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Fault Activity Control on the Upper Jurassic-Lower Cretaceous Wedges in the Snorre Fault block and its Surrounding Area

By

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MASTER THESIS

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Abstract

In this study, the question" how fault activity controlled the infill and geometry of the Upper Jurassic-Lower Cretaceous wedges in the Snorre Fault Block and surrounding area" is addressed. To achieve the goal, three-dimensional seismic data, core description and well log data are used. The study improves the understanding of the tectonostratigraphy evolution of the wedges in the Snorre Area.

The result of the study shows that two wedges are present in the hanging wall of main faults in the study area. The main wedge is located in a large area along the hanging wall of Inner Snorre Fault. Well correlation shows that the Upper Jurassic-Lower Cretaceous stratigraphy of the wedges includes the Heather Formation, the Draupne Formation and the Cromer Knoll Group. Seismic facies analysis, time-thickness and time-structural maps reveals that development of the initially segmented major faults of the study area greatly influenced the internal character, the thickness and the geometry of the wedges along their strike and in perpendicular direction to the strike. In addition, fault activity led to rotation and tilting of hanging wall and footwall areas. The study shows that the Upper Jurassic-Lower Cretaceous succession of the wedges have possible potential for the hydrocarbon exploration purposes.

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Table of Contents

List of Figures

List of Tables

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Chapter 1

Introduction

Different geological variables play key roles in infill and geometry of rift systems. These variables are tectonic, subsidence, eustasy, climate, volcanisms, sediment type, and supply rate (Álvaro, 2013; Marin et al., 2018; Ravnås & Steel, 1998). Sedimentary packages in rift settings are conventionally named pre-rift, syn-rift, and post-rift (e.g. (Ravnås et al., 2000)). Pre- and post-rift packages types and styles are mainly controlled by variables other than tectonism and faulting (Ravnås et al., 2000; Ravnås & Steel, 1998). A major unconformity separates the syn-rift from the following post-rift phase, and is generally more evident on rift shoulders and flanks of uplifted fault blocks (Álvaro, 2013; Ravnås & Steel, 1998). Rifting is not a continuous event and three stages can be distinguished in any rift event: initiation of the rift, rift climax and rift cessation (Ravnås & Steel, 1998); these stages are recorded unequally throughout the whole basin (Ravnås & Steel, 1998). The type and style of sedimentation and architecture of associated basin in each stage is also unique and controlled by complex interaction of the variables mentioned above (Álvaro, 2013; Marin et al., 2018; Nøttvedt et al., 1995; Prosser, 1993; Ravnås & Steel, 1998).

The Late Middle-Jurassic to Early Cretaceous rift episode in the northern North Sea is characterized by multiple rift-phases separated by intra-rift tectonic quiescence (Ravnås et al., 2000). The Snorre fault block of the Tampen Spur area in the northern North Sea formed during the Late Middle Jurassic-Early Cretaceous rift episode. The Snorre fault block is host to the Snorre field, which is located between 61ºN and 62ºN (Figure 1-1). The field is producing from the Lunde Formation of the Late Triassic and the Statfjord Formation with an age ranging from the Late Triassic to the Early Jurassic (Dahl & Solli, 1993). Presence of hydrocarbon has been proved in the Late Jurassic Cook Formation of the Dunlin Group and in the Paleocene sands (Dahl & Solli, 1993). In addition, there is exploration potential in the Upper Jurassic Draupne Formation deposited within wedges in the hanging wall of major faults in the study area (Evans et al., 2003).

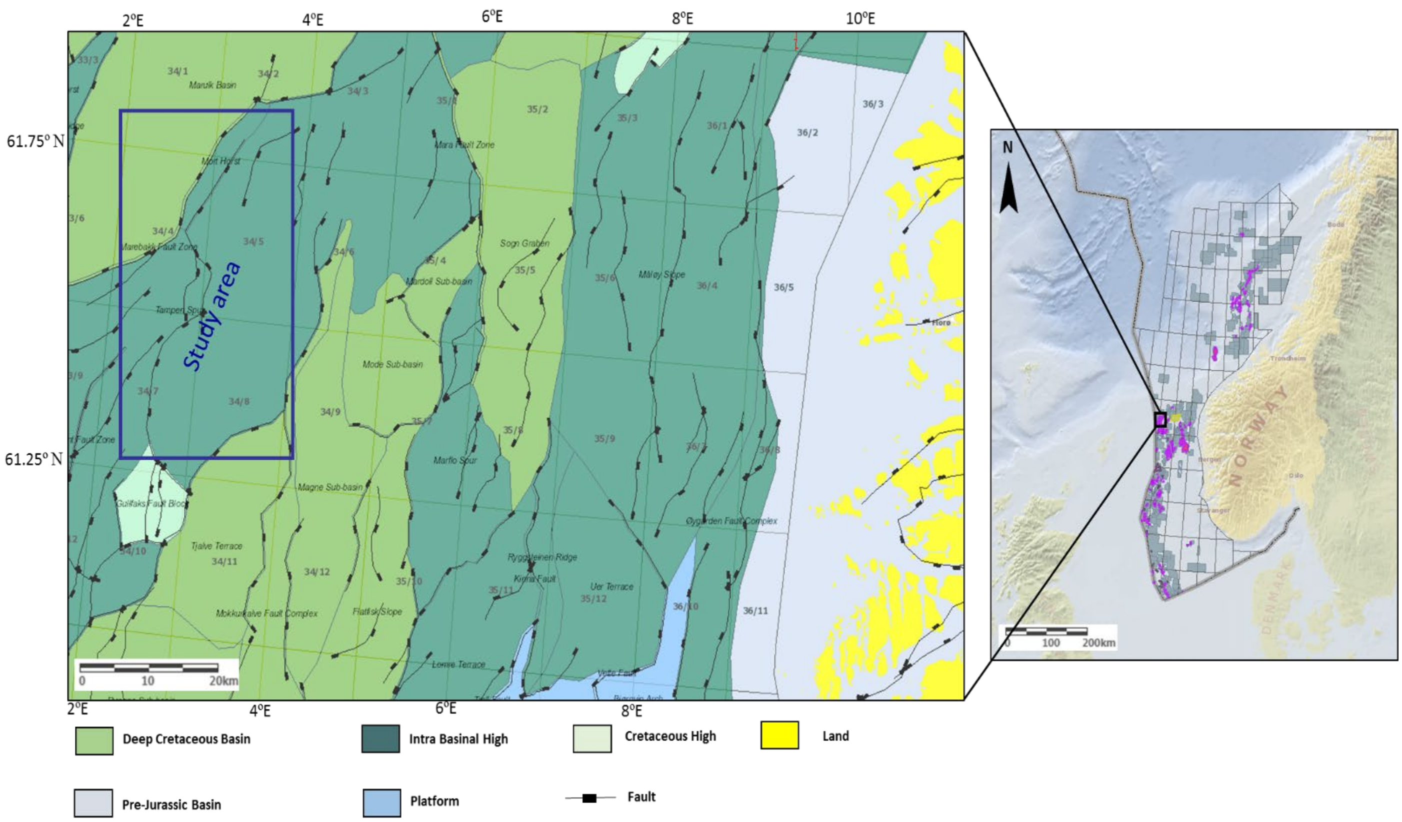


Figure 1-1 Location of the study area (modified from (npd, 2019)).

1.1 Background

The main findings of previous publications on the Snorre area regarding the Late Middle Jurassic-Early Cretaceous rifting in the northern North Sea are summarized below:

Structural and sedimentological facies analysis of syn-rift succession of the southern part of the Snore Fault Block suggests that formation of the Snorre sub-basins and its syn-rift succession is strongly linked to the development of the basin bounding East Statfjord Fault (Nøttvedt et al., 2000). This study also shows that growth and development of the Statfjord East Fault led to the northward migration and back stepping of the upper Jurassic syn-rift infill along the Snorre hanging wall dip-slope axis. This study has also suggested reservoir potential in the upper Draupne Formation related to basin floor sands deposited to the south of the Snorre Fault Blok

Tectonostratigraphic evolution of the Snorre fault block and its neighboring Statfjord and Visund Fault Blocks has been proposed by Ravnås et al., 2000.This study suggests a five-stage development of the neighboring fault blocks from Late Bathonian-Post Ryazanian. According to this study, fault activity strongly controlled the stratigraphy of the syn-rift succession

(Dawers et al., 1999) suggested that facies distribution and facies geometry are controlled by the segmented nature of the fault system.

In the study by Færseth, 1995 domino model of extensional faulting has been applied in the Visund Fault Block to test stratigraphic and structural implications of the model. The study focuses on detailed analysis of implications of rifting on syn-rift stratigraphy and attempts to find rift stages signature within the syn-rift infill. In addition, record of the rift development and cease on the Visund footwall areas have also been investigated.

(Dahl & Solli, 1993) in their study focused on the structural evolution of the Snorre area during the Late Middle Jurassic-Early Cretaceous rifting. They propose a multi-phase rift event that has influenced stratigraphy and structure of the Snorre Area.

1.2 Motivation

The Late Middle Jurassic-Early Cretaceous sedimentary wedges have hydrocarbon exploration importance. In the Snorre area, these wedges remain under-explored and few publications are available on their origin and geometry. The result of this study will therefore enhance the stratigraphic and structural understanding of these wedges in the Snorre Fault Block and its surrounding area.

1.3 Aim of the study

This study aims to document how fault activity have influenced the infill and geometry of the sedimentary wedges in the Snorre Fault Block and its surrounding areas during the Late Jurassic-Early Cretaceous rifting (Figure 1-1). In order to achieve the objective, the following workflow have been followed: 1) well correlation; 2) synthetic seismogram generation; 3) seismic interpretation of main horizons and major block-bounding faults; 4) core description and seismic facies analysis; and 5) paleogeography maps integrating all the findings

Chapter 2

Geological setting

2.1 Tectonic framework

Tampen Spur area as part of the northern North Sea comprises a series of westerly rotated and tilted fault blocks (Dahl & Solli, 1993). The fault blocks range in size from 50-70km long and 15-50 km wide (Færseth, Knudsen, Liljedahl, Midbøe, & Søderstrøm, 1997). The block-bounding faults are east dipping and NNE-SSW to NE-SW trending. In cross section, the consecutive rotated fault blocks form a series of half grabens. The Snorre Fault Block is one of these half grabens that is located in the Tampen Spur area (Figure 2-1) (Dahl & Solli, 1993; Færseth et al., 1997; Nøttvedt et al., 2000a; Ravnås et al., 2000; YIELDING, 1990).

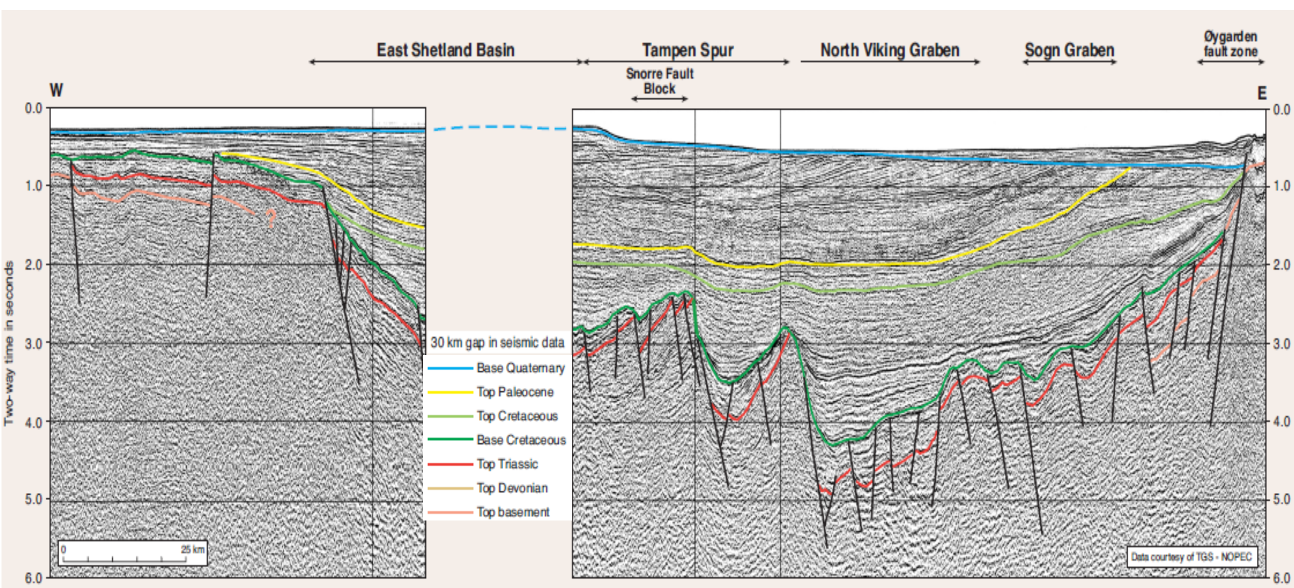


Figure 2-1 Regional seismic line across the northern North Sea (Zanella et al., 2003).

Tampen Spur area as part of North Sea underwent three major rifting events during late Paleozoic and Mesozoic eras. Each rifting event followed by a period of tectonic quiescence (Ravnås et al, 1998). During the Late Permian-Early Triassic rifting, the northern North Sea was a continental basin. N-S trending, west dipping normal faults are evidence of the Late Permian-Early Triassic rifting. These faults are parallel to the long axis of the rift. In general, the Late Permian-Early Triassic rift concealed by the Middle-Late Jurassic rifting (Dahl & Solli, 1993). The Early to Middle Jurassic was a period of tectonic quiescence. During this time, thermal cooling and subsidence occurred throughout the northern North Sea (Ravnås et al, 1998; Nøttvedt et al, 2000). The second rifting event during which present basin configuration and rotated fault block formed, initiated in the Late Middle Jurassic and continued to the Earliest Cretaceous. The signature and timing of this multiphase rifting event has been recorded unequally throughout the northern North Sea (Ravnås et al, 1998; Nøttvedt et al, 2000). The early stage of the Jurassic rifting (end of Bajocian (Dahl & Solli, 1993)) is characterized by low fault block rotation and the presence of no major footwall island (Nøttvedt et al, 2000). Larger extension and faster fault block rotation (Nøttvedt et al, 2000) characterize rift climax stage beginning at the end of Callovian (Pegrum & Spencer, 1990). As a result, deep hanging wall half grabens and footwall islands formed. The late rift stage (Kimmeridgian-Ryazanian) coincides with decreasing fault block rotation resulting in filling basin and progradation of the strata. During the earliest Cretaceous, basin underwent a rapid subsidence. At the same time most of the faults were inactive and only major faults continued with minor activity (Dahl & Solli, 1993).

In general, Tampen Spur area is situated in an intermediate position in the rift system compared to deep Viking Graben that coincides with rift axis. As a result, Tampen Spur area has experienced lower intra-rift and early post-rift subsidence compared to Viking Graben (Pegrum et al, 2016). It is worth to mention that the Late Jurassic rifting together with the Jurassic-Cretaceous subsidence made the Snorre fault block a prominent structural high in the area (Dahl & Solli, 1993).

2.2 Stratigraphy

The Snorre half-graben includes a Bathonian to Ryazanian shallow-to-deep marine syn-rift sediments (Ravnås et al., 2000). With onset of rifting in the early Bathonian, transgression occurred in the northern North Sea and fine-grained sediments of the Heather Formation were deposited in a marine depositional environment (Dahl & Solli, 1993). The Heather Formation consists of silty mudstone with few sandstone stringers. As marine condition continued towards the Ryazanian, the Draupne Formation deposited. It consists of a lower dark and pyritic claystone and an upper micaceous sandstone unit (Ravnås et al., 2000). The lower Draupne fine-grained sediments are one of the main source rocks in the North Sea that charges the North Sea reservoir rocks. In some areas, the Draupne Formation lies unconformably on the Heather Formation. Both formations are considered as syn-rift infill. The Draupne Formation is time equivalent to the development of syn-rift wedges in the North Sea (Dahl & Solli, 1993; Nøttvedt et al., 2000b; Ravnås et al., 2000). In the late Ryazanian towards the Albian/ early Cenomanian (Early Cretaceous) (npd, 2019), the fine-grained Cromer Knoll Group fills the paleo-bathymetry. Thus, it is thicker in the grabens and thins in the footwall areas. The Cromer Knoll Group is considered as early post-rift succession. The basal part of the Cromer Knoll Group in the Snorre Fault Block consists of limestone and marl. The lithostratigraphy and the tectonic framework of the Snorre Fault Block is summarized in Figure 2-2.

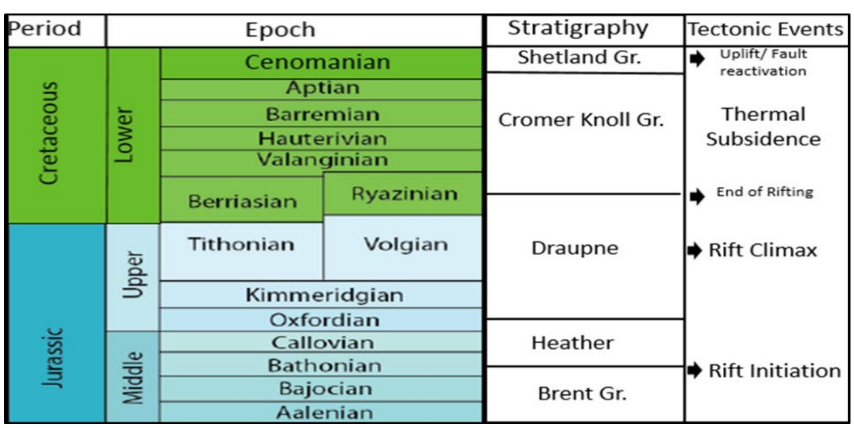


Figure 2-2 Lithostratigraphy and main tectonic events in the study area.

Chapter 3

Data and methodology

3.1 Dataset

In this study, three 3D seismic cubes from DISKOS database were interpreted using DescisionSpace software of Landmark Halliburton. The utilized surveys have considerable overlap, covering parts of blocks 34/4, 34/5, 34/7 and 34/8 (Figure 3-1). The seismic data have variable quality with frequencies ranging from 12- 25Hz. For the purpose of this study, the seismic interpretation has not been depth converted. Table 3-1 summarizes information regarding 3D seismic cubes.

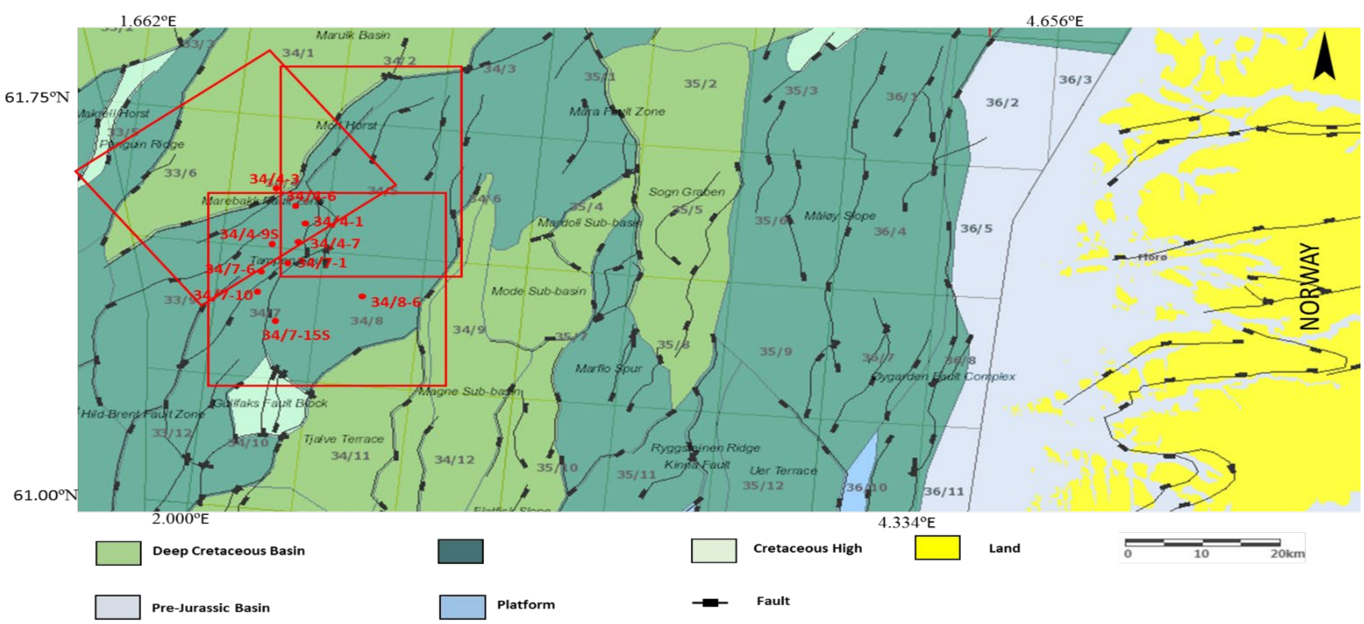


Figure 3-1 3D seismic cube (red rectangles) and wells used in the study area (modified from (npd, 2019)).

Table 3-1 Seismic Data and main use

3D cube	Polarity	Frequency (Hz)	Seismic Resolution (m)	Main Use
NH02M2	Reverse	15	167-319	Well tie
MN9601Mfmigfloat32	Reverse	12	209-447	Interpretation
MN9401Mfmigfloat32	Normal	-	-	Interpretation
SG9701_Merge_fmigfloat16bri	Reverse	-	-	Interpretation

10 wells with a full set of well logs (location on Figure 3-1) from DISKOS database were utilized to perform well log correlation and to tie seismic data to well data. Of these 10 wells, 7 wells are located in the Snorre footwall high and the other three wells are located in the hanging wall of the main faults in the area. Well 34/4-3 penetrated in a wedge in the hanging wall of the main fault in the northwest of the Snorre Fault Block has a core coverage of 16.5m from upper part of the Upper Jurassic Draupne Formation. The cores were also described. Sedimentary log was generated using SedLog 3.1 and was modified using Adobe Illustrator. The cores were provided by Equinor and were viewed in Weatherford Corelab. Table 3-2 summarized information regarding well data.

Table 3-2 Well data and main use

Well	Application
34/4-3	Well correlation, well tie and core description
34/4-6	Well correlation
34/4-1	Well correlation
34/4-7	Well correlation
34/4-9S	Well correlation
34/7-1	Well correlation
34/7-6	Well correlation
34/7-10	Well correlation
34/7-15S	Well correlation and well tie
34/8-6	Well tie

3.2 Methodology

3.2.1 Core description

Approximately sixteen meters of cores from well 34/4-3 located in the hanging wall of a major fault in the northwest of the study area were described in a scale range of 1-50cm in Weatherford Core Lab. The description includes primary composition, texture (size and sorting), color, degree of bioturbation, fossil content and sedimentary structure. The interpretation of identified lithofacies includes depositional processes and depositional environment (Reading, 1996).

3.2.1 Well correlation

In order to obtain an understanding of lateral and vertical variations of the formations in study area during the Late Jurassic-Early Cretaceous time, structural and stratigraphic well log correlation were performed. Well tops were used based on Norwegian Petroleum Directorate factsheets (npd, 2019).

3.2.2 Seismic-Well tie

In order to tie well to seismic data, synthetic seismograms were generated. All wells in study area have Time-Depth Curve to generate synthetic seismogram.

Synthetic seismogram for well 34/7-15S was generated based on extracted wavelet from a cube with reverse polarity, frequency of about 15 Hz and vertical seismic resolution in the range of 167--319m. There is no time shift on synthetic. Result shows a satisfactory tie between the synthetic and the seismic traces for the Base Viking and the Base Cretaceous reflectors (Figure 3-2a). In order to tie Base Draupne (Top Heather) and Top Cromer Knoll Group reflectors from well to seismic, synthetic seismogram was generated for well 34/8-6. The synthetic generated (Figure 3-2b.) using an extracted wavelet from the same seismic cube as in well 34/7-15S. No time shift was applied on synthetic. Gamma Ray and Caliper logs were used to quality check the Sonic and Density logs.

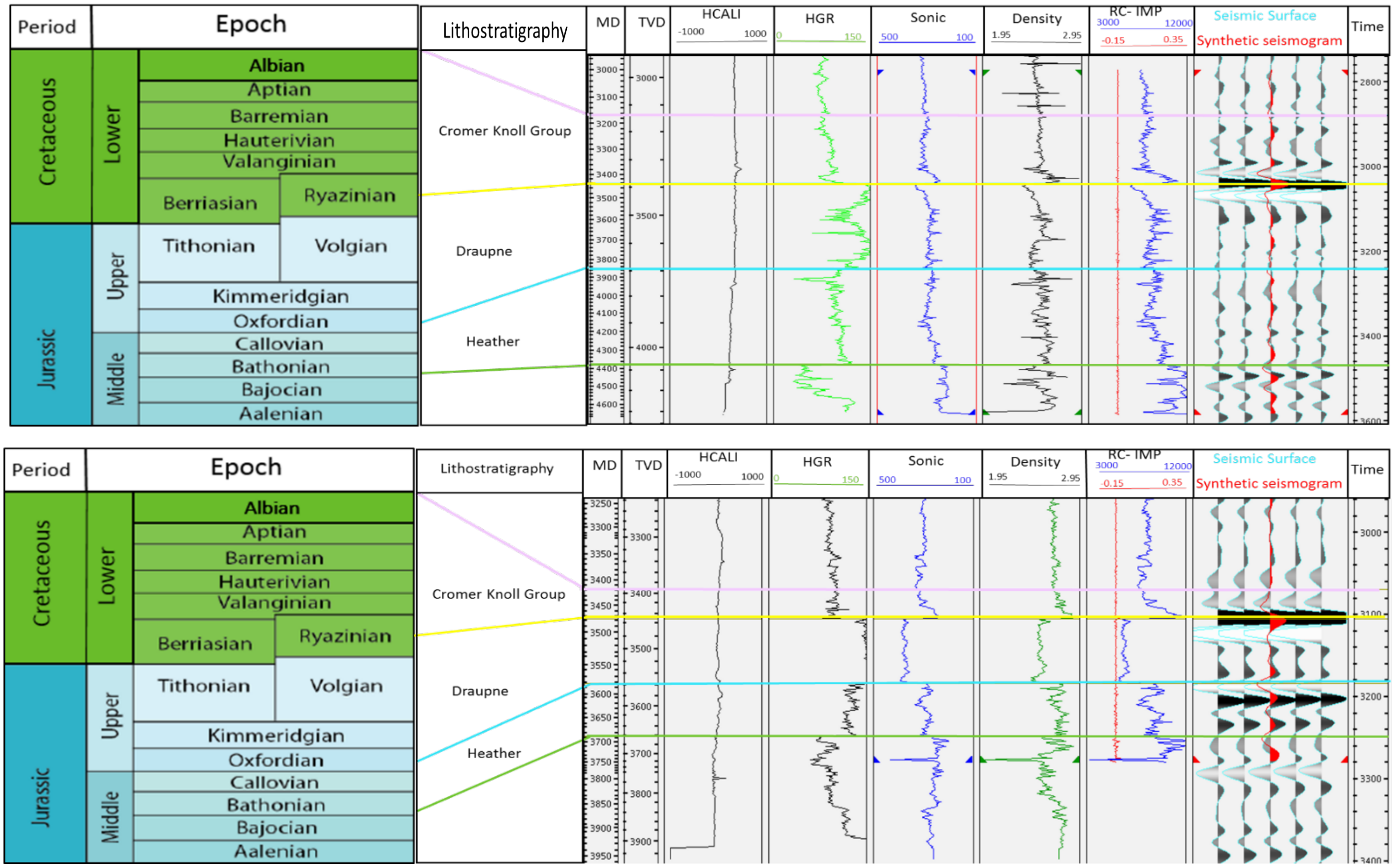


Figure 3-2 a) Upper: Synthetic seismogram for well 34/7-15S; b) Lower: Synthetic seismogram for well 34/8-6.

3.2.3 Seismic interpretation

Four Upper Jurassic to Lower Cretaceous seismic horizons including the Base Viking Group, Top Heather Formation, Base Cretaceous Unconformity (equivalent to the Top Draupne Formation in the hanging wall areas) and the Top Cromer Knoll Group were interpreted. Faults affecting the Upper Jurassic and the Lower Cretaceous succession were also interpreted. Time structural maps for four horizons and time thickness maps for the Heather Formation, the Draupne Formation and the Cromer Knoll Group were generated. Visual seismic facies analysis for the Upper Jurassic and the Lower Cretaceous succession performed based on seismic reflection parameters including reflection configuration, internal character, reflection continuity and amplitude and internal geometry (Lobo et al., 1999; Marin et al., 2018; Prather & Steffens, 1998; Sangree & Widmier, 1979).

It is worth to mention that in northwest of the study area, due to low seismic quality and very few well control (only well 34/4-3 drilled in the wedge), only the Base Cretaceous Unconformity and the top Cromer Knoll Group were mapped with confident. In south of the study area (hanging wall of Inner Snorre Fault (ISF)), there is uncertainty in tracing top Cromer Knoll Group reflector and particularly the Base Heather (Base Viking Group) reflector.

3.3 Limitations

Only three wells have penetrated the Late Jurassic-Early Cretaceous interval of the wedges in study area. Moreover, of these three wells, only one well with a limited core coverage from upper part of the Upper Jurassic Draupne Formation is available. The core is also discontinuous and has missing sections. These limitations restrict my understanding of the internal character of the wedges and overall understanding of stratigraphy and structural evolution of the study area including the wedges. In addition, insufficient well data largely reduces control on tracing reflectors on seismic cubes and in case of low-quality seismic data, which is the case in this study, brings limitation in synthetic seismogram generation and well-tie process. Moreover, seismic data of various quality brings an uncertainty in seismic facies analysis especially in the areas where the two seismic cubes have an area of overlap. Above all, this study utilizes different scales of data ranging from mm in core data to km in seismic data. Though utilizing data of different scale improves understanding of the study area and provides detail information (core and well log data), however, process of integration of data of various scale with lateral and vertical limitations leads to some degree of uncertainty in the analysis of the data.

Chapter 4

Results: observations and interpretation

4.1 Well correlations

Observations

Stratigraphy and structural well correlations (Figure 4-1, Figure 4-2, and Figure 4-3) have been performed in order to obtain an understanding of lateral and vertical variations of the Upper Jurassic to Lower Cretaceous succession within the study area. In order to avoid repetition, a detailed description of correlation and well log signatures in each interval has been presented in well character section of each interval in sections 4.3.2.1, 4.3.2.2 and 4.3.2.3.

Stratigraphic well correlation between wells 34/4-6, 34/4-1, 34/4-7, 34/4-9S, 34/7-1, 34/7-6 and 34/7-10 (Figure 4-1) was performed in an N-S direction and was flattened on top Cromer Knoll Group horizon. Correlation shows that the Upper Jurassic succession is not present in all wells. However, the Lower Cretaceous Cromer Knoll Group is present in all wells. The thickness of the Cromer Knoll Group shows variation between wells. In general, it increases from north to south. The GR log motif is irregular and the log pattern show a slightly fining-upward formation.

Stratigraphic well correlation between wells 34/4-3, 34/7-15 and 34/8-6 (Figure 4-2) has been performed. The correlation has been flattened on top Cromer Knoll Group horizon. The correlation shows thickness increases from well 34/4-3 in the north to well 34/7-15S in the south and decreases again in well 34/8-6 towards the northeast.

Structural well correlation between wells 34/4-3, 34/4-6 and 34/7-15S (Figure 4-3) show that the Heather Formation is not present in well 34/4-6 as mentioned above. However, it has a large thickness in wells 34/4-3 and 34/7-15S and thickness is larger in well 34/7-15S. The GR log motif is overally aggradational with internal irregular pattern in both wells. The Draupne Formation has also a large thickness in wells 34/4-3 and 34/7-15S while it is not present in well 34/4-6. The thickness is larger in well 34/7-15S. The overall GR log pattern is similar in both wells and several coarsening and fining upward packages are observed in both wells (Figure 4-3). Correlation shows that the Cromer Knoll Group is very thin in wells 34/4-3 and 34/4-6 while it has a large thickness of about 300m in well 34/7-15S. The overall GR log pattern of Cromer Knoll Group is slightly fining upward in all wells.

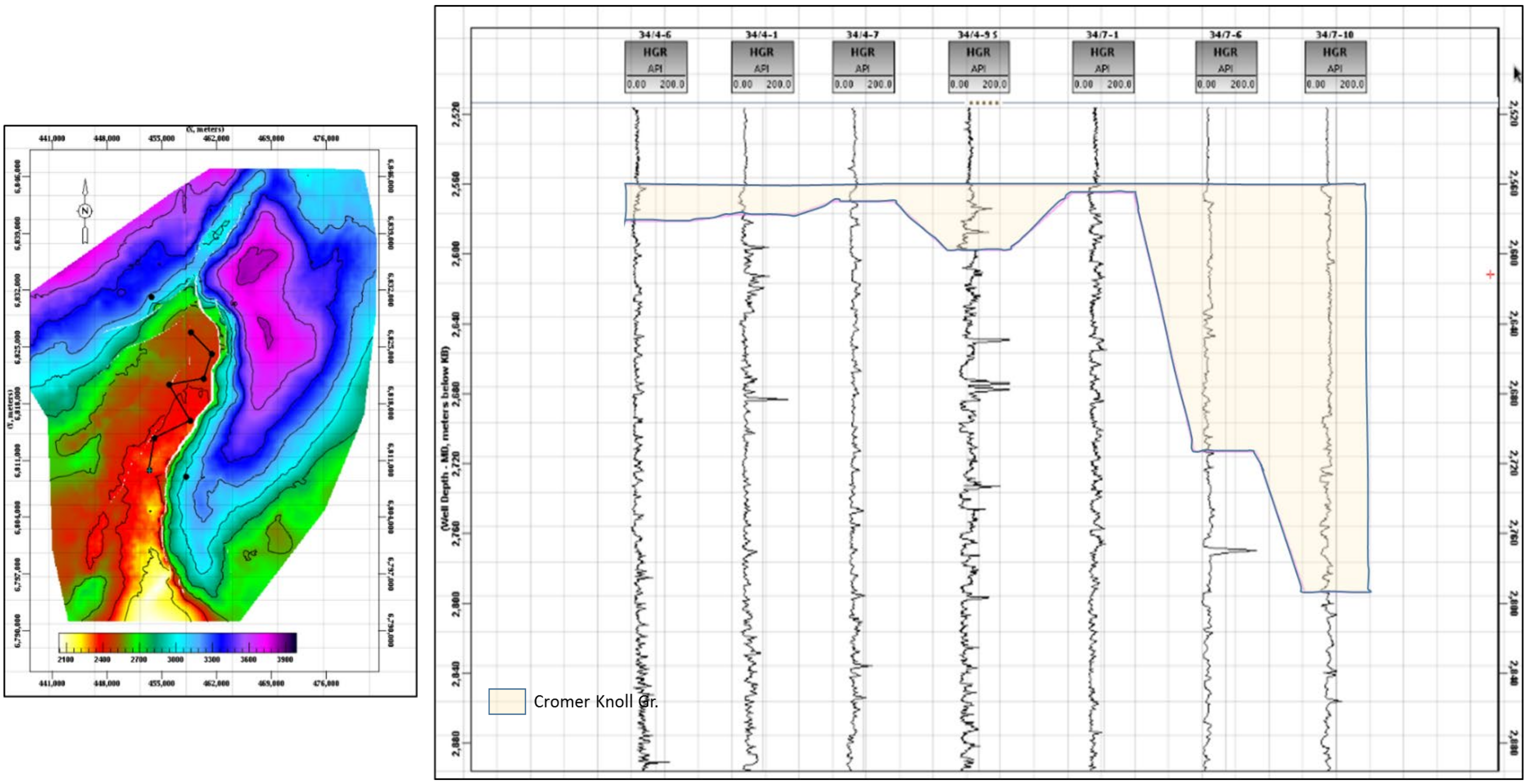


Figure 4-1 Stratigraphy well correlation over the Snorre footwall. Correlation line is shown in black line on the Base Cretaceous Time Structure map of the study area.

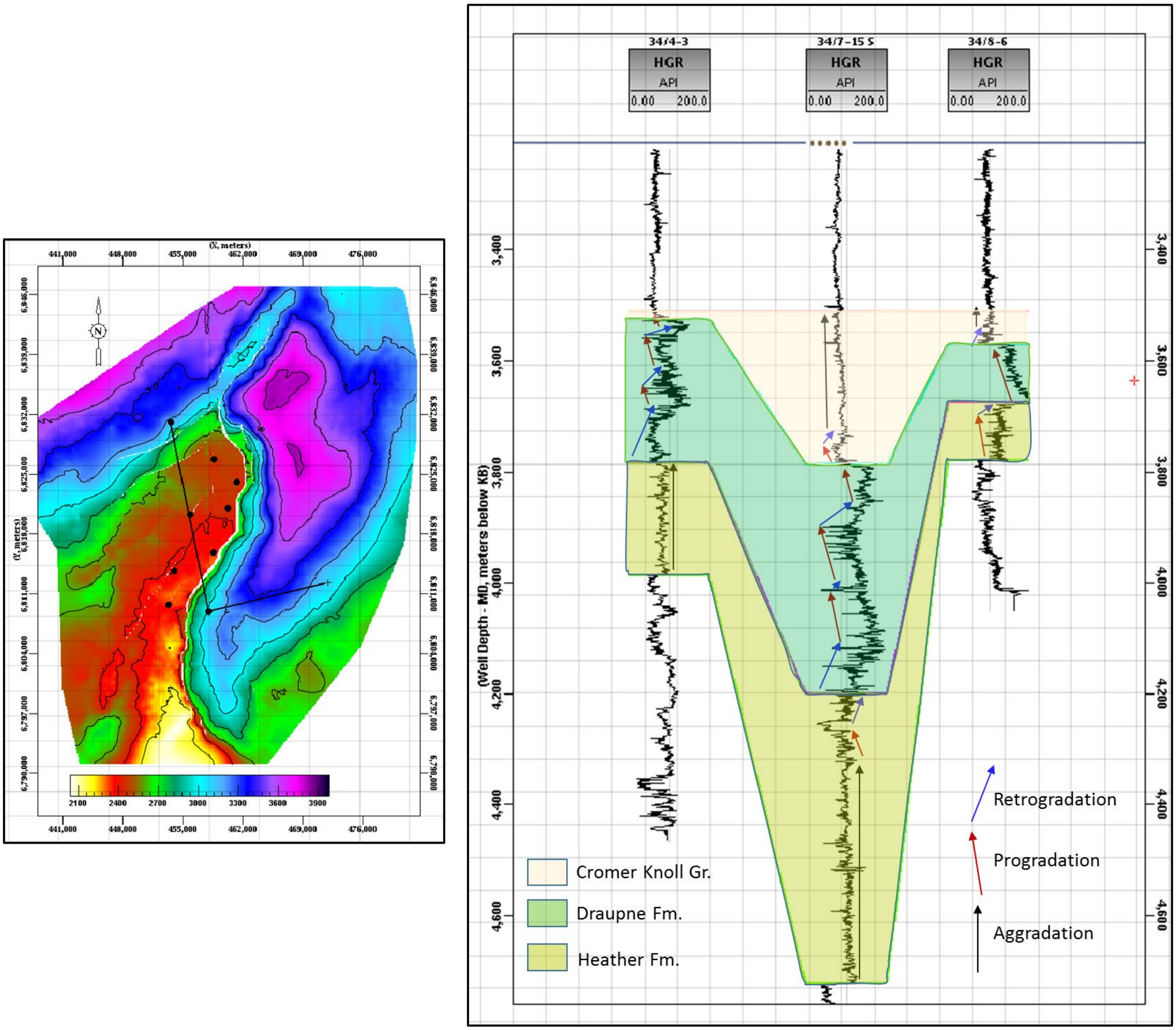


Figure 4-2 Stratigraphy well correlation in the hanging wall areas. Correlation line is shown in black line on the Base Cretaceous Time Structure map of the study area.

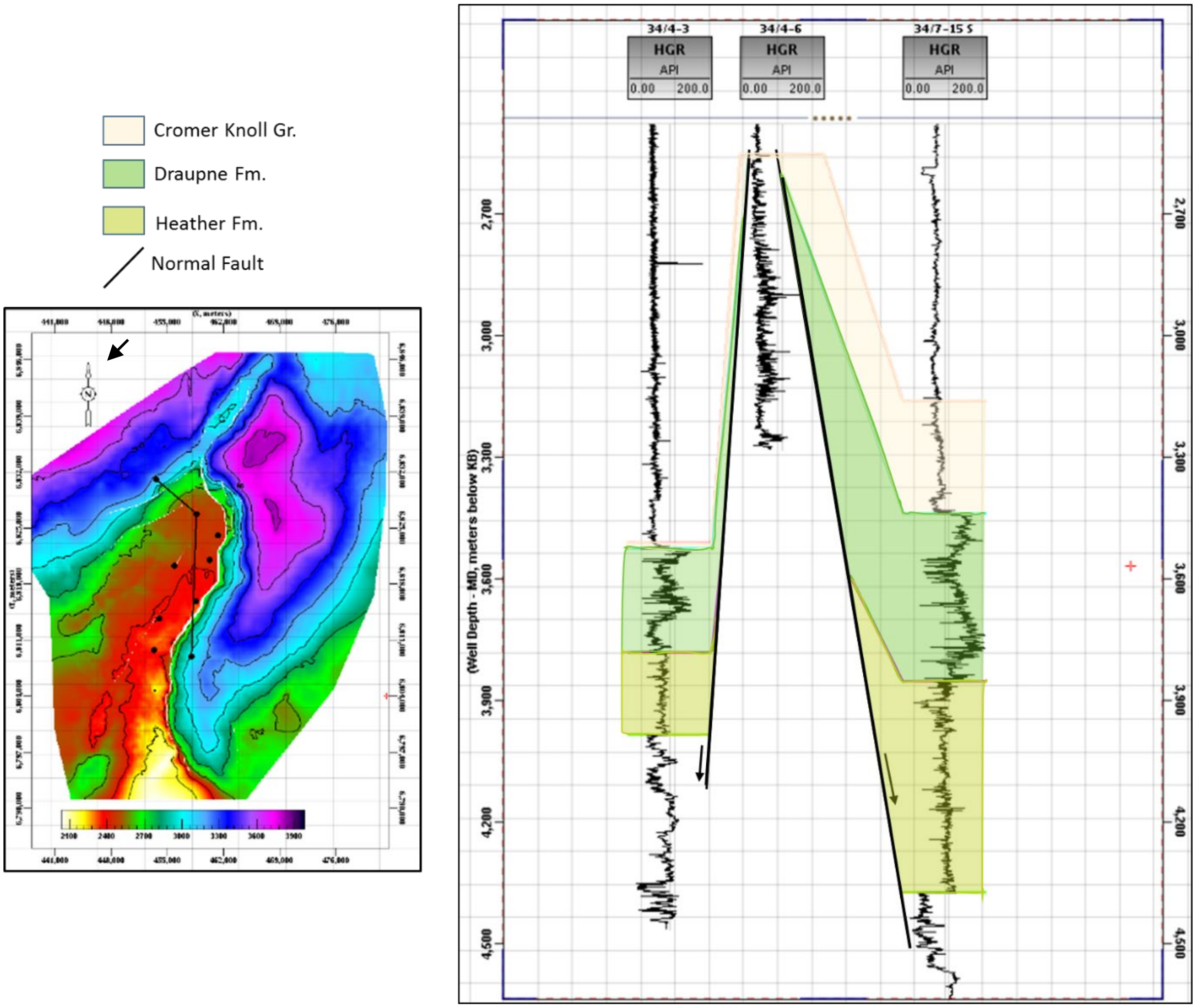


Figure 4-3 Structural well correlation. Correlation line is shown in black line on the Base Cretaceous Time Structure map of the study area.

Interpretation

Well correlations suggest that the Upper Jurassic succession in wells 34/4-6, 34/4-1, 34/4-7, 34/4-9S, 34/7-1, 34/7-6 and 34/7- 10 has either been eroded or has not been deposited at all in these wells located over the Snorre High. This means that the Snorre High has remained above sea level at least for some periods during the Middle Jurassic-Early Cretaceous time. Therefore, over the Snorre high, the Cretaceous succession underlie directly by Triassic succession. In addition, thickness variations of the Heather and the Draupne formations and the Cromer Knoll Group in well correlations show that the thickness of the Upper Jurassic-Lower Cretaceous succession increases strongly from north to south. This conclusion suggests a deeper basin in the southern part of the Snorre area than in the northern part during the Late Jurassic-Early Cretaceous time.

The irregular GR log pattern of the Heather Formation suggests that the formation is a fine-grained heterolithic. The Draupne Formation is also interpreted as a fine-grained (shaly) formation with some coarse-grained (sandstone) intervals. The retrogradation and progradation patterns of GR logs of the Draupne Formation (Figure 4-2) reflects changes in facies and depositional setting of the formation. The Cromer Knoll Group is also interpreted as a fine-grained succession. For detailed interpretation of well correlation see sections 4.3.2.1, 4.3.2.2 and 4.3.2.3.

4.2 Core description and interpretation

The Upper Jurassic Draupne Formation was the focus of the core interpretation. The purpose is to obtain information about facies, depositional processes and depositional environment of the Draupne Formation within a wedge in northwest of the study area. About sixteen-meter-long core in interval of 3567.4m to 3584.65m penetrating upper part of the Draupne Formation in well 34/4-3 were described. There were some missing intervals. This will result in some degree of uncertainty on interpretation of the lithofacies. Four lithofacies were identified (Table 4-1). The lithofacies were then classified as one facies association. The overall sedimentological log pattern is fining upward (Figure 4-5).

Table 4-1 Summary of lithofacies identified within the Upper Jurassic Draupne Formation. The orange ellipse marked on the lithofacies F2 and F3 shows syn-sedimentary faults. The white dashed line and white ellipse show different clasts in the lithofacies F3. The area marked with black ellipse is showing dewatering (fluid escape) structure in the lithofacies F1. The light and dark blue stars shown in lithofacies F3 are the two sub-lithofacies for this lithofacies.

	Example	**Grain Size**	**Description**	**Depositional Process**
F1		Medium	**Structureless Sandstone** Light gray to light brown, well sorted, and sub-rounded to rounded grains sandstone. No sedimentary structure. No stratification. Scale bar: 5cm	High density turbidity currents
F2		Fine to medium	**Graded Laminated Sandstone** Light gray, well sorted, sub-angular to rounded grains sandstone. Flaser bedding Clasts and sand injectite. No trace and body fossils Scale bar: 10cm	Low to medium density turbidity flow or distal storm deposit
F3		Very fine	**Heterolithic** Greenish gray, well sorted sandstone. Syn-sedimentary faulting. Clasts of varying size Calcite cement. Fluid scape and pseudo-layers. Scale bar: 10cm	Hybrid flow and slide/ slump

F4		Mud, clay	**Mudstone** Dark gray mudstone. Structureless. 30cm thick. Scale bar: 10cm	Suspension fall-out

Table 4-2 Facies association

Facies Association	**Lithofacies**	**Group**
FA1. Turbidites and slide/slump	A, B, C and D	Offshore- Deep marine

Lithofacies F1 (Structureless Sandstone)

Description

This lithofacies is an epiclastic sandstone with well-sorted medium-sized grains. The grains are sub-rounded to rounded. No sedimentary structure and no stratification are found. It is in light gray color but occur in light brown color, too (Figure 4-4). Usually occurs in less than 10cm thick. Often occur in maximum 5cm thick, more common in 2-3cm thick, in between/within lithofacies 2. The lower and upper boundary is usually sharp but sometime erosional or transitional.

Interpretation

Lack of sedimentary structures indicative of current activity and grain size suggest that the facies was deposited from suspension (Collinson, 1969) from a high density turbidity flow (Reading, 1996; Stow & Johansson, 2000) in a low to medium energy environment of deposition.

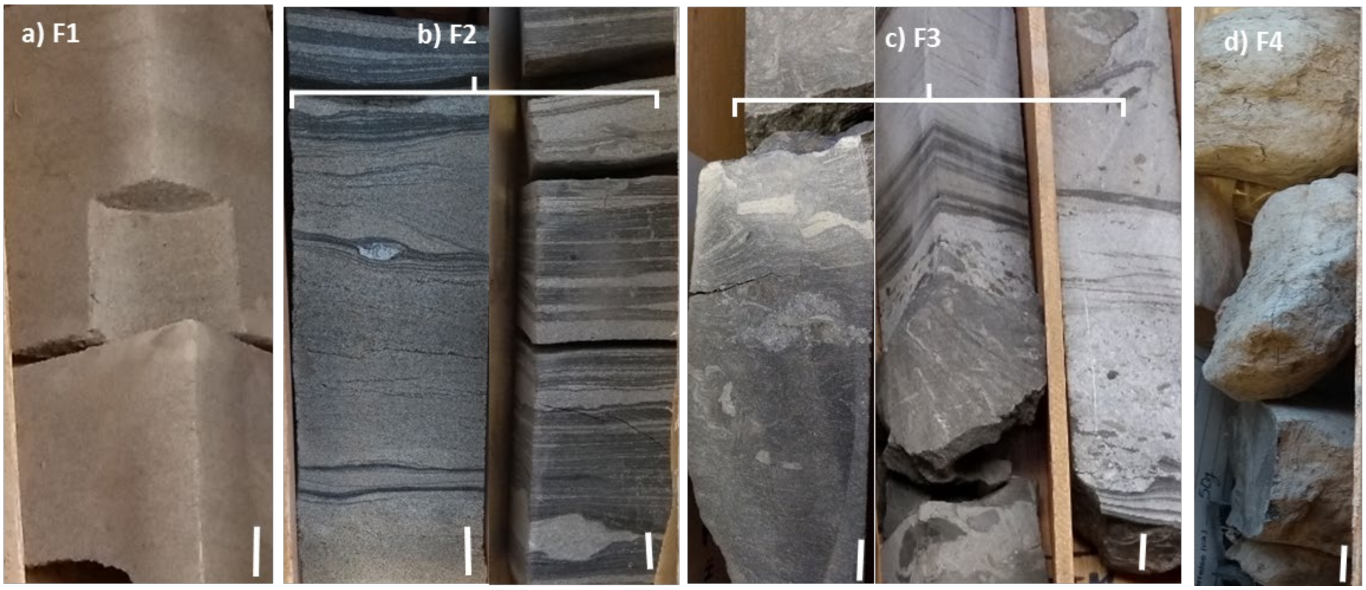


Figure 4-4 Lithofacies seen in the core: a) lithofacies F1:light gray/brown sandstone occur within the lithofacies F2 or as an isolated layer; b) lithofacies F2 showing sand injectite (lower right corner of the figure), clast and cross lamination; c) sublithofacies of lithofacies F3 (hybrid flow to the left and slide/slump to the right); and d) lithofacies F4. Scale bar: 1cm

Lithofacies F2 (Graded Laminated Sandstone)

Description

This lithofacies is fine to medium-sized grain, well sorted, sub-angular to rounded grains epiclastic sandstone. Horizontal isolated and parallel double silt and shale lamination are common. Core-scale syn-depositional faulting, fluid escape and post depositional features are also observed. Clasts of 1-2cm in scale and sand injectite (Figure 4-4b) are observed. A large clast of 5cm in diameter are observed that is composed of several smaller sized clasts supported by finer grain matrix. Sometime the background lithology is silt and shale and the sandstone occurs in mm scale lamination. Change in flow direction and ripple are common in sandstone. Body fossils and trace fossils are absent. The color is light gray but sometime is light brown. This is the dominant lithofacies in the whole core bounded at the base by F3.

Interpretation

Presence of ripple and cross stratification in the background sandstone is an indication of water current influence. Absence of features indicative of current activity within the laminations, show that the finer grain lamination were deposited from suspension. The fine to medium grains indicate a low to medium energy environment below wave base (Reading, 1996), possibly with sandstone as background sediments. The lack of trace and body fossils suggest a deep marine environment. Presence of clast suggest a transportation mechanism other than water current or wind and most possibly is an indication of turbidity mechanisms (*sensu* (Reading, 1996)).

Lithofacies F3 (Heterolithic)

Description

Very fine-grained size and well sorted chaotic epiclastic sandstone. Syn-sedimentary core scale faulting during the deposition of light sand exists. Calcite cement is common. Fluid scape and unorganized pseudo-layers are also common. Clasts with a size range from 3mm-5 cm in diameter is common. This lithofacies can be considered as two sub-lithofacies (Figure 4-4c) based on the sedimentological character as it is shown with two stars of light blue and dark blue color.in table 4.3. The color is greenish gray. Maximum 30cm thick.

Interpretation

The grain size represents a low energy environment. Fluid scape structure is an indication of primary sedimentary structure modification and/or post depositional deformation and/or may be entirely new (Sylvester & Lowe, 1978). The modification may come from pore fluid movement, current and/or gravity forces (Sylvester & Lowe, 1978). Presence of clasts with different sizes

Lithofacies F4 (Mudstone)

Description

This lithofacies is a structureless dark gray mudstone. The thickness of unit is about 30cm.

Interpretation

The absence of any feature indicative of current activity and the fine-grained nature of the lithofacies suggest that the lithofacies was deposited mostly from suspension.

Facies Association (FA): Slope Turbidites and slide/slump

For the purpose of this study, the four lithofacies were classified as one facies association described and interpreted below

Observation

The association mostly consists of graded laminated, fine- to medium-grained, light gray sandstone. The laminations are siltstone and shale. In some intervals, however, the siltstone and shale are the background lithology and laminations are sandstone. The facies association is bounded at the base by the lithofacies F3 which consists of two sub-lithofacies of slide/slump and hybrid flow. The mudstone of the association occur in a 20cm thick layer in the interval of 3575.95-3576.15m. The structureless medium-grained sandstone occurs often in a thickness range of 3-10 cm within the lithofacies F2. Ripples, stratifications and dewatering (fluid escape) are the main common sedimentary structures within the association.

Interpretation

The prominent grain size and thin lamination of shale, silt and sometime sandstone reflects a marine condition for the deposition of the lithofacies from suspension. The clasts of different size suggests a slide/slump over a slope environment. Ripples and stratification within the prominent lithofacies of F2, water current influence from slope channels.

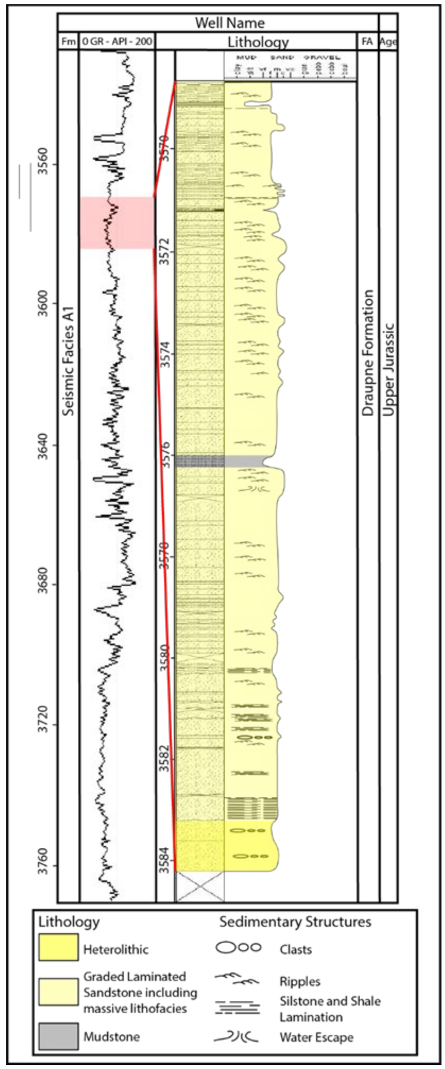
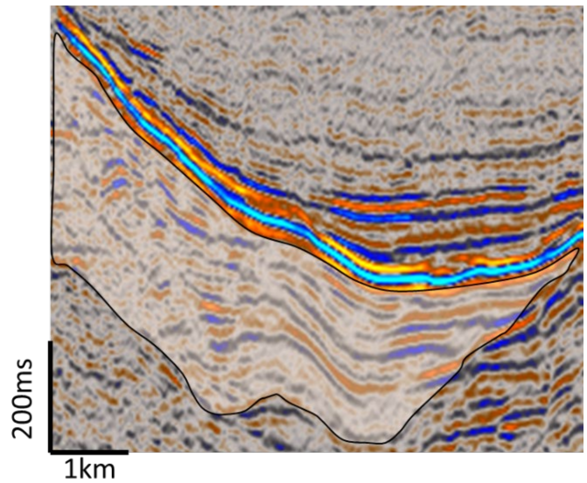
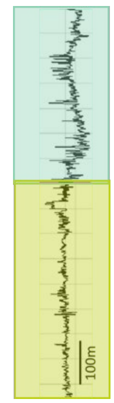
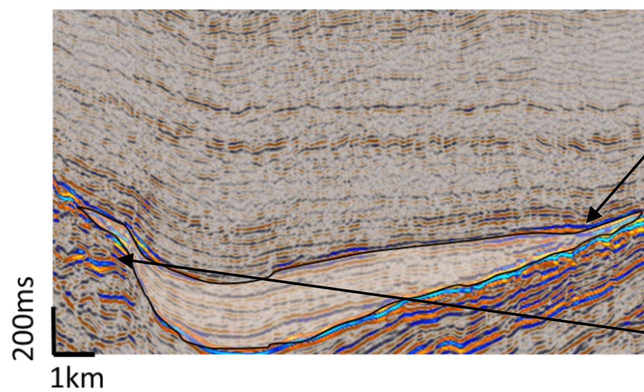
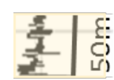
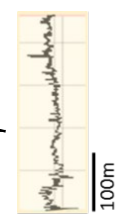


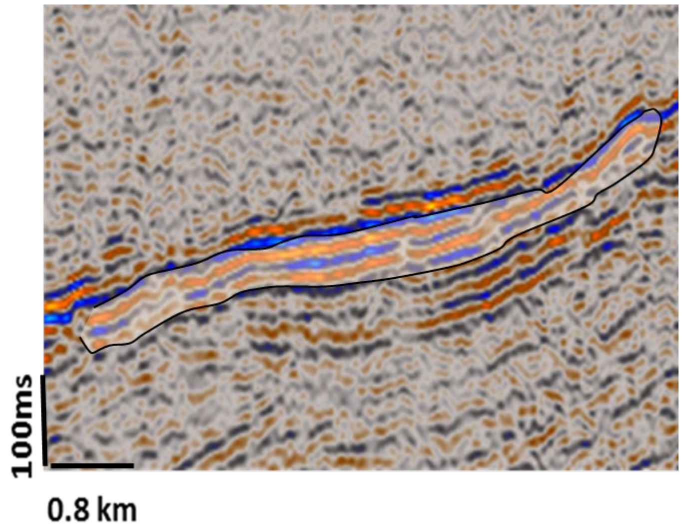
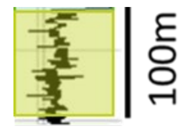
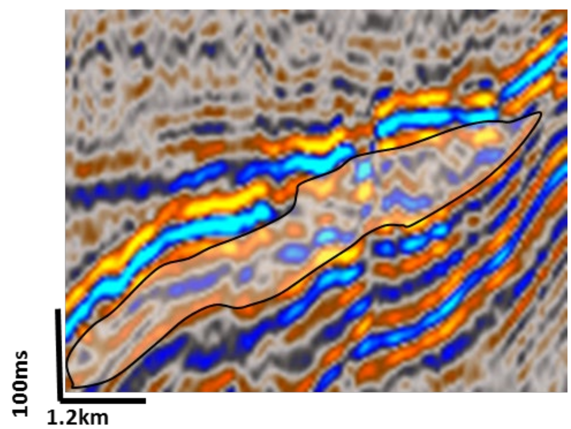
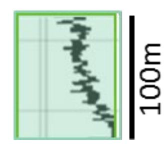
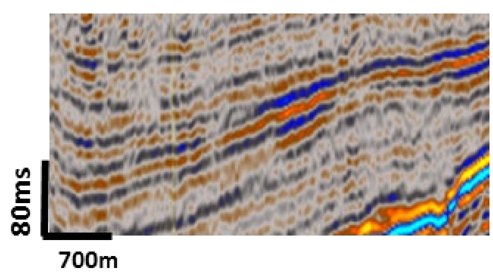
Figure 4-5 Sedimentological log and the GR log for well 34/4-3. Note that the lithofacies correspond to seismic facies A1.

4.3 Seismic facies analysis

Five seismic facies have been defined within the Upper Middle Jurassic-Lower Cretaceous succession of the wedges in study area. Table 4-3 summarizes the identified seismic facies.

Table 4-3 Summary of seismic facies identified within the study area.

Facies Description	Interpretation	Example	GR Log Pattern
A1 Wedge, Low-medium-High amplitude. Moderately continuous sometime chaotic reflector.	Syn-rift deposit in rotated fault block.		well 34/7- 15S 
A2 Wedge, low to high amplitude, continuous.	Post- rift deposits in a subsiding bain.		Well 34/8-6  Well 34/7-15S 

B Oblique, continuous, parallel reflector. Medium to high amplitude.	Syn- rift deposit over the rotated and tilted high		well 34/ 8- 6 
C Chaotic, Medium to high amplitude.	Late syn- rift deposit in a tilted and rotated fault block		Well 34/8-6 
D Parallel, highly continuous reflectors. Low- high amplitude.	Post- rift deposit		Not drilled

Seismic Facies A1 (Wedge)

Description

A wedge with moderately continuous but sometimes chaotic reflectors. Internal reflection continuity appears greater on strike-parallel seismic lines. Amplitude ranges from moderate to high. Internal reflectors downlap/ onlap the fault plane and change to seismic facies B or C laterally. The lower and the upper boundary downlap/ onlap the fault plane and onlap/ toplap the adjacent high (the Visund High). Where continuous, aggradation and sometime progradation towards the fault plane are observed. This seismic facies is always seen next to the major basin bounding faults in the hanging wall areas, forming a laterally continuous feature along the strike of the faults. The thickness, geometry and internal character of the wedge changes regularly along the strike of the faults (Figures 4-13a and b). Wells 34/4-3 and 34/7-15S have penetrated this seismic facies (Figures 4-2 and 4-3). See Section 4.4 (the Draupne and the Heather formations sub-chapters) for description of the GR within the wedges. Core data of well 34/4-3 from upper portion of the wedge show turbidite sandstone, mudstone and slump/ slide deposits.

Interpretation

The location of the wedge indicate that this seismic facies is associated with fault activity. Therefore, the wedge is interpreted as syn-rift deposits. The aggradation is an indication of increasing accommodation due to fault activity. The progradation towards the fault plane suggests increase in fault movement from the base towards the top of the wedge. Core data suggests deep marine depositional environment of most likely slope for the upper portion of the wedge.

Seismic Facies A2 (Wedge)

Description

This seismic facies consists of low to high amplitude reflectors that diverge basinward and away from the major fault and the adjacent high (the Visund High). Reflectors are continuous but sometime chaotic and grade to seismic facies D. Reflectors onlap the fault and the high (the Visund

High). Lower and the upper boundary reflectors are continuous. Upper boundary onlap the fault plane and the Visund High. This seismic facies is observed only within the Cromer Knoll Group. Wells 34/7-15S and 34/8-6 have penetrated this seismic facies. GR logs show a mostly aggradational pattern, slightly fining upward with values around 100API in both wells.

Interpretation

Thinning of the seismic facies towards the fault suggests that fault has been inactive during the deposition of the wedge. Therefore, this seismic facies is interpreted as post-rift deposits. GR logs suggest carbonaceous fined-grained sediments deposited in marine (shallow to deep) environment.

Seismic Facies B (Oblique, continuous reflectors)

Description

Oblique, divergent and locally parallel reflectors with moderate to high amplitude. This seismic facies is commonly observed next to the seismic facies A1. The lower and upper boundaries onlap the fault plane on their western end and toplap but sometime locally onlap the adjacent high (the Visund High) on their eastern end. Well 34/8-6 has penetrated this seismic facies and gamma ray log shows an overall aggradational pattern with internal irregularities. The GR log values are usually higher than 100API with some thin intervals of low values.

Interpretation

The lateral change of this seismic facies to seismic facies A1 suggests that this seismic facies is also associated with fault activity. Therefore, this seismic facies is also considered as a syn-rift The GR log suggests a marine environment. Oblique, divergent moderately continuous reflectors suggest shelf environment similar to what (Lobo et al., 1999) have mentioned in their work.

Seismic Facies C (Chaotic)

Description

High amplitude chaotic, discontinuous reflectors with common erosional base and locally mounded. Due to chaotic nature of the reflector, internal reflection terminations obscured. The lower boundary onlap/toplap the Visund High and is continuous basinward toward the fault plane. The upper boundary is continuous. Well 34/8-6 has penetrated this seismic facies. The gamma ray log shows a coarsening upward pattern with values higher than 100API.

Interpretation

The lateral change of this seismic facies to seismic facies A1 (wedge) suggests that this seismic facies is also associated with fault activity. Therefore, this seismic facies is also considered as syn-rift. GR log suggest a marine depositional environment.

Seismic Facies D (Parallel)

Description

This seismic facies consists of low- high amplitude parallel, highly continuous and sometime discontinuous reflectors. The seismic facies is laterally continuous parallel to the strike of the major fault.

Interpretation

The parallel and laterally continuous reflectors suggests a low energy marine depositional environment in a quiet tectonic setting. In addition, lateral changes of this seismic facies to seismic facies A2, suggests that this seismic facies has been deposited in a quiet tectonic setting. Therefore, this seismic facies is considered as post-rift.

4.4 Seismic interpretation

This section starts with an overview of the main structural elements of the study area from seismic data followed by observations and interpretation of main stratigraphic units within the study area.

4.4.1 Structure of the Snorre and its surrounding areas

Seismic data show that the main structure of the study area is a half graben (Panne Kake basin) with a NNE-SSW trend bounded to the west by an about 50km- long, NNE- SSW striking, E or SE dipping master fault (Inner Snorre Fault, ISF). This graben is situated between the NNE-SSW oriented highs of the Snorre to the west, the Visund High to the east and the Mort Horst in the north (Figure 4-6). The width of the graben ranges from 4 km in the south of the study area to more than 20 km in central part of the master fault and decreases to about 10 km in the northern part of the study area. The structure in the northwest of the study area, (the Marulk basin) is a relatively small graben bounded to the east by a NE-SW striking, NW-dipping master fault of about 25km long (Marebakk Fault, MF). This graben is situated between the Snorre High in the southeast, the Mort Horst in the northeast and a relatively small topography in the northwest. The average width of the graben is about 3km.

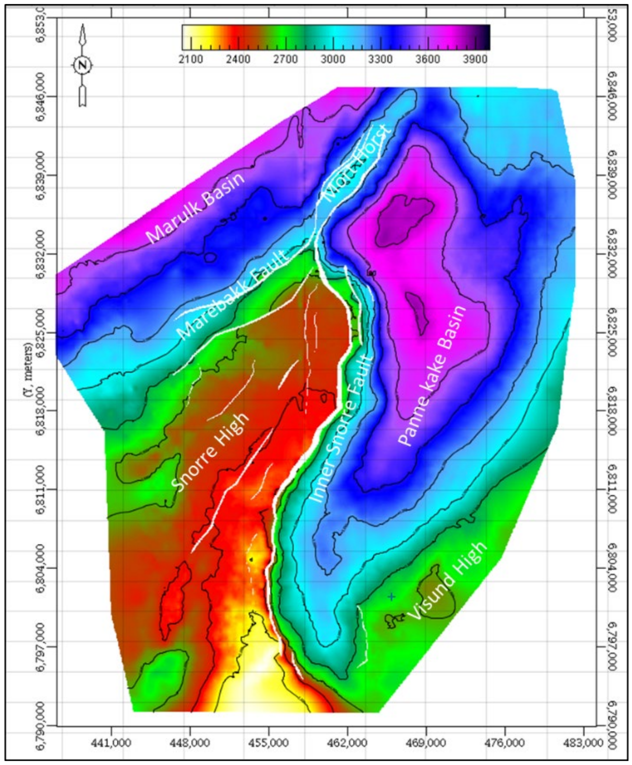


Figure 4-6 BCU time structure map showing major structural elements in study area

4.4.2 Stratigraphy of the Snorre Fault Block and its surrounding areas

4.4.2.1 Heather Formation (Early Bathonian- Mid Oxfordian)

Observation

Well Character

Of 10 wells in the study area, the three wells, 34/4-3, 34/7-15S and 34/8-6 have encountered the Heather Formation (Figure 4-2and Figure 4-3). In the well correlation panels, the formation has been encountered in interval of 3800- 4000MD (Measured Depth) in well 34/4-3 (located 3km into the hanging wall of MF), in interval of 3700 -4100 MD in well 34/7-15S and in interval of 3581-3686MD in well 34/8-6. Gamma Ray log of the Heather Formation shows an overall aggradational pattern with internal irregularity in all wells. However, differences are also observed. In Well 34/4-3, the GR log values are mostly around 100API. In addition, there are some very thin intervals of very low/ very high GR log values. In well 34/7-15S, the GR log values are also usually around 100 API except in the interval of 4240-4320 MD which the average log values is less than 100API. In addition, there are some high/low-values spike in GR log. In well 34/8-6, the GR log values are higher than 100API. The GR log shows a slightly fining upward pattern. The thickness of the Heather Formation increases from well 34/4-3 to well 34/7-15S and then decreases to well 34/8-6. The lower boundary of the formation in all wells is marked with considerably low gamma ray value of Tarbert Formation of Brent Group. The upper boundary character of GR log.is different in the wells. The upper boundary of the Heather Formation in well 34/4-3 is characterized by a change from higher GR values to a thin interval of lower GR. values while this is reversed in well 34/7-15S. The boundary between the Heather Formation and the Draupne Formation in well 34/7-15S is marked with higher GR values of the Draupne Formation. In well 34/8-6, the upper boundary is marked with strong high GR log values of the Draupne Formation.

Seismic Character

The Heather Formation is present across the hanging wall areas of ISF and MF. The overall external geometry of the formation is wedge-shaped. The internal character of the formation changes regularly along the strike of the fault and in cross sectional view from the Visund High towards the Snorre High and from the Snorre High towards the Marulk basin. Three seismic facies are observed within the formation which are: 1) seismic facies A1 (wedge) observed next to the major bounding faults of ISF and MF, creating a laterally continuous feature along the strike of the faults, 2) seismic facies B (oblique, parallel reflectors) that is observed next to seismic facies A1 in southern part of the ISF hanging wall areas and next to facies C towards the north in ISF hanging wall areas; and 3) seismic facies C (Chaotic) that occurs between facies A and B parallel to strike of ISF. The distribution of seismic facies is shown on seismic facies map in Figure4-14.

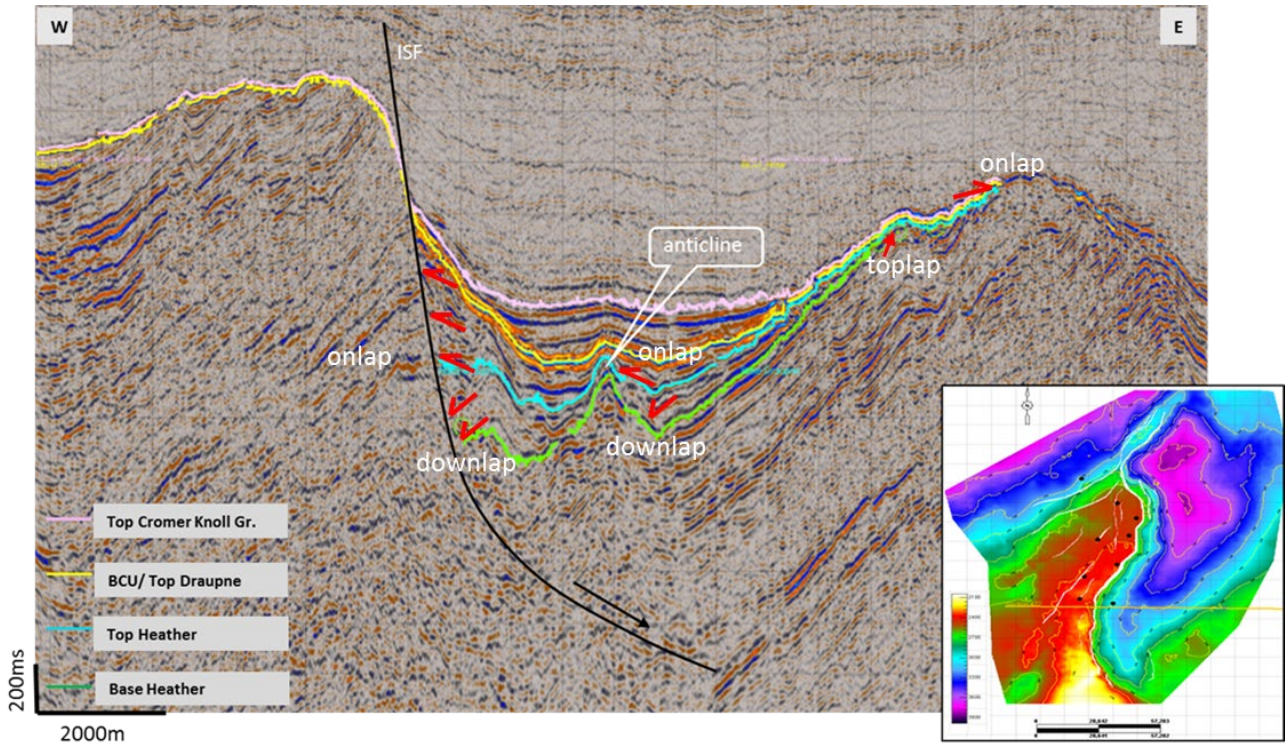


Figure 4-7a. Seismic section showing anticline within the syn-rift succession (the Heather and the Draupne). Location of the section on BCU time structure map (lower right corner). Stratal termination are shown as an example

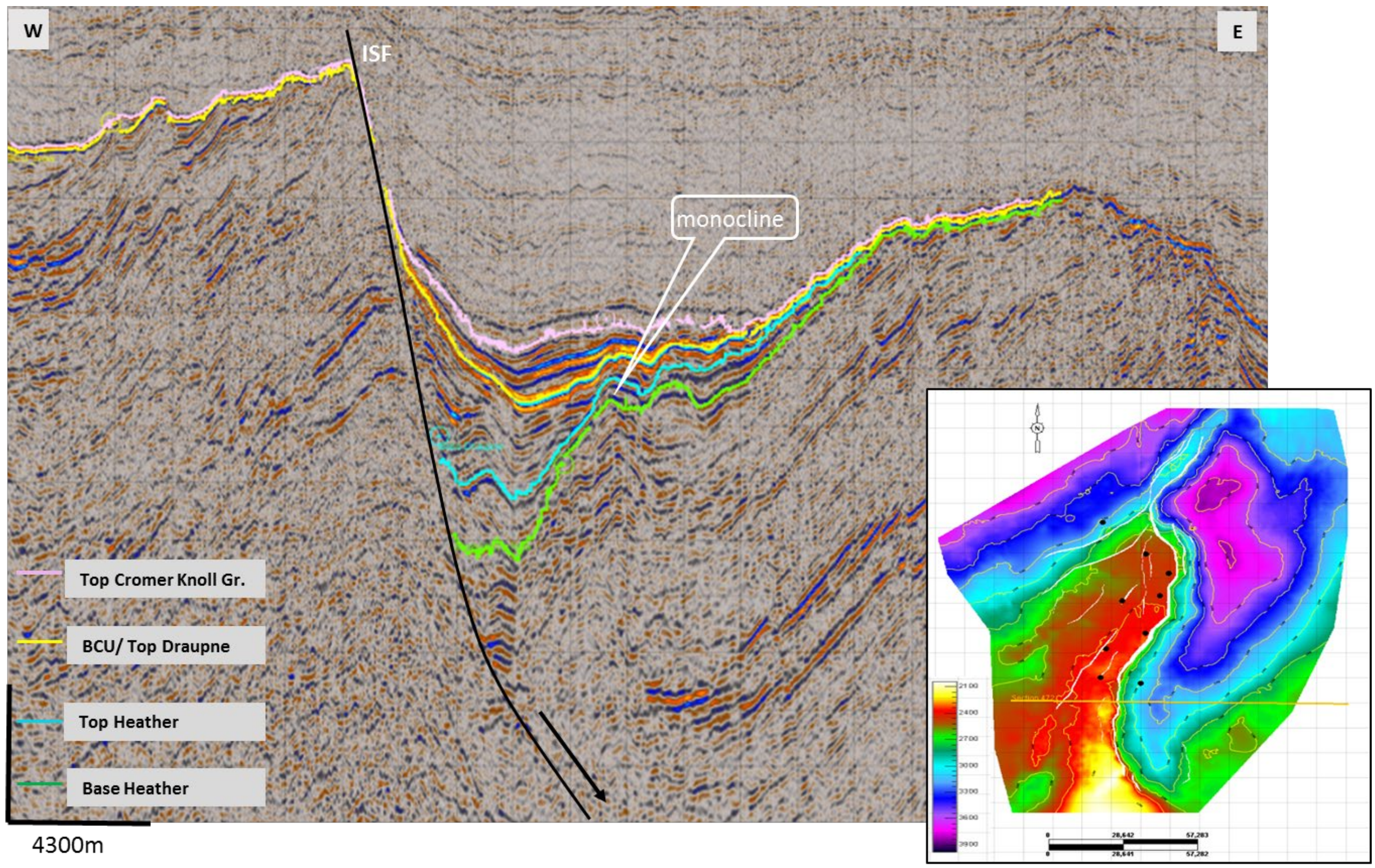


Figure 4-7b. Seismic section showing anticline, monocline and syn-cline within the syn-rift succession (both the Heather and the Draupne formations). Location of the section on BCU time structure map (lower right corner).

Folds and monoclines are commonly observed within the formation along the strike of the fault (Figure 4-7a and Figure 4-7 b). In addition, a composite seismic line along the strike of ISF (Figure 4-8) show that there are scoop-shape features within the formation near the fault plane. These structural features are mostly observed in the hanging wall of ISF.

The lower boundary of the Heather Formation in the hanging wall areas of ISF, onlap/downlap/offlap ISF on the western side. On the eastern side, onlap/ toplap the Visund High and sometime locally drapes over the Visund High. The upper boundary, which is the Base Draupne reflector, is usually continuous and concordant. It onlaps/downlaps/offlap the fault plane to the west and onlaps/toplaps the Visund High to the east sometimes, however, locally drape over the adjacent high.

In northwest of the study area, the lower and upper boundaries onlap on a topography 2-3km away from MF. However, sometime locally drapes over the topography (Figure 4-9) Otherwise they are continuous.

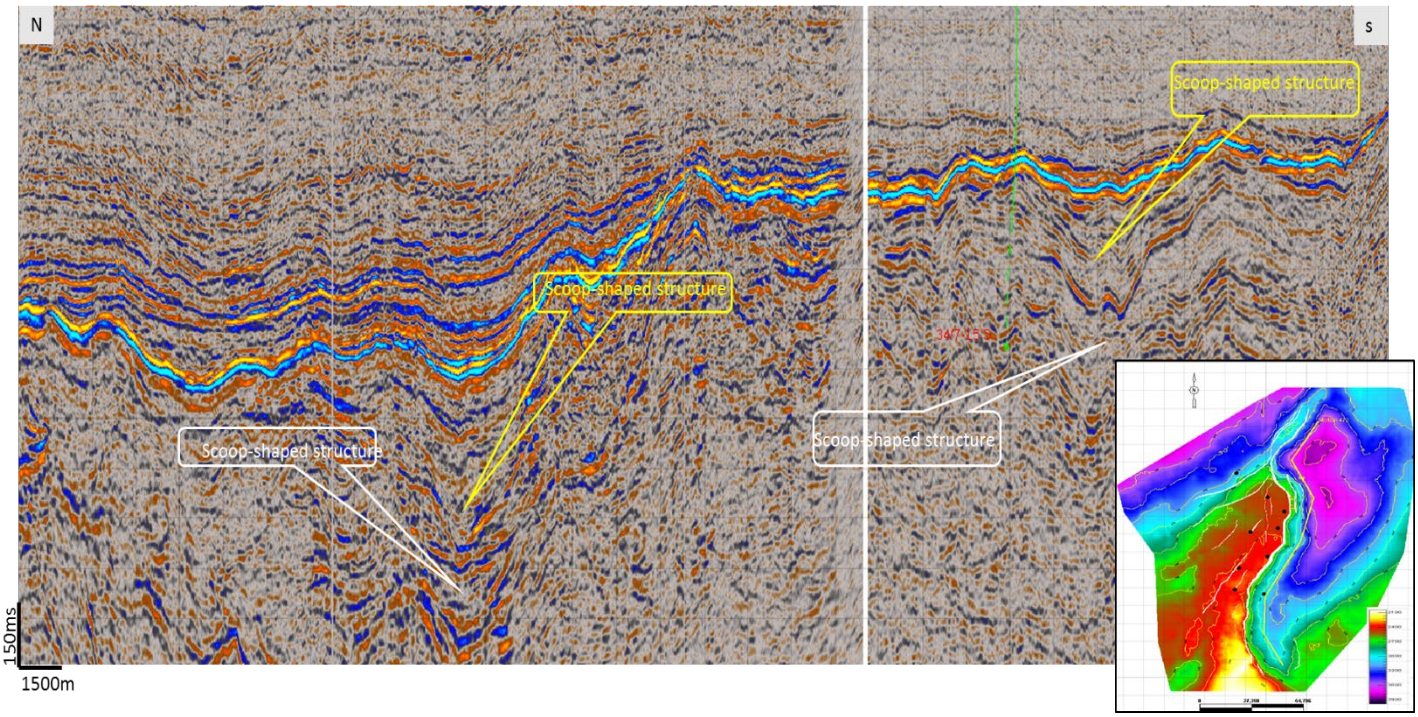


Figure 4-8 Un-interpreted seismic section showing scoop-shape structure within the syn-rift. (White-colored labels: related to the Heather Formation and yellow-colored labels are related to the Draupne Formation). Note variations in thickness, internal character and geometry of the Heather and the Draupne formations.

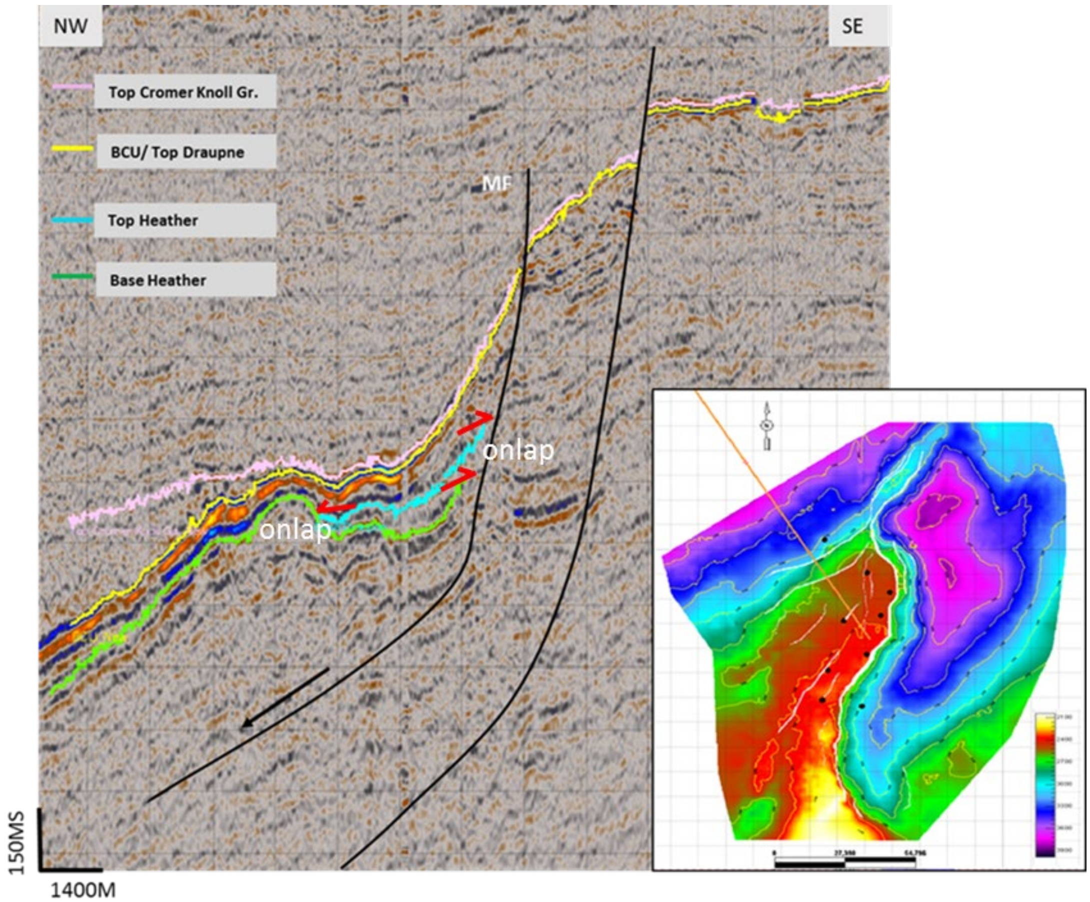


Figure 4-9 Seismic section showing the northwest structure. Note the stratal termination of the upper and lower boundaries. In addition, thickness of the syn-rift (the Heather and the Draupne formations) is relatively low.

Faults Description

Many normal faults that have influenced the Upper Jurassic and Lower Cretaceous Succession including the Heather Formation are observed in the study area. However, focus has been made on those faults that have had the main control on the geometry and the stratigraphy of the graben infill including the Heather Formation. Based on this, only main graben bounding faults (ISF and MF) and main faults that have only influenced the Heather Formation are described. The latter do not reach reflectors above the Heather Formation (Figure 4-10and and Figure 4-11)

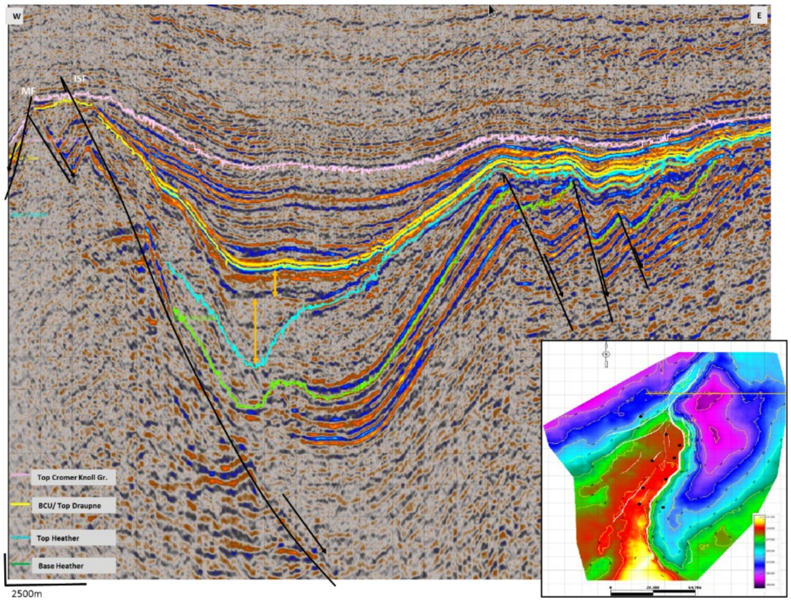


Figure 4-10 Seismic section showing faults affecting the Heather Formation. Orange arrows within the Draupne Formation is the two packages of the Draupne Formation (See Section seismic character of the Draupne Formation).

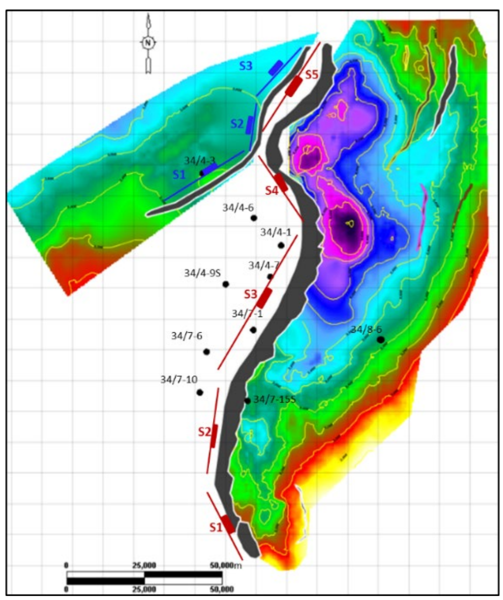


Figure 4-11 Time structure map for the Base Heather showing fault haeves. Wells in study area are also shown.

ISF as partly described in sections 4.4.1., is the most significant fault in the area. In cross sectional view, it is a curverd-shape normal fault (listric) (Spahic´ et al., 2011) that has a large throw with an average value of 1500msTWT at the Late Middle Jurassic level. The throw of ISF in Cretaceous succession is small and is in average value of 4msTWT (e.g. Figure 4-7). The throw changes also along the strike of the fault. In addition, the strike of the fault changes several times from south to north. According to this observation, five segments (S1-S5) are defined for the fault based on the strike of the fault in each segment on the map view (Figure 4-11).

F1 is a synthetic listric fault to S4 of ISF that at depth connects to ISF and detaches on the same detachments level (Figure 4-12).

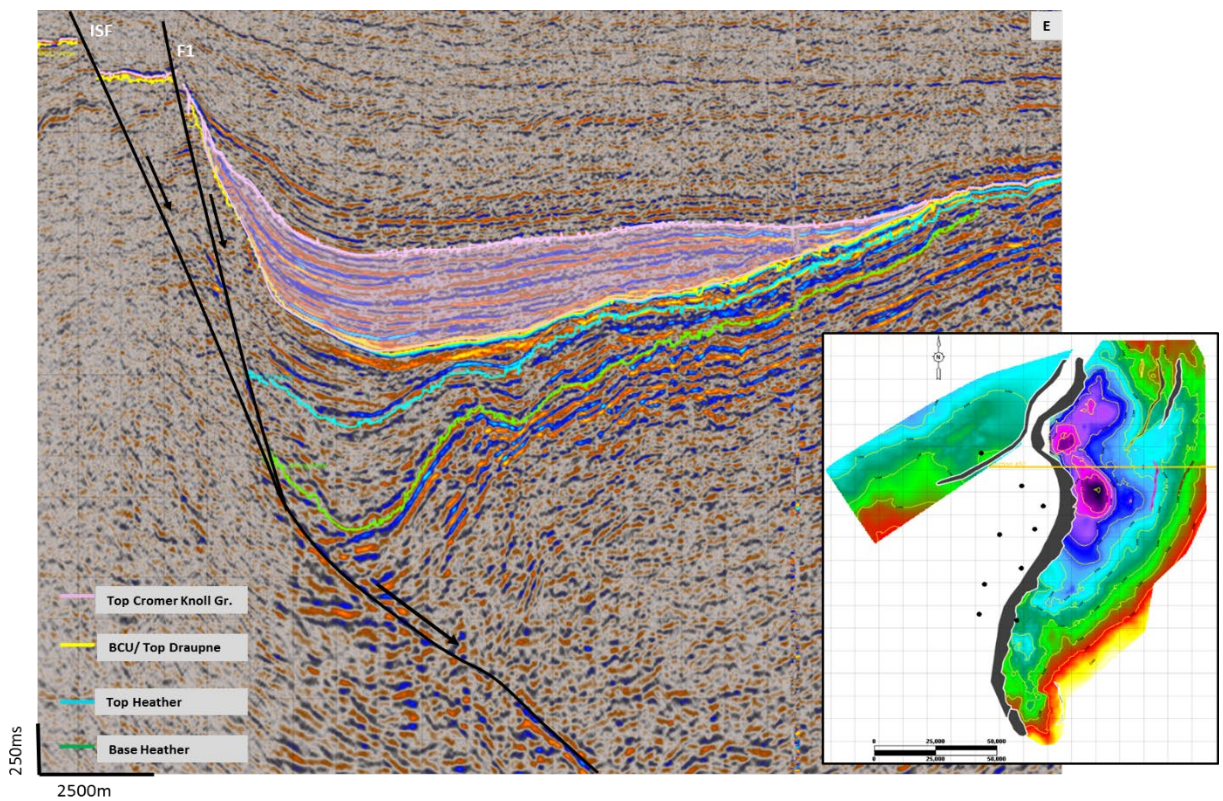


Figure 4-12 Seismic section showing F1 as a synthetic fault to ISF that detaches on the same level at depth. (F1 is hidden by ISF on map). Geometry of the Cromer Koll Group has been highlighted fort eh purpose of observations on the group in section 4.3.3.

The other major basin bounding normal fault as partly described in section 4.4.1, is Marebakk Fault (MF) in the northwest of the study area (Figure 4-10a and Figure 4-11). MF is also a listric fault with an average throw of minimum 500msTWT. The throw of this fault also changes in vertical and lateral directions. In addition, the strike of this fault is not constant too. Based on change in the strike of the fault, the fault is assumed that is composed of three segments (S1-S3) (Figure 4-11).

A group of normal faults exists in northeast of the study area that has only influenced the Heather Formation ((Figure 4-10a and Figure 4-11). They have a strike of NE-SW and mostly dipping towards east. They sometime extend from strata about 100 msTWT below the base Heather Formation up to the top Heather Formation. In very small area, some of these faults might reach Base Cretaceous Reflector.

Geometry of the Snorre High in immediate footwall of ISF and MF changes regularly. The geometry is sometime flat-topped, sometime rounded and sometime very sharp (Figure 4-13a and b). In addition, accordingly, the dip of the layers in the footwall of ISF and MF changes regularly (Figure 4-13 a and b). In general, the Snorre footwall is flat-topped and has higher elevation in the south in areas along S1 and S2 of ISF. Towards north, the footwall become rounded (along S5) and has lower elevation.

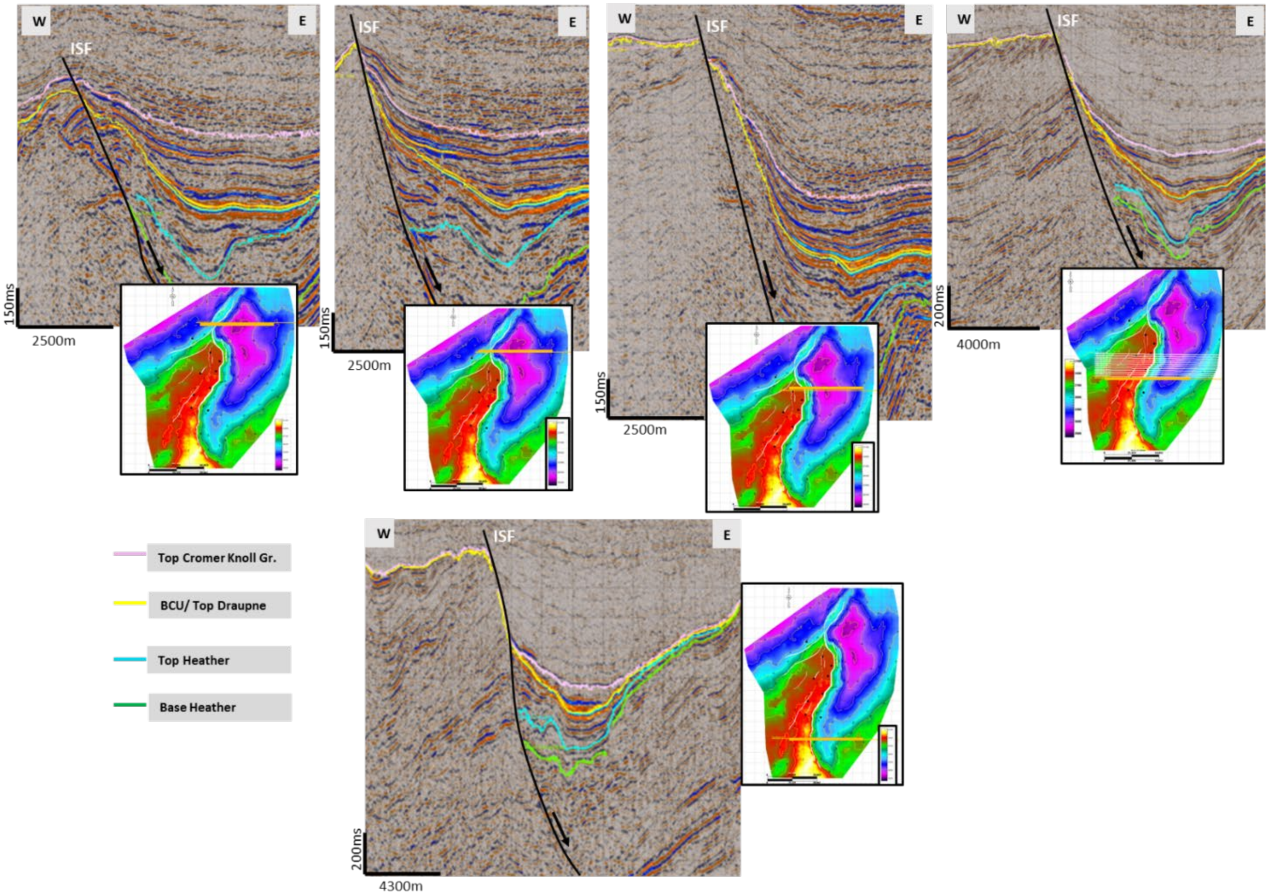


Figure 4-13 a. Seismic sections showing geometry of the Snorre footwall and the associated layering. Note changes in the geometry, internal character and thickness of the wedge from north to south.

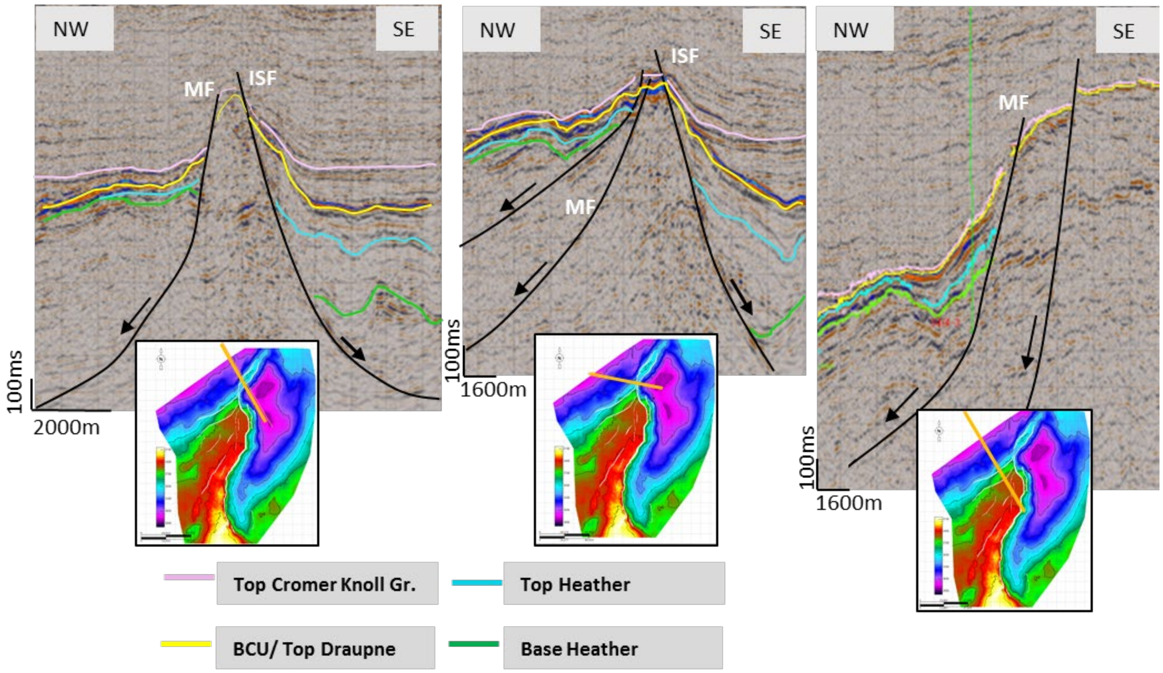


Figure 4.13b. Seismic sections showing footwall geometry along MF. Note changes in the thickness, internal character and geometry of the wedge northwest to southeast.

Seismic Facies Map

Figure 4-14 shows the seismic facies map of the Heather Formation. See table 4-3 and seismic character of the Heather Formation for complete information

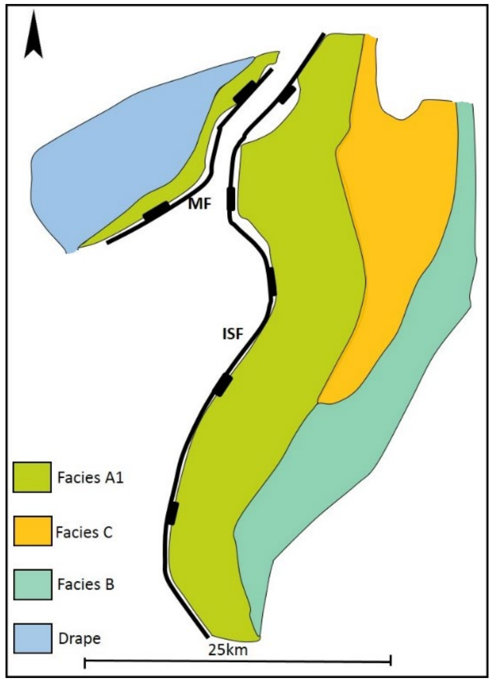


Figure 4-14 Seismic facies of the Heather Formation showing seismic facies observed within the formation. ISF and MF have their present-day configurations. Drape is not included in the facies analysis and is beyond the wedge limit in the northwest of the study area. The black arrow shows the north.

Time Structure and Thickness Maps

The time structure map for the base and top Heather Formation have been generated and have shown in (Figure 4-15a and Figure 4-15b). Time structure maps show that the Heather Formation is not present over the structural highs (the Snorre, the Visund and the Mort Horst) in the area. Time structure map of the base Heather reflector show that elevation is generally in the range of 2600ms in the shallowest part to around 4800ms in the deepest areas and for the top Heather reflector is in the range of 2600 until 4300ms TWT(downward direction is positive). Elevation increases towards ISF. Faults that offset the formation are observed on both maps.

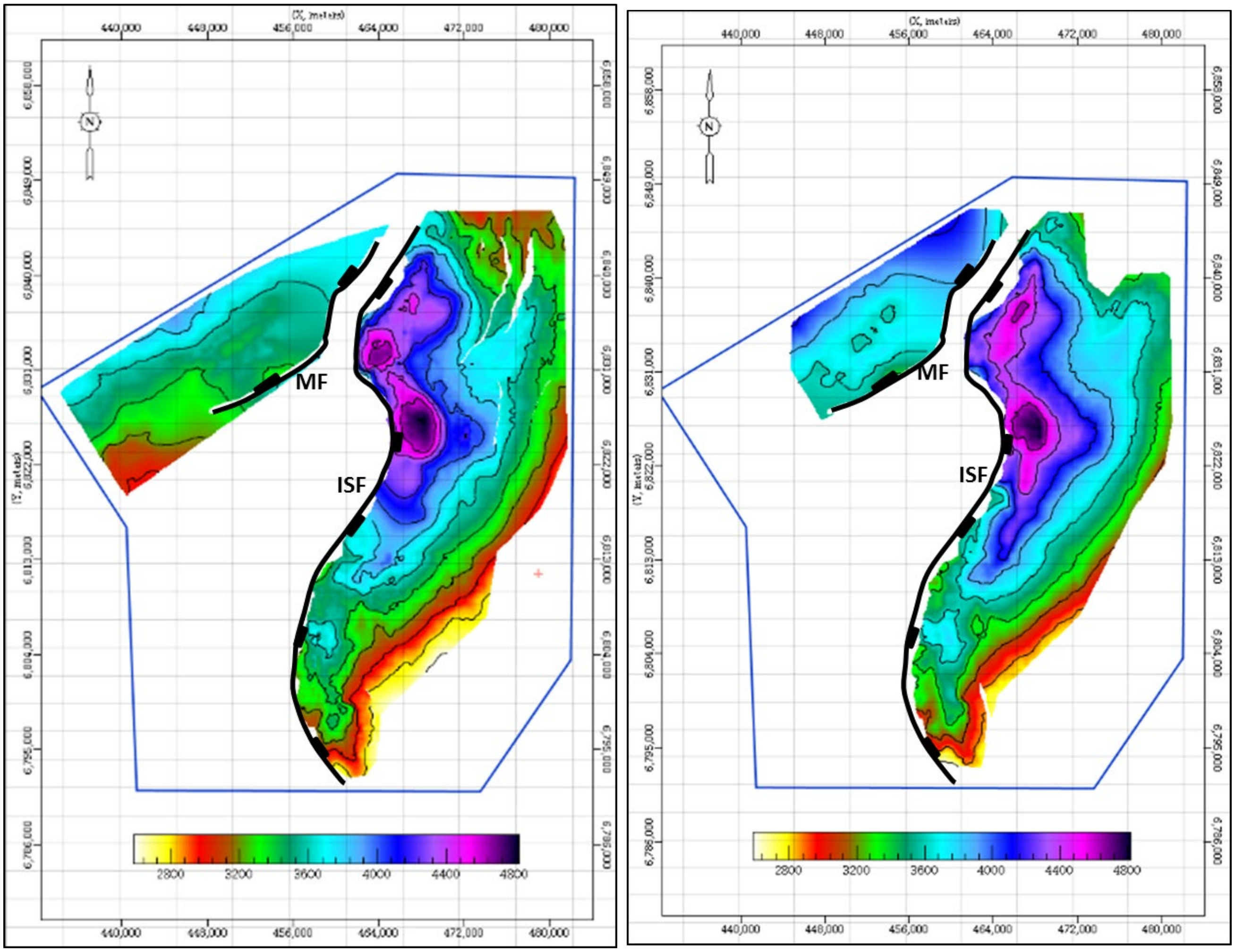


Figure 4-15a (left) and b (right) Time-structure map of the Base Heather reflector (left) and the Tope Heather Formation (right). The area marked with blue line is the border of the study area.

Time thickness map Figure 4-16 shows thickness variation of the Heather Formation across the study area that changes from 0 to 750ms TWT. Thickness increases towards main faults. Major and minor isolated depocenters are observed on the map. Major depocenters are located in the immediate hanging wall of segments three and four of ISF. Minor depocenters are located in the immediate hanging wall of segments one, two and five the ISF and segment one of MF.

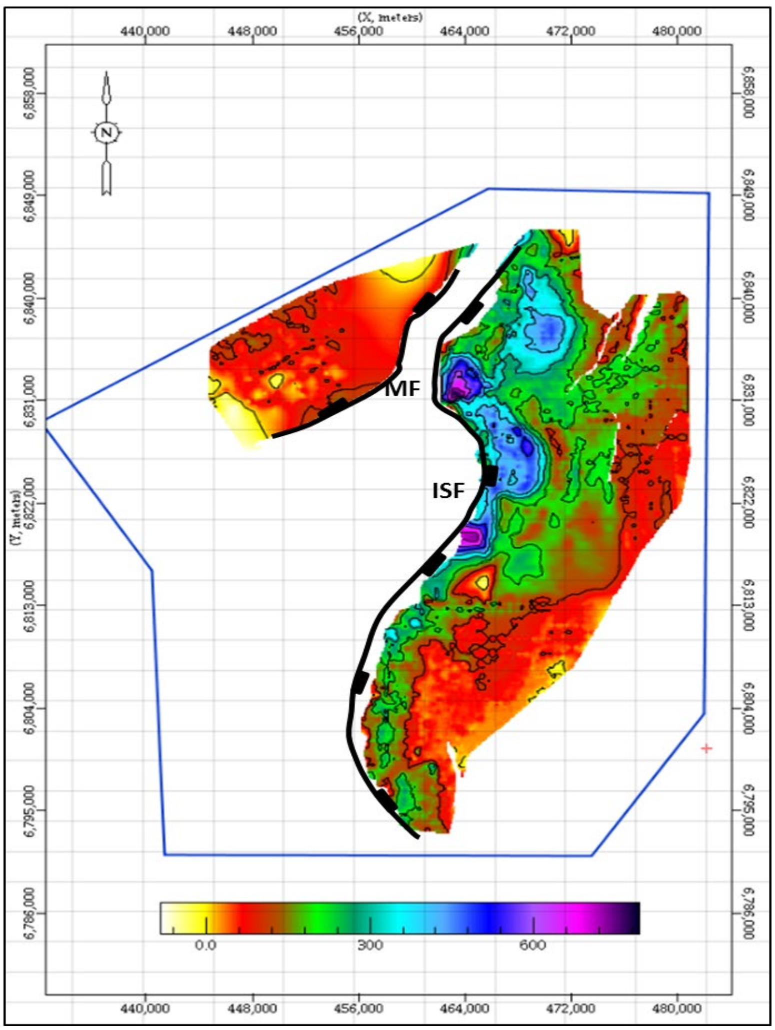


Figure 4-16 Time-thickness map of the Heather Formation. The area marked with blue line is the border of the study area

Interpretation

Well log signature of wells 34/4-3, 34/7-15S and 34/8-6 suggests that the Heather Formation consists mainly of fine grains heterolithic meaning that it has been deposited in marine environment. The change from low gamma ray (clean sandy facies) in the interval below the Heather Formation to higher gamma ray log values of the formation suggest onset of transgression (sea level rise) at the start time of deposition of the Heather Formation.

Regular lateral and vertical change in internal character and geometry of the Heather Formation (Figure 4-14, Figure 4-7and Figure 4-8) in combination with thickness variation (Figure 4-16) suggest an active tectonic setting during the deposition of the Heather Formation (Early Bathonian-Mid Oxfordian). In particular, seismic facies A1 with an overall thickening towards the main basin bounding faults suggest that the formation was deposited during fault-movement. Thus, fault activity greatly controlled sedimentation and geometry of the wedge and the formation in general. Therefore, the Heather Formation is interpreted as syn-rift deposits.

The toplap pattern of the Heather Formation on its eastern end (on the Visund High) suggests periods of erosion and non-deposition over the eastern highs after the deposition of the Heather Formation. The onlap and the discordant relationship of the formation with older strata over the Visund structure suggest that the Visund fault block has been tilted during the deposition of the Heather Formation (Færseth et al, 1995; Ravnås and Steel, 1998). Fault activity, in addition, has led to a great subsidence in the hanging wall areas (seismic facies A1). In addition

4.4.2.2 Draupne Formation (Mid Oxfordian- Ryazanian)

Observation

Well Character

Of all 10 wells in correlation panels, three wells 34/4-3 and 34/7-15S and 34/8-6 have encountered Draupne Formation. Structural and stratigraphic well correlation between wells 34/4-3, 34/4-6, 34/7-15S and well 34/8-6 (Figure 4-2, Figure 4-3), show that the Draupne Formation is absent in well 34/4-6 as stated in sections 4.1. In addition, structural well correlation in the Snorre footwall high, show that the Draupne Formation is not present over the entire Snorre footwall highs. The formation has been encountered in the interval of 3526- 3784MD in well 34/4-3, in the interval of 3440- 3855MD in well 34/7-15S and in the interval of 3477-3581MD. Gamma Ray log pattern in wells 34/4-3 and 34/7-15S looks similar and from base to top of the formation show packages of coarsening, fining, coarsening and again fining upward respectively (as is shown in the Figure 4-3). However, the GR log pattern is different in well 34/8-6. It has strongly high values with and shows a strong coarsening upward log pattern. Overall log pattern for the other two wells is also coarsening upward. Several thin intervals with low gamma ray log values are observed in wells 34/4-3 and 34/7-15S. The boundary with the formations at the base and top does not show a prominent change in case of wells 34/4-3 and 34/7-15S while it changes from lower values of GR in the heather Formation to strongly high values of the Draupne Formation in well 34/8-6.

Seismic Character

The Draupne Formation is present only in the hanging wall areas of ISF and MF. It is also present locally as a drape over the Visund Structure. The thickness of the Draupne Formation is not constant and its maximum value is about 700msTWT in areas next to segment three and four of ISF.

The seismic character of the Draupne Formation changes regularly along the strike of the main faults and in cross sectional view from east to west. The Draupne Formation in the hanging wall areas of ISF can be divided vertically into two distinct packages (shown in Figure 4-10 as an example). The uppermost reflector of the Draupne Formation is a high amplitude reflector that is observed over the entire hanging wall areas of ISF including the Visund High. This reflector is following the BCU reflector in the area. This subdivision of the Draupne Formation is not observed in northwest of the study area.

Two seismic facies were identified within the Draupne Formation: 1) seismic facies A1 (wedge): this seismic facies is always seen next the main fault. It is laterally a continuous feature along the strike of the main faults. The internal character, thickness and geometry of this facies changes regularly along the fault plane; and 2) seismic facies C: a chaotic seismic facies is commonly observed over the graben tail, up dip slope of the Visund structure.

As in the Heather Formation, folds and monoclines are observed within the formation (Figure 4-7a and b). In addition, a composite seismic line along the strike of ISF (Figure 4-8) shows that there are scoop-shape features within the Draupne, too (shown in yellow color labels on Figure 4-8).

In the northwest of the study area, the internal seismic character of the Draupne Formation is almost constant and it consists of only seismic facies A1. The formation is relatively thin (Figure 4-8).

The lower boundary of the Draupne Formation (the Base Draupne reflector) is continuous and concordant with the Heather Formation. The Base Draupne reflector onlaps/ downlaps/offlaps the fault plane to the west and onlaps/ toplaps over the Visund High in the east. However, in areas along to segments four and five of ISF, the Base Draupne reflector is continuous over the Visund High as a drape. The upper boundary is a continuous and high amplitude reflector that can be easily traced in all areas. However, in immediate hanging wall of major faults it is not really a reflector. In these areas, clear difference in reflectors dip is a guide to map this reflector. This reflector is the Base Cretaceous Unconformity (BCU).

In the northwest of the study area, the lower boundary (the Base Draupne reflector) onlaps the fault plane to the southeast and onlaps the small topography in the basin or the base Heather reflector. Otherwise, it is continuous toward southwest. The upper boundary corresponds to BCU reflector and is continuous.

Fault Description

Figure 4-18.shows the normal faults that have influenced the Draupne Formation. For a full description of the Draupne Formation faults, see section” fault description for the Heather

Formation" Those faults of the Heather Formation located in the northeast of the study area, have not offset the Draupne Formation.

Seismic Facies Map

Figure 4-18 shows the seismic facies map of the Draupne Formation. The formation consists of two main seismic facies. See Table 4-3 and seismic character of the Draupne Formation for complete information

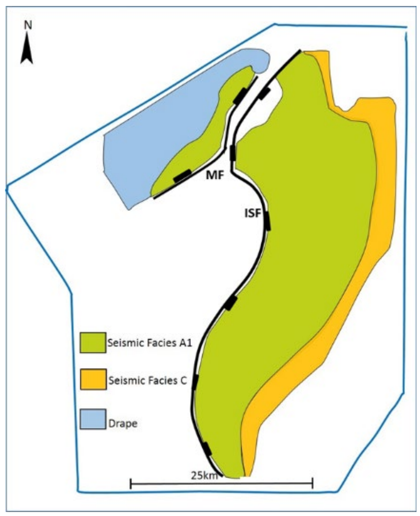


Figure 4-17 Seismic facies of the Draupne Formation showing seismic facies observed within the formation. ISF and MF have their present-day configurations. Drape is not included in the facies analysis and is beyond the wedge limit in the northwest of the study area. The study area is shown in blue line

Time Structure and Thickness Maps

The time structure map of top of the Draupne Formation (equivalent to Base Cretaceous) is shown in Figure 4-6. This is in fact the time structure map of the Base Cretaceous in the study area. The elevation in the hanging wall areas of ISF, ranges from 2500ms to 3900ms TWT and in the footwall areas ranges from 2000ms to 2600ms TWT. In the hanging wall areas of ISF, elevation increases from east to west (downward direction is positive). In the northwest of the study area, the elevation increases basinward and away from MF. The time- structure map shows the mapped fault to the Base Cretaceous level, too. It can be seen that with few exceptions, the strike of the faults in the study area (including the structural highs and the grabens) is NNE- SSW. Time-structure map of the Base Draupne Formation (equivalent to top Heather Formation) has been described in section 4.3.2.1.

Figure 4-18 shows the time thickness map of the Draupne Formation and it reveals thickness variation across the basin from 0ms to 700msTWT. Thickness of the Draupne Formation increases from east to west in the southern and northern wedge. The minimum thickness is across the Visund structure highs and along the border of the map in the northwestern areas in the Marulk basin. The maximum thickness occurs in depocenters near ISF and MF. Several depocenters are observed in immediate hanging wall of ISF and MF. The major depocenter is located in the area between segments three and four of ISF. Depocenters look more elongated.

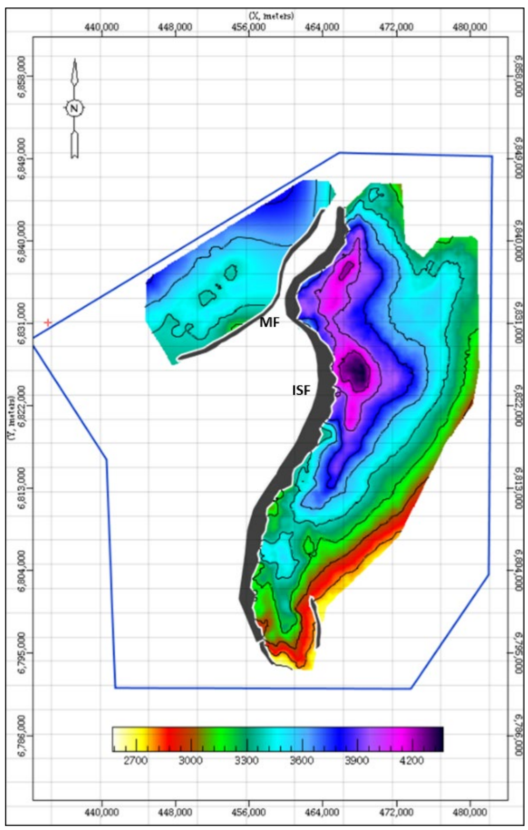


Figure 4-18 Time-structure map of the Base Draupne. Fault heaves. The area marked with blue line is the border of the study area

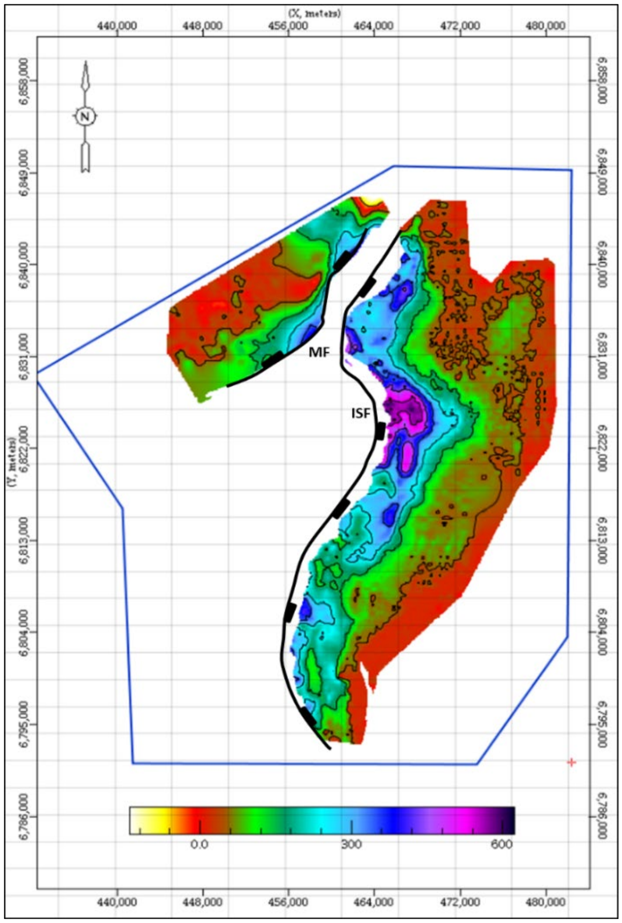


Figure 4-19 Time-thickness map of the Draupne Formation. Note the depocenters along ISF and MF.

Interpretation

Based on the GR log values and pattern the Draupne formation is interpreted as fine grained Formation that includes coarse-grained intervals. Core data from upper portion of the formation show turbidite sandstone with mudstone, slide and slump deposits representative of deep marine environment. Therefore, the formation is interpreted as has been deposited in a marine environment ranging from shelf to deep basin (GR, core and seismic facies)

Regular lateral and vertical change in internal character and geometry of the Draupne Formation (e.g. Figure 4-8, Figure 4-13a, and Figure 4-13b) in combination with thickness variation (Figure 4-19) suggest an active tectonic setting during the deposition of the Draupne Formation (Mid Oxfordian- Ryazanian. In particular, seismic facies A1 with an overall thickening towards the main basin bounding faults suggest that the formation were deposited during fault-movement. Thus fault activity controlled sedimentation. Therefore, the Draupne Formation is interpreted as syn-rift deposits

The toplap pattern of the base Draupne Formation on its eastern end (on the Visund High) suggests periods of erosion and non-deposition over the eastern highs after the deposition of the Draupne Formation. The onlap and the discordant relationship of the formation with Heather Formation over the Visund structure (locally) suggest that the Visund fault block has been tilted during the deposition of the Draupne Formation (Færseth et al, 1995; Ravnås and Steel, 1998). Fault activity and growth, in addition, has led to a great subsidence in the hanging wall areas (seismic facies A1).

Presence of two distinct packages and that both having seismic facies A1, within the Draupne Formation suggests two episodes of fault activity during the deposition of the formation. GR log pattern also supports this claim. Periods of tectonic quiescence (Nøttvedt et al., 2000a; Ravnås et al., 2000) were not observed!

Time thickness map of the formation and its comparison with time-thickness map of the Heather Formation suggest more fault activity during the deposition of the Draupne Formation. In addition, change in locality and geometry of the depocenters is an indication of different fault geometry (Figure 4-17 and Figure 4-19).

4.4.2.3 Top Cromer Knoll Group (Ryazanian- Albian/Early Cenomanian)

Observation

Well character

All wells in study area have penetrated the Cromer Knoll Group. Structural and stratigraphic well log correlation (Figure 4-2 and Figure 4-3) show that, the thickness of the formation generally increases from north to south over the footwall areas. The GR log values are normally less than 100API. The Gamma Ray log pattern shows variation is all wells. Wells 34/4-1 and 34/4-71 show an aggradational (blocky) pattern with a higher value pick at the top. Wells 34/7-6 and 34/7-10 show also similar GR log pattern with a generally fining upward motif. At least three similar packages are found within the two wells. The packages are thicker in well 34/7-10. Wells 34/4-6, 34/4-1 and 34/4-9S GR log show completely different irregular patterns. The lower boundary in the hanging wall areas, show a change from high GR, low sonic velocity to lower GR and higher sonic velocity. The lower boundary over the hanging wall areas show different characteristics.

Seismic Character

The characteristic of the Cromer Knoll Group is parallel and continuous reflectors across the entire hanging wall areas (Seismic facies D). The overall geometry of the Cromer Knoll Group is synclinal wedge in shape. However, the wedge geometry thins towards the ISF and the Visund High (e.g. seismic facies A2 and Figure 4-12). Over the Visund and the Snorre Highs, it is very thin. However, in some areas locally over the Visund (parallel to segments four and five of ISF), the thickness increases. Two seismic facies are observed within the Cromer Knoll Group: 1) Seismic facies A2. This seismic facies consists of low- high amplitude reflectors diverging basinward that changes to seismic facies D; and 2) seismic facies D which consists of low- high amplitude, highly continuous reflectors.

The lower boundary of the formation is the high amplitude, highly continuous Base Cretaceous reflector that covers the entire basin. The upper boundary onlaps the faults' plane and the Visund Structure. Otherwise, it is continuous.

Fault Description

In the hanging wall areas, the only major faults that have offset the Cromer Knoll Group are ISF, MF and F1. (See section fault description for the Heather Formation for the description of these faults).

Over the Snorre High, several normal faults have offset the Cromer Knoll Group (Figure 4-20). These faults dip either west or east. They sometime extend beyond the Cromer Knoll Group. The throw of these faults, however are very small and are in the range of 2-5 msTWT

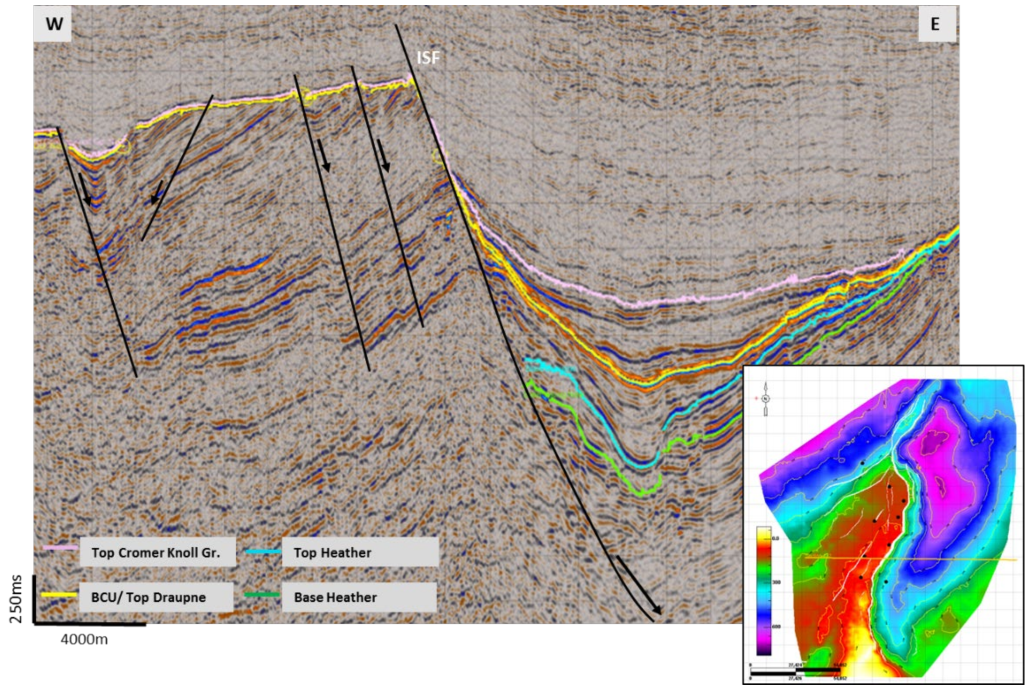


Figure 4-20 Seismic section showing faults that have offset the Cromer Knoll Group. Note the wedge geometry and thinning of the Cromer Knoll Group towards east and west in the hanging wall of ISF. Note also footwall geometry and layering in footwall below BCU. The location is shown on Cromer K. Group time-structure map (lower right corner)

Seismic Facies Map

The Cromer Knoll Group consists of two seismic facie. Seismic faceis analysis for the Cromer Knoll Gr. performed only within the graben areas, therefore, the seismic facies map does not show the formation over the Highs (Figure 4-21).

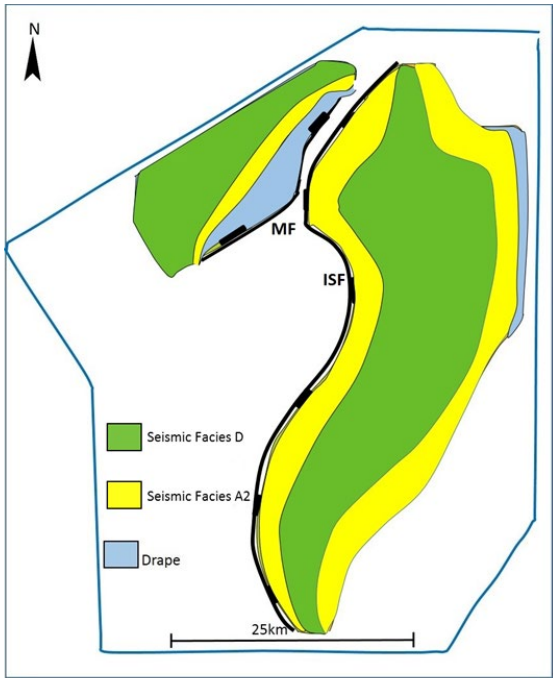
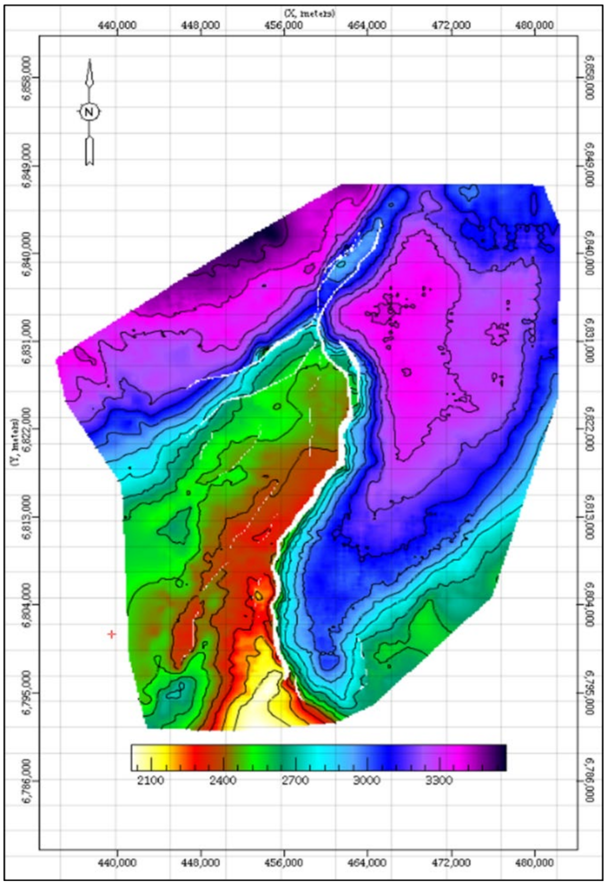


Figure 4-21 Seismic facies of the Cromer Knoll Gr. showing seismic facies observed within the formation. ISF and MF have their present-day configurations. Drape is the thin part of the group within the graben areas and is not included in the facies analysis. The study area is shown in blue.

Time Structural and Time Thickness Maps

The time structure map of the top Cromer Knoll Group reflector (Figure 4-22) show that the Cromer Knoll Group is present across the entire basin except along the fault scarp of ISF. Over the footwall areas of the Snorre and the Visund fault block, it is observed as a thin layer (average 20-30 msTWT thick) The time structure map shows that elevation ranges from 2100ms TWT in shallowest areas (Snorre footwall high) to almost 3600ms TWT in the deepest part within the northwest basin. In the northwest of the study area, elevation is increasing towards northwest. Faults affecting the Cromer Knoll Group are also observed in the time- structure map. As it is described for the BCU time structure map, faults show generally NNE- SSW strike in the time structure map of the Cromer Knoll Group top.

Time thickness map (Figure 4-23) shows thickness variation of the Cromer Knoll Group across the basin ranging from 10ms to about 500msTWT. The minimum thickness is over the Snorre and the Visund highs. The maximum thickness occurs in depocenters in areas parallel to segments four and five of ISF and away from the fault. In the northwest of the study area, depocenter is located in the northwest of the basin and far away from MF. In this area, thickness increases toward the northwest. In hanging wall of ISF, the thickness increases from east to west and from south to north.



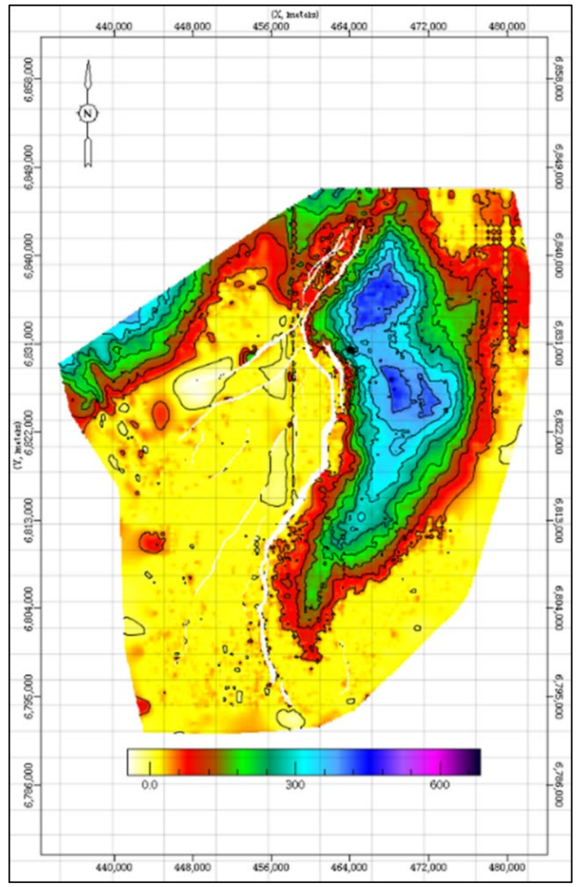


Figure 4-22(left) and Figure 4-23 (right) Time-structure map of the top Cromer Knoll Group reflector (left). Time-thickness of the Cromer Knoll Group (right). Note the location of depocenters

Interpretation

GR log values suggest that the Cromer Knoll Group consists of fine-grained sediments. The internal parallel and continuous reflector, uniform external geometry and minor fault activity within the group suggest that the group has been deposited in a tectonic quiescence setting.

However, presence of a northward deepening syncline in the group suggests a period of active subsidence during the deposition of the group. Because of minor fault activity during the deposition of the group, the subsidence in the basin is not associated with the faulting. The large thickness of the group in the graben shows a large accommodation space with a good sediment preservation potential. Large thickness and seismic facies analysis suggests a low energy marine environment of deposition.

Chapter 5

Discussion

5.1 Stratigraphic evolution

The syn-rift stratigraphy of the sedimentary wedges in this study includes the Heather and the Draupne formations known as the Viking Group in the North Sea. These formations have been deposited in a graben structure bounded by major faults and exhibit a wedge-shaped external geometry. Both formations have approximately equal thickness in the study area. The syn-rift stratigraphy has been bounded at the top and base by unconformities. The basal unconformity has been clearly recorded over the Visund High as suggested by toplap termination of the Base Heather reflector over the Visund structure.

Based on the GR log, the Heather Formation was deposited mainly as fine-grained in the study area (Figure 4-2 and Figure 4-3) in response to deepening of the basin due to created subsidence in the hanging wall of the fault and rise in sea level. In some very thin intervals, pulses in fault activity have been recorded with the influx of coarse-grained sediments. The on-going fault activity including the pulses have been accommodated by onlap to hanging wall up-dip slope and aggradation of the sedimentary packages in immediate hanging wall areas (e.g. Figure 4-7a and Figure 4-7b).

GR log suggest that the Draupne Formation is also a fine-grained formation with high organic content (suggested by strong GR spikes) that is recognized as the most prolific source rock (Kimmeridgian clay) in the North Sea (Figure 4-2 and Figure 4-3). Seismic facies A1, presence of large depocenters on time-thickness map, onlap stratal termination over the Visund High and its discordant relationship with the Heather Formation suggest that sediments deposited in response to increased fault activity with increased fault block tilt and footwall degradation (Figure 4-13a). GR log pattern (coarse-grained interval with low GR value) (Figure 4-2 and Figure 4-3) reflects two large pulses of fault activity recorded within the Draupne Formation reflecting intra-rift tectonic quiescence with the input of coarse-grained clastics (Ravnås et al., 2000). Large thickness of the formation with an aggradational pattern in immediate hanging wall areas and presence of major depocenter are indication of stronger tectonic activity during the deposition of the formation. This indicate that rift-climax has been at the time of deposition of the Draupne Formation.

Transition from the syn-rift to early post-rift is marked with cessation of the hanging wall tilt, decrease in regional subsidence (Prosser, 1993), change from divergence pattern of the strata away from fault in syn-rift (seismic facies A1) to parallel build-up (seismic facies D) and onlap of post-rift strata to the fault plane (seismic facies A2) (Nøttvedt et al., 1995) as clearly been recorded in the study area. The fine-grained Cromer Knoll Group (based on GR log values) (Figure 4-1, Figure 4-2, and Figure 4-3) deposited in a basin with a configuration and bathymetry inherited from last rifting event. The quiescence state of the basin during the deposition of the Cromer Knoll Group is accommodated by thinning of the Group towards the fault plane, the onlap of the Group on the BCU and the fault plane and the continuous parallel reflector (seismic facies A2) (e.g. Figure 4-6).

5.2 Fault development and interaction

The implication of fault growth and linkage on syn-rift stratigraphy has greatly been studied (e.g. (Dawers et al., 2000; Gawthorpe et al., 2003; Gupta et al., 1999; JACKSON et al., 2002). In my study, syn-rift stratal geometry and stratigraphy have clearly been controlled by growth of the anticlines, monoclines and escarpments because of fault activity (Figure 4-7a, Figure 4-7b; and Figure 4-13a and Figure 4-13b).

Early Syn-Rift: Early Bathonian- Mid Oxfordian (Heather Formation)

Time structure and thickness maps of the Heather Formation (Figure 4-15a, Figure 4-15b, and Figure 4-16) show that the maximum thickness (depocenter) of the formation occur in immediate hanging wall of the major basin bounding faults, particularly ISF. In addition, thickness of the formation decreases away from fault in a perpendicular direction to the fault plane. These observations suggest that thickness of the formation has been controlled by fault activity. Several major and minor isolated depocenters are observed along the strike of the fault. Minor depocenters are mainly located in the south of ISF (segments one and two). Major depocenters are located in the hanging of segment three and the area between segments four and five. These isolated depocenters are most probably in relation to individual fault segments and the glide of each segment (Kairanov et al., 2019). Based on these observations, it is concluded that at the time of deposition of the Heather Formation, ISF was in the form of five individual segments of 5-10 km long (Figure 4-11).

In case of MF, only a single minor depocenter is observed in the south of the hanging wall of MF meaning that at the time of deposition of the Heather Formation, only this segment of MF was present and active.

Late Syn-Rift: Mid Oxfordian- Ryazanian (Draupne Formation)

Time-structure and thickness maps of the Draupne Formation (Figure 4-18a, Figure 4-18b; and Figure 4-19) shows three depocenters in immediate hanging wall of ISF. The most prominent depocenter is located in the area between segments three and four. The other two depocenters are located one in the south in areas between segments one and two and one in the north in the hanging wall of segment five. These observations suggest that during the deposition of the Draupne Formation, most fault movements happened in areas between segments three and four. In addition, by comparing the Draupne and the Heather thickness maps, it can be concluded that there has been more fault movement during the deposition of the Draupne Formation.

In the case of MF, two minor depocenters exists in the hanging of each segment that are partially linked. This observation suggest that the two segments of MF have been active as isolated segments. However, by the end of the Draupne Formation, they have started to link.

Post-Rift: Ryazanian- Albian/ Early Cenomanian (Cromer Knoll Group)

Time-structure and thickness maps of the Cromer Knoll Group (Figure 4-6, Figure 4-22 and Figure 4-23) show that maximum thickness occurs in hanging wall areas parallel to segments four and five of ISF. The depocenters are not located in immediate hanging wall areas. In the case of

MF, the depocenter is located far from fault. In addition, thickness variation does not exhibit a particular relation to the faults. Moreover, seismic facies A1 exhibits thinning in areas next to ISF and show that thickness increases basinward and away from fault. These observations suggest that during the deposition of the Cromer Knoll Group, there was no fault movement. However, the fault have been reactivated, after the deposition of the Cromer Knoll Group (Figure 4-6 and Figure 4-22). The existing depocenters are most likely in relation to background subsiding basin as suggested by (Ravnas & Steel, 1998).

The analysis above which is based on structural and stratigraphic observations of the seismic data show that ISF and MF development follow the segment-linkage model (Figure 5-1) (Cartwright et al., 1995; Cowie et al., 2000). This model proposes that normal faults in extensional setting develop and propagate in three distinct stages.

Applying this model on my observation and interpretation above, I conclude that by the end of deposition of the Heather Formation (Mid Oxfordian) the initially created isolated segments (8-10 km long) of ISF and MF during the earliest stages of extension, continued to nucleate separately in each segment as suggested by minor and major depocenters in the hanging wall of segments (Figure 4-16 and Figure 5-2a). By the end of the Heather Formation, most fault activity centered on segments three and four as suggested by the time-structure map of the top Heather Formation that shows maximum elevation (downward is positive) in these areas. And time-thickness map also show major depocenters in these areas. In northwest of the study area, the two isolated segments of MF are also active as individual faults. The fault activity centered in the southern segment though there is not much fault movement in these areas in general (Figure 4-16). This stage of fault in the study area, can be recognized as mid-rift initiation as described by (Cowie et al., 2000).

By the time of deposition of the Draupne Formation (Ryazanian), the ISF segments, fully- linked as a fault array suggested by a large depocenter in the areas of segments three and four. The new system behaves as a through- going fault system with displacement and depocenters accumulated localized in areas around segments three and four (Figure 4-19 and Figure 5-2b). This corresponds to shift in fault activity towards the main area of linkage. This stage of fault development in the study area, is referred to as rift climax transition (Cowie et al., 2000). In my study area, this stage marks transition from syn- to post- rift.

During deposition of the Cromer Knoll Group, no fault activity occurred and the basin fell in a period of tectonic quiescence suggested by local depocenters in the hanging wall areas of ISF and MF but away from fault plane and the seismic facies A1 and D. However regional thermal subsidence (Gabrielsen et al., 2001) and eustasy (Prosser, 1993) controlled the development of depocenters as it witnessed by the location of depocenter in the Cromer Knoll Group far away from ISF (Figure 4-23and Figure 5-2c).

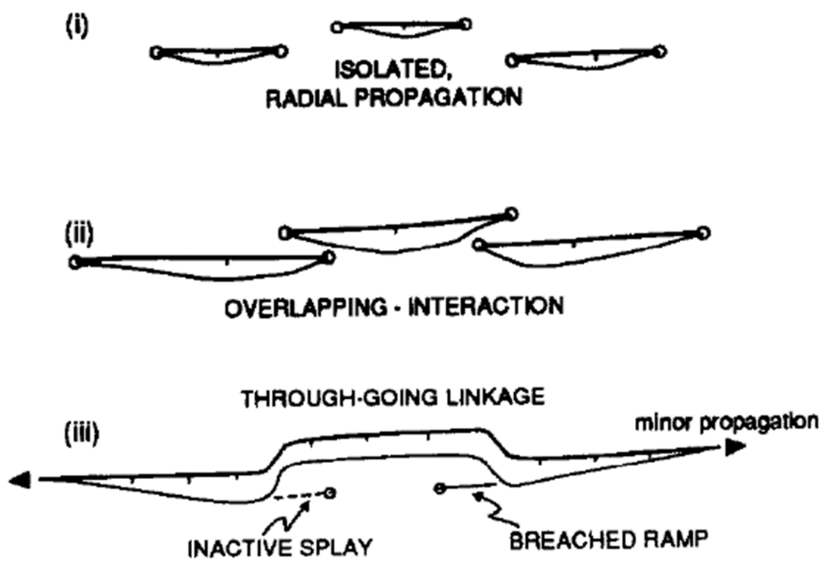


Figure 5-1 Segment-linkage model for normal fault development (map view) (Cartwright et al., 1995)

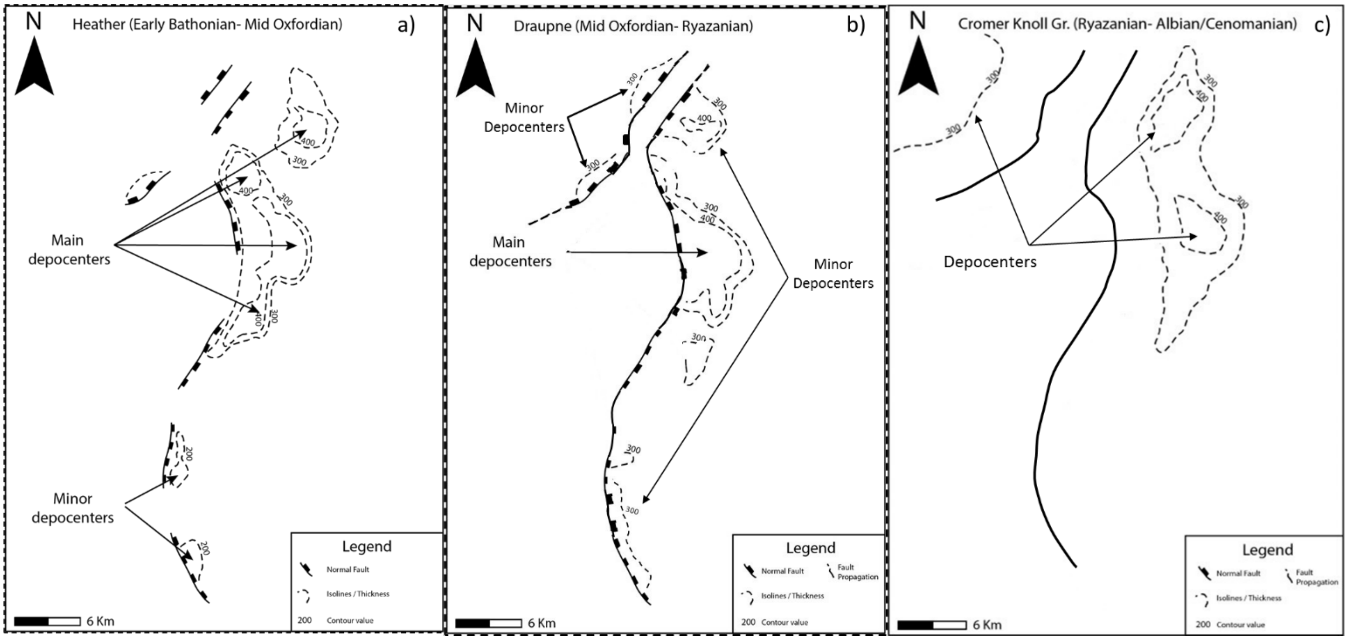


Figure 5-2 Fault development control on development of depocenters during the Late Jurassic-Early Cretaceous. Note that at the end of the Cromer Knoll Group, faults are not active.

Based on well and seismic data observations, the tectonostratigraphic evolution of the study area during the Late Jurassic-Early Cretaceous is presented as follow.

5.3 Paleogeography Maps

Tectonostratigraphic evolution of the study area during the Late Jurassic-Early Cretaceous (Late syn-rift to Early post-rift) is proposed based on the well, core and seismic data, is tied to studies by e.g. (Nøttvedt et al., 2000; Nøttvedt et al., 1995; Ravnås et al., 2000) and is summarized in paleogeography maps (Fig. 5.3 a, b and c).

Early Bathonian- Mid Oxfordian

The isolated normal faults' movement and associated subsidence together with sea level rise in the beginning of the Bathonian created a marine condition for the deposition of the Heather

Formation (Figure 4-2and Figure 4-3). The Heather Formation was deposited as a fine-grained heterolithic sediments in a NNE- SSW trending graben located between the Snorre and the Visund Highs. The continued fault movement led to the formation of wedge geometry in the immediate hanging wall of ISF. Stratal termination, discordant relationship of the Heather Formation with older strata, variations in footwall and associated layering geometries and lack of the Heather Formation over the footwall and hanging wall high areas (the Visund and the Snorre High) suggest that the fault activity also led to uplift and tilt of the Snorre and rotation of the Visund structures. The Snorre structure remained above sea level during the deposition of the Heather Formation suggested by aggradational pattern of the formation in immediate hanging wall of ISF. In the case of the Visund High, the structure might have remained above sea level as a footwall island in some periods during the deposition of the Heather deposition as suggested by local toplap of the upper and lower boundaries of the Heather Formation over the High. The absence of the formation over the southern part of the Visund High and very small thickness of the formation in the hanging wall dip-slope over the Visund High in these areas suggest that the southern part of the Visund structure, remained above sea level during the whole Heather interval. Therefore, the Snorre and the Visund Highs were the main source for the sediment input during deposition of the Heather Formation.

In northwest of the study area, not much fault activity is observed during the deposition of the Heather Formation as suggested by basin geometry, gentle dipping of the older strata below the Heather Formation, approximate horizontal layering of the older strata in the Snorre footwall, time-thickness and time-structural maps of the Heather Formation (e.g. Figure 4-9). The wedge geometry of the sediment infill and the graben structure similar to that in the hanging wall of ISF, has not developed in this area This suggest that, overally, this part of study area has not underwent a major fault activity and rifting during the deposition of the Heather Formation.

The Sediments of the Heather Formation were deposited in a range of shallow to deep marine environments as suggested by seismic facies (and seismic facies map), thickness maps and depocenters. Paleogeography map at the end of the Heather Formation (Figure 5-3a) shows the basin configuration at this time.

Mid Oxfordian- Ryazanian

The isolated fault's movement continued with higher rate into the rest of the Late Jurassic suggested by thicker and highly aggradational package in immediate hanging wall of ISF. This resulted in a more subsided deeper basin Therefore, the Draupne Formation deposited mostly as a fine-grained formation in a deeper basin. However, coarser grains and sandy facies were also delivered during periods of lower/ pulsed fault's movement as suggested by the GR log and the core data in upper part of the Draupne Formation. The Snorre footwall island remained certainly as the main source for sediment input during the deposition of the Draupne Formation.

Towards the end of the Early Cretaceous (Ryazanian), fault activity began to decrease. Therefore, subsidence and accommodation space tend to decrease too. Drape of the youngest Draupne reflector over the Visund High parallel to segments one, four and five of ISF is an indication of submergence of the Visund High The Snorre High, however, remained above sea level at the end of the Draupne Formation (Figure 3-2b) The latest Jurassic fault activity led to a large bathymetry in the hanging wall of ISF. However, in northwest of the study area, in the immediate hanging wall of MF very limited accommodation space was available for the later sedimentation. In these area, not much fault activity recorded in the basin during the deposition of the Draupne Formation as suggested by time-thickness and time-structural maps. Basin configuration, footwall geometry and layering support this claim. The wedge geometry of the sediment infill and the graben structure similar to that in the hanging wall of ISF, has not developed in this area

The Sediments of the Draupne Formation were deposited in a range of shallow to deep marine environments as suggested by seismic facies (and seismic facies map), time-thickness and time-structural maps and depocenters. Paleogeography map at the end of the Draupne Formation (Figure 5-3) shows the basin configuration at this time.

Ryazanian- Albian/ Early Cenomanian

The fault activity stopped by the Early Cretaceous. The marine condition of the Late Jurassic continued to the Early Cretaceous and the fine-grained calcareous (based on well log data) sediments of the Cromer Knoll Group deposited in a more subsiding marine basin inherited from the Late Jurassic fault activity (Figure 5-3c). However, over the structural highs, especially the Snorre High and the immediate hanging wall areas of MF due to very low accommodation space (shallow marine) a thin layer of the Cromer Knoll Group has the possibility to (Figure 4-9 and Figure 4-10 for example)

The low thickness of the Group as a drape in immediate hanging wall of MF suggests that there was not much bathymetry and therefore accommodation space was available for the deposition of the Group. This is turn reflect low fault movements during the previous rifting in the area. In this area, the Cromer Knoll Group deposited in a westward subsiding basin.

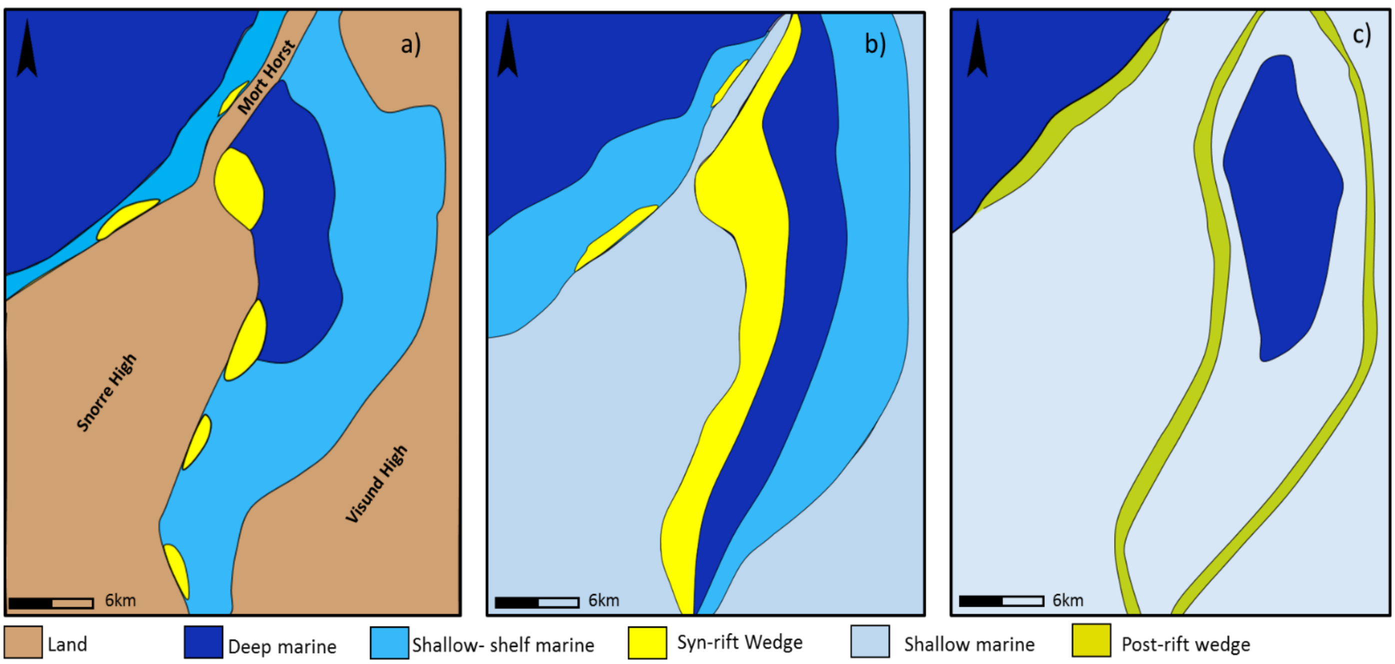


Figure 5-3 Paleogeography maps: a) top of the Heather Formation, b) top of the Draupne Formation; and c) top of the Cromer Knoll Group

Chapter 6

Conclusion

The study of the Late Jurassic-Early Cretaceous sedimentary wedges in the Snorre Fault Block and its surrounding areas, improves the understanding of the basin evolution during this time, particularly in the northern part of the basin that has not received much attention in literature. This study documents that successive extensional fault movements influenced the sedimentary infill and led to formation of wedge-shaped packages in the Snorre area. The main findings of this study are:

a) Two sedimentary wedges were identified in the study area. The main wedge is located in the hanging wall of Inner Snorre Fault whereas the wedge located in the hanging wall of Marebakk Fault is comparatively small.

a) Syn-rift stratigraphy of the wedges consists mainly of fine-grained sediments of the Draupne and the Heather formations deposited in marine environments. Coarse-grained intervals including sand-rich turbidites are present within the Draupne Formation. The type and style of sedimentation controlled mainly by fault movements. Intensive fault activity occurred during the deposition of the Draupne Formation

b) Post-rift stratigraphy of the wedge includes carbonaceous fine-grained sediment deposited in marine environment. The type and style of sedimentation was controlled mainly by inherited physiography from rifting and subsidence

c) Major basin bounding faults of the Inner Snorre Fault and the Marebakk Fault were the main controlling factor for the infill, geometry, and lateral extent of the wedges The faults have evolved through segments-linkage model during the Late Jurassic rifting event.

d) Fault activity occurred with a larger intensity in the hanging wall of Inner Snorre Fault relative to the hanging wall of Marebakk Fault. This implies that northwest of the study area has not undergone major rifting. In addition, the northern part of ISF (segments three and four) has been more active during the whole rifting time where major fault activity occurred.

e) At the end of rifting and termination of fault activity, the Snorre High which was above sea level through the whole rifting interval, drowned and was fully covered by water. The northern part of the high, towards the Mort Horst, was deeper at this time.

f) Basin configuration in the hanging wall of Marebakk Fault in northwest of the study area is different to that of the hanging wall of Inner Snorre Fault, suggesting possibly different structural style.

g) The late syn-rift and early post-rift successions of the study area have a good potential for oil exploration purposes as suggested by stratigraphy and structure of this deposits. Structural and stratigraphic traps are common trap types in the area. Thick reservoir (sandstone facies) and source rocks (shale/ mudstone) are also present.

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