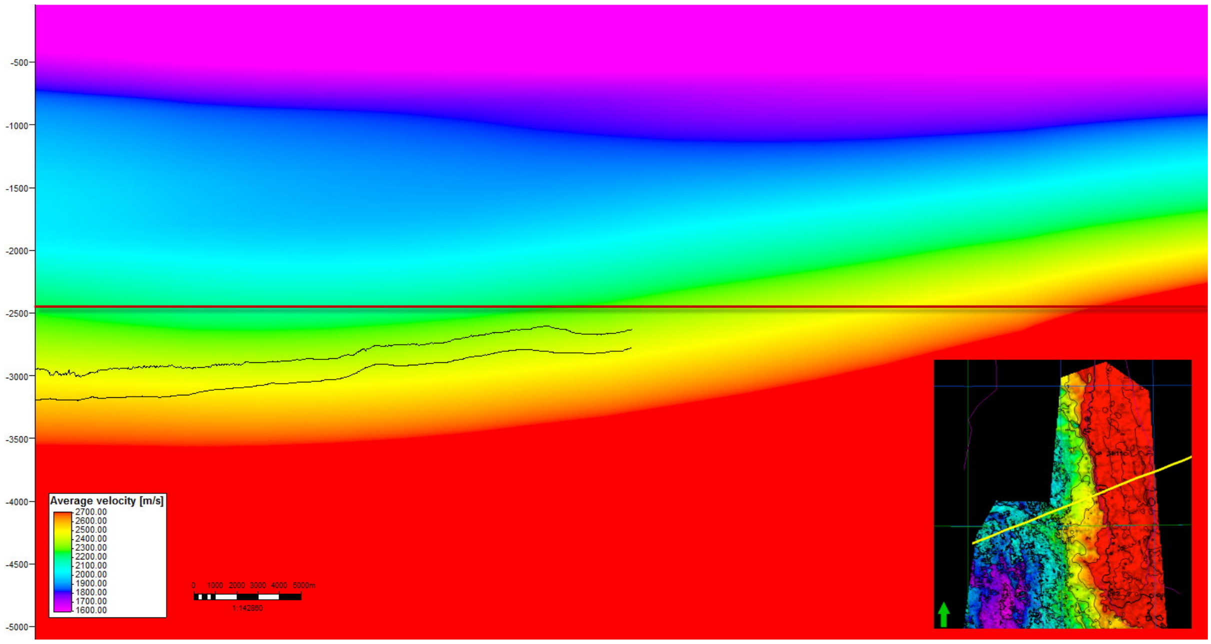


Fig. 6.14 Vertical velocity profile. *The vertical velocity profile across the Stord Basin illustrates the significant lateral variations in the average velocity field. Location of the velocity line is shown to the right. Note the lateral variations along the red vertical line. The black horizons are the Top Statfjord (upper) and the Top Hegre (lower). X-axis in TWT [ms].*

7 Discussion

Two seismic horizons were mapped in the Stord Basin from the Utsira High towards the centre of the basin. The first mapped horizon is interpreted to be the Top Hegre Group, which is the equivalent to the base of the Statfjord Group. The second mapped horizon is interpreted to represent the Top Statfjord Group.

Several public 2D lines and some 3D cubes are available in the study area. There are few available wells in the Stord Basin and only one well is drilled through the Early Jurassic succession including the Statfjord Group. Notably there are no boreholes drilled through the entire sedimentary succession in the Stord Basin, introducing uncertainty to the deep stratigraphic succession. The lack of well control in the basin makes the reconstruction somewhat speculative. A well tie for well 26/4-1 is used to confirm younger formations and as a guidance in placement of the Top- and Base Statfjord Group.

The Top Hegre Group (equivalent to Base Statfjord) and Top Statfjord Group reflectors are proven to be relatively difficult to map over larger distances of the basin. In order to map the Statfjord Group on seismic data, two points have been important:

- The interpretation is done by starting interpreting at the location of well 26/4-1. From this basis, the interpretation is extended towards the centre of the basin.
- The interpretation is confirmed by intersecting lines.

These two points have been used to map the horizons throughout the study area. The seismic data has been blurry in some lines. In these areas it has been necessary to use structural interpretation and qualified guessing together with the geological setting and tectonic history of the basin to map the horizons.

Tectonic events have led to faulting which makes the interpreted horizons locally discontinuous. This makes lateral changes of the horizon and manual tracking needs to be done to avoid pitfalls in the results. A discontinuous horizon affected by numerous faulting makes the interpretation less time efficient compared to a continuous and laterally consistent horizon that can be interpreted using auto tracking with a higher speed.

Results of the seismic interpretation of this thesis indicate that the Stord Basin is affected by extensional tectonic events. Several normal faults are seen in the seismic lines throughout the basin. These normal faults indicate extension of the basin. Extensional events beginning in Triassic age is what has formed the Stord Basin. The rifting is characterised by N-S faults forming easterly and westerly tilted half-grabens. Result of the rifting is a N-S trending basin, the Stord Basin. The fact that normal faults are interpreted in the seismic lines correlates to the previous studies and literature which states that the forming of the Stord Basin started in Triassic age. The tectonic evolution of the Stord Basin appears to be dominated by the tectonic activity in Triassic.

A geoseismic section across the Stord basin is presented in Fig. 7.1.

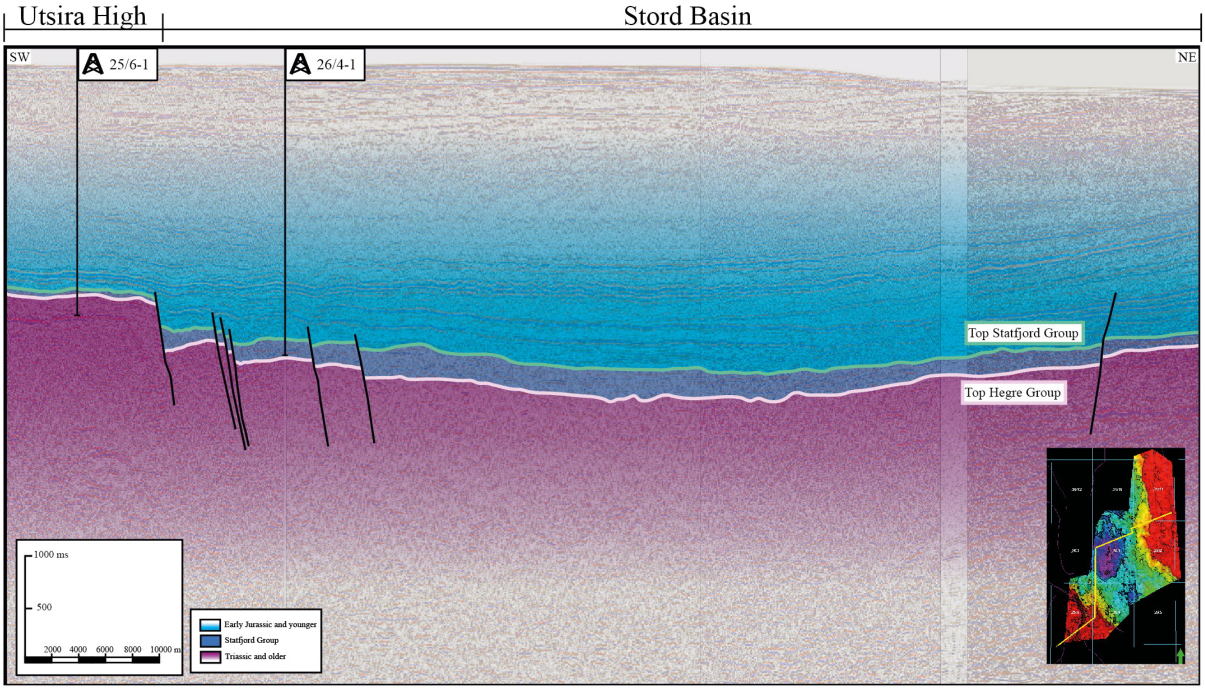
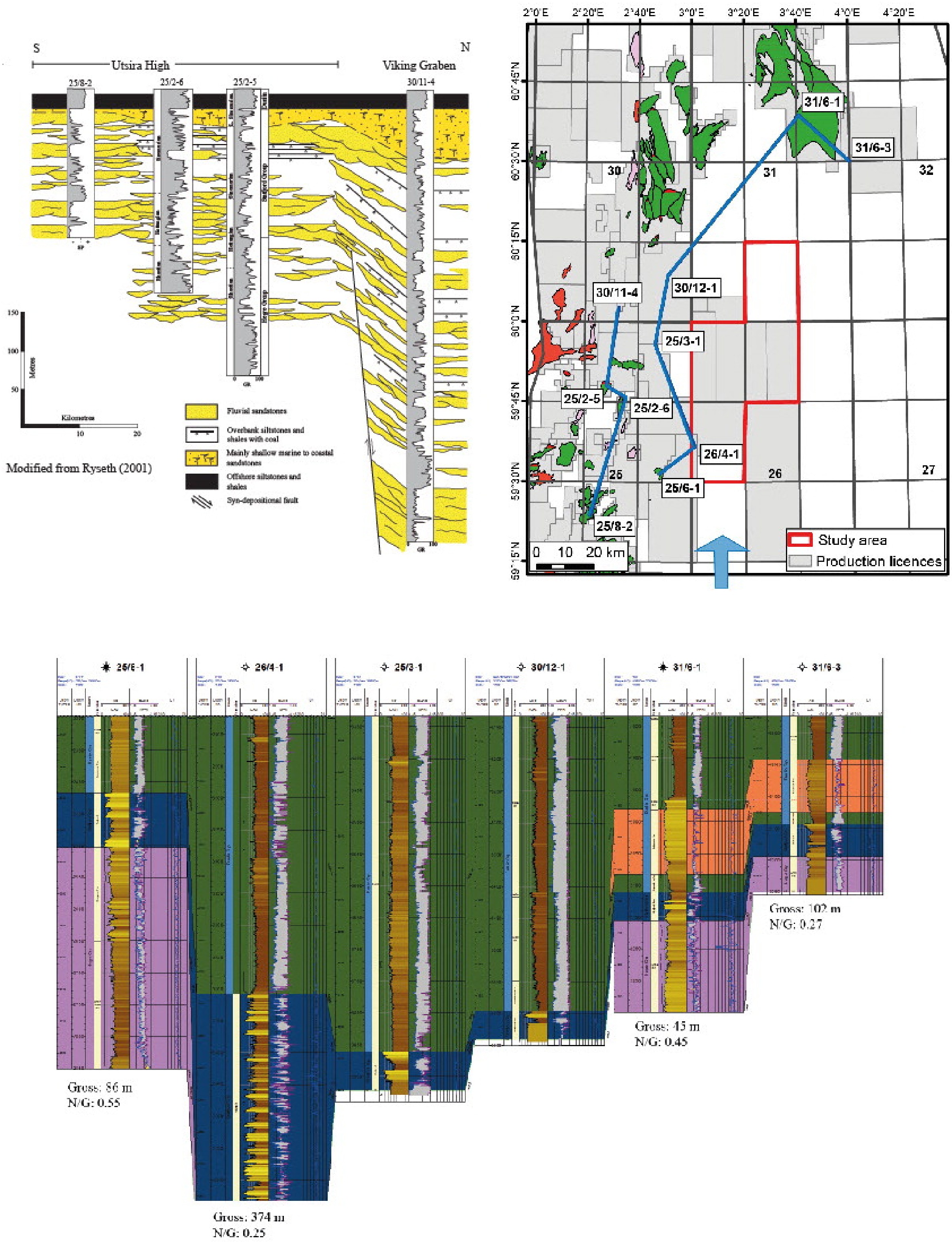


Fig. 7.1 Geoseismic section across the Stord Basin, illustrating the accommodation space and thickness variations of the Statfjord Group. *Right corner: The Top Statfjord TWT map shows the location of the line.*

Fig. 7.1 illustrates available accommodation space in the Stord Basin. The Utsira High is a horst located to the left in the figure. This horst is located significant shallower than the flanks and centre of the Stord Basin. Faults are causing differential depths of the interpreted horizons and differential subsidence is illustrated. This differential subsidence results in differential accommodation space. Changes of the accommodation space likely affected the later infill of the Statfjord Group in the basin. Seismic interpretation of the thesis suggests that the Statfjord

Group succession is thickening into the Stord Basin, as indicated by the geoseismic secion in Fig. 7.1. The geoseismic section also indicates a minor thinning towards the northeast.

The Statfjord Group in the Stord Basin is interpreted to comprise mostly terrestrial sediments capped by a thinner marginal marine Nansen Formation at the top. This is supported by well correlations from the Utsira High to well 30/11-4, representing a continental succession. Braided river systems may be more prevalent in areas of less accommodation space such as to the NE of the study area, which is in close proximity to sediment source area. Accommodation space is indicated by isochor maps of the Early Jurassic succession, and interpreation of the stacking pattern of the wells included in this study indicate typical depositonal facies that can be used to predict generalized depositional facies in the Stord Basin. Fig. 7.2 shows that increasing accommodation space give rise to more meandering channel systems and generally lower net-to-gross, and observation supported also in this study.



Modified from Ryseth (2001)

Fig. 7.2 Well correlation panel

Although periods of reduced subsidence in the Stord Basin potentially could result in deposition of more braided systems, a lower net-to-gross is predicted in this area due to significant accommodation space overall. This is also supported by well 30/11-4, comprising a thick succession of floodplain fines interfingered with channel deposits.

Well 30/11-4 (Fig. 7.3) comprises a very thick succession of floodplain sediments, indicating that sediment rate keeps pace with the subsidence rate due to the lack of marine sediments in the succession. The well has also very little coals, further supporting this interpretation. High sediment rates will dilute organic matter, preventing the formation of coals (Felix 2014).

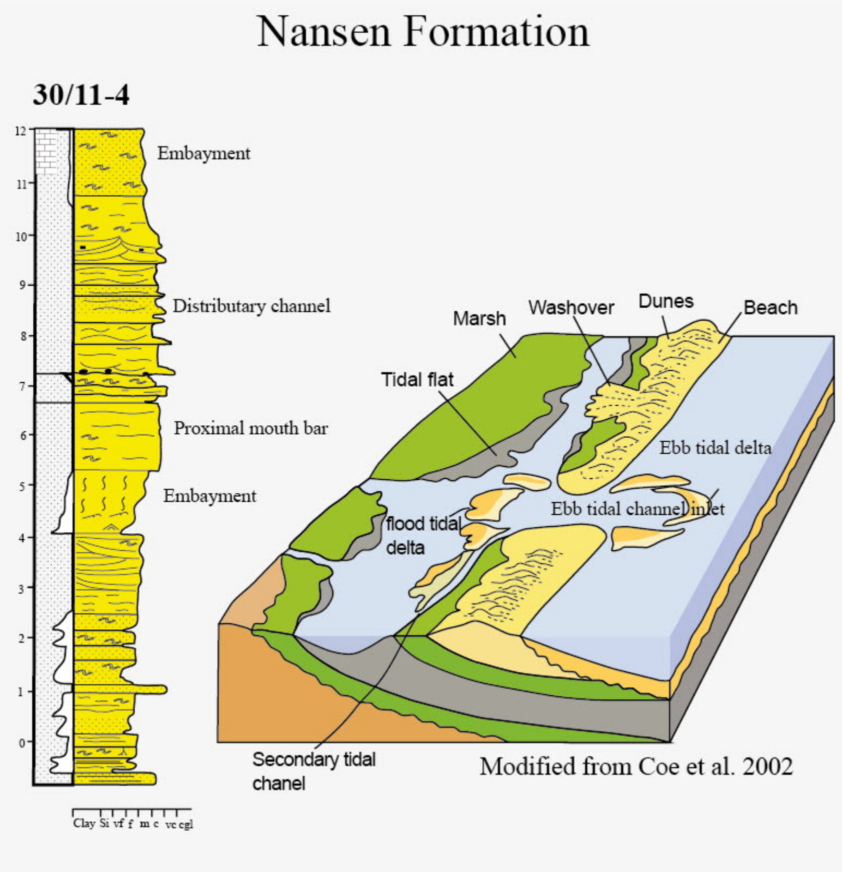


Fig. 7.3 Nansen formation core description and schematic depositional environment. *The core description is modified from Ryseth (2001).*

Facies correlations on the Utsira High also indicate high net-to-gross ratios at low subsidence rates. Stacked channels from Ryseth (2001) 5 Stratigraphy of The Statfjord Group illustrate lateral migration of isolated sandstone bodies and multistorey channel complexes. A facies correlation for the Eiriksson Formation at the Utsira High are shown in Fig. 7.4 .To tie one blocky stacked channels facies to another is hard just from logs.

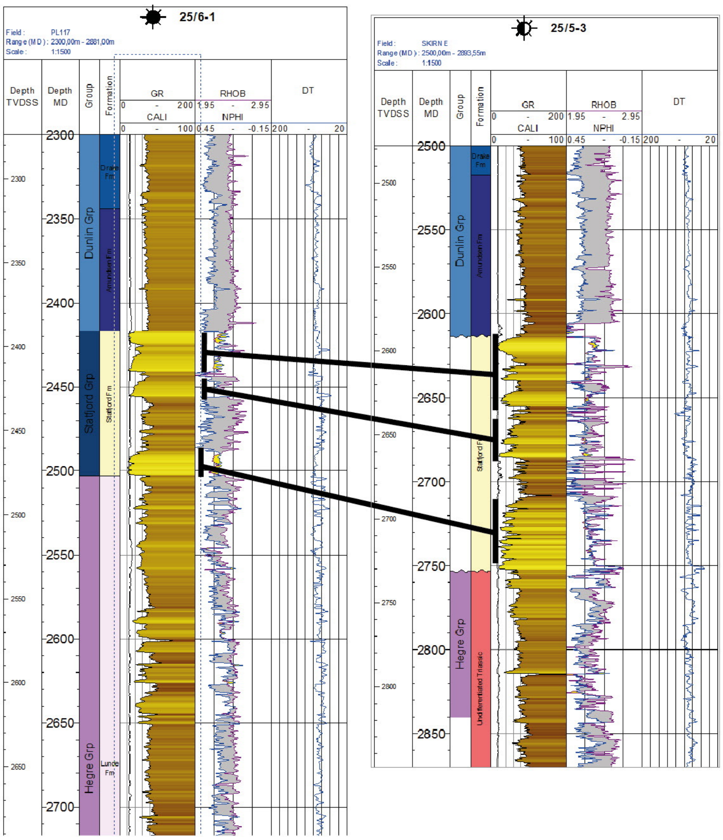


Fig. 7.4 Facies comparison on the Utsira High. *Well 25/5-3 has a N/G of 0.5. Well 25/6-1 to the right has a N/G of 0.55. The values are approximate.*

Shallow boreholes to the southeast in the Stord Basin prove presence of Jurassic sediments in the basin. Only one well (26/4-1) penetrates the Statfjord Group. Well 26/4-1 is located on the western flank of the basin. A well correlation panel in the study area is shown in Fig. 7.2. The correlation panel indicates a dominantly continental succession with large lateral variations in stacking patterns. The large lateral variations make it challenging to correlate sequences within the Statfjord Group. The stacking patterns of fluvial channels were likely affected by changes in accommodation space. In the Stord Basin, the western areas had higher subsidence rates and these areas are interpreted to comprise of lacustrine and overbank successions with isolated fluvial channel deposits, see [Fig. 7.5] and Fig. 7.6. Marine flooding occured from the south according to Ryseth (2001).

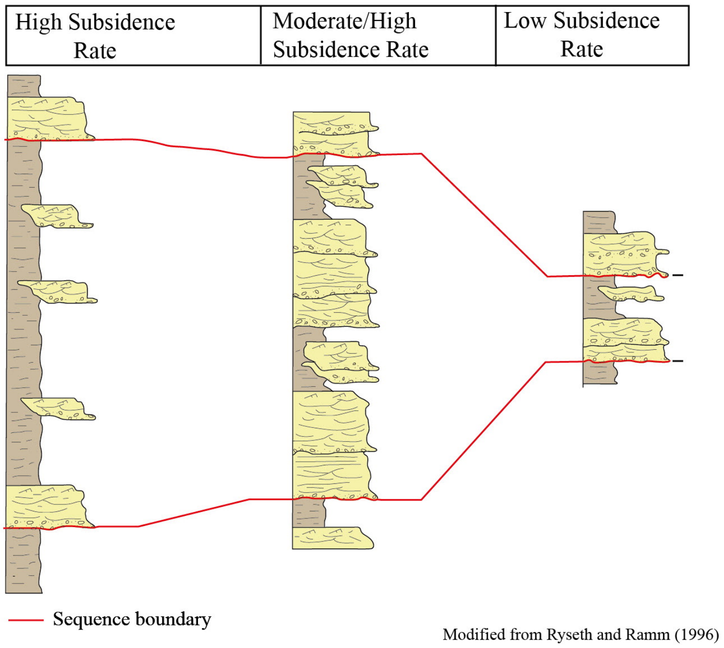


Fig. 7.5 Eirikson Formation stacking patterns related to available accommodation space

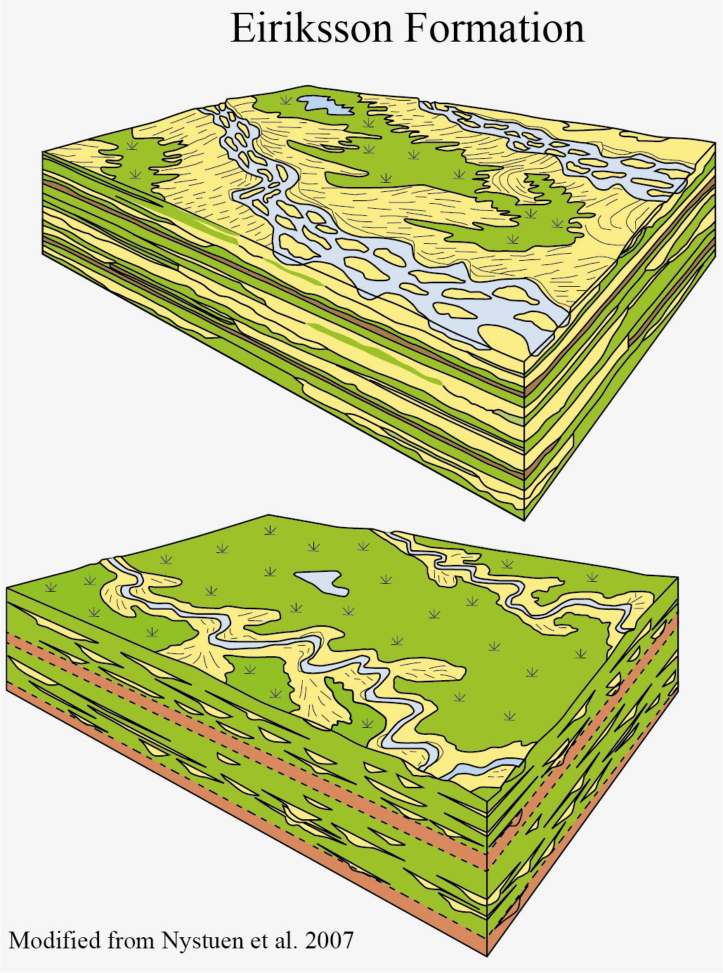


Fig. 7.6 Eirikson Formation schematics depositional environment.

Utsira High was an intrabasinal high during deposition of the Statfjord Group relative to the Stord Basin. However, the group varies in thickness between 80 - 200 m in thickness over the Utsira High. The Early Jurassic succession on the Utsira High exhibits large lateral variations in depositional facies, indicating that fluvial channels were not a part of a large braided system. This is in slight contrast to the description above discussing accommodation space versus fluvial stacking patterns. The Utsira High is located in the middle of the basin, and is therefore further away from the sediment source area to the east and northeast. Moreover, fluvial channels tend to migrate in areas of higher subsidence and avoid topographic highs (Gawthorpe and Leeder, 2000). As published by Ryseth & Ramm (1996), fluvial channels comprise only 40% of the succession on Utsira High, and core photos indicate more coastal facies.

Seismic interpretations indicate that the direction of sediment infill could be from both northeast and soutwest, but the indication of Utsira High to be a paleogeographic high during deposition of Early Jurassic sediments do not correspond to sedimentation from southwest. Sediments from this direction would not be able to climb over the Utsira High and further into the Stord Basin. Areas with pinch out of the Statfjord Group in the isochore map in chapter 6.7 imply to be at southwest. This supports a sediment depositional direction from northeast. The well correlation panel with pinch out of the Johansen formation in Fig. 7.2 support this direction. Seismic clinoforms progrades from north to south as illustrated in chapter 4.

The sedimentary facies in the Middle Jurassic are dominated by fluvial and sand-prone deposits, where there are observed severe thickness variations with growth fault activity. Organic rich (TOC=2-6%) shale prone facies dominate the sedimentary facies of the Late Jurassic sequence. However, the sequence changes from shale-prone to more silt- and sand-prone in eastward direction. A sediment source area east of the Stord Basin was subjected to a tectonic uplift as indicated in Fig. 4.2. Several prograding wedges are observed on the Horda Platform as a response to this uplift. These prograding units are correlated to the Fensfjord, Krossfjord and Sognefjord Formations and are interpreted to represent shallow marine delta systems becoming more distal in westward direction (Vollset & Dore 1984). There are no wells on the flanks of the Utsira High penetrating these sediments. However, subcropping bedrocks described in a Sintef report (1989) proves a shallow marine depositional environment (Fig. 7.7). Except for some thin intervals with thin coal layers or coaly debris, the shallow borehole 27/9-U-1 contains only poor concentrations of thermally immature organic matter. Subsidence in the Stord Basin continued throughout the Jurassic and Cretaceous, resulting in deposition of conformable sediments, with flooding of the shallow marine Upper Jurassic sediments in Volgian/Tithonian and deposition of the Draupne Formation.

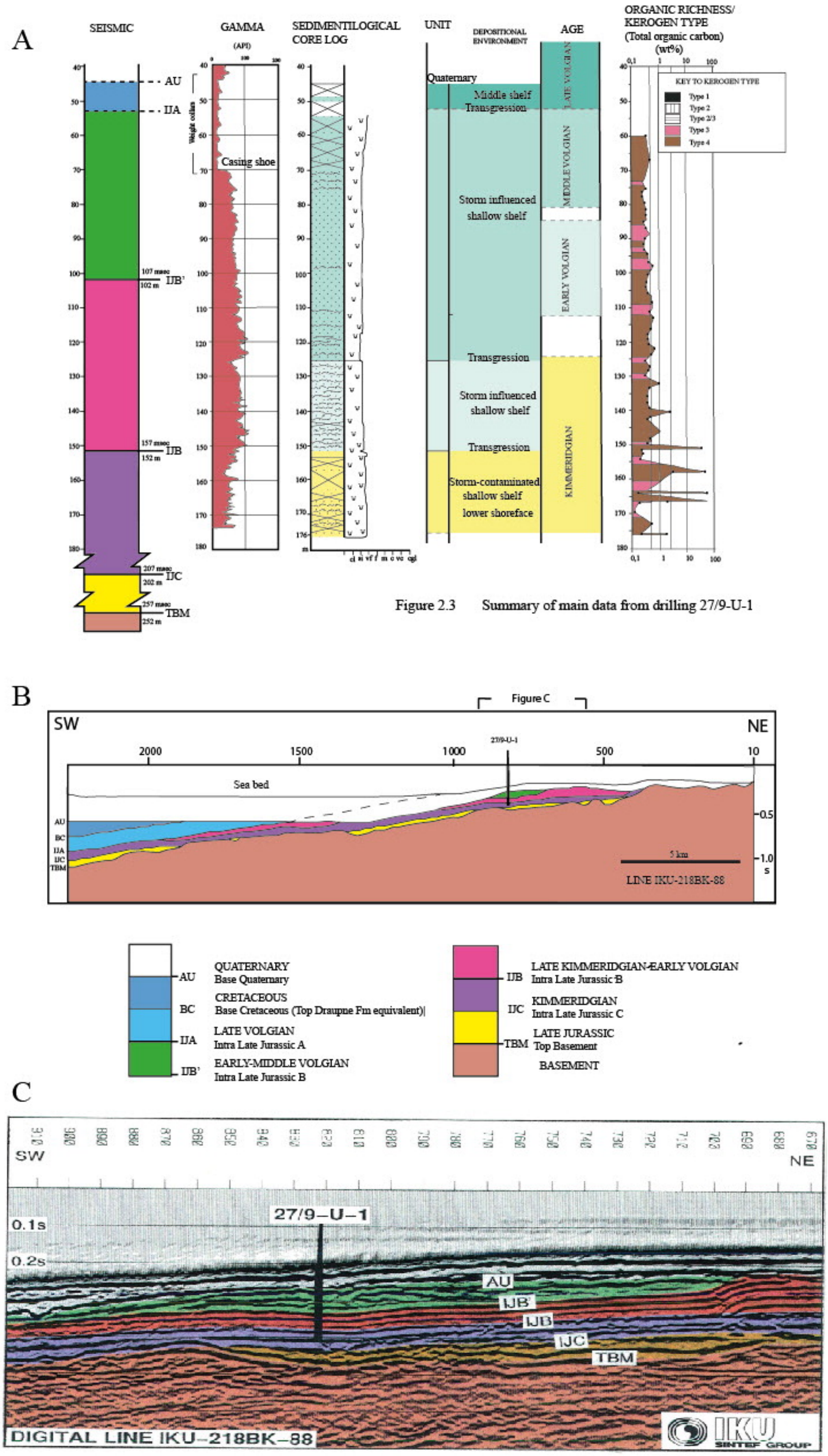


Fig. 7.7 Shallow boreholes in the Stord Basin. *The IKU shallow cores were drilled on the southeastern flank of the Stord Basin. They penetrated an overall transgressive succession from lower shoreface sand to shelfal clayey deposits ranging in age from Kimmeridgian to Late Volgian.*

The Early Jurassic succession in the Stord Basin was likely terrestrial as observed also in well 30/11-4, with a potential for coastal to slightly marginal marine deposits in the Nansen Formation. Water depth at the time of transgression of the Erikson Formation was likely very shallow, and in the order of 0-5 m water depth. Rapid drowning and transgression of the Stord Basin is assumed due to the lack of thick shoreline facies and a gradual facies transition being observed in the wells. This rapid transgression indicate increased subsidence in the Stord Basin. The Dunlin Group was deposited across the Stord Basin, with shale thicknesses up to 360 m in 26/4-1. Uplift of the hinterland is indicated by the progradation of clastic sequences from the east within the Dunlin Group, represented by the Johansen, Krossfjord and Fensjord formations. Seismic clinofroms (Fig. 4.5) are observed, supporting this interpretation.

No active faulting occurded during depositon of the Early Jurassic succession, and faulting mainly occurred in Late Jurassic times. This is indicated by the isochore map in chapter 6.6.

The paleogeographic reconstruction of the Statfjord Group in the Stord Basin is based on the above seismic correlation of the Lower Jurassic interval and accomodation space as indicated by isopach maps, but the lack of well control in the basin makes the reconstruction somewhat speculative. The resulting gross depositional maps are shown in Fig. 7.8 and Fig. 7.9.

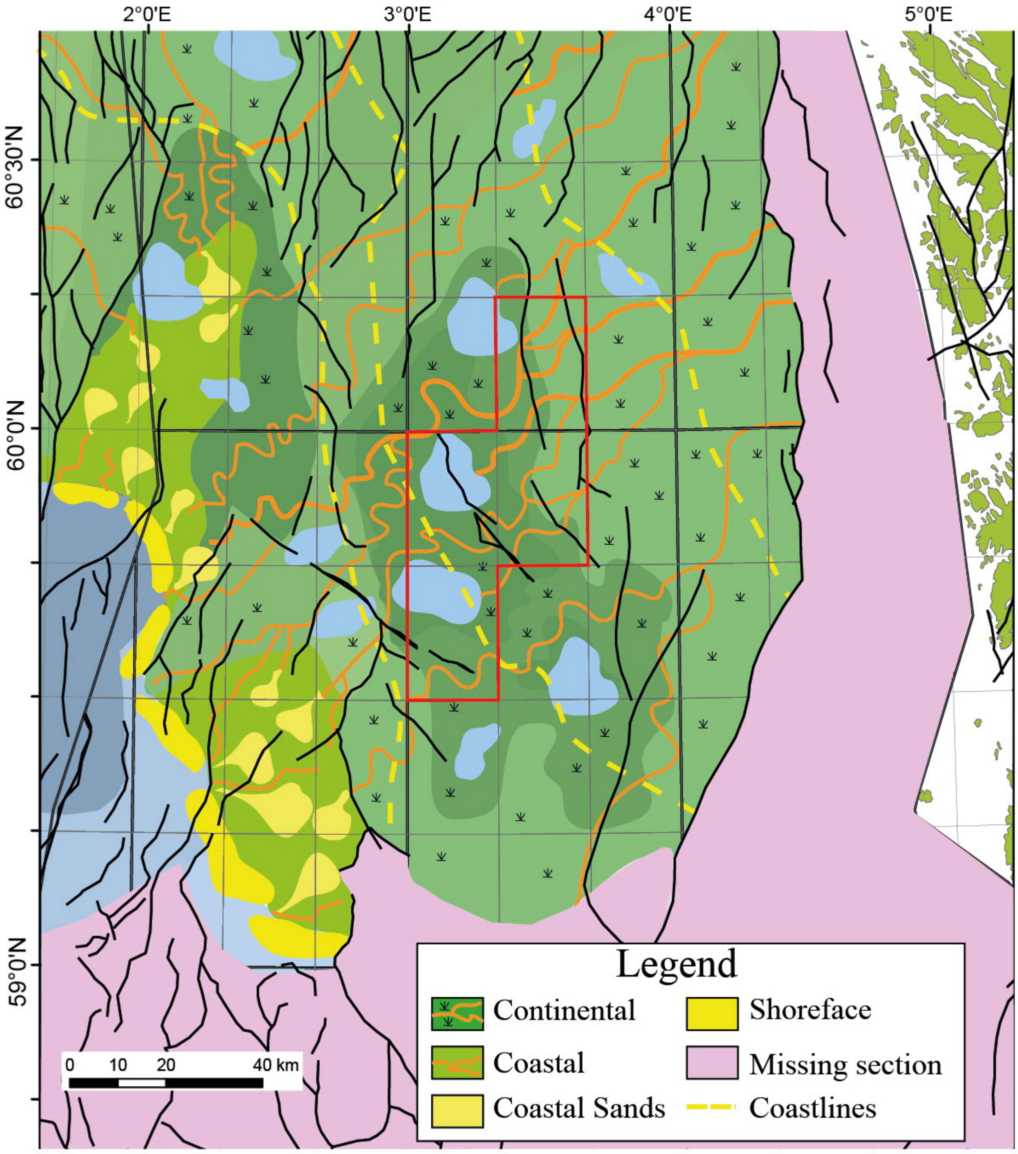


Fig. 7.8 Statfjord Group paleogeographic map.

The direction of flooding from from the south is also reflected in the paleogeographic reconstruction of the Stord Basin and surrounding area. The gradual flooding from the southwest is indicated, with a shoreline stepping towards the northeast through time. The Nansen Formation on the Utsira High is of Early Sinemurian age. In wells further north and northeast time equivalent continental deposits are identified. This identification supports the interpretation of marine incursion from southwest.

As a result of marine transgression into an increasingly subsiding basin, the Statfjord Group sediments are directly overlain by the shallow marine siltstones and shales of The Dunlin Group. The Dunlin group is subdivided into five formations (Vollset & Dore 1984). The basal formation is named Amundsen and is further capped by the Johansen-, Burton-, Cook- and Drake Formation at top, see the lihtostratigraphic column of Fig. 4.2. The Dunlin Group comprise mainly of inner-to-outer-shelf marine sediments, depositet in a ramp setting. The Johansen Formation is a marginal unit, time-equivalent to the Amundsen Formation, prograding from the east to the west in the Stord Basin (Fig. 7.9).

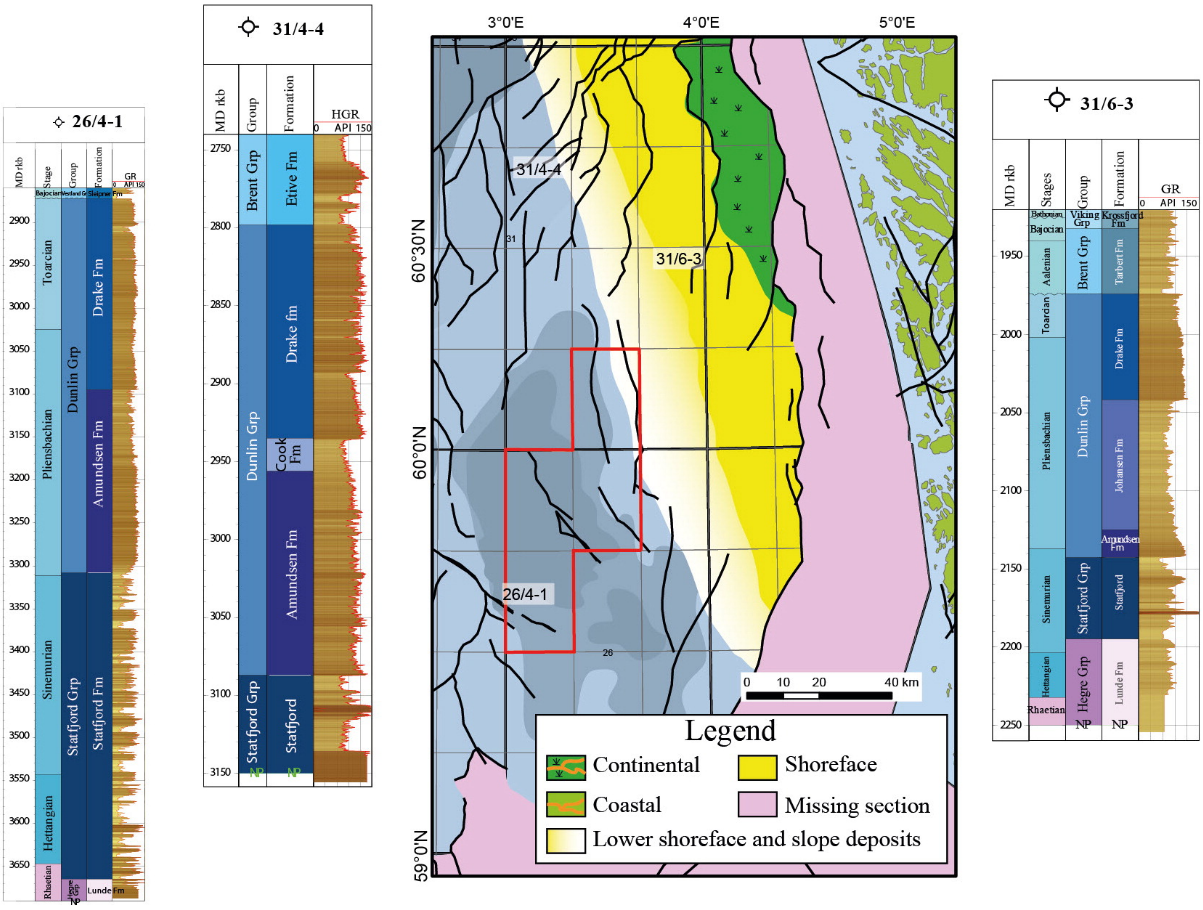


Fig. 7.9 Johansen Formation paleogeograohy. *Distribution of the upper Sinemurian Johansen Formation in the Stord Basin. The wells indicate that the formation pinches out to the west.*

8 Conclusion

In this study the tectonostratigraphic framework of the Early Jurassic succession of the Stord Basin has been examined and interpreted in attempt to understand the available accommodation space of the Statfjord Group. This is mainly done by mapping 2D and 3D seismic data in the area. A sub-regional seismic mapping of two seismic markers in the Lower Jurassic succession from the Stord Basin onto the Utsira High has been accomplished. Seismic reflectors are tied to the Top Statfjord Group and the Top Hegre Group.

Available well data in is used to establish a framework of the Stord Basin and to understand the regional evaluation of the area. Seismic facies analysis and isochor maps are built to understand the available accommodation space and possible missing sections of the Statfjord Group in the area.

Core photos of key wells surrounding the Stord Basin are further used in interpretation of the sedimentary facies and depositional systems of the Statfjord Group. Wireline log correlations are built to study the available accommodation space and the resulting net-to-gross within the Statfjord Group.

The understanding of the depositional systems of the Statfjord Group in the Stord Basin onto the Utsira High has resulted in deliverables of GDE (Gross Depositional Environment) maps for selected intervals in Early Jurassic/Early Sinemurian and Late Sinemurian. The GDE maps illustrate the paleogeographic reconstruction of the Stord Basin and Utsira High at time of deposition of the Statfjord Group.

A geoseismic section and an isochore map of the Early Jurassic succession indicate that the Utsira High was a topographic high during deposition.

The seismic interpretation also resulted in composition of an isochore map of the Statfjord Group intervall from the Stord Basin onto the Utsira High. Analysis of the map point toward a Statfjord Group pinch out to the southwest, at the Utsira High area. The sediment source area is located to the northwest of the study area.

Marine flooding occurred from the south which is reflected in the paleogeographic reconstruction of the Stord Basin and surrounding area. A gradual flooding from the southwest is indicated, with a shoreline stepping towards the northeast through time.

No active faulting occurred during deposition of the Early Jurassic succession. Faulting of the study area mainly occurred in Late Jurassic times. This is indicated by isochor maps.

Further appraisal of depositional systems and accommodation space in the Stord Basin relative to the Utsira High was used in reconstructions of paleogeographic maps. Analysis of the thickness distributions and facies variations of the study area indicate that the Utsira High likely was a paleo-topographic high relative to the Stord Basin during deposition in Early Jurassic.

9 References

References

Ryseth, A., & Ramm, M. (1996). Alluvial architecture and differential subsidence in the Statfjord Formation, North Sea: prediction of reservoir potential. In *Petroleum Geoscience 2*.

Ramm, M., & Ryseth, A. E. (1996). Reservoir quality and burial diagenesis in the Statfjord Formation, North Sea. In *Petroleum Geoscience Volume 2*.

Ryseth, A. (2001). Sedimentology and palaeogeography of the Statfjord Formation (Rhaetian-Sinemurian), North Sea. In O. J. Martinsen, & T. Dreyer, *NPF Special Publications 10*.

Færseth, R. B., Gabrielsen, R. H., & Hurich, C. A. (1995). Influence of basement in structuring of the North Sea Basin, offshore southwest Norway. Norsk Geologisk Tidsskrift 75.

Badley, M.E., Price, J.D., Rambech Dahl, C. & Agdestein, T. (1988). The structurla evolution of the northern Vikin Graben and its bearing upon extentional modes of basin formation. *Journal of the Geological Society 145.*

Fraser, S., Robinson, A., Johnson, H., Underhill, J., Kadolsky, D., Connel, R., et al. (2002). Upper Jurasic. In D.Evans, C. Graham, A. Armour, & P. Bathurst, The Millienium Atlas, Petroleum Geology of the central and northern north sea. The geological society of london.

Gabrielsen, R. H., Færseth, R. B., Steel, R. J., Idil, S., & Kløvjan, O. S. (1990). Architectural styles of basin fill in the northern Viking Graben. In D. J. Blundell, & A. D. Gibbs, *Tectonic Evolution of the North Sea Rifts*. International Lithosphere Programme 181.

Ziegler, P. A. (1990). Tectonic and paleogeographic development of the North Sea rift system. In D. J. Blundell, & A. D. Gibbs, *Tectonic Evolution of the North Sea Rifts*. International Lithosphere Programme 181.

Underhill, J. R., & Partington, M. A. (1993). Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence. In J. R. Parker, *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. London: The Geological Society .

Gradstein, F., Ogg, J., & Smith, A. (2004). *A Geological Time Scale.* Cambridge University Press.

Færseth, R. B. (1996). Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea. *Journal of the Geological Society.*

Steel, R. & Ryseth, A. (1990) The Triassic - Early Jurassic succession in the Northern North Sea: megasequence stratigraphy and intra-Triassic tectonics. In: Hardman, R.F.P. and Brooks, J. (eds). Tectonic Events Responsible for Britain's Oil and gas reserves. Geological Society , London, Special Publication 55

Stewart, D. J., Schwander, M., & Bolle, L. (1995). Jurassic depositional systems of the Horda Platform, Norwegian North Sea: practical consequences of applying sequence stratigraphic models. In R. J. Steel, V. L. Felt, E. P. Johannessen, & C. Mathieu, *Sequence Stratigraphy on the Northwest European Margin*. Norwegian Petroleum Society Special Publication 5.

Sneider, J. S., de Clarens, P., & Vail, P. R. (1995). Sequence stratigraphy of the Middle to Upper Jurassic, Viking Graben, North Sea. In R. J. Steel, V. L. Felt, E. P. Johannessen, & C. Mathieu, *Sequence Stratigraphy on the Northwest European Margin*.
Norwegian Petroleum Society Special Publication 5.

Lippard, S. (1996) Structural Setting and Prospectivity of the Stord Basin, Norwegian North Sea. EAGE 58th Conference and Technical Exhibition.

Biddle, K.T., & Rudolph, K. W. (1988). Early Tertiary structural inversion in the Stord Basin, Norwegian North Sea. *Journal of the Geological Society 145,*

Vollset, J., & Doré, A. G. (1984). *A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea.* Oljedirektoratet.

Rattey, R.P. & Hayward, A. B. (1993) Sequence stratigraphy of a failed rift system; the Middle Jurassic to Early Cretaceous basin evolution of the central and northern North Sea. In: Parker, J.R. (ed.). Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 215-249; doi: 10.1144/0040215.

Coward, M. P., Dewey, J., Hempton, M., & Holroyd, J. (2003) Tectonic Evolution. In D.Evans, C. Graham, A. Armour, & P. Bathurst, *The Millennium Atlas, Petroleum Geology of the Central and Northern North Sea* (pp. 27-65). London: Geological Society

Kjennerud, T., Ottesen, D., Hamborg, M., Lorentsen, B., Knudseth, J. O., Antobreh, A. A., et al. (2011). *Cenozoic Geology of the North Sea and Norwegian Sea.* Internal report exclusively for Det norske oljeselskap ASA.

Deegan, C.E. & Scull, B.J. (1977) A standard lithostratigraphic nomenclature for the Central and Northern North Sea. Inst. Geological Sci. Bullitin., 77/25, Norwegian Petroleum Directorate 1.

Lervik, K.S. (2006) Triassic lithostratigraphy of the Northern North Sea Basin. Norwegian Journal of Geology, vol. 86.

Hermanrud, C., Eggen, S. & Larsen, R.M. 1991: Investigation of the thermal regime of the Horda platform by basin modelling: implications for the hydrocarbon potential of the Stord basin, northern North Sea. Special Publication of the European Association of Petroleum Geoscientists No.1

Husmo, T., Hamar, G., Høiland, O., Johannessen, E. P., Spencer, A., & Titterton, R. (2002). Lower and Middle Jurassic. In D. Evans, C. Graham, A. Armour, & P. Bathurst, *The Millennium Atlas, Petroleum Geology of the Central and northern North Sea*.
London: Geological Society.

Sneider, J. S., de Clarens, P., & Vail, P. R. (1995). Sequence stratigraphy of the Middle to Upper Jurassic, Viking Graben, North Sea. In R. J. Steel, V. L. Felt, E. P. Johannessen, & C.

Mathieu, *Sequence Stratigraphy on the Northwest European Margin*. Norwegian Petroleum Society Special Publication 5.

Røe, S.-L., & Steel, R. (1985). Sedimentation, sea-level rise and tectonics at the Triassic-Jurassic boundary (Statfjord Formation), Tampen Spur, Northern North Sea. *Journal of Petroleum Geology, 8,2*.

Rokoengen, K., Bakke, S., Elvebakk, G., Rise, L., Weiss, H. M., Århus, N., (1989), Shallow Drilling Strord Basin, Main Report. Sintef.

Goldsmith, P. J, Hudson, G. & van Veen, P. 2003. Triassic. *In*: Evans, D. Graham, C., Armour, A. & P. Bathurst, P. (editors and coordinators), *The Millennium Atlas: Petroleum geology of the central and northern North Sea*. The geological society of London.

Nystuen, J.P., Müller, R., Mørk, A., Nøttvedt, A., (2007) Fra ørken til elveslette - fra land til hav. In: Landet blir til, Norsk Geologisk Forening.

Peters, K.E., Walters, C.C., Moldowan, J.M. (2005) The Biomarker Guide. The University Press, Cambridge.

Kirk, R.H. (1989) Statfjord Field - A North Sea Giant. In: Halbouty, M.T. (ed) Giant oil and gas fields of the decade 1968-1978. AAPG Memoir 30.

Chauvin, A.L. & Valachi, L.Z. (1980) Sedimentology of the Brent and Statfjord Formations of Statfjord Field. In: Anonymous (ed.) The Sedimentation of the North Sea Reservoir Rocks, Conference, Geilo, May 11-14, 1980. Proceedings, Norwegian Petroleum Society, 1-17.

Gawthorpe, R. L., & Leedert, M. R., (2000) Tectono-sedimentary evolution of active extensional basins. Basin Research 12.

Peters, K. E., (1986) Guidelines for Evaluating Petroleum Source Rock Using Programmed Pyrolysis. The American Association of Petroleum Geologists Bulletin Volume 70.

Isaksen, I.L. & Ledje, K.H.I. (2001) Source rock quality and hydrocarbon migration pathways within the greater Utsira High area, Viking Graben, Norwegian North Sea. AAPG Bulletin 85 (5).

Felix, M., (2013) A comparison of equations commonly used to calculate organic carbon content and marine palaeoproductivity from sediment data. Marine Geology 347, Sintef.

Fossen, H. & Hesthammer, J. (1998) Structural geology of the Gullfaks Field, northern North Sea. In: Coward, M. P., Daltaban, T. S., & Johnson, H. Structural Geology in Reservoir Characterization. Geological society, London, Special Publications, 127.

Reineck, H.E., (1970) Das Watt: Ablagerungs- und Lebensraum. Senckenberg-Buch; 50, Frankfurt am Main

Galloway, W. E., & Hobday, D. K., (1996) Terrigenous clastic depositional systems, Springer, New York.

Coe, A. L., Bosence, D. W. J., Church, K. D., Flint, S. S., Howell, J. A., Wilson, R. C. L., (2002) The Sedimentary Record of Sea-Level Change, Cambridge.

Fact pages

www.NPD.no, Fact Pages, May, 2014.

Unpublished papers

Østebø, Carina Høie (2013), "Seismic mapping of the Early Jurassic succession in the Stord Basin", NTNU, project thesis.

Software

Petrel 2013.2

Adobe Illustrator CS5

Oilfield Data manager 3.8

Appendix

AJ.A Source rock characterisation of the Statfjord Group

The Stord Basin is known to be marginal with respect to maturity of mid/late-Jurassic source rocks. The Draupne Formation especially is buried too shallow to have generated and expelled significant amounts of petroleum; hence, alternative source rocks can be discussed in this basin. The Statfjord Group has mainly deposited under a continentally dominated depositional system, and source rock quality has so far been assessed as sub-ordinate. However, Det norske did a study to evaluate the potential of lacustrine and terrigenous source rocks in the Stord Basin.

A source rock can be described as following:
"Petroleum source rocks are fine-grained organic-rich rocks that could generate (potential source rock) or have already generated (effective or active source rock) significant amounts of petroleum." Peters et al. (2005)

The aim of this chapter is to give an overview of the geochemical screening method and results of the source rock analysis of the Statfjord Group. A formations ability to generate hydrocarbons depends on the amount of organic carbon and hydrogen. For an petroleum source rock to be effective, it must satisfy requirements as to the quantity, quality and thermal maturity of the organic matter (Peters et al. 2005).

The first complete penetration of the Statfjord Group was performed by Conoco in UK well 211/24-1 in 1972-1973 (Deegan & Scull 1977). In retrospect several wells have comprised discoveries and the Statfjord Group is one of the main reservoir intervals in several Norwegian hydrocarbon fields (Ryseth & Ramm 1996).

Sediments from the Statfjord Group have experienced sufficient thermal stress and are within the hydrocarbon generation window. The transformation ratio depends on the geothermal stress, the organic matter type, and the position within the basin i.e. the sediment burial depth. The only drilled well (26/4-1) with available sample data for the Statfjord Group in the Stord Basin so far has been classified as mature with regard to the Statfjord Group sediments. This well exhibits considerable variations for the source rock.

The Statfjord Group is a potential source rock in the Stord Basin. The majority of the Statfjord Group represents lower alluvial plain and braided stream deposits (Kirk 1979; Chauvin & Valanchi 1980) with a higher marine influence (coastal to shallow marine influence) towards the top of the group (Deegan & Scull 1977).

Rock-Eval parameters

Rock Eval pyrolysis is a geochemical method used to screen rocks for organic matter composition. The parameters from a Rock Eval pyrolysis provide indications for organic matter type, organic matter richness and maturity (Peters et al. 2005).

In Rock-Eval pyrolysis, pulverized samples are temperature-programmed heated under an inert atmosphere (Fig. 1). This heating evaporates the free organic compounds (bitumen), then cracks pyrolytic products from the insoluble OM (kerogen). (Peters 1986)

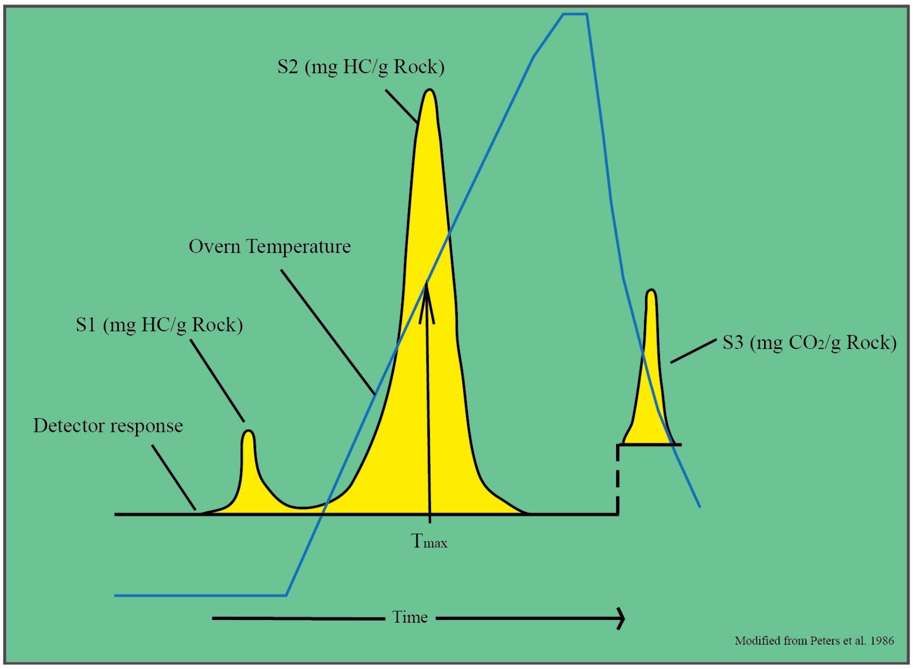


Fig. 1 Schematic pyrogram. *The pryogram shows the evolution of organic compounds from a rock sample during pyrolysis. The intersection between the S2 peak and temperature curve (in blue) is the Tmax, the temperature where the generation of hydrocarbon is maximised. Time is increasing from left to right.*

Direct measurements

Direct measurements from a Rock Eval pyrolysis include S1, S2, S3 and T_{max}. (Peters 1986).

S1: S1 is the first peak, representing the amount of free hydrocarbons already present in the sample. Rock Eval S1 provides the amount hydrocarbons thermally evaporated from the rock, measured in mg HC/g rock (Peters 1986).

S2: When the temperature is further increased the actual pyrolysis process starts. The second peak, S2, corresponds to the amount of hydrocarbon generated during this stage. This measurement represents the amount of hydrocarbons generated through thermal cracking of kerogen. S2 indicate the potential quantity of hydrocarbons that the rock may generate if the maturation continues. (Peters 1986)

S3: The third peak, S3, represent the amount of CO_2 in the sample in mg CO_2/g dry rock) (Peters 1986).

T_{max}: T_{max} represents the oven temperature at which the generation of hydrocarbons is the highest. Maximum generation of hydrocarbons occurs at the S2 peak, and T_{max} is measured at this peak, see Fig. 1. This temperature should not be confused with the geological temperature. The analysis yields a value we can use to estimate the maturity of the source rock. Higher temperatures correspond to higher maturities (Peters 1986).

Derived parameters

TOC (total organic carbon): The total organic carbon is a measure of the quantity of organic carbon in rock samples. However, it does not account for the quality with regard to hydrocarbon quantity and quality of the organic carbon in question (Peters et al. 2005).

HI (Hydrogen Index): The hydrogen index is a derived index, measuring the ratio of S2 hydrogen to TOC:

$HI=(S2\bullet 100/TOC)$ [mg hc/g TOC].

The Hydrogen index is defined as the quantity of hc from S2 relative to the total organic content. The index provides a measure of hydrogen richness in the source rock and it can infer the kerogen type. High values of HI indicate a greater potential to generate oil. An estimate of the thermal maturity can be provided when the kerogen type is already known (see Fig. 2.C) (Peters et all 1986).

Analysis of the Statfjord Group sediments in well 26/4-1

Description of Statfjord Group sediments indicates strong variations of lithological facies from pure sands to full shales, interbedded by various coals. The lithology of analysed samples is normally described as a mixed facies. Total organic carbon (TOC) content and Hydrogen Index (HI) values exhibit large variations (Fig. 2).

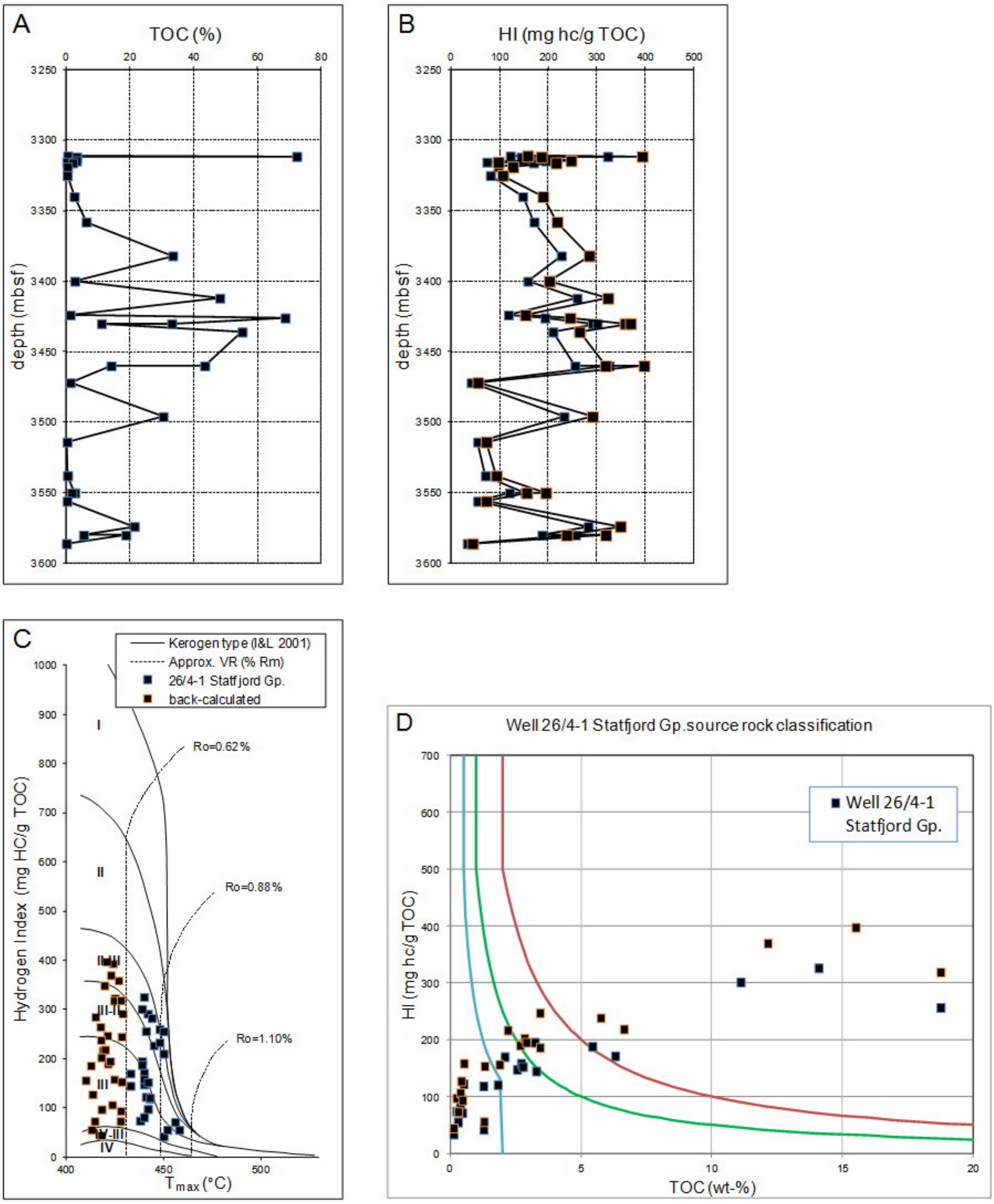


Fig. 2 Measurements from samples of the Statfjord Group comprising well 26/4-1:. *Each datapoint provides average weighted values from core samples of the interval. A. Total organic carbon (TOC in %wt.) versus depth (mbsf). B. Hydrogen Index (HI in mg hc/g TOC) versus depth (mbsf). C. Source rock maturation. HI versus Tmax for Statfjord Group sediments in the well comprising quality and thermal maturity. D. Source rock classification. HI versus TOC content indicating source quality and richness. Lines delineating areas of different source rock quality from poor to very good.*

Fig. 2.C comprises a HI versus T_{max} plot with roman numbers denoting kerogen type (I = lacustrine; II = marine; III = terrigenous; IV = inertinite). Approximate maturity trajectories are indicated as by Isaksen and Ledje (2001). Dashed lines provide the approximate maturity as indicated by vitrinite reflectance (%Ro). Blue data points represent the measured data from the Rock Eval pyrolysis performed by GeoLabNor, now CGG. The orange data points are back-calculated to initial values.

The variations are ranging from almost organic carbon barren samples to full coals. To generate significant amounts of hydrocarbons a sedimentary rock requires both richness in organic carbon and hydrogen. To classify the Statfjord Groups source rock potential the classification scheme of Peters et.al (2005) is followed, see Table 1-Table 3. Approximately half of the samples have good source rock potential. A significant number of samples have even very good source rock potential.

Table 1 Generative potential (quantity) of immature source rock (Peters et al. 2005).

Source rock potential (quantity)	TOC [wt. %]	Rock Eval S2 [mg hc/g rock]
Poor	<0.5	<2.5
Fair	0.5-1	2.5-5
Good	1-2	5-10
Very Good	2-4	10-20
Excellent	>4	>20

Table 2 Kerogen type and expelled products (quality) (Peters et al. 2005).

Kerogen (quality)	HI [mg hc/g TOC]	Main product at peak maturity
I	>600	Oil
II	300-600	Oil
II/III	200-300	Oil/Gas
III	50-200	Gas
IV	<50	None

Multiple factors need to be considered to determine the source rock potential. Geochemical results for well 26/4-1 were evaluated. This well is located on the flank of the Stord Basin and may be one of the best analogues for Statfjord Group sediments deposited in the Stord Basin. By using maturity data, hydrogen indexes and TOC contents were back-calculated to initial

Table 3 Thermal maturity (Peters and Cassa 1994).

Maturity	Tmax [°C]
Immature	<435
Mature	0.5-1
Early	435-445
Peak	445-450
Late	450-470
Postmature	>470

values, to a period before the organic matter has experienced substantial thermal stress. It is generally assumed that shales with TOC content above 2% have a source rock potential. The source rock quality/potential is increased at higher levels of TOC content.

Results

Approximately 52% of the samples generate less than 5 mg hydrocarbons/g sediment. Following the classification scheme by Peters et.al (2005) this classifies these samples as fair/poor source rock quality. Samples that generate more than 5 mg hc/g sediment have a good source rock potential and those exceeding 10 mg hc/g sediment have a very good source rock potential (-see table 1). This gives a result of 52% samples with fair/poor quality, 3% with good and 45% with very good source rock quality. In the latter rock class, the very good quality samples, 45% have a TOC content of more than 10% and are presumably either coals or coaly shales.

By considering both the TOC content and mg hc/g sediments, the geochemical analysis exhibit approximately 28% of the samples with a good or very good source rock potential not dominated by coaly facies.

Table 4 lists the result of the geochemical analysis. Well 26/4-1 is located on the western border of the Stord Basin, close to Utsira High. Therefore a higher maturity can be assumed in the deeper parts of the Basin.

Table 4 Results of the geochemical analysis of the Statfjord Group in well 26/4-1.

	Source rock quality class (%)				
	Poor	Fair	Good	Very Good (<10% TOC)	Very Good (>10% TOC)
Well 26/4-1	36	16	3	25	20