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3D Geological Model of the Garn and Not Formations in Norne Field, Mid-offshore Norway

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Acknowledgements

I would like to express my gratitude as well as to dedicate this thesis to my beloved parents Armando and Dulce, without setting the right values of courage, determination, and perseverance, I would not have grown into the person completing this master's thesis. Also, I thank my dear brothers, Ardul and David, my dear sister in law Sandy, and my adorable nephew Alex for their support. All of you are at the core of my heart, all of you are my pride, and I thank you for always being there for me.

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abroad in this country; having the change to view the spectacular aurora borealis, experience the fantastic midnight sun, and breathe the purest of airs at the top of the Norwegian fjords, summarizes some of my wonderful and unforgettable Nordic experiences.

I did it!

Abstract

Norne Field is one of the hydrocarbon fields in the Norwegian Sea. This field has an area of approximately 9km x 3km which lies in the transition between two structural elements that are the Dønna Terrace and the Nordland Ridge. The main reservoir of Norne Field is in the Jurassic Sandstones. The hydrocarbons were mainly found in the Ile, Tofte, Garn, and Not Formations. This study will focus on the Middle Jurassic intervals which are the Not and the Garn Formations.

The objective of the study is to create a 3D geological model through the integration of well logs, cores, and 3D seismic interpretation to provide the better understanding of the geological settings, in which, depositional environments, fault network, and stratigraphy.

Garn and Not Formations are siliciclastic sediments deposited in the shallow marine environment. In the seismic data, the top of the Middle Jurassic reservoir is Top of Garn Formation in the northeastern part of the area and Top of Not Formation in the southwestern part. There is a facies change that is represented with a pinch out geometry observed in the seismic horizon interpretation and further confirmed by the well data, as well as by the seismic facies analysis. Two sources area has been predicted as the source of the sediment in these two formations. Based on the well log and core interpretation, the sediments in the Not Formation came from the southwestern source which prograded in the northeastern direction. The Garn formation is predicted to come from northeastern source area and prograded in the southwestern direction.

The structural setting of the Norne Field is dominated by extensional structure. One horst block which was predicted formed around the late Middle Jurassic until the Early Cretaceous formed the major structure of the Norne Field. The major faults in the study area are oriented NE-SW with some minor fault oriented NW-SW.

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Chapter 1

Introduction

Norne is located on the Nordland II area of the Norwegian Sea region, in blocks 6608/10 and 6508/1. The field has an area of approximately 9km x 3km which lies in the transition between two structural elements that are the Dønna Terrace and the Nordland Ridge, close to the Revfallet Fault Complex as seen on figure 1.1. This project aims to use real subsurface oil field data from the Norne field released by the Norwegian Petroleum Directorate to perform a geological study of the Middle Jurassic formations within this field.

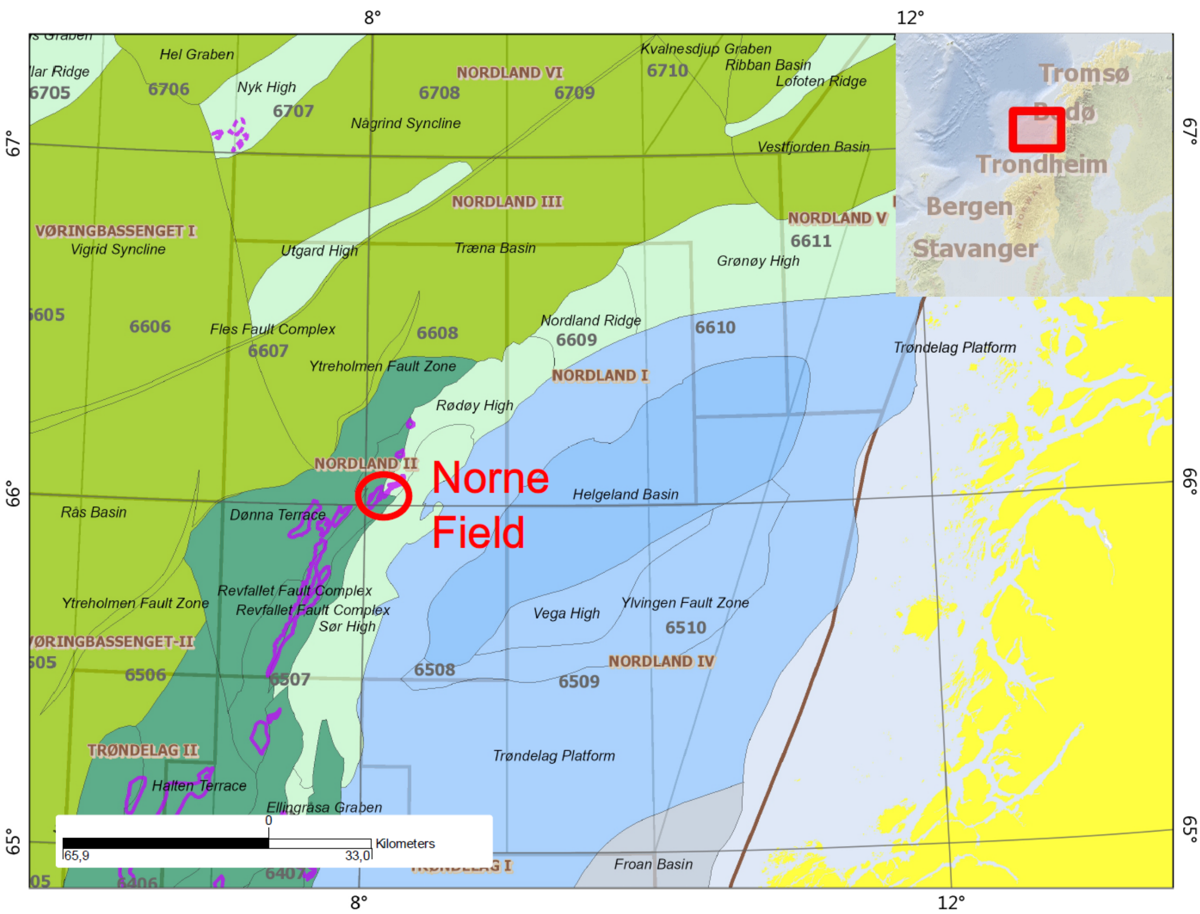

Figure 1.1: Location of the Norne Field, on the Norwegian Sea region. The field is located in the transition of the Dønna Terrace and the Nordland Ridge, in the area of the Revfallet Fault Complex, modified from NPD (2015).

The main goal of this study is to create a 3D geological model through the integration of well logs, cores, and 3D seismic interpretation of Norne Field. The resulting 3D geological model aims to provide a better understanding of the geological settings of these Middle Jurassic formations, in which, depositional environments, fault network, and stratigraphy.

The two formations that are studied in detailed for the geologic model are the Middle Jurassic Not Formation and the Middle Jurassic Garn Formation which belong to the upper part of the Fangst Group. These formations are Aalenian to Early Bathonian in age (Dalland et al., 1988).

Although studies been done on the Fangst Group type area, i.e., the Halten Terrace, this thesis offers an understanding of the distribution of the Not and Garn formations North of the Halten Terrace, about 80 km north of the Heidrun field. Furthermore, this study is also valuable to understand the geological settings of the field in three dimensions. Understanding the geological settings of a field plays a key factors for reservoir engineering efforts.

The 3D geological model is achieved by the accomplishment of the following objectives:

1. Norne well log interpretation using Petrel software for lithology estimation and depositional environment interpretation.

2. Formation and lithological well correlations.

3. Examination of available core images, integration with the formation and lithological correlations, and definition of sedimentological electrofacies of the Not and Garn formations.

4. Loading and interpretation of the seismic data from Norne field, and perform seismic well ties, seismic interpretation of faults, and seismic interpretation of horizons.

5. Implementation of horizontal slicing, seismic attributes analysis, seismic facies analysis of the Garn and Not formations.

6. Combination of all of the above for the creation of a geologic model of the upper Fangst group in the Norne area. Conclusion on the Not and Garn lithology distribution, depositional environments, and possible recreation of a paleogeography map for the Norne area based on the compilation of the completed objectives of this study.

Chapter 2

Geological Background

The study area of this thesis is the Norne field which is located offshore Norway, on the mid-Norwegian margin. First, this chapter briefly outlines the geological evolution of this margin, then it transitions into the Jurassic tectonic settings, emphasizing on the Dønna and Halten Terrace areas and on the upper Fangst Group interval.

2.1 Tectonic Setting

The mid-Norwegian margin is situated within the Norwegian continental shelf between the latitudes 62°N and 69°30'N and it contains various basins that have their distinct tectonic history and structural style (Ziegler et al., 1986). The mid-Norwegian margin was described by Blystad et al. (1995) as a rifted passive continental margin with plate tectonic episodes ranging from the Caledonian Orogeny to the break-up of the North Atlantic.

The Caledonian Orogeny marks the beginning of the tectonic evolution of the mid-Norwegian margin and also the first stages in the development of the Halten and Dønna Terraces, which can be traced as far back as the earliest Devonian Period, when the Iapetus Ocean closed as Norway was sutured to Greenland (Baltic to Laurentia). The Caledonian tectonic activity started during the Early Devonian, and the suturing took place along a series of north-easterly aligned zones with an axis that corresponds to the present Norwegian-Greenland Sea(Gage and Doré, 1986). The continental convergence between these two plates, resulted in obduction of oceanic crust, continent-continent collision with lithospheric thickening and finalized with the development of a large shear zone (Swiecicki et al., 1998). Later, this shear zone was reactivated when the convergent tectonic regime was replaced with an extensional tectonic regime, during the Norwegian-Greenland Sea rifting system that occurred in Carboniferous times.

Several authors, i.e. (Blystad et al., 1995; Brekke et al., 2001; Ziegler et al., 1986; Gage and Doré, 1986; Swiecicki et al., 1998), have presented an overview of the tectonic evolution of the mid-Norwegian region within two major plate tectonic episodes, from the Caledonian Orogeny until the break up of the North Atlantic. The tectonic history that dominated the area after the Caledonian Orogeny has been divided slightly different by several authors, though they all agree in that the mid-Norwegian margin has been dominated by extensional events following the Caledonian Orogeny:

Blystad et al. (1995) divided the tectonic history of the area into two extensional events: the Late Devonian to Paleocene, and the early Eocene to Present. Brekke et al. (2001) divided the tectonic history into three main rifting episodes: Early Carboniferous to Middle Triassic times, Middle Jurassic to Late Cretaceous times, and Late Cretaceous/Early Tertiary times. Ziegler et al. (1986) presented two main phases with extensional structural style: Middle Permian to Late Cretaceous times, and the Eocene to present.

The Jurassic Period falls under the Blystad et al. (1995) and Ziegler et al. (1986) first episode of extension, and under Brekke et al. (2001) second episode of extension.

A sea-level rise commenced during the late Triassic and continued into the early Jurassic. This sea-level rise led to the development of a seaway in between Norway and Greenland, where the Boreal Sea was connected with the Tethys Ocean (Nøttvedt et al., 2008). This seaway influenced the stratigraphy of the area with a shallow clastic marine shelf environment. The Late Triassic and Early Jurassic seemed to have been a quiet tectonic period except during the Sinemurian/Pliensbachian time, when NNE trending growth faults may be observed to have detached Triassic sediments(Blystad et al., 1995). Seismic and well evidence of mid-Norway suggests that only minor tectonism occurred during the Early to Middle Jurassic, further confirming that this was a relatively quiet tectonic period (Swiecicki et al., 1998). The minor Early Jurassic growth faulting possibly ceased after the deposition of the Lower Jurassic Tofte Formation. Tofte deposit was followed by the deposition of the Middle Jurassic Fangst Group (including the Ile, the Not, and the Garn Formations) during a period of tectonic quiescence through Aalenian, Bajocian, and most of Bathonian times of the Middle Jurassic (Blystad et al., 1995).

The late Bathonian time was a transition period from quiet tectonics into a tectonically active late Middle Jurassic-Early Cretaceous rifting as seen on figure 2.1.

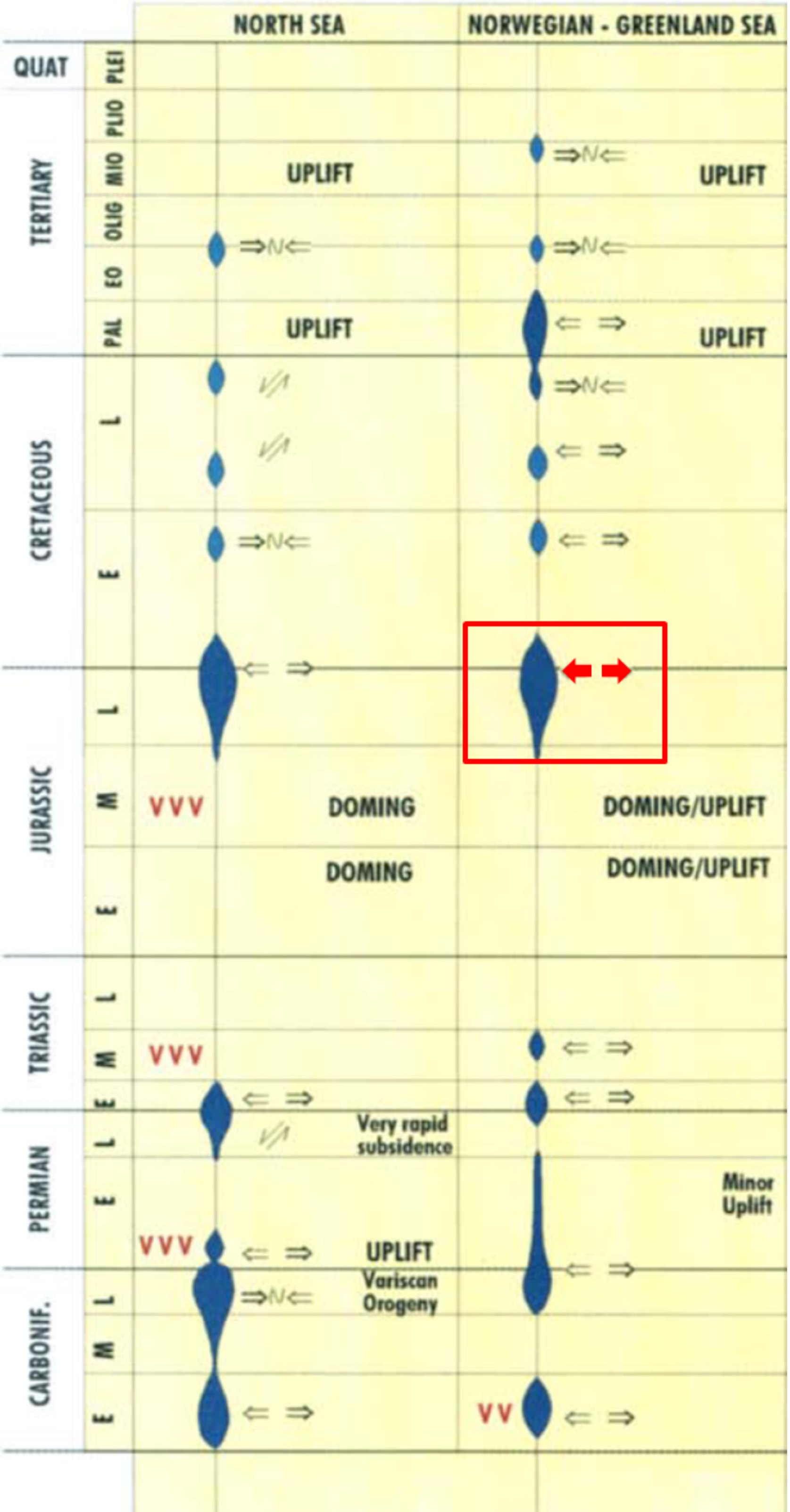

Figure 2.1: Tectonic and magmatic evolution of the Norwegian and North Seas, blue patches indicate timing and duration of tectonic events, red v indicate timing of significant magmatic events, arrows indicate sense of tectonic movement: extension, compression, or strike-slip movement. The red box highlights the late Middle Jurassic-Early Cretaceous active rifting period (red arrows highlight extensional movement); modified from Brekke et al. (2001).

As far as the study area goes and according to Brekke et al. (2001) 2000, the Dønna and Halten Terraces were created by faulting during this active Late Jurassic time, and also at this time these terraces were at the same height as the Trøndelag Platform. The active Jurassic period of rifting was further divided by Blystad et al. (1995), into three episodes: Bathonian/Callovian time, Kimmeridgian time, and Neocomian time. During the Bathonian/Callovian and Kimmeridgian time, the Halten and Dønna Terraces constituted the western and tectonically most active parts of the Trøndelag Platform with pronounced flexuring and faulting taking place on the eastern flanks of the Møre and Træna Basins (Blystad et al. (1995). The further separation of the Trøndelag platform from both terraces occurred during the third episode of rifting (Neocomian).

2.1.1 Structural Elements

The Norne field lies on a horst block at a depth of 2500-2700 meters. The structural elements of the Norwegian continental shelf are presented on Figure 2.2, where the location of the Norne field is highlighted. The Norne field is located in the transition between two structural elements which are the Dønna Terrace and the Nordland Ridge, at the Revfallet Fault Complex area.

Figure 2.3 presents a SE-NW profile section (A-A') beginning at the Trøndelag Platform, crossing near the Norne field, and ending towards the Vøring High. This profile illustrates the Dønna Terrace and the Revfallet Fault Complex as part of the Vøring Basin, and the Nordland Ridge as part of the Trøndelag Platform. Bordering the study area to the south, the Halten Terrace is found. The Halten Terrace area is important for this study because it is the type area of the Middle Jurassic Fangst Group, where its two upper formations (the Not and the Garn) are the main interest of this thesis study.

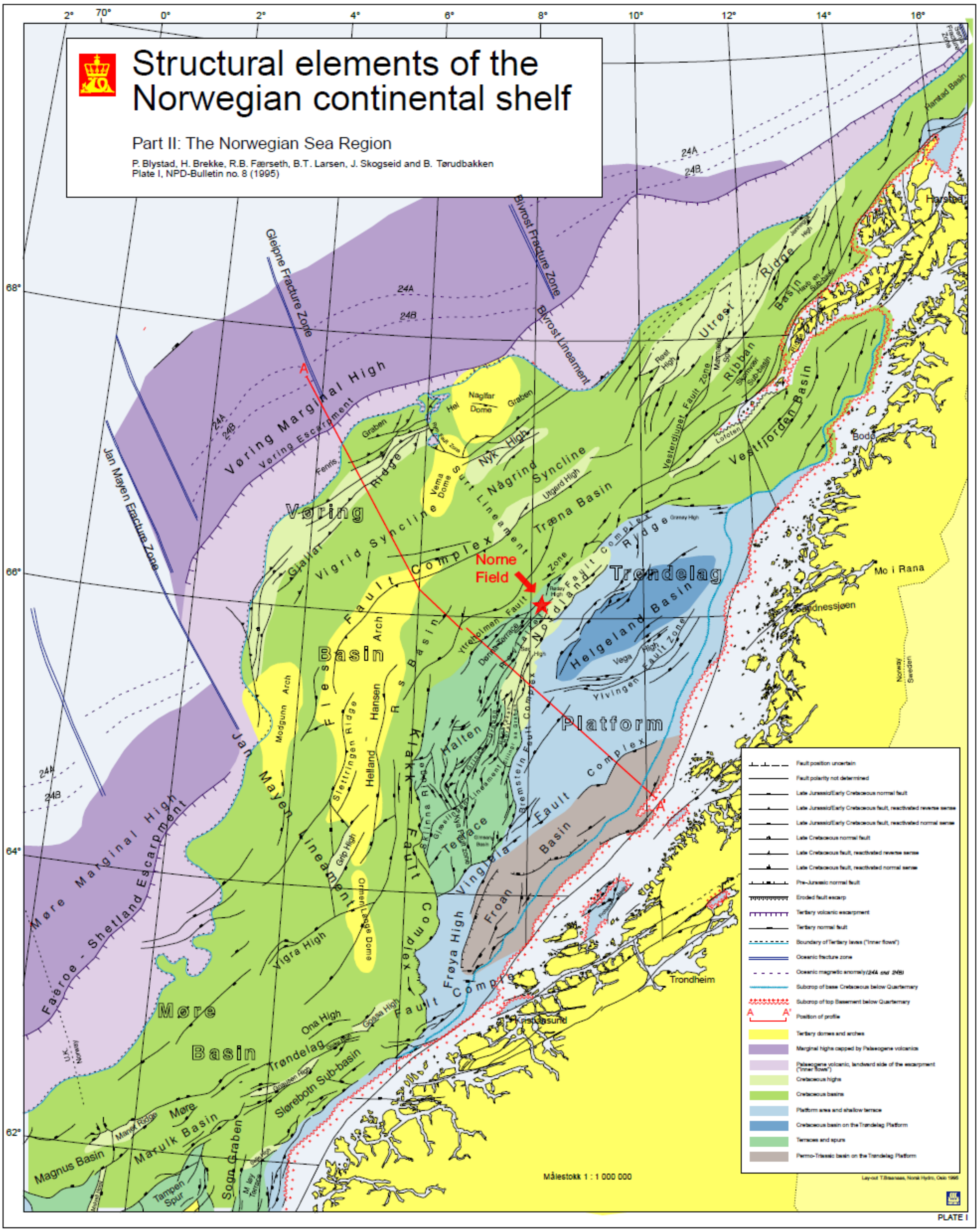

Figure 2.2: Structural elements of the mid-Norwegian margin, with the location of the Norne field, and with profile line A-A' close to the Norne area; modified from Blystad et al. (1995).

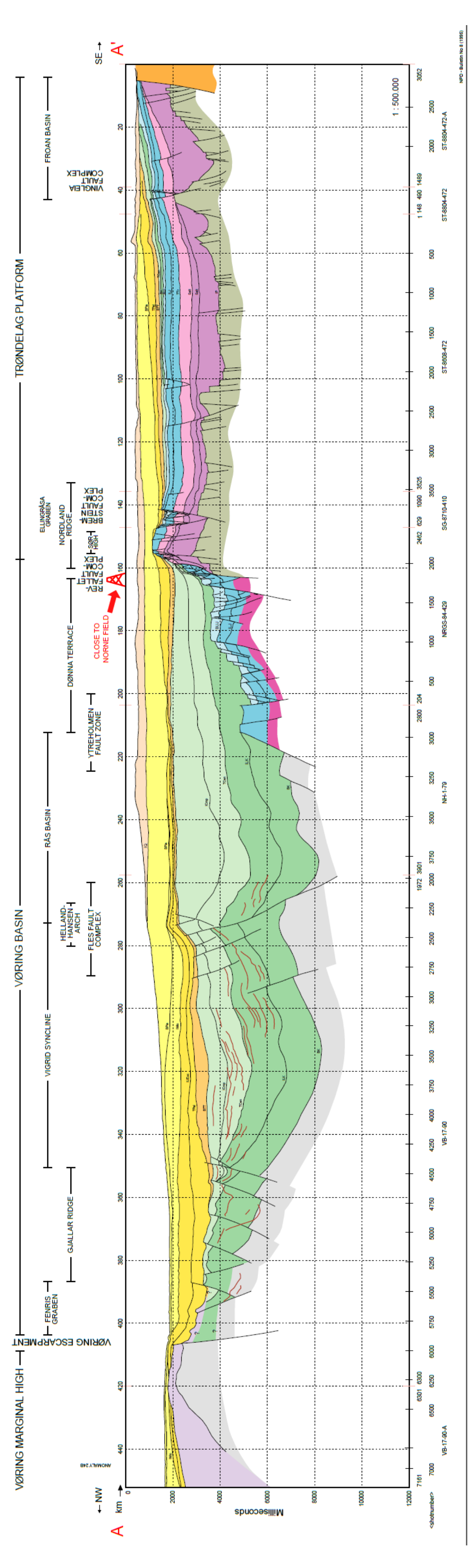

Figure 2.3: Profile across the mid-Norwegian margin, close to the Norne Field (refer to legend in figure 2.2), modified from Blystad et al. (1995).

The following descriptions of the structural elements that surround the Norne field area are based on Blystad et al. (1995):

Dønna Terrace

The Dønna Terrace is located at 65°20'N - 66°30'N and 6°40'E - 8°30'E, between the Revfallet Fault Complex to the east, the Ytreholmen Fault Zone to the west, the Halten Terrace to the south, and the Rødøy High in the north. The terrace is cut by faults that form local horsts, grabens, and rotated fault blocks. A thick Jurassic sequence composed of sediments from the Båt, Fangst and Viking groups got deposited, overlaying Upper Triassic sediments.

Revfallet Fault Complex The Revfallet Fault Complex is located at 65°15'N - 66°50'N and 7°E - 12°E, at the boundary between the Dønna Terrace to the west and the Trøndelag Platform to the east. In the southern part, the fault is composed of westerly-dipping, en echelon normal faults oriented NNE-SSW. In the north part, this fault complex a downflexed slope, where Cretaceous basin sequences onlap, indicating that the Revfallet Fault Complex formed in the Late Jurassic-Early Cretaceous due to the crustal stretching and subsidence during the rift episode.

Halten Terrace

The Halten Terrace is located at 64°- 65°25'N and 6°E - 7°40'E, between the Trøndelag Platform to the east, the Rås Basin to the west, and the Dønna Terrace to the north. Moreover, the terrace merges into the narrower Dønna Terrace towards the north. This terraces started to form at the same time as the Dønna Terrace, that it, during the late Middle Jurassic-Early Cretaceous rifting phase. The terrace has normal faults of different ages and trending N-S and NNE-SSW.

Trøndelag Platform

The Trøndelag Platform The Trøndelag Plaform is located at 65°15'N - 66°50'N and 7°30'E - 12°30'. It is bounded by the Revfallet Fault Complex (along the Nordland Ridge) to the north and west separating it from the Træna Basin in the North, the Dønna Terrace in the south, and the Halten Terrace further south. The Platform was created during the late Middle Jurassic-Early Cretaceous rifting episode when the Nordland Ridge and Frøya High were uplifted.

The Nordland Ridge

The Nordland Ridge is a subelement of the Trøndelag Platform, and is located at 65°15'N - 66°50'N and 7°30'E - 12°30'E, between the Revfallet Fault Complex to the west and the Helgeland Basin to the east. The ridge is characterized by an unconformity which makes up a major hiatus, where rocks that are truncated by the unconformity vary from Late Permian to Jurassic in age.

2.2 Stratigraphy of the Fangst Group

The Middle Jurassic Fangst Group includes the Ile, Not, and the Garn Formation, as seen on the Lithostratigraphic chart of the Norwegian Sea made by the Norwegian Petroleum Directorate (NPD). 2.4. As mentioned before, the type area for this group is located in the Halten Terrace.

On Aalenian to early Bajocian time, two regression- transgression cycles occurred. The first cycle was started with a regressive, shallowmarine, prograding eastward shoreface sandstone of the Ile Formation; followed by the deposition of a transgressive, shelfal mudstones of the lower Not Formation (Swiecicki et al., 1998). At about 80km south of Norne, in the Heidrun field area, this Ile-Not boundary is described also described by Whitley (1992) as a transgressive-regressive boundary that can be regionally well recognized.

The second cycle of regression-transgression occurred in the late Bajocian to mid Callovian age, starting with a deltaic to shoreface sandstones of the middle Not and Garn formations; succeeded by the open marine claystones of the lowest Melke Formation (Swiecicki et al., 1998).

Harris (1989), describes the Not as a thin marine shale or mudstone with a marine muddy sandstone to sandstone unit above, with bioturbation in all units indicating a deposition in a quiet-water marine shelf and this coincides with the depositional environment proposed by Dalland et al. (1988) for the Not formation, i.e., lagoonal or sheltered bays for the lower Not and prograding deltaic to coast front sediments for the top of this unit.

In the Halten area, the Garn Formation is classified as almost entirely sand, with thicknesses ranging from 14 to 144m, with a regressive sequence character of which deposition

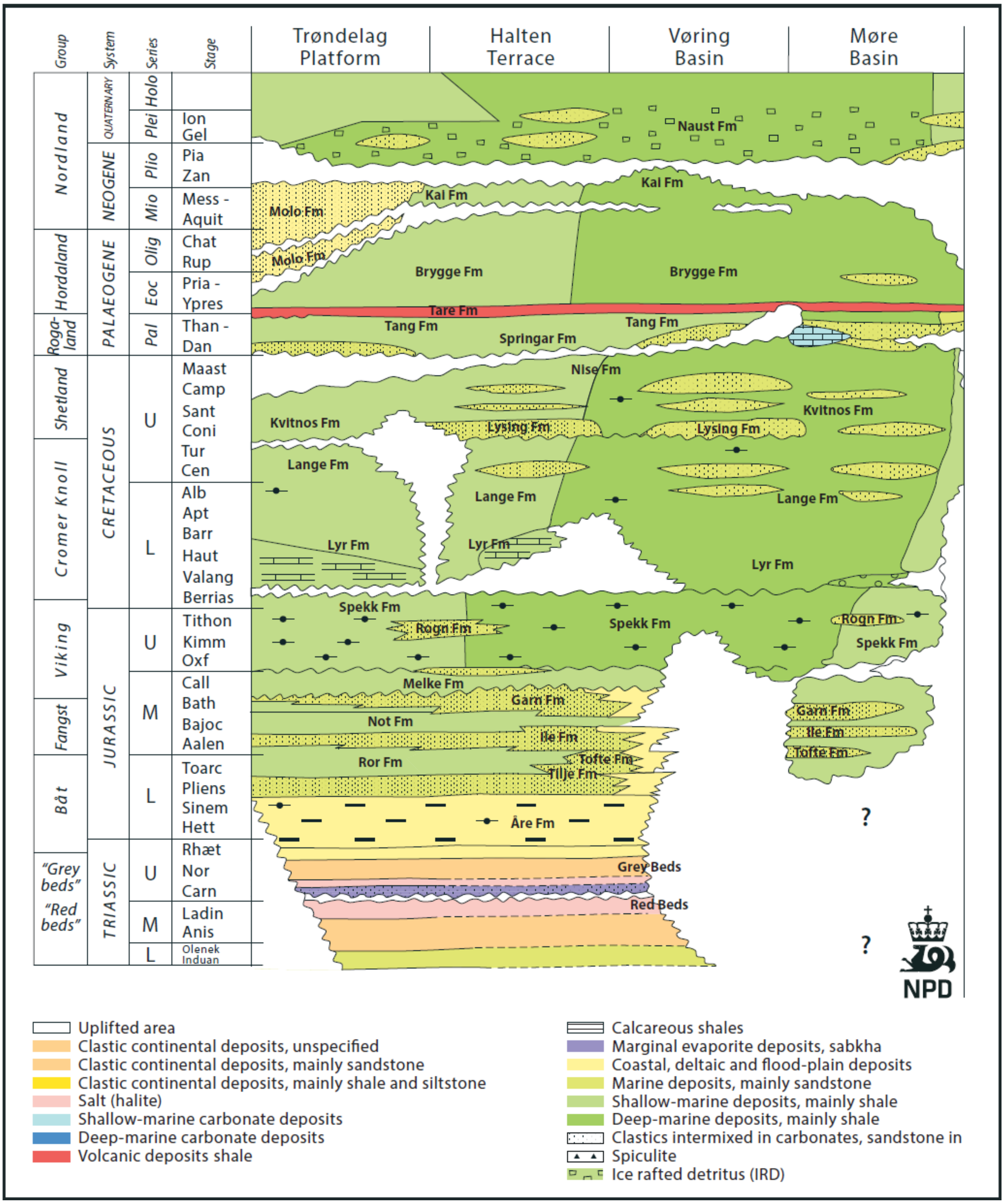

Figure 2.4: Lithostratigraphic chart of the Norwegian Sea, from Brekke et al. (2001)

occurred under both fluvial and near-shore marine conditions Ehrenberg (1990). Moreover, the overall Garn Formation depositional setting has been described as a fan delta by Heum et al. (1986), referring to sand which derived from a tectonically uplifted terrane and deposited at the mouth of a river system.

After thorough literature review of the regional and surrounding areas of the Norne field, provenance areas for the Norne field point to multiple source areas. Heum et al. (1986), discussed that at least the lower part of the Fangst Group prograded westerly or south-westerly, and that this was the main reason for the rapid eastward thinning of the Not formation.

On the other hand, Brekke et al. (2001) argues that the present deep Cretaceous Møre and Vøring Basins were areas of uplift, sub-aerial exposure, and erosion due to evidence of influx of sand from the west onto the Halten and Dønna Terraces during the Early to Middle Jurassic (figure 2.5).

Brekke et al. (2001) further argues a western hinterland supported by NPD studies, demonstrated by a transition of proximal sands in the west into distal marine shales toward the northeast on the Halten Terrace and Trøndelag Platform during Early to Middle Jurassic times. In the same publication, Brekke et al. (2001) comments that NPD had revealed a support to his westerly hinterland argument by revealing a study that proposed the transition of proximal sands in the west to distal marine shales in the northeast on the Halten Terrace and Trøndelag Platform during Early to Middle Jurassic times; however, no source of that study was cited.

A third article written by Gage and Doré (1986) on the regional perspective between the margins of the Norwegian and Grennland shelves (during the Middle Jurassic), proposes that the area received sediments both from the adjacent shield areas (Laurentia and Baltica) and also from a westerly mid-rift source area (central rift province) (Figure 2.6).

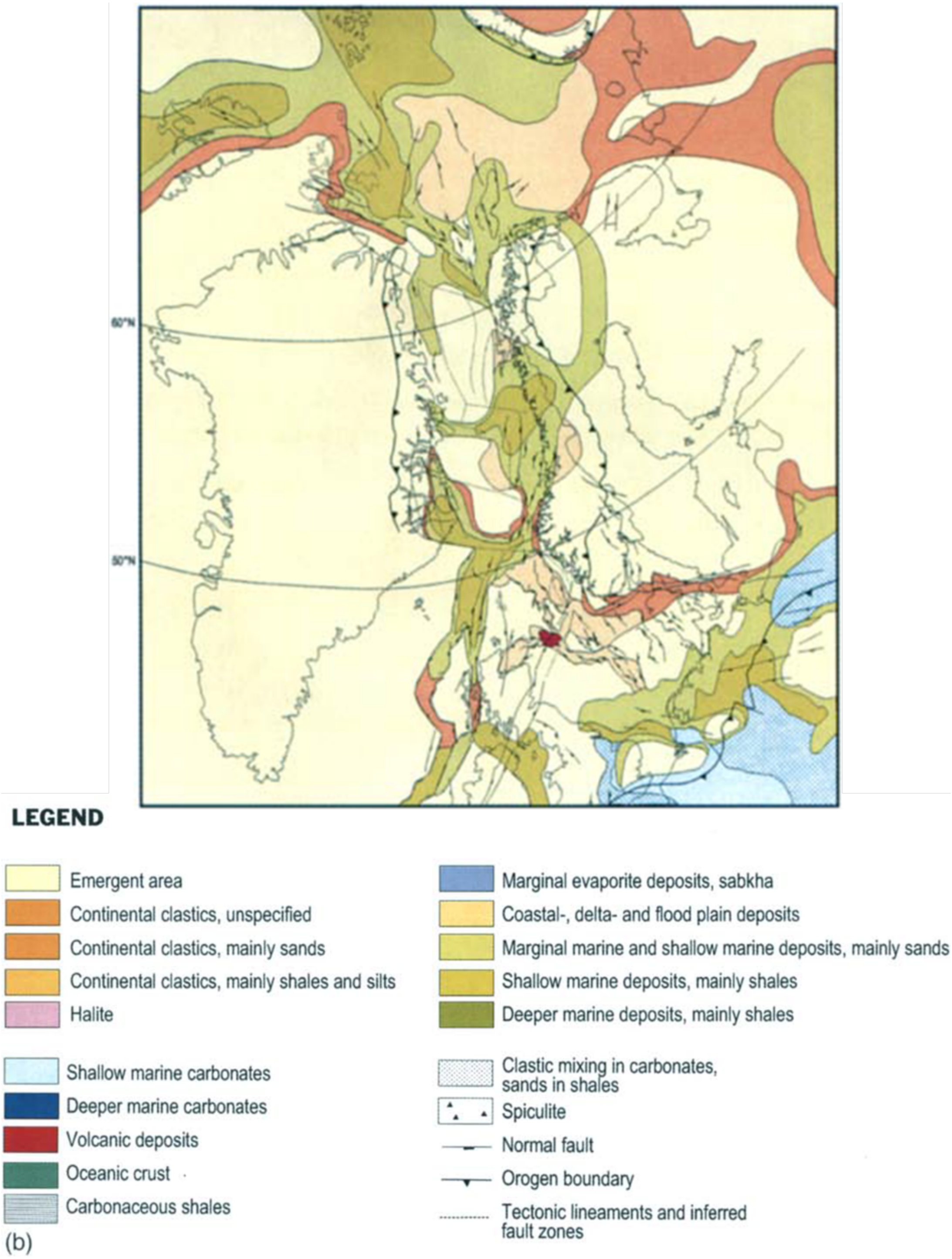

Figure 2.5: The paleogeography of the late Bajocian times, from Brekke et al. (2001).

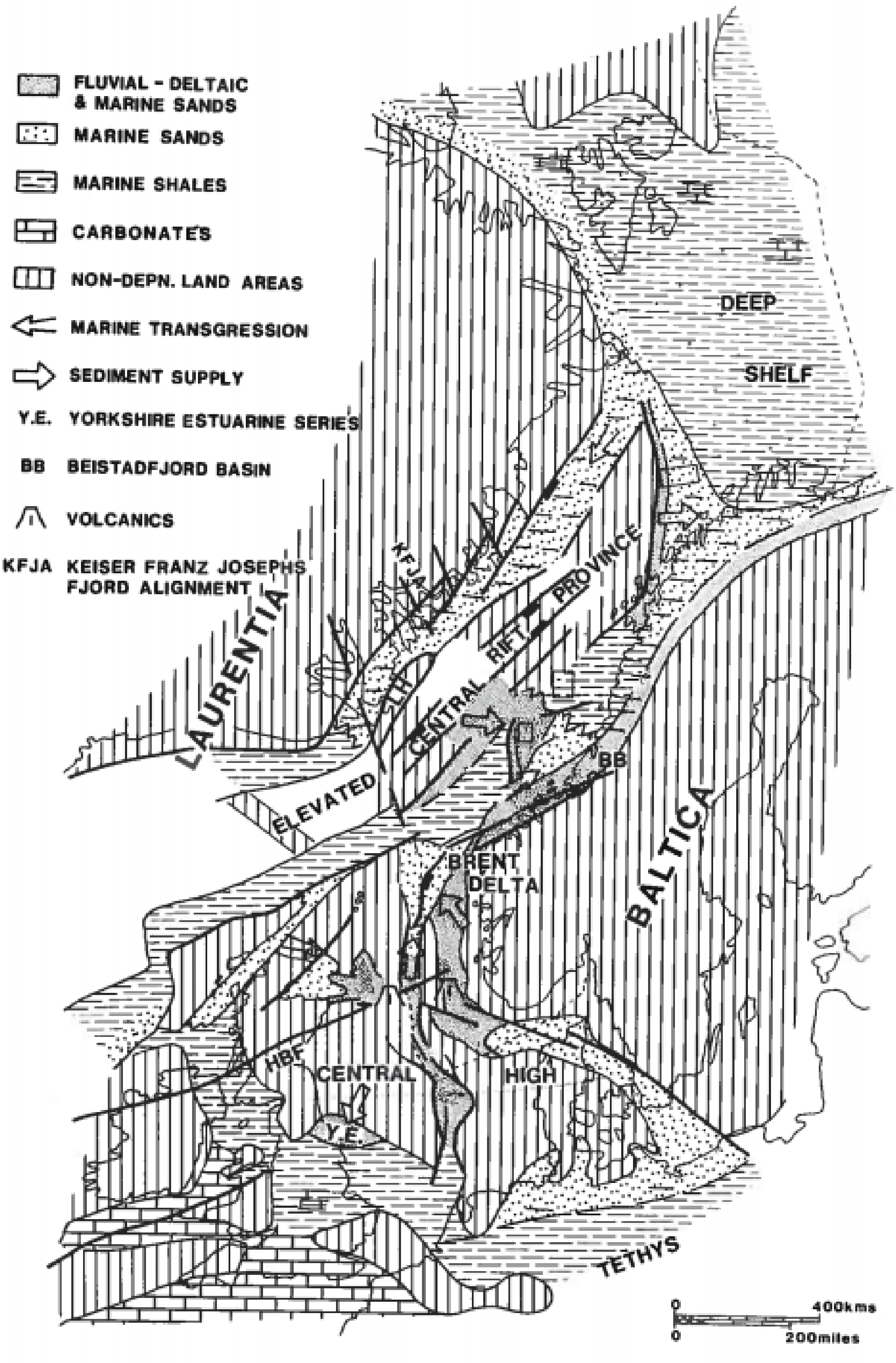

Figure 2.6: Middle Jurassic paleotectonic map, from Gage and Doré (1986).

Chapter 3

Methodology

3.1 Data and Software

The data that has been used for this study is 3D seismic survey and well data of Norne Field which was released by the Norwegian Petroleum Directorate and organized by Schlumberger as part of the 'Petrel Ready Data' database. The seismic survey ST9203R02 covers about 8.5 km x 13.5 km area elongated towards northeast-southwest (Figure 3.1). This survey was completed in December 1992 by Den Norske Stats Oljeselskap A.S.

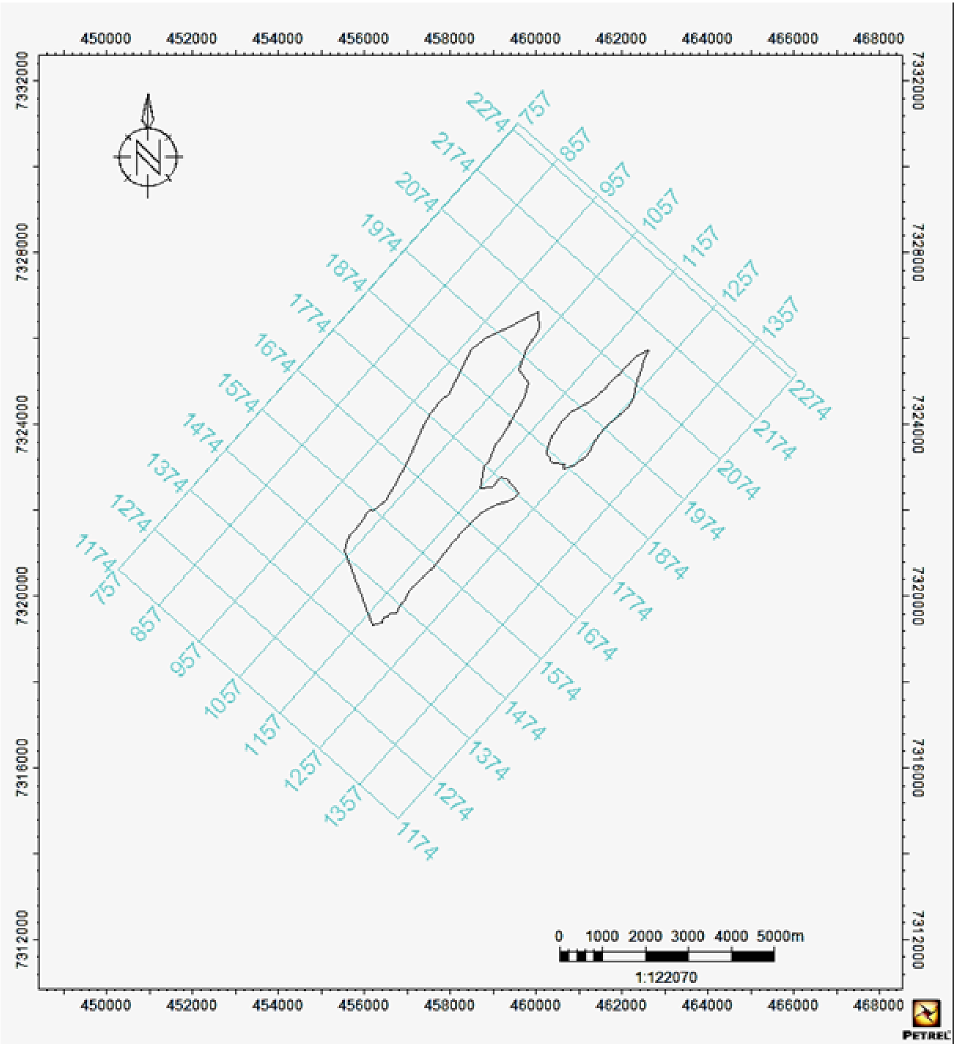

Figure 3.1: Seismic data cube ST9203R02, Norne Field, from NPD (2015).

The well data is part of NPD's DISKOS database. Four exploration wells which are 6507/3-8, 6608/10-2, 6608/10-3, and 6608/10-4 are located in this area and as part of this study. Well 6507/3-8 was drilled by StatoilHydro Petroleum in 2009. Well 6508/10-2 was drilled by Den norske stats oljeselskap a.s in 1991. Well 6508/10-3 and well 6608/4 were drilled by Den norske stats oljeselskap a.s in 1993. Core photos that were taken for wells 6608/10-2, 6608/10-3, and 6608/10-4 were used in this study. Petrel 2013 is the software used in this thesis for the interpretation of the seismic data and for the well correlation and interpretation.

3.2 Workflow

The workflow on Figure 3.2 was followed to accomplish the 3D geological model of the Norne field.

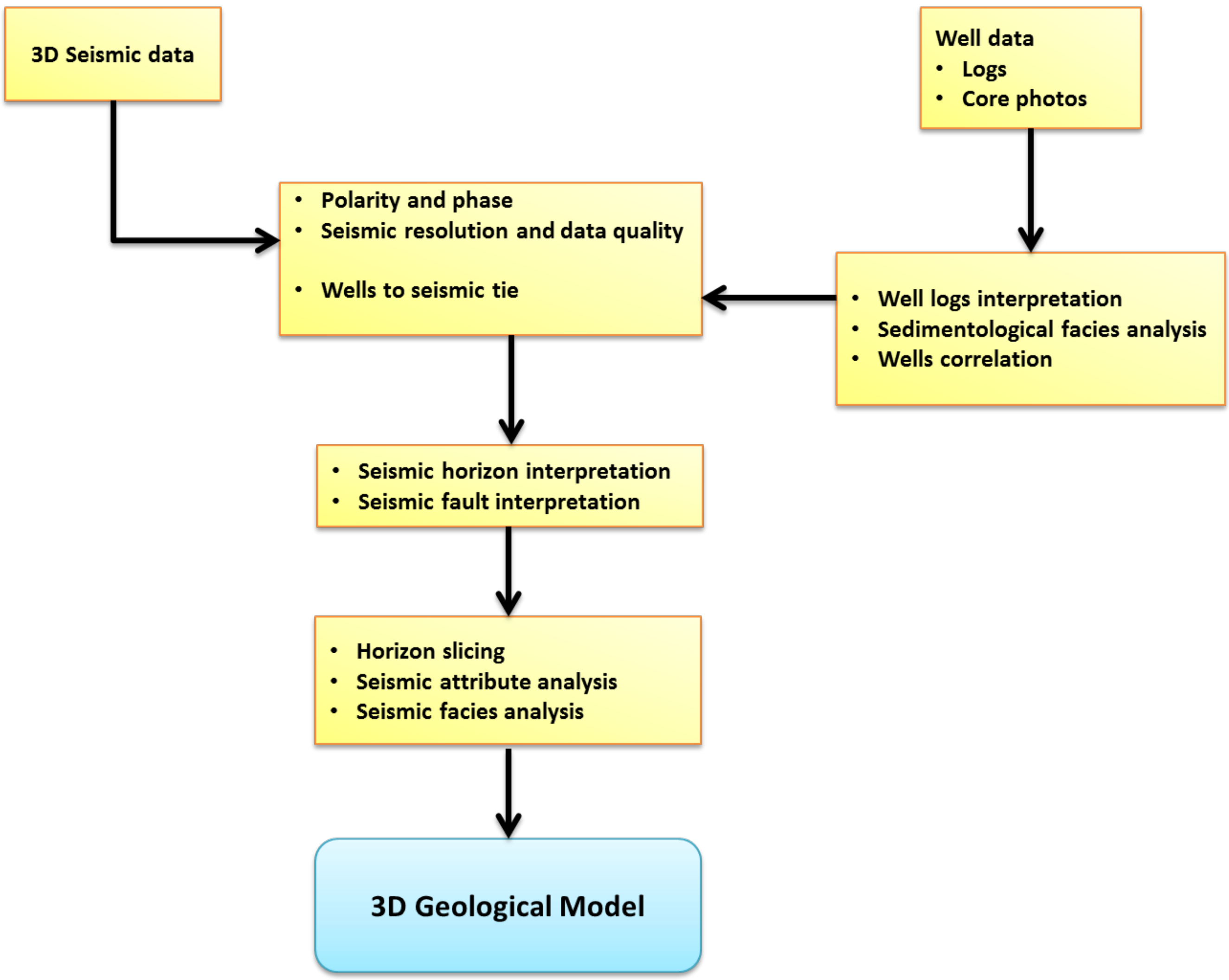

Figure 3.2: Thesis workflow.

The level of analysis in the seismic interpretation involved addressing details of the Garn and Not formations, such as, faults, horizon, and seismic facies analysis. Moreover, the interpretation of 3D seismic data combined with well log data was used to obtain a better understanding of the geological settings of these Middle Jurassic formations, in which, depositional environments and stratigraphy. This workflow sets the framework for the technical part of this thesis work.

3.3 Quality and Seismic Resolution

Generally, the data quality of the seismic in the study area is good. The horizon reflectors in the interest interval are the bottom of Middle Jurassic Not Formation and the top of Middle Jurassic Garn Formation. However, the thickness of the Not Formation in most of the area is only around 10m. Therefore, this interval is merged with the Garn Formation into one horizon in the seismic section. Some poor resolutions also occur around some of the fault zones.

3.4 Polarity and Phase

Polarity is the relationship between amplitude and the change of acoustic impedance which results into a peak or through on the seismic. There are two different polarity standards of seismic, normal polarity and reverse polarity. The normal polarity is the positive amplitude for increasing acoustic impedance and negative amplitude for decreasing acoustic impedance. On the other hand, reverse polarity is negative amplitude for increasing acoustic impedance and positive amplitude for decreasing acoustic impedance. The sea water in the study area has low acoustic impedance and the sea bed has high acoustic impedance. Therefore, polarity of the seismic in study area is normal polarity 3.3

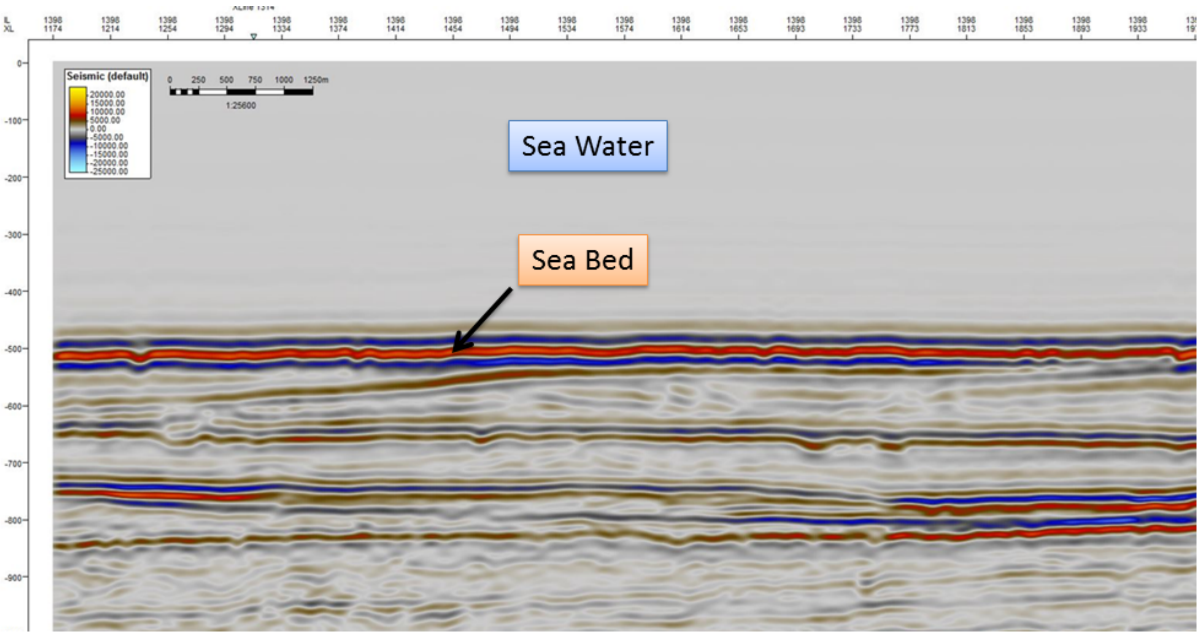

Figure 3.3: Seismic profile showing sea water and sea bed for polarity definition

Phase describes the relative timing relationships of the various frequency components that make up the seismic wavelet (Simm and White, 2002).

The phase that is used in the seismic of the study area is zero phase which has symmetrical wavelet, better resolution, and the maximum amplitude is in the center of the wavelet on Figure 3.4.

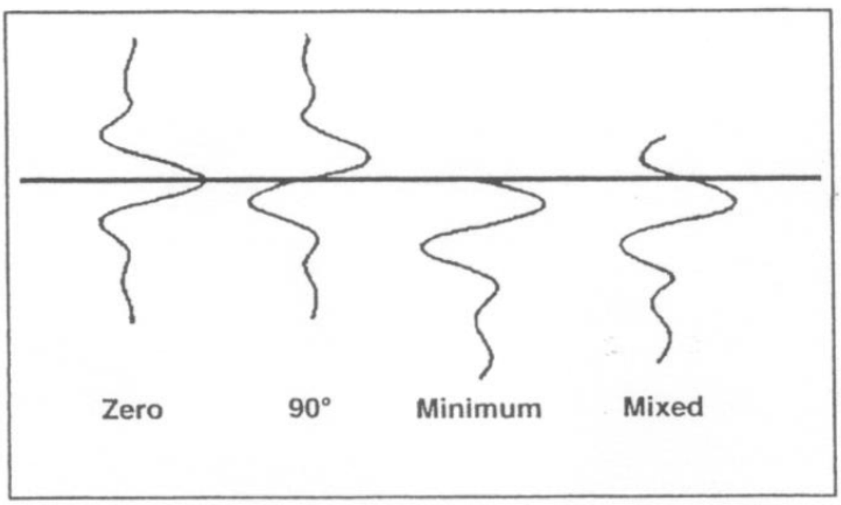

Figure 3.4: The various types of seismic phase (Brown et al., 2004).

3.5 Wells to Seismic Tie

Seismic data have a great lateral extent but low vertical resolution and in time domain. On the other side, well data has good vertical resolution in depth domain but no lateral extent. These two subsurface data can be combined with each other to support the interpretation. By doing well to seismic tie, the horizon that identified in the well can be referred to one particular reflector on the seismic.

Three out of the four wells have been tied to seismic in this study area, 6507/3-8, 6608/10-3, 6608/10-2. Sonic and density logs are the main well data used in this process. The first step of the well seismic tie process is sonic calibration and the result is seen on Figures 3.5, 3.6, 3.7 . During this step, despiking the sonic log was done to remove spike values that will disturb the trend.

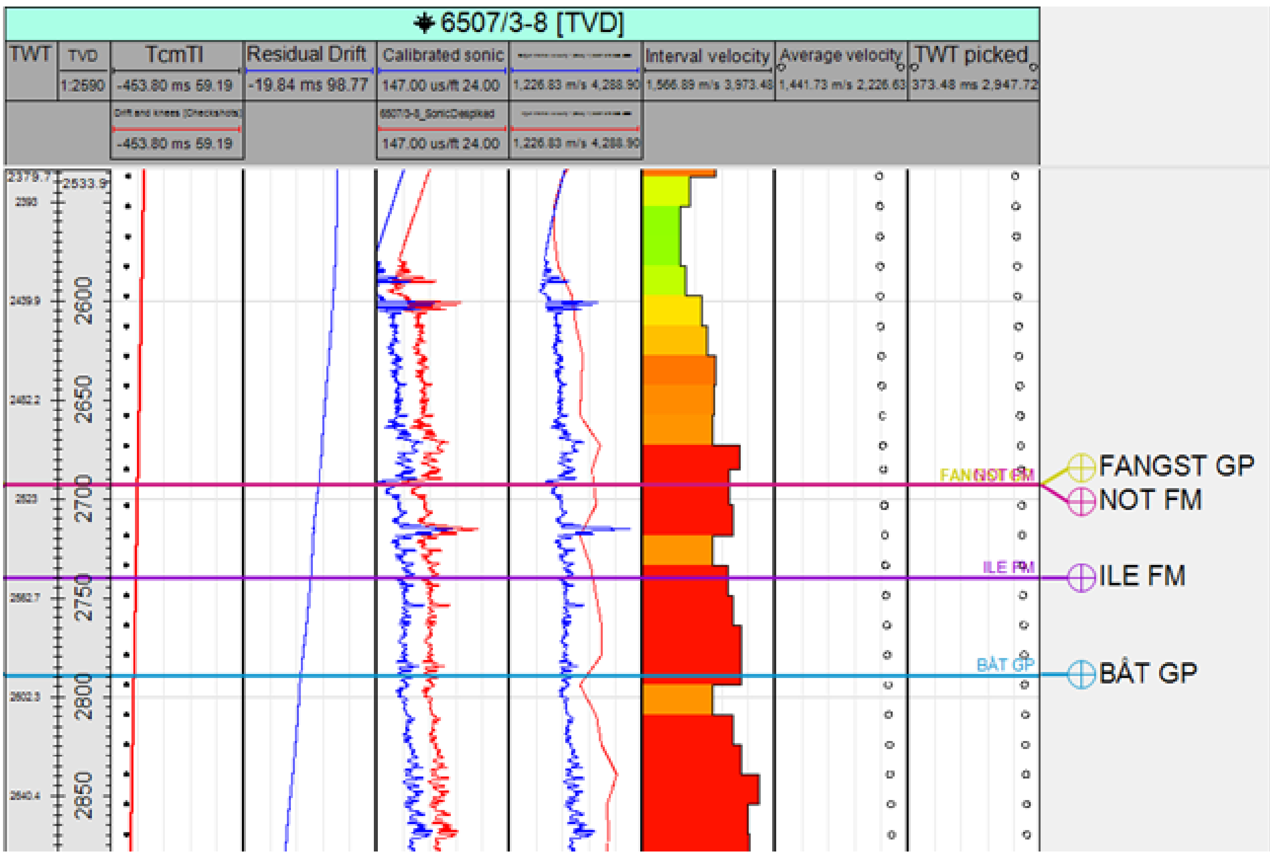

Figure 3.5: Well seismic tie, sonic calibration of 6507/3-8 well.

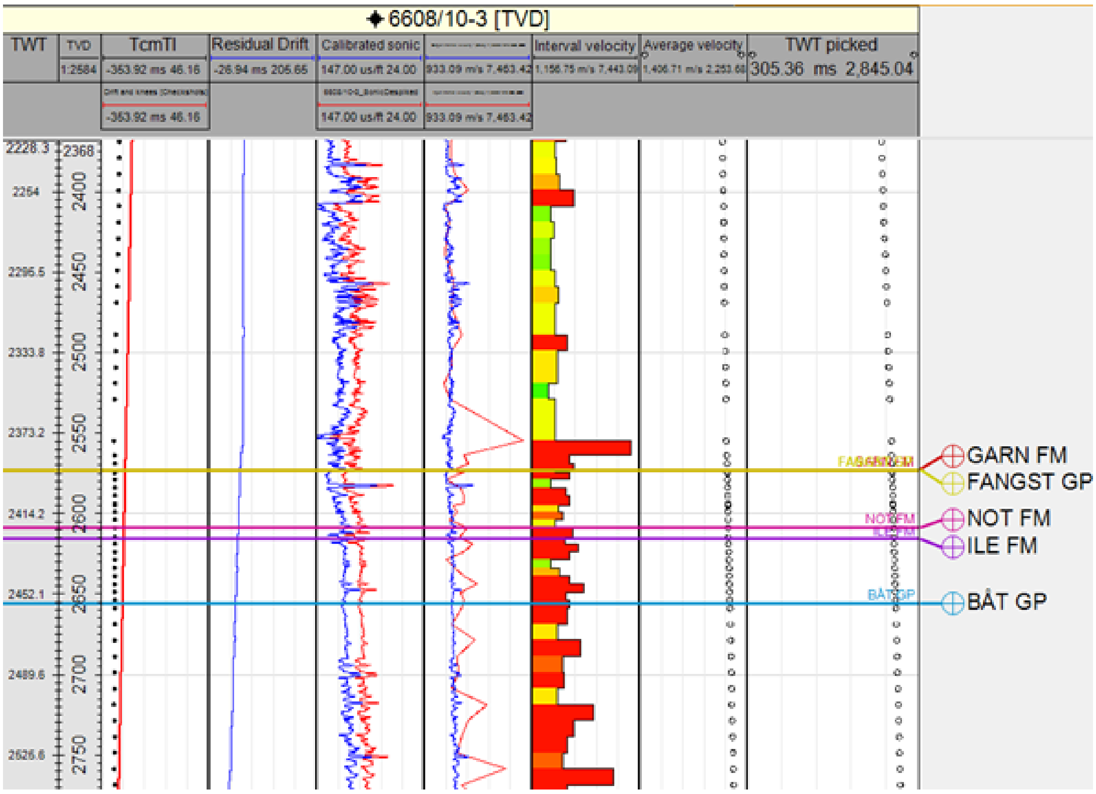

Figure 3.6: Well seismic tie, sonic calibration of 6608/10-3 well.

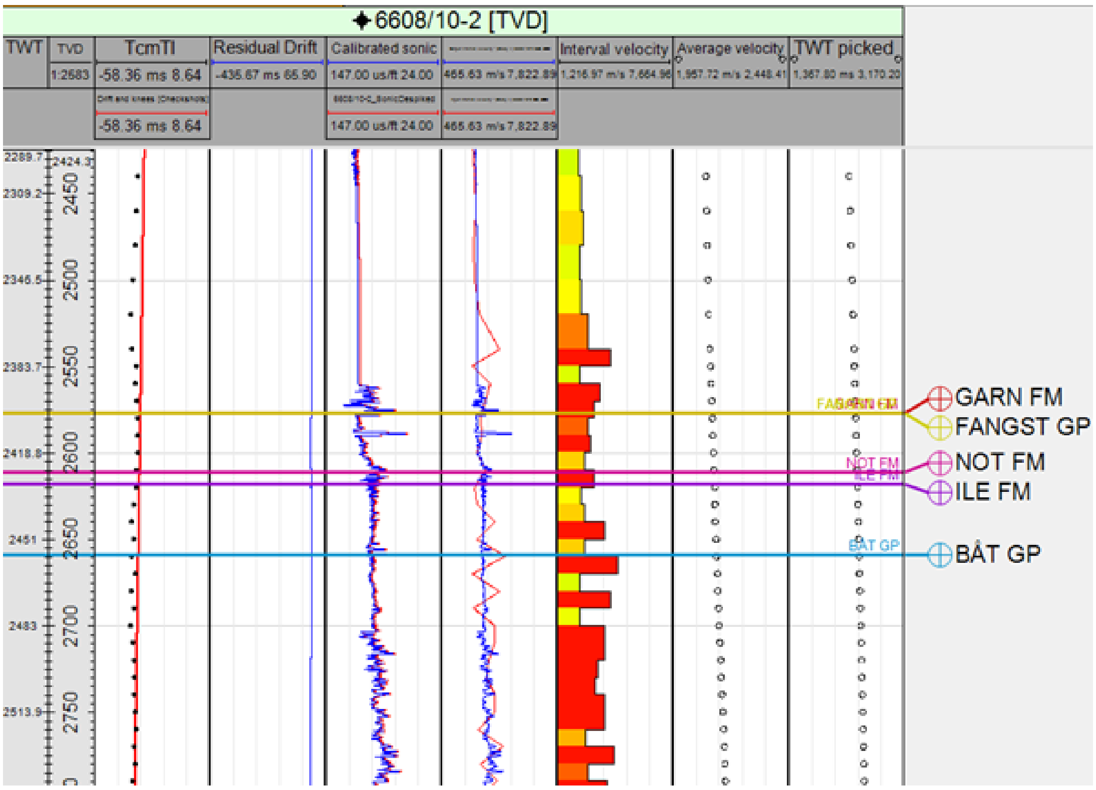

Figure 3.7: Well seismic tie, sonic calibration of 6608/10-2 well.

The second step of the well seismic tie is to generate synthetic seismogram from density log, sonic log, and a seismic wavelet by calculating acoustic impedance and reflection coefficients. A synthetic seismogram is matched to a real seismic trace and feature from the well are correlated to the seismic data (Simm and White, 2002). It will allow the interpreter to tie the geological marker to the seismic horizons, generate accurate time-depth relationships, understand the seismic response of lithologies and fluids at well location, and allowed the interpreter to understand the phase characteristics of the seismic data (Schlumberger, 2013).

The synthetic seismogram studies on these three wells are relatively tied to the geological marker on the seismic, as seen on Figures 3.8, 3.9, 3.10. Note that on well 6507/3-8 the density is missing above the Fangst group causing a missalingment. However, it can be mentioned that within interval of interest (Fangst Group) the alignment occurs due to the presence of the density curve.

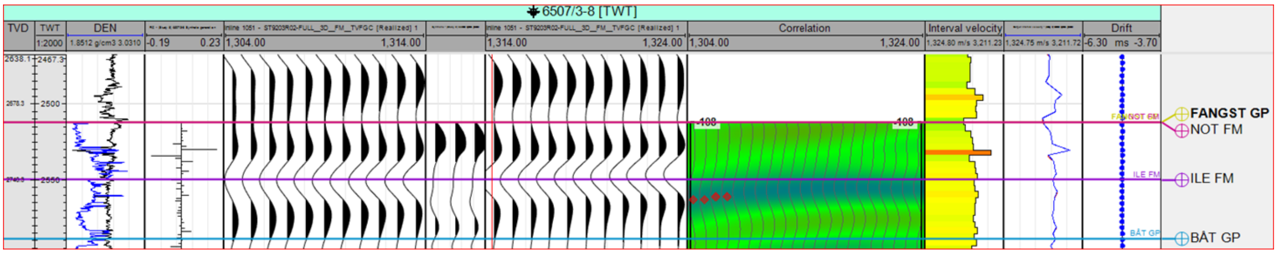

Figure 3.8: Well seismic tie, synthetic generation of 6507/3-8 well.

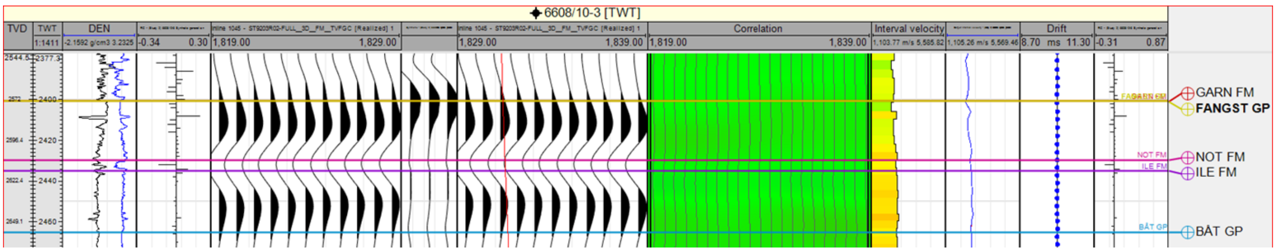

Figure 3.9: Well seismic tie, synthetic generation of 6608/10-3 well.

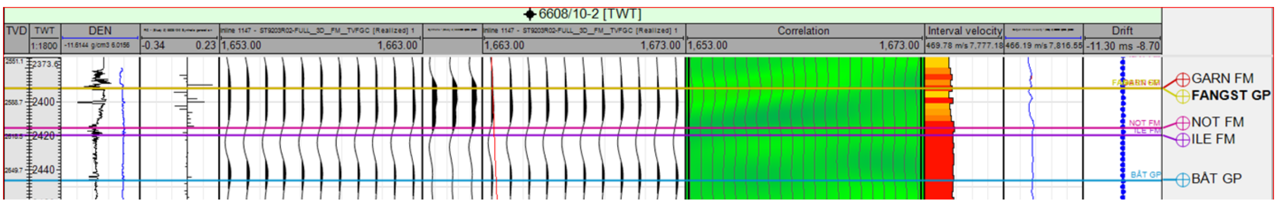

Figure 3.10: Well seismic tie, synthetic generation of 6608/10-2 well.

Chapter 4

Well Log Interpretation

4.1 Sedimentological Electrofacies Analysis

Determination of electrofacies is used for the identification of clusters of well logs responses with similar characteristics (Lee and Datta-Gupta, 1999).

Behavior of individual well logs responses against reservoir results in separation of distinct responses sets better known as electrofacies. This response against reservoir rocks is in fact a reflection of variability related to geological and petrophysical properties of the reservoir recorded continuously along the well (Kadkhodaie-Ilkhchi et al., 2013).

Four exploration wells are included in the well log interpretation to define the electrofacies; 6507/3-8, 6608/10-2, 6608/10-3, 6608/10-4. The gamma ray log is used to define the stacking pattern of the reservoir related to shaliness content. The shaliness of the rocks often occurs gradually with depth. This gradual change is indicative of lithofacies and contributes to interpret the depositional environment of the sediments (Figure 4.1).

This study is focused on the Garn and Not Formations (Middle Jurassic) which are siliciclastic sediments sandstones interbedded with shale. Several transgression-regression cycles were observed within this interval. Progradational deltaic and shoreface environment occurred during late Bajocian to mid Callovian age when the Not and Garn Formations were deposited. Based on the electrofacies interpretation of the four previously mentioned wells, there are at least three progradational cycles observed in the Middle Jurassic time. These progradational cycles represent an upward increase of depositional energy within a shallowing upward environment. These cycles which are indicated by coarsening upward sequences (orange arrows) were observed in the four wells (Figures 4.2, 4.3, 4.4, 4.5.)

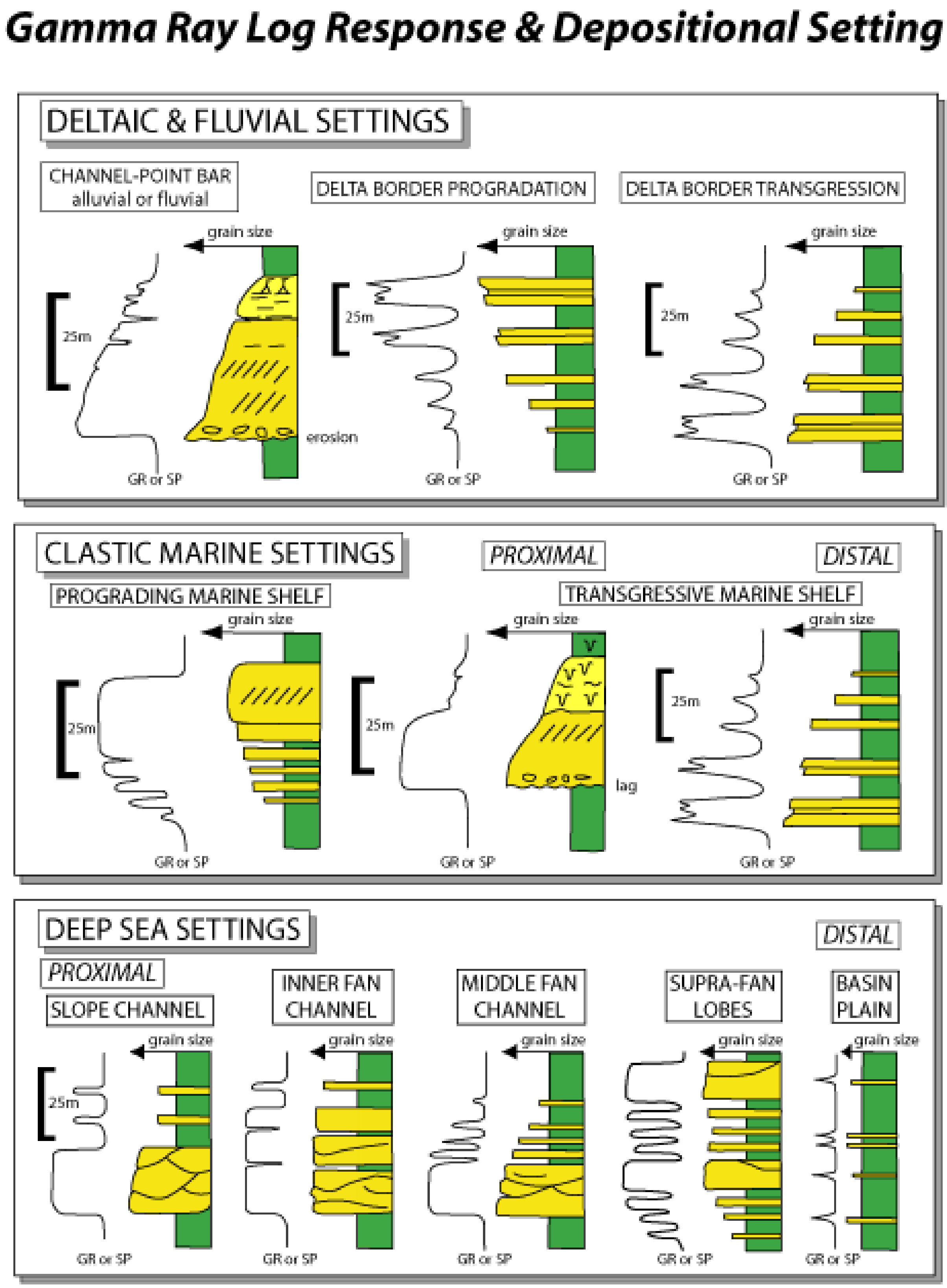

Figure 4.1: Gamma ray log response related with the depositional setting, from SEPM (2015).

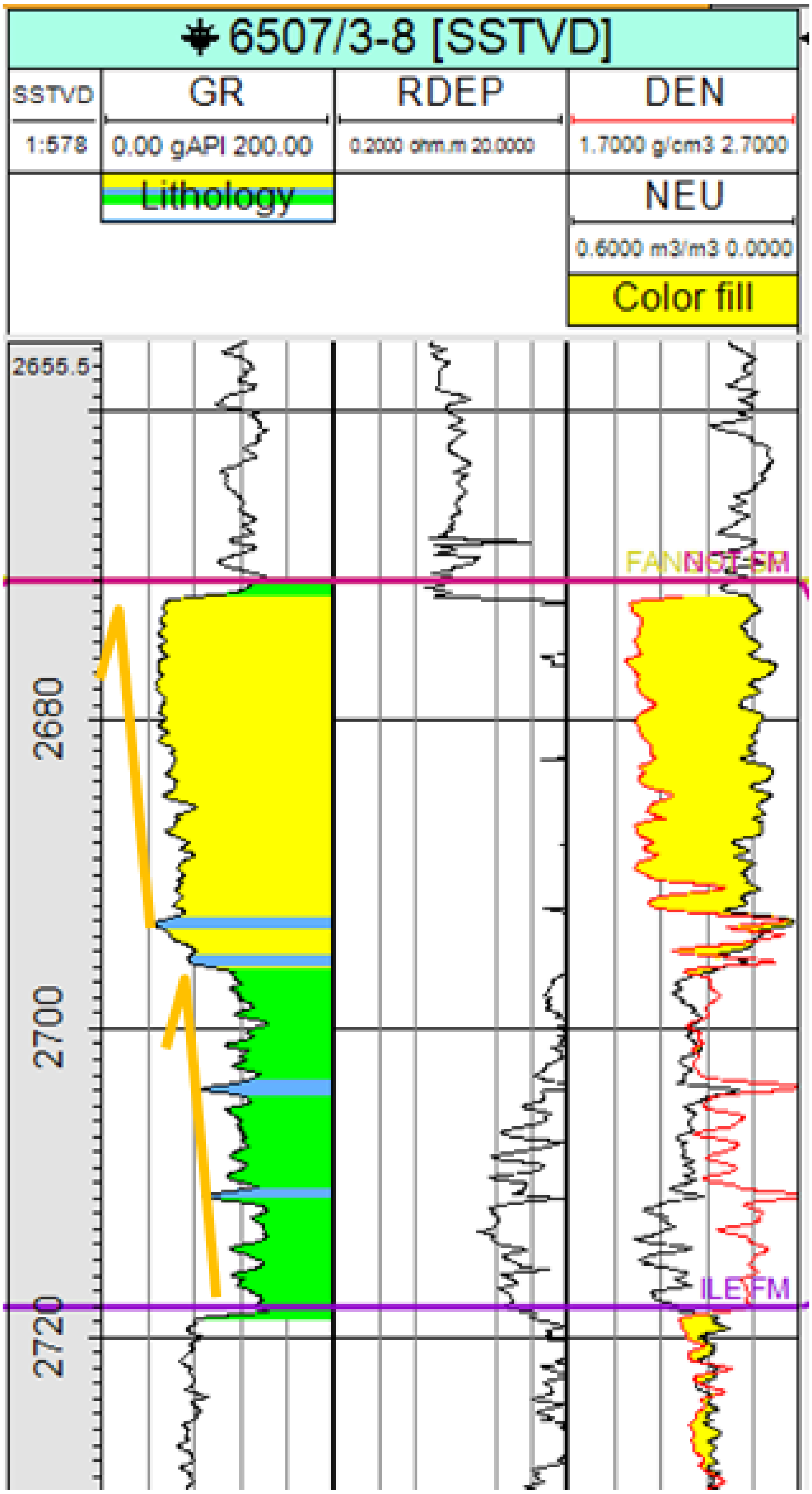

Figure 4.2: Sedimentological electrofacies of Not Formation (Middle Jurassic) in well 6507/3-8 (vertical well). Yellow color is sandstone, green color is shale, blue color is limestone, and orange arrow is a coarsening upward trend.

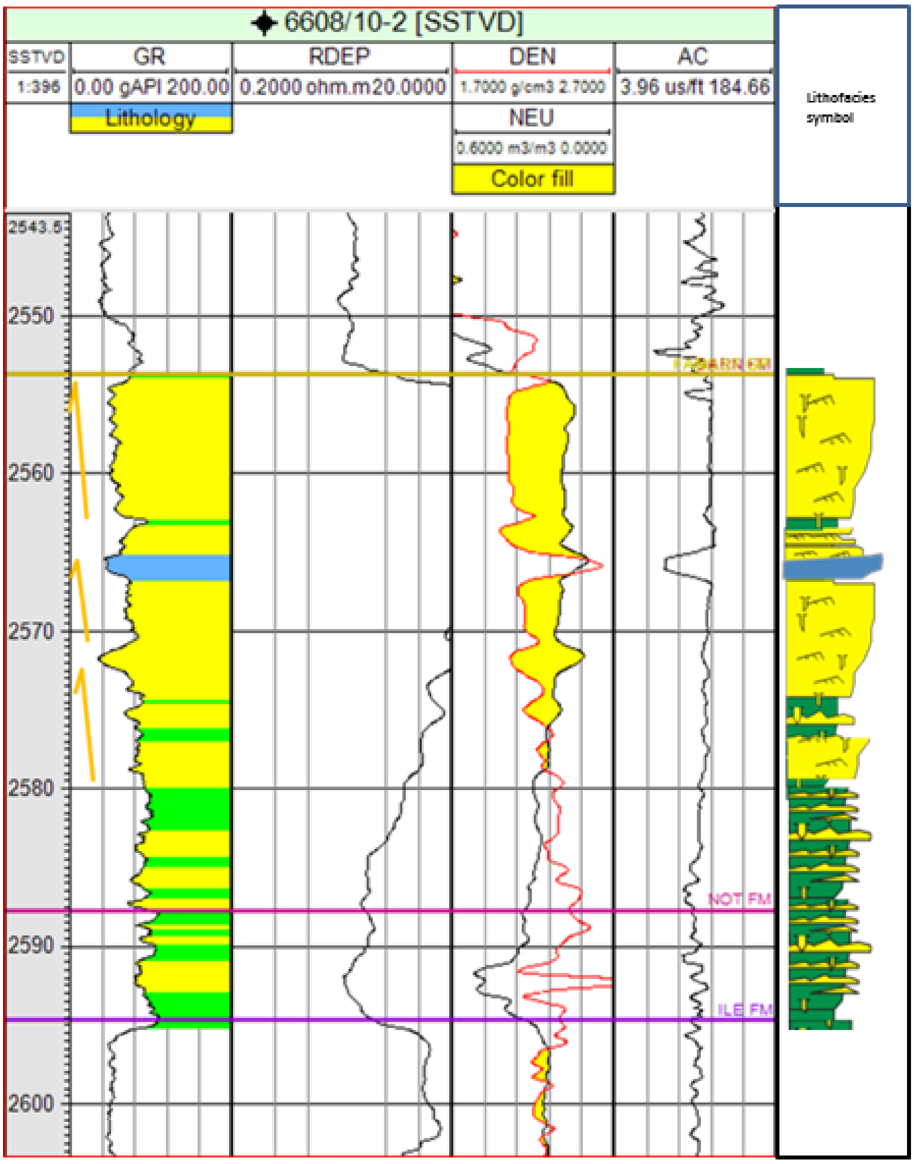

Figure 4.3: Sedimentological electrofacies of Not and Garn Formation (Middle Jurassic) in well 6608/10-2 (vertical well). Yellow color is sandstone, green color is shale, blue color is limestone, and orange arrow is a coarsening upward trend.

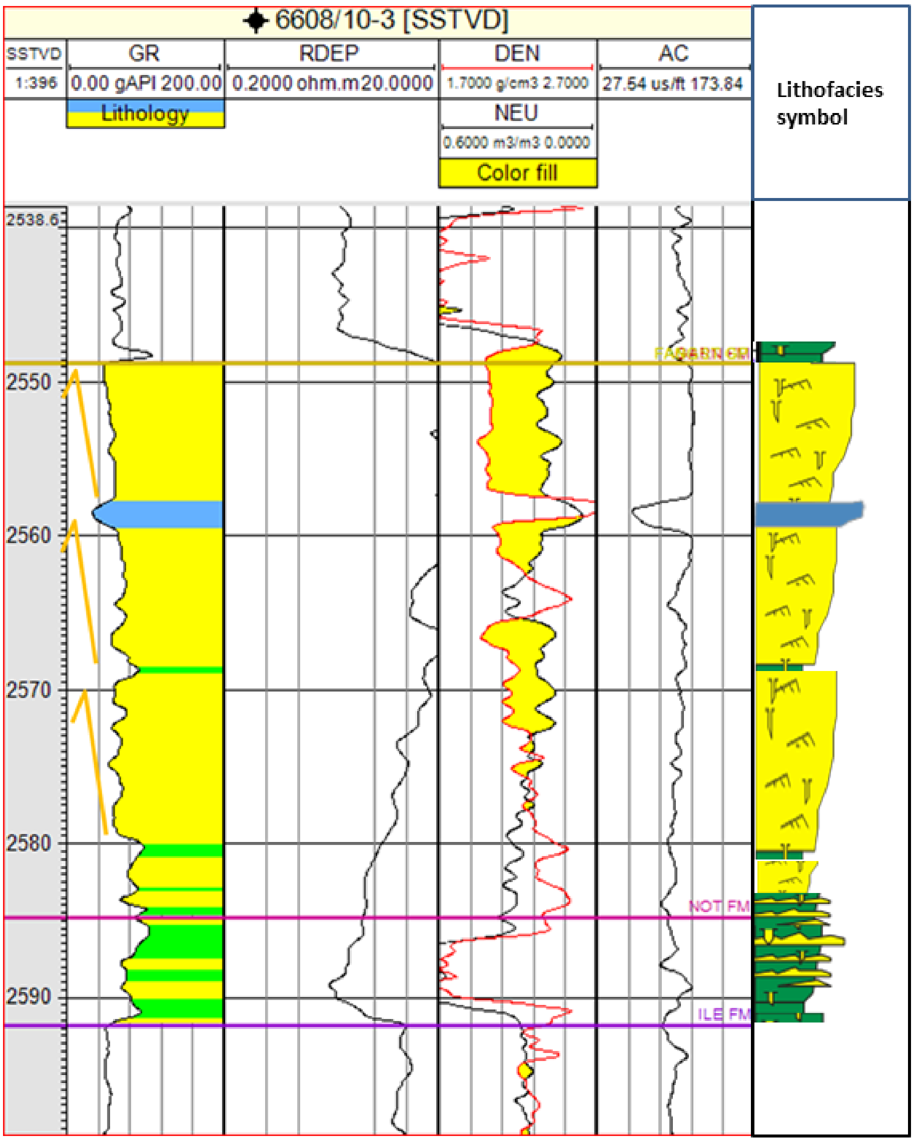

Figure 4.4: Sedimentological electrofacies of Not and Garn Formation (Middle Jurassic) in well 6608/10-3 (vertical well). Yellow color is sandstone, green color is shale, blue color is limestone, and orange arrow is a coarsening upward trend.

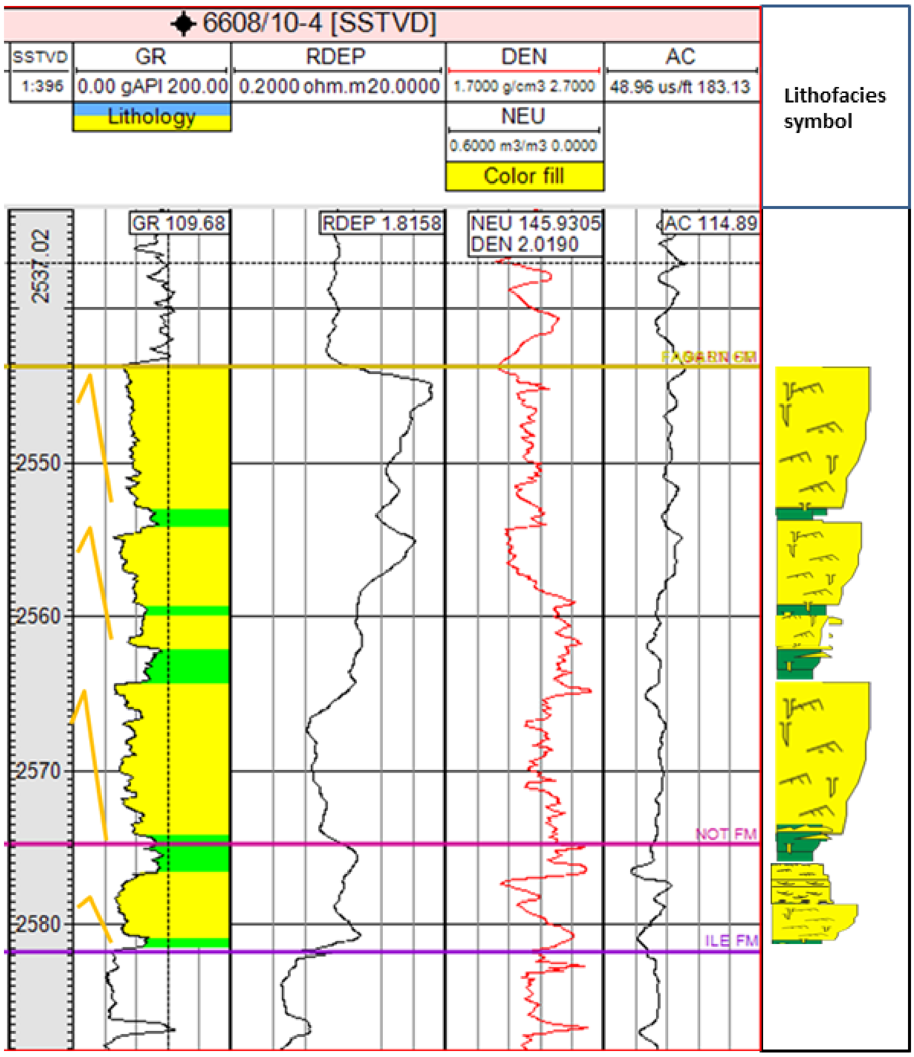

Figure 4.5: Sedimentological electrofacies of Not and Garn Formation (Middle Jurassic) in well 6608/10-4 (vertical well). Yellow color is sandstone, green color is shale, blue color is limestone, and orange arrow is a coarsening upward trend.

4.2 Core Interpretation

Conventional core has been taken in three wells in the study area, 6608/10-2, 6608/10-3, 6608/10-4 within the Not and Garn Formation interval. The depths of the core interval in these three wells are listed below in Table 4.1 . From those depths, core photos made available by NPD were studied for facies recognition.

Based on core photo interpretation, there are four lithofacies in the Middle Jurassic. The bottom most interval is dominated by dark shales with high organic material. Several thin sandstone layers exist in between the shales. This lithofacies is interpreted to be

Table 4.1: Core interval of wells 6608/10-2, 6608/10-3, 6608/10-4 in Garn and Not Formation.

Well Name	Garn Core Interval(MD)	Not Core Interval(MD)
6608/10-2	2590 - 2611m	2611 - 2616m
6608/10-3	2574 - 2577m/ 2606 - 2610m	2610 - 2616.5m
6608/10-4	2567 - 2598m	2598- 2605m

deposited as shallow marine shales. Above this shale, the sand portions are increased and create heavily laminated very fine grain sandstone. This represented increase in the energy of sedimentation due to the increase of the sandy portion.

Above the heavily laminated very fine grain sandstone, laminated medium grain sandstone was deposited with some shale insertion. This still indicated higher energy and shallowing upward environment. At the top of the interval of interest (Garn Formation), cross laminated intervals of coarse grained sands occurred interbedded within bioturbated intervals of coarse grained sands. This is the highest energy environment based on the grain size and the sedimentary structure.

These four lithofacies groups are observed best in well 6608/10-2 where core was taken in both Garn and Not Formations (Figure 4.6). The cross laminated and bioturbated sandstone facies are best observed in well 6608/10-4, where the interest interval in this well was dominated by a stacked coarsening upward sandstone (Figure 4.8). Massive coarse grained sandstone was observed in well 6608/10-3 at the top of the interest interval (Figure 4.7).

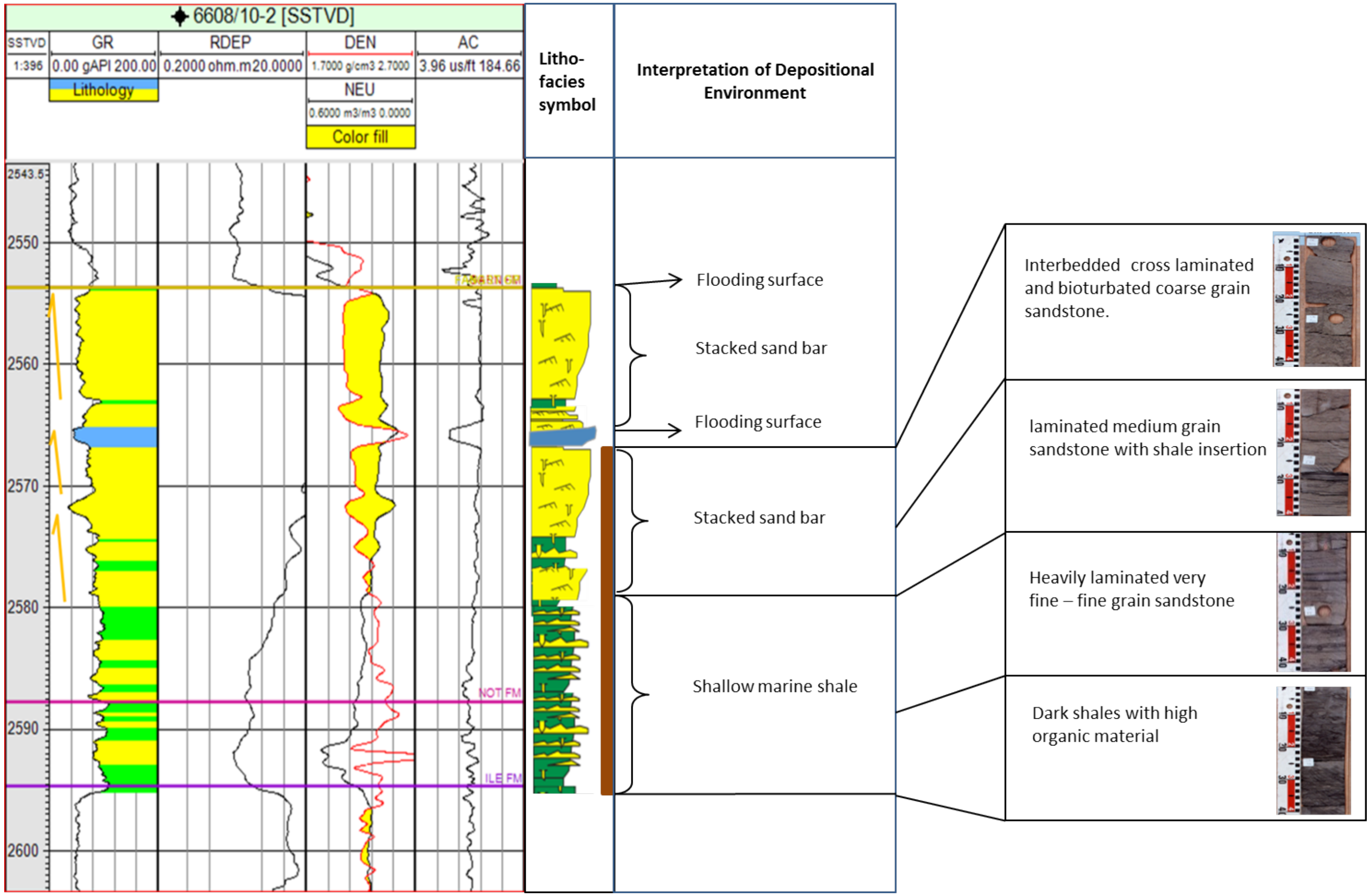

Figure 4.6: Well log and core interpretation of well 6608/10-2 showing four group of lithofacies within the Garn and Not interval.

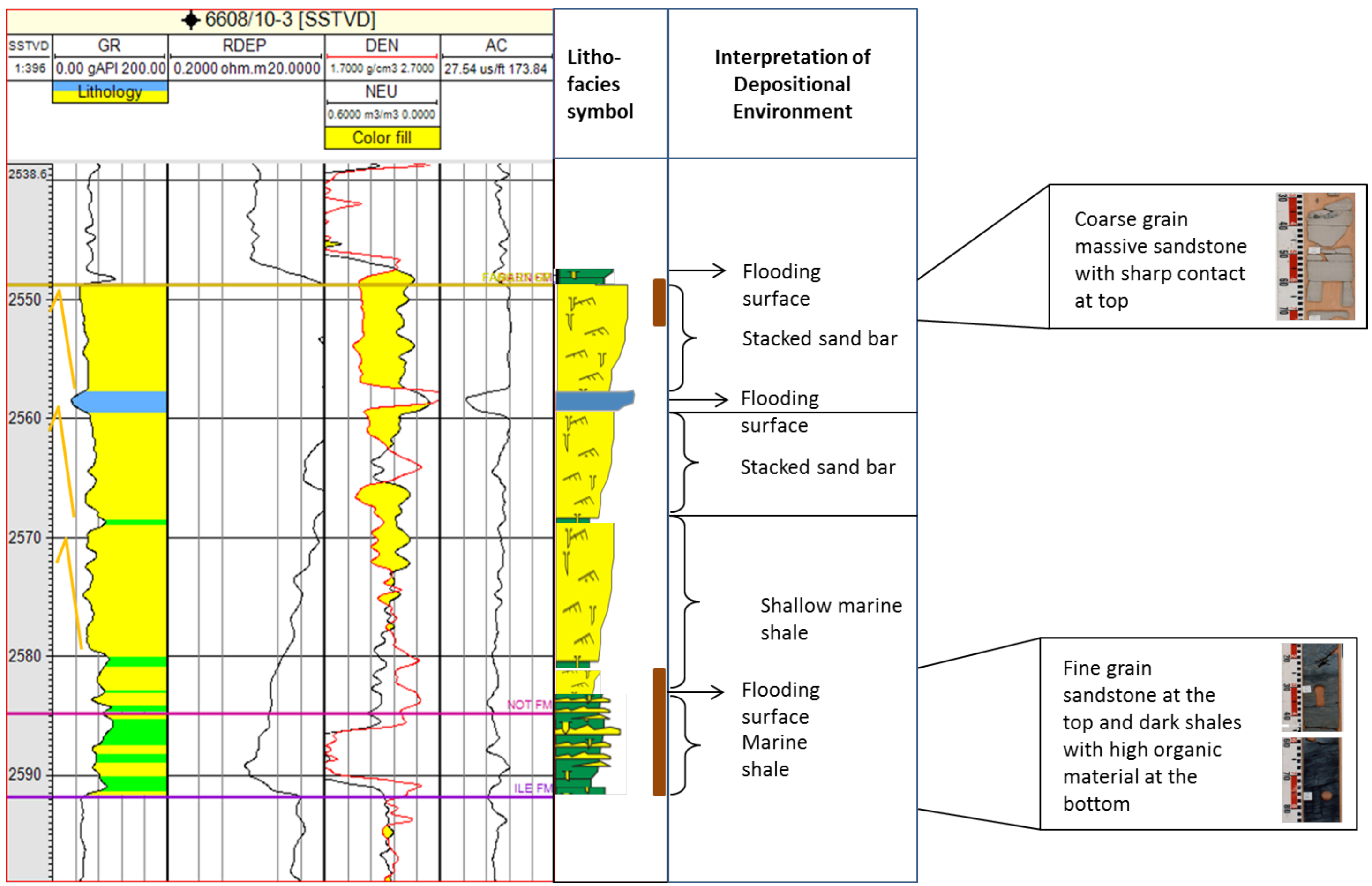

Figure 4.7: Well log and core interpretation of well 6608/10-3 showing two groups of lithofacies within the Garn and Not interval.

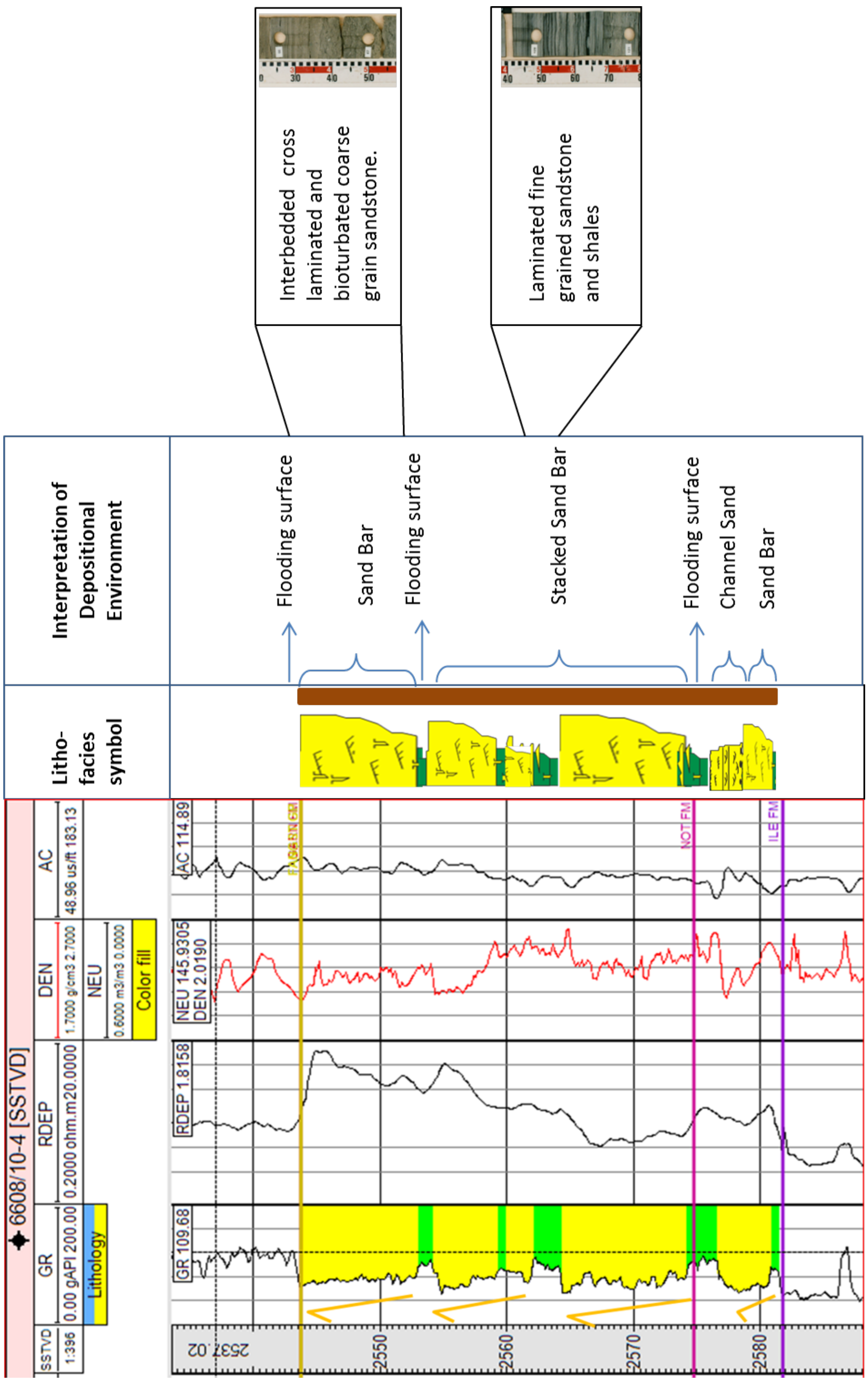

Figure 4.8: Well log and core interpretation of well 6608/10-4 which was dominated by stacked sandstone.

4.2.1 Wells Correlation

Four exploration wells were available to correlate in the Norne field area; 6507/3-8, 6608/10-2, 6608/10-3, and 6608/10-4. The starting point of the correlation is the lithostratigraphy tops data which is available from the NPD website. Three lithostratigraphy tops are available throughout the well sections, i.e., the top of the Ile Formation, the top of the Not Formation, and the top of the Garn Formation. Each lithostratigraphy top represents the existence of a flooding surface, denoted by a high gamma ray log value (Figure 4.9.)

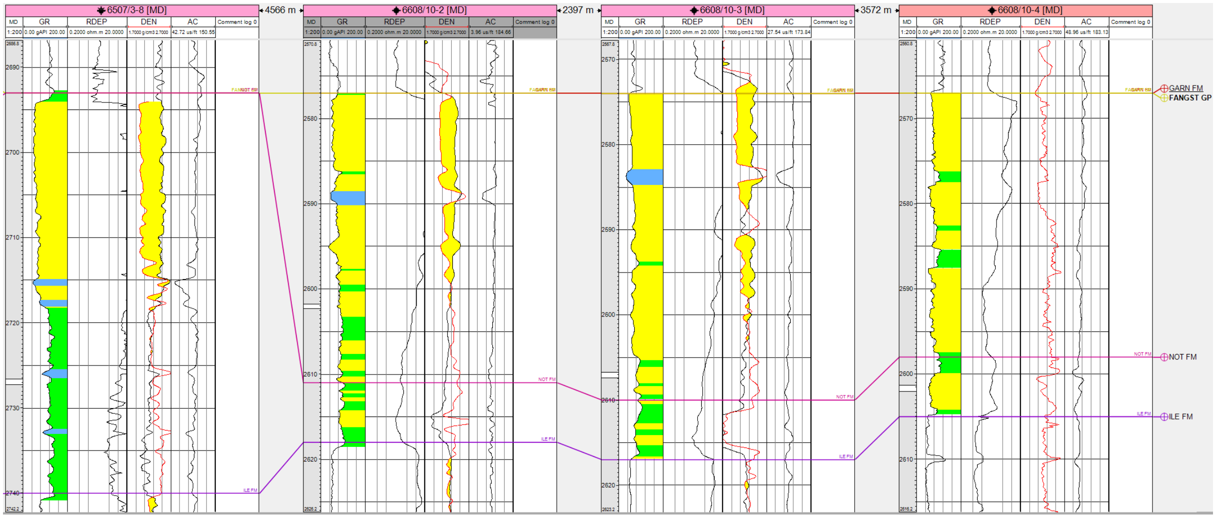

Figure 4.9: Lithostratigraphic tops within the Not-Garn interval.

Flattening on one of these flood surface, i.e., the top of the Fangst Group, was done to interpret the sediments below this surface at the time of their deposition. Doing this will allow for a lithological correlation that takes into account the paleogeography and depositional environment of the Not and the Garn Formations. The stratigraphic correlation (Figure 4.10) with flattening on the Fangst Group was made with the help of the previous electrofacies analysis and observations from the core pictures available.

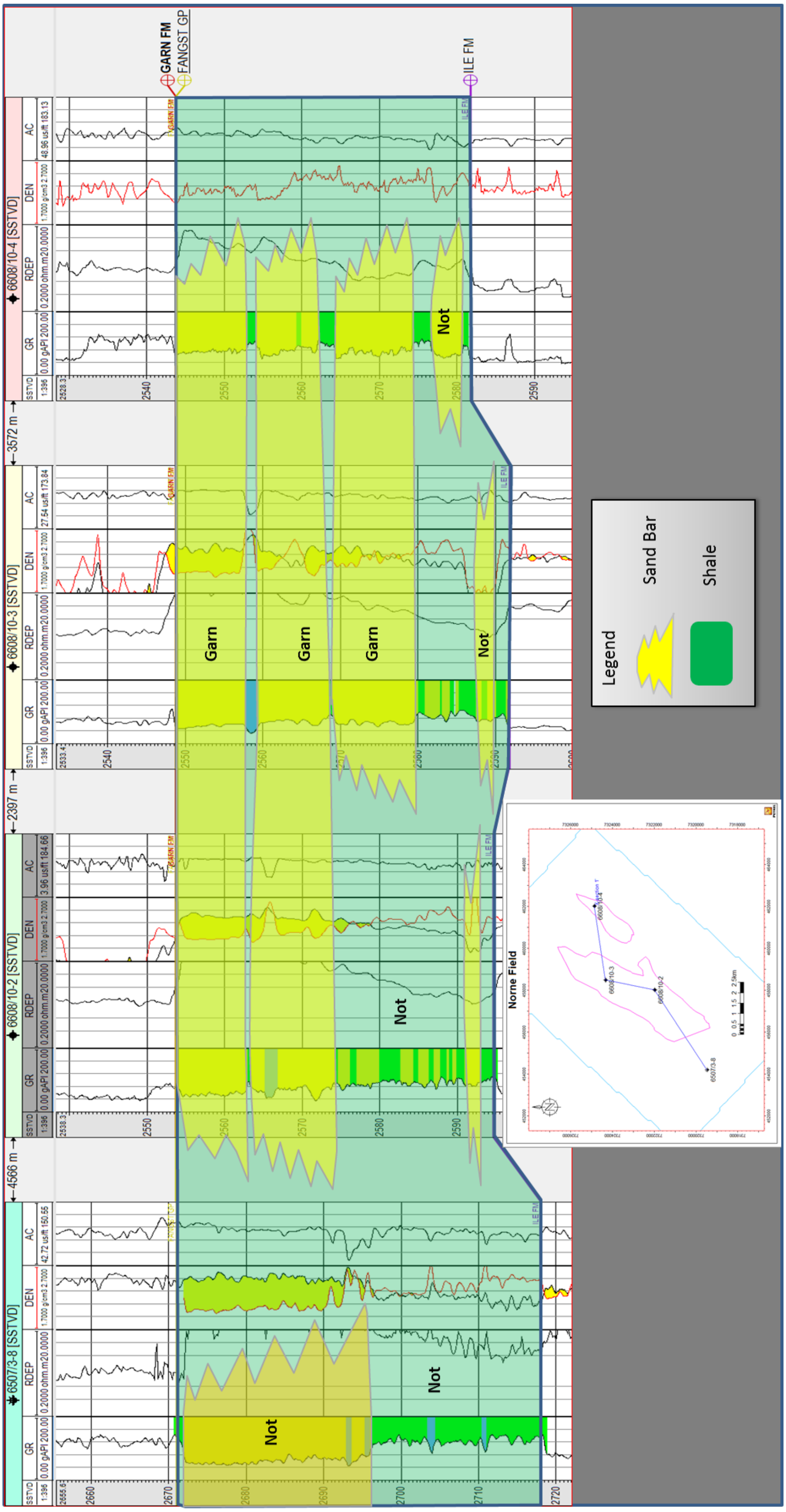

Figure 4.10: Stratigraphic correlation in Norne Field, with flattening on the Fangst Group.

At the east-northeast part of the field, the wells are interpreted at the bottom (Not Formation) as shallow marine shale with marine muddy sanstone interbeds that increase upward, and as thicker progradating packages of crossbedded and bioturbated sandstone (Garn Formation) at the top which still suggests existing marginal marine conditions. Similar observations are made going from well 6608/10-4 in the northeast of the field towards well 6608/10-3. Moreover, in well 6608/10-2, the three prograding packages of the Garn dimish to two packages and the underlying Not increases in both thickness and sand content. Further southwest of the field on well 6507/3-8 the Not formation and the Garn formation are the same stratigraphic age, where the signature of the Not changes dramatically from a muddy bottom succession into an almost blocky, yet still coarsening upward top part. The overall correlation observations/interpretation are summarized below:

The Not and Garn are two different formations, but in the southwest of the field, they are the same geological age on well 6507/3-8.

The Not and Garn are interpreted as possibly interfingering in between wells 6608/10-2 and 6507/3-8 due possible different provenances.

The Garn has three prograding packages in the northeast-east of the field, and since the packages decreases to the west-southwest, this is interpreted as the Garn progradating westerly in this area.

The Not is considered to have a western provenance due to the thick sand content in the southwest of the field, and muddier content towards the eastern wells. The lack of wells with only the Not present, makes this interpretation challenging, therefore, this interpretation was also based on the literature reading that presented different sediment sources around the Dønna and Halten Terraces during Mid-Jurassic time (Brekke et al., 2001; Swiecicki et al., 1998; Gage and Doré, 1986).

Chapter 5

Seismic Interpretation

5.1 Seismic Fault Interpretation

Norne Field is situated at the transition between Nordland Ridge and the Dønna Terrace, in an area called the Revfallet Fault Complex as seen in the figure. There are several period of rifting occurred in around Norne Field. During Permian and Late Jurassic–Late Cretaceous rifting, faulting affected a wide part of the area. Normal faults oriented towards NE-SW trends are common in this period (Verlo and Hetland, 2008). The faults system in the study area was dominated by extensional faulting. The Norne Field is composed of one major horst block extend approximately 9 km x 3 km (Ouair et al., 2005). This horst block consists of several series of normal faults. These normal faults are mostly oriented towards northeast – southwest and cut the sediments until the Cretaceous age (Figure 5.1).This indicates that most likely the structure that composed the study area occurred or reactivated no later than Cretaceous. Late Jurassic–Cretaceous rifting is believed correlated with the form of these structure. Time structure map on the Top of Garn and Not Formation was made to understand the structure setting of the study area (Figure 5.2). The Garn formation occur in the northeastern part of the study area and in the southwestern part it is equivalent with Not Formation. Some minor faults are observed in the study area oriented relatively towards NE-SW direction. These minor fault are extending around 2–5 km laterally with highly dipping fault plan (Figures 5.3, 5.4). Several synthetic faults were also observed in Norne Field with some syncline geometry in the hanging wall block which most likely is associated with the fault itself (Figure 5.3).

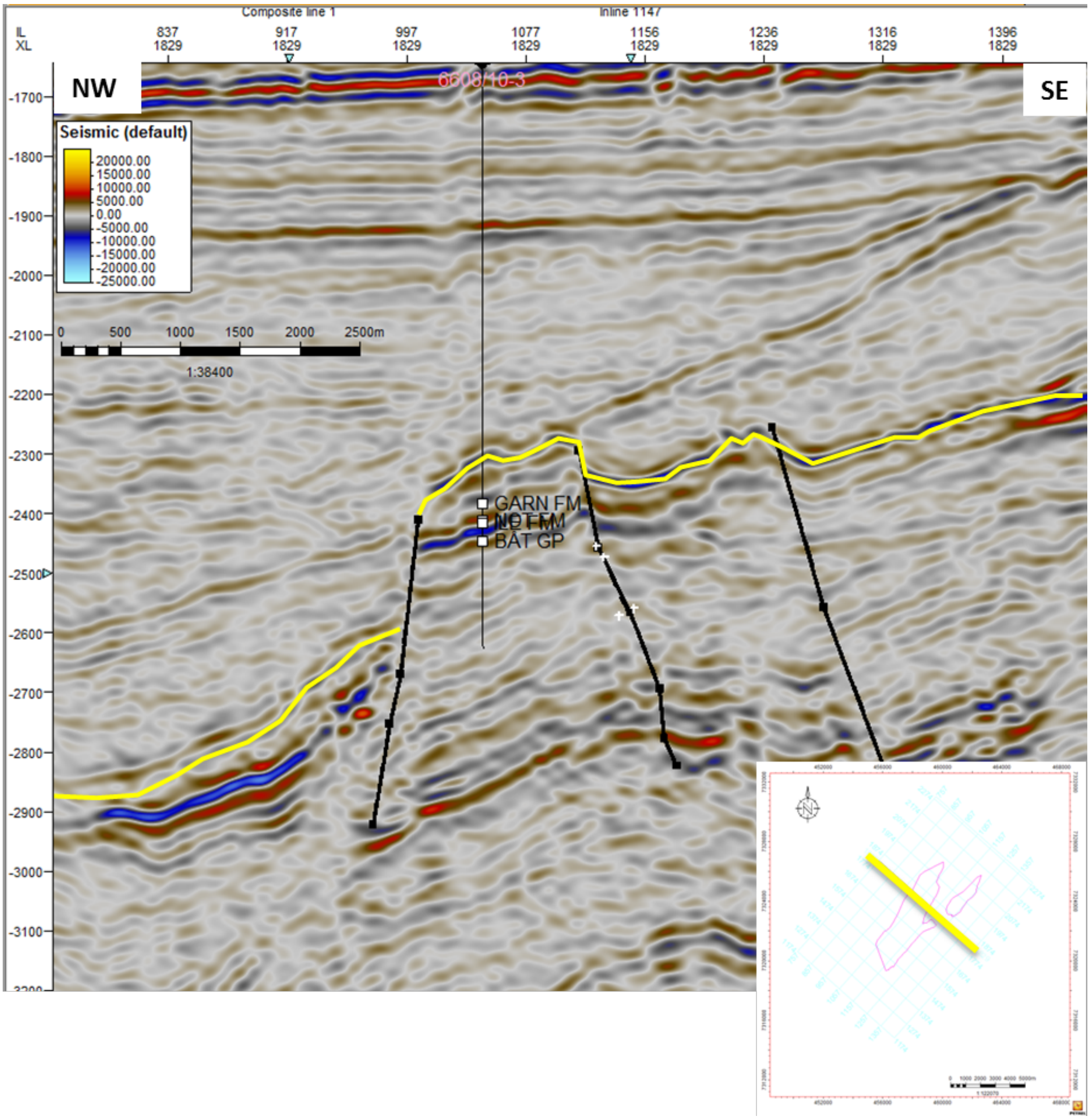

Figure 5.1: Crossline seismic section in the study area showing the horst block in Norne Field and most of the faults cut until the Base Cretaceous Unconformity (yellow color).

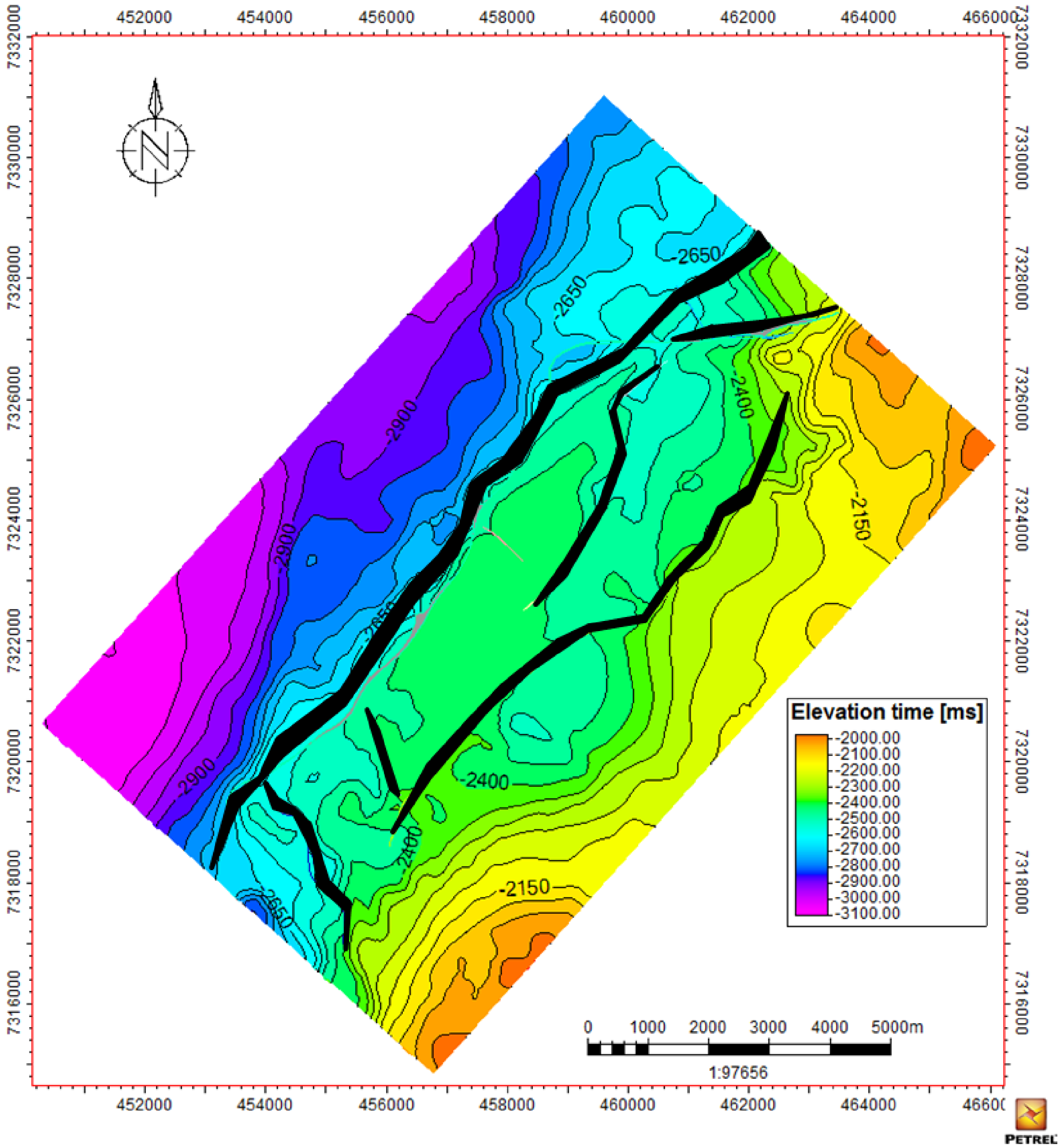

Figure 5.2: Time structure map of Top Garn in the NE part and Top Not in the SW part showing SE-NW major structural trend and NE-SW minor structural trend.

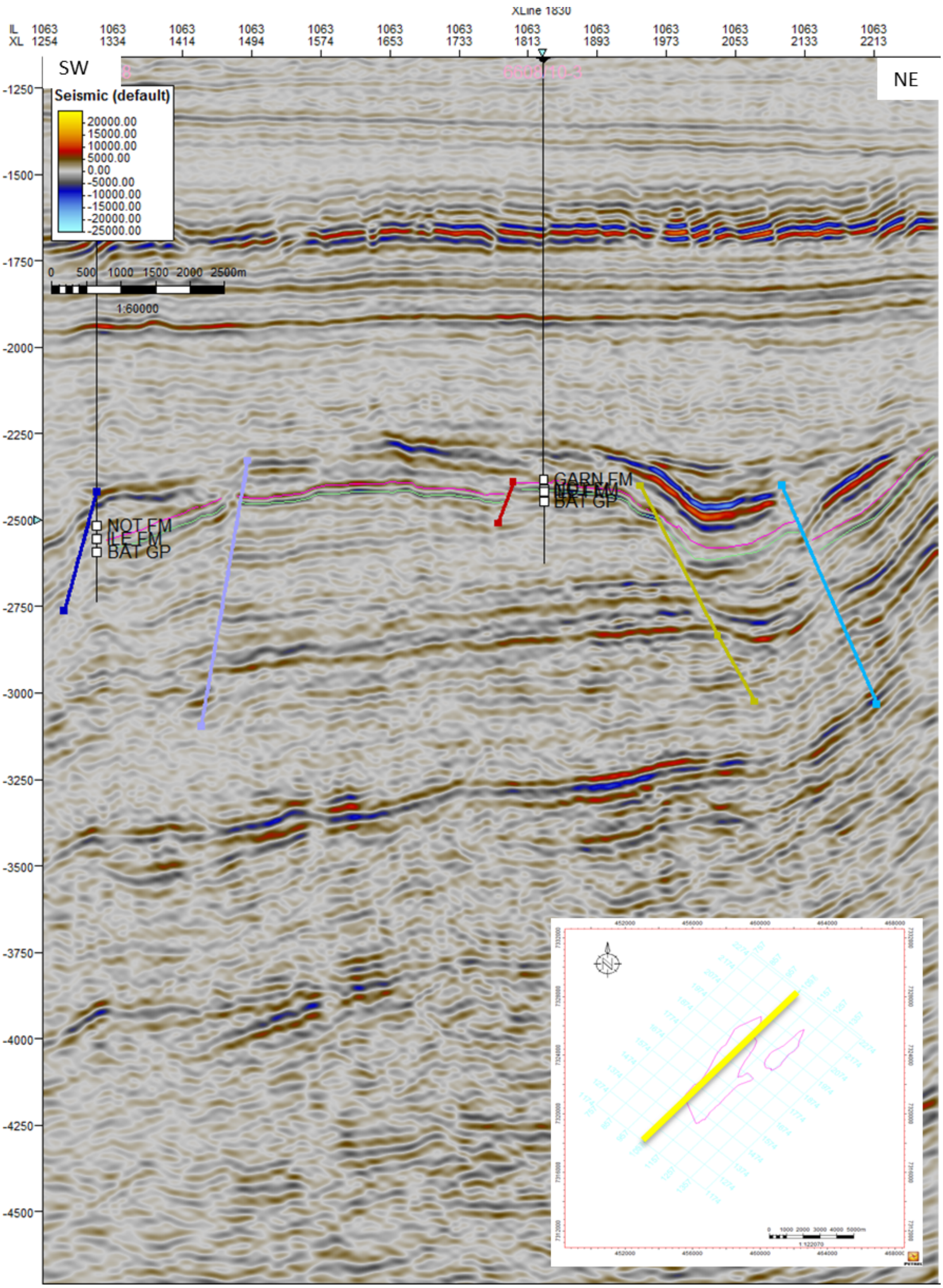

Figure 5.3: Inline seismic section in the study area showing the north-south structural setting in Norne Field with several synthectic fault and hanging wall syncline in north-eastern part.

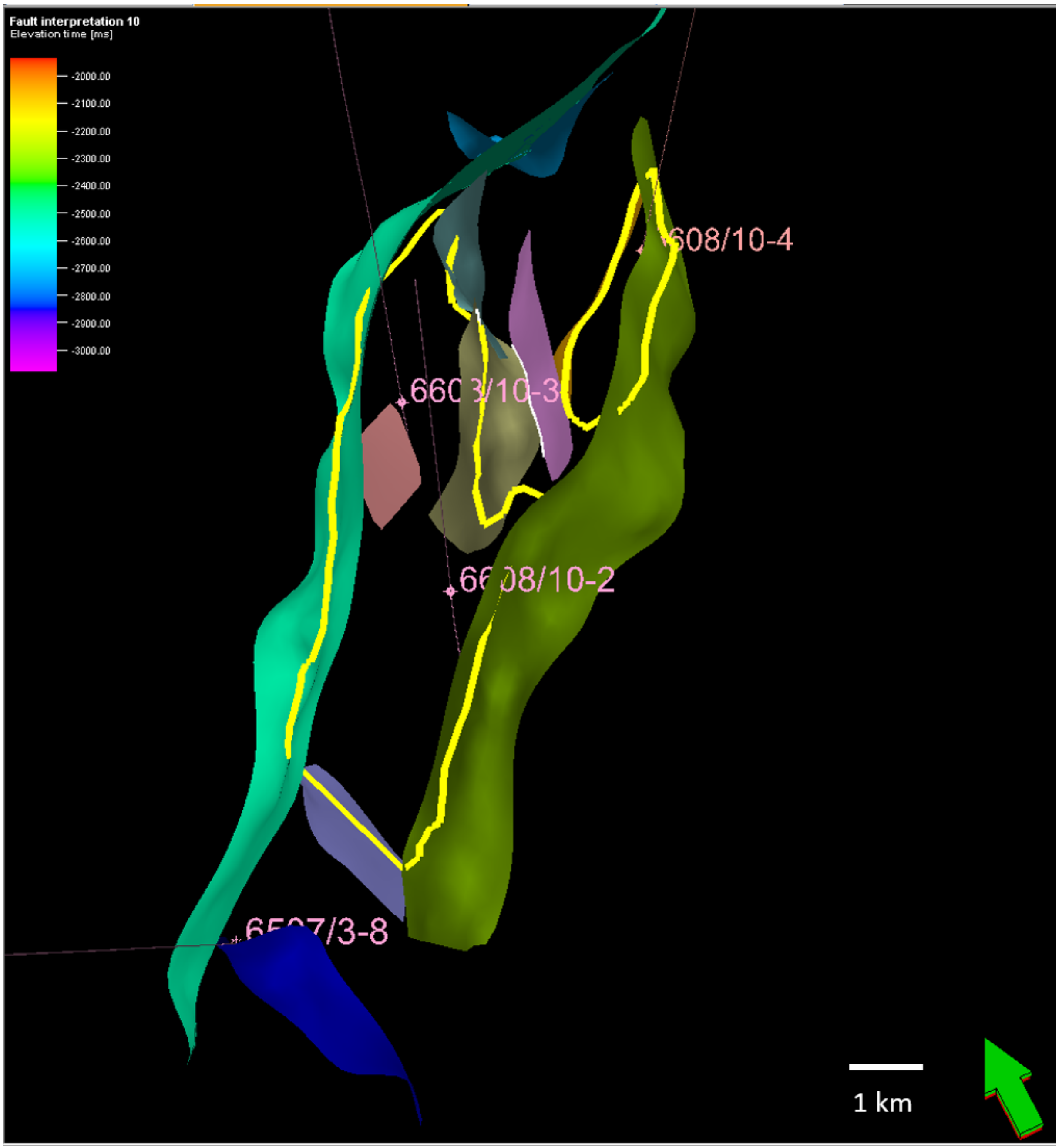

Figure 5.4: Fault model of the Norne Field showing relatively highly dipping fault with longer fault oriented NE-SW and shorter fault oriented NW-SE. The outline of the field is shown in yellow.

5.2 Seismic Horizon Interpretation

Two main horizons are interpreted in the study area. These horizons are of Middle Jurassic age with facies changing from Not Formation in the southwestern part of the field into Garn Formation in the northeastern part. These horizons are interpreted based on the geological markers of four wells, 6507/3-8, 6608/10-2, 6608/10-3, 6608/10-4, which are published on the NPD website. Generally, these horizons can be followed throughout the field, though uncertainty is introduced due to the highly faulted character of the field.

Based on the well data, the combined thickness of the Garn and Not Formation is only around 40 to 50 m. The Not Formation is too thin all over the field (under 10 m), therefore it cannot be detected by the seismic resolution. An exception is near well 6507/3-8 in the southwest of the field where it is around 50m. The top of Ile Formation was interpreted to define the base of Garn and Not (Figure 5.5). The interest formation is represented by 20-30 ms of two way travel times in seismic which is one wiggle trace.

As mentioned above, that Middle Jurassic has facies changing from Garn Formation into Not Formation. Not Formation has higher shale content when compared to the Garn Formation. This was also represented in the seismic reflector where the top of the Garn has stronger amplitude in the northeastern part of the field than the top of the Not formation in the southwest (Figure 5.6). This is most likely because Garn has higher sand portion which results into higher contrast of acoustic impedance in comparison with the Not Formation. The thickness change of the Not is observed in the southwestern part of the area close to well 6507/3-8 (Figure 5.6). This was interpreted as the pinch out point where the Not Formation in the southwest changes into the Garn Formation towards the in the northeast.

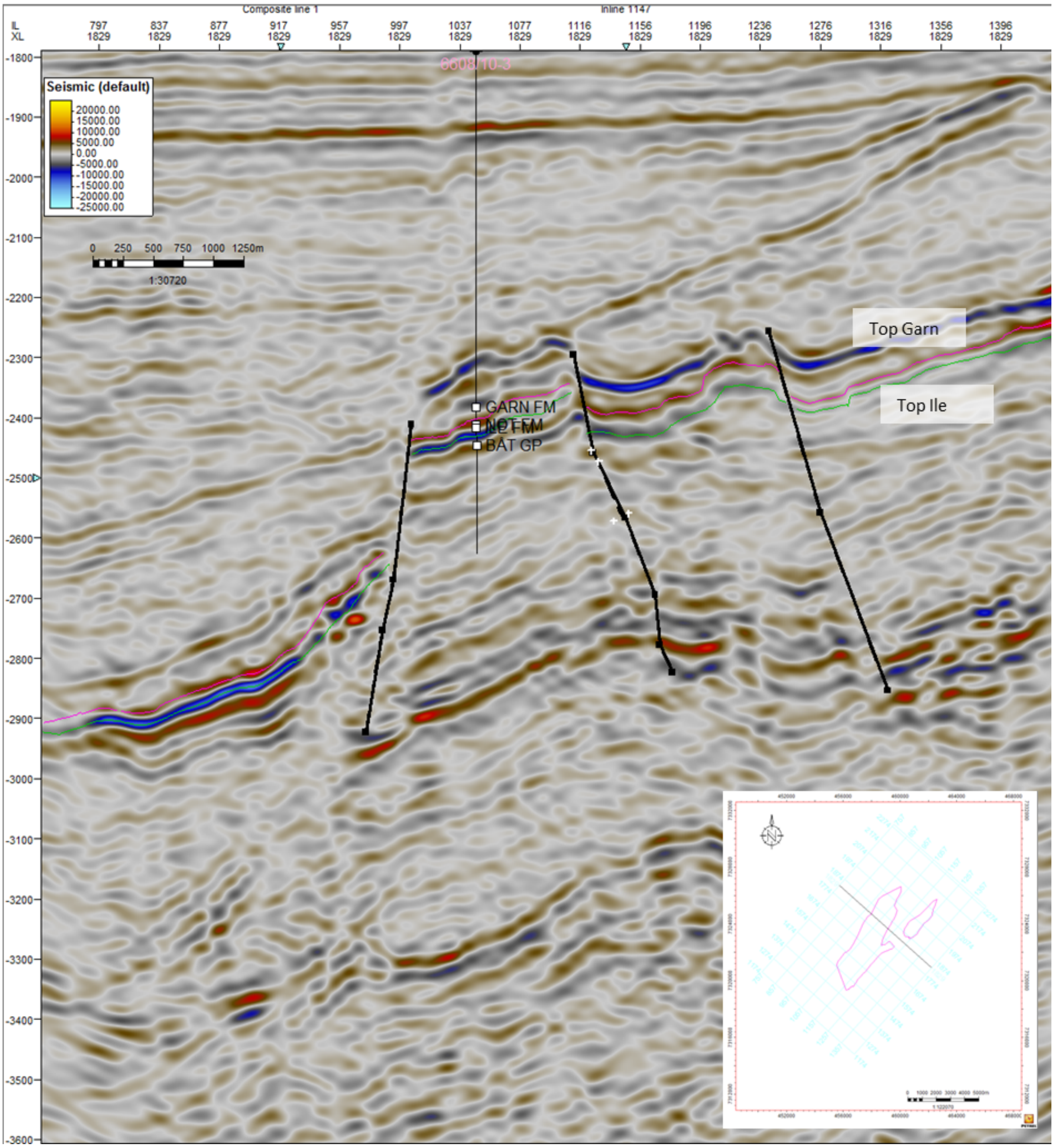

Figure 5.5: Crossline seismic section showing Top Middle Jurassic, Top Garn and Not Fm (red color) and the Top Ile (green color). The interest formation is represented only around 20-30 ms TWT on the seismic section.

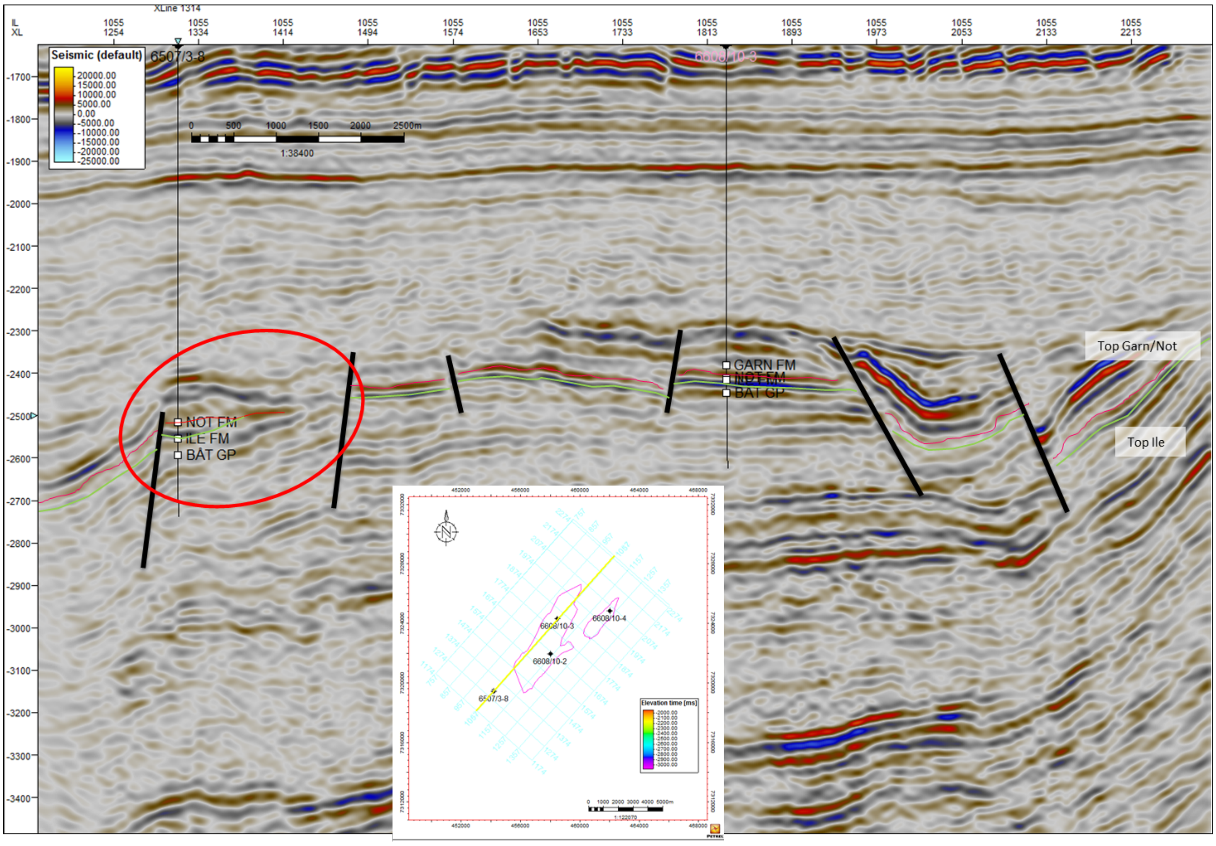

Figure 5.6: Inline seismic section showing the thickness change (pinch out) of Not into Garn Formation and the amplitude change from Not (less strong) into Garn Formation (stronger reflector).

Chapter 6

Seismic Horizon Analysis

6.1 Horizon Slicing and Seismic Attribute

From a 3D seismic survey, it is possible to make a horizon slice to view a particular reflection, obtaining displays for visual inspection of seismic attributes, such as amplitude. In this study, a horizon slice along the Garn-Not horizon was implemented for depositional screening and distribution of the Garn and Not sands.

The Norne field lies on highly faulted horst block, therefore, this created difficulties in tracing the Garn-Not horizon, creating high uncertainty is parts of the field. The horizon slice created was used for seismic attribute analysis, i.e., the maximum amplitude which measures the reflectivity within a time or depth window. Attributes such as the maximum amplitude, are useful to make a better connection in between the seismic and the geological settings (structure, stratigraphy, and depositional environments), which can lead to better geological or geophysical interpretation of the data.

Figure 6.1 presents the map view of the Garn-Not horizon, representing the maximum amplitude, or in other words, a seismic attribute map. This map has some uncertainties, especially off the horst block, within the heavy faulting areas, bringing difficulties in tracing the Garn-Not. However within the horst, where the Garn-Not horizon can be traced with ease, the seismic attribute map was helpful for distinguishing the reflectivity between these two formations, which appear in the well logs and in the seismic as the same age in the southwest part of the Norne area.

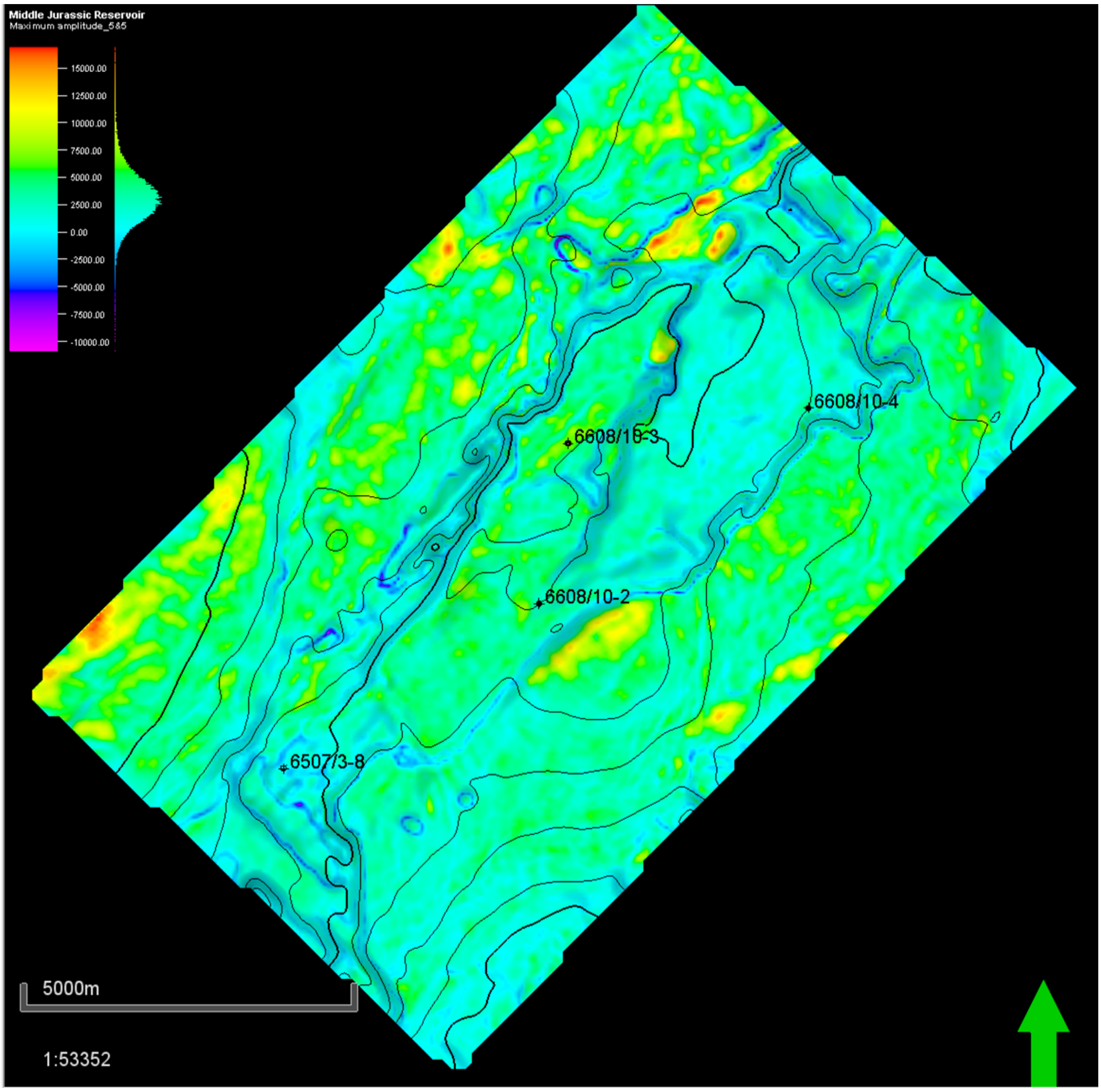

Figure 6.1: Seismic attribute map of the Garn- Not. Map view of the horizon, representing the maximum amplitude

The following figures present the difference in reflector amplitude of the Garn versus the Not. A seismic horizon crossline taken on well 6608/10-3 shows a Garn with strong amplitude (Figure 6.2) in the North Central part of the field when compared to the weaker amplitude of the Not (Figure 6.3) shown in a crossline southwest of the field on well 6507/3-8.

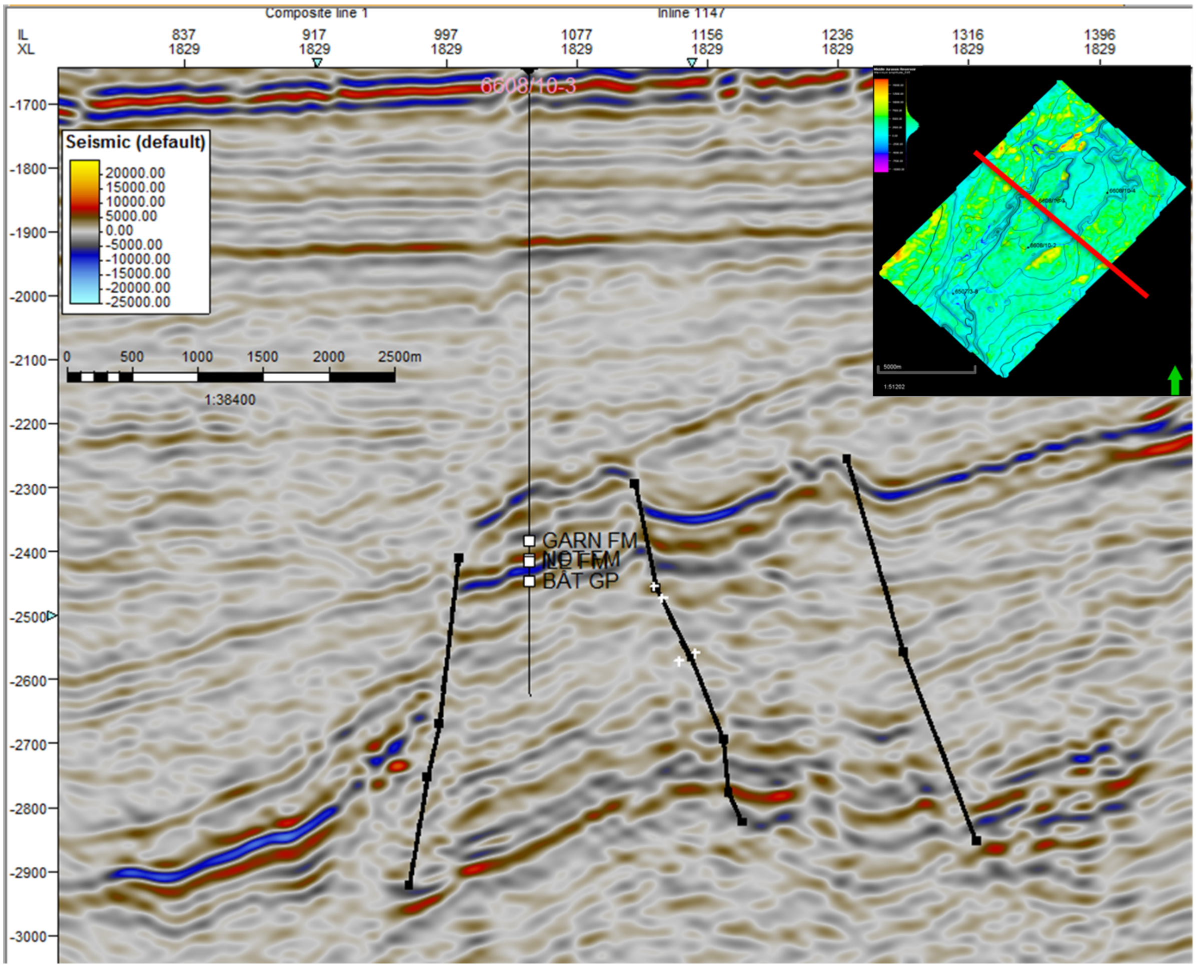

Figure 6.2: Seismic signature of the Garn, shown by a crossline accross well 6608/10-3. Inset map shows maximum amplitude surface.

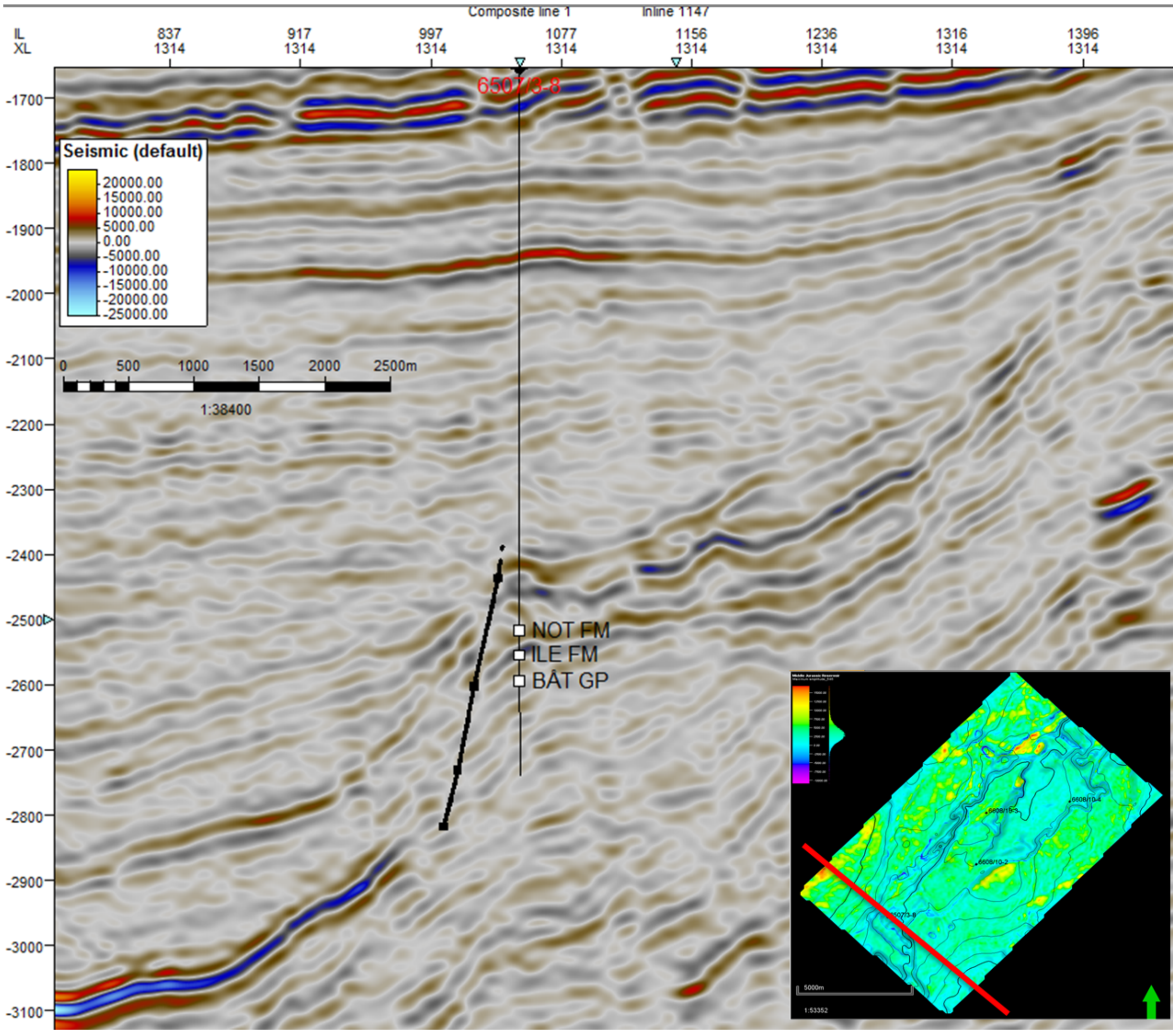

Figure 6.3: Seismic signature of the Not, shown by a crossline across well 6507/3-8. Inset map shows maximum amplitude surface.

6.2 Seismic Facies Analysis

Seismic facies units are interpreted in terms of the depositional environments, the energy of the depositing medium, and the potential lithologic content of the strata generating the seismic facies reflection pattern (Mitchum Jr et al., 1977). Seismic reflection is a fundamental aspect of seismic facies analysis. Seismic reflections are composites of the individual reflections generated by surfaces separating strata of differing acoustical properties (Mitchum Jr et al., 1977).

The study interval is in the Middle Jurassic (Garn and Not formations). Well logs data shows that Garn and Not formation in the Norne area have a combined thickness of about 40-50 meters (Figure 4.10). Based on vertical seismic resolution, those formations are represented by two peaks of wavelets and one through of wavelet (Figures 3.8 , 3.9, 3.10.)

Interesting features come from a NE-SW inline section that goes through the wells 6507/3-8 and 6608/10-3, where at least three types of seismic facies according to Mitchum Jr et al. (1977) different types of facies can be differentiated.

Parallel configuration, mostly located in the central part of the inline 1055 seismic section (Figure 6.4). This seismic configuration also confirmed on the crossline (Figure 6.5). Parallel pattern suggests uniform rates of deposition on a uniformly sub-siding shelf of stable basin plain setting (Mitchum Jr et al., 1977). On the northeast side of inline 1055, seismic section is influenced by tectonic activity after deposition (syncline geometry in the hanging wall block which most likely is associated with the fault itself) and in this area **sub-parallel configuration**, is representing uniform rates of deposition on a uniformly sub-siding shelf of stable basin plain setting with a wave influence (Mitchum Jr et al., 1977).

As observed on the well correlation panel 4.10), Garn sandstone is not present in well 6507/3-8, but a thick Not sandstone appears instead. This condition is solved by seismic facies analysis in which, **lenticular configuration** (pinching out) seismic reflection configuration in the 6507/3-8 well area (Figure 6.4). Lenticular configuration is caused by the release of transport energy in the depositional basin (probably in the deltaic sand bar system).

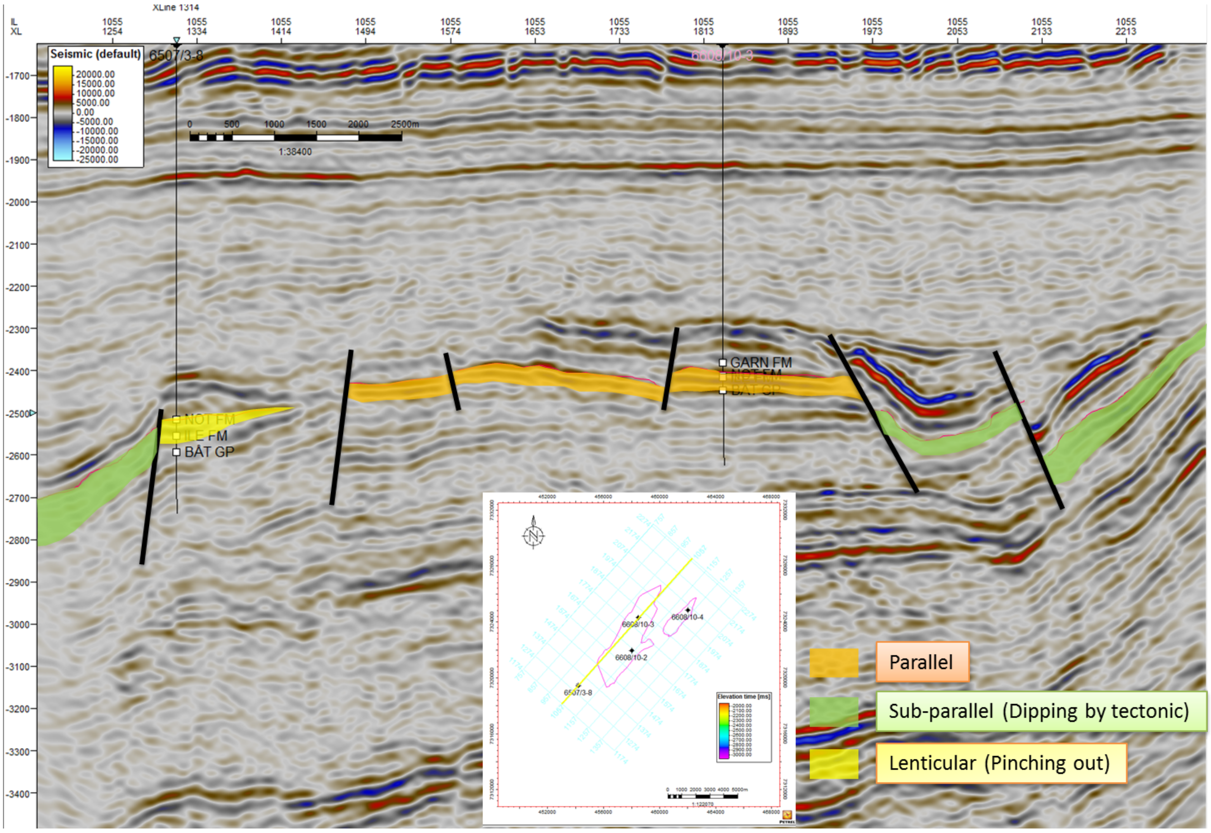

Figure 6.4: Seismic reflections configuration of seismic inline section 1055 in the study interval of the Norne field.

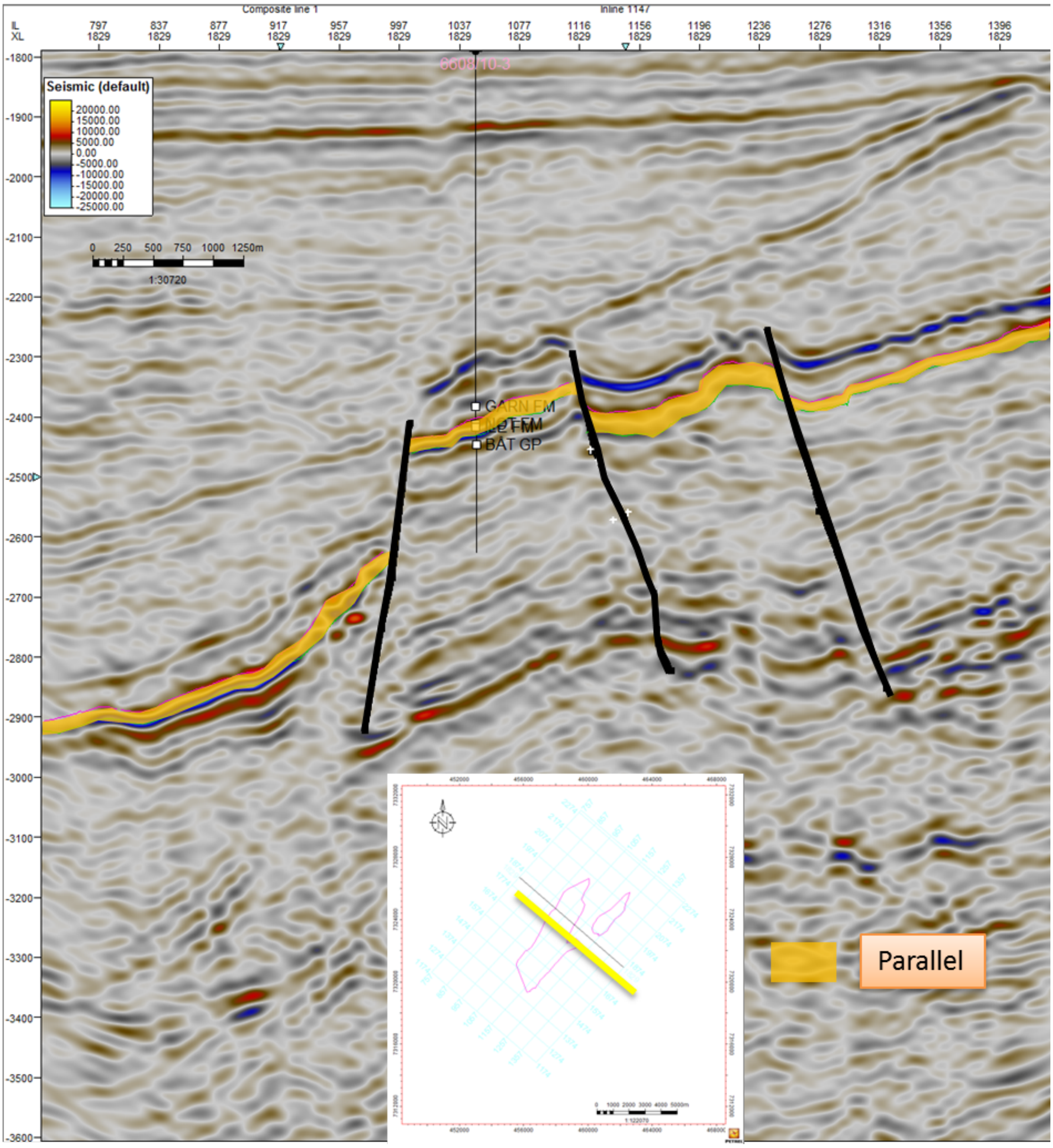

Figure 6.5: Seismic reflections configuration of seismic crossline section 1829 in the study interval of the Norne field.

Chapter 7

Geological Models

7.1 3D Geologic Model

Geological model is of high importance to better understand structural and stratigraphy aspects from a petroleum field. Recent technology makes possible the construction of a geological model represented by a three dimensional point of view. Some uncertainties on the 3D geological model comes from seismic data quality as a main input for the structural model. Horizon and fault are two main inputs for this 3D geological model. Those things come from 3D seismic interpretation. 3D horizon and fault forms a structural model as an outline for 3D geological model. Zonation comes from the top and bottom horizon that is controlled by wells stratigraphy (Formation). 3D geological model will represented the structural configuration of the area and thickness distribution of the interest zone (Garn – Not reservoir).

This 3D geological model shows the field with the faults that occurred later than depositional time during the Late Jurassic and Early Cretaceous period. The following characteristics are observed from the 3D geological model in Figure 7.1

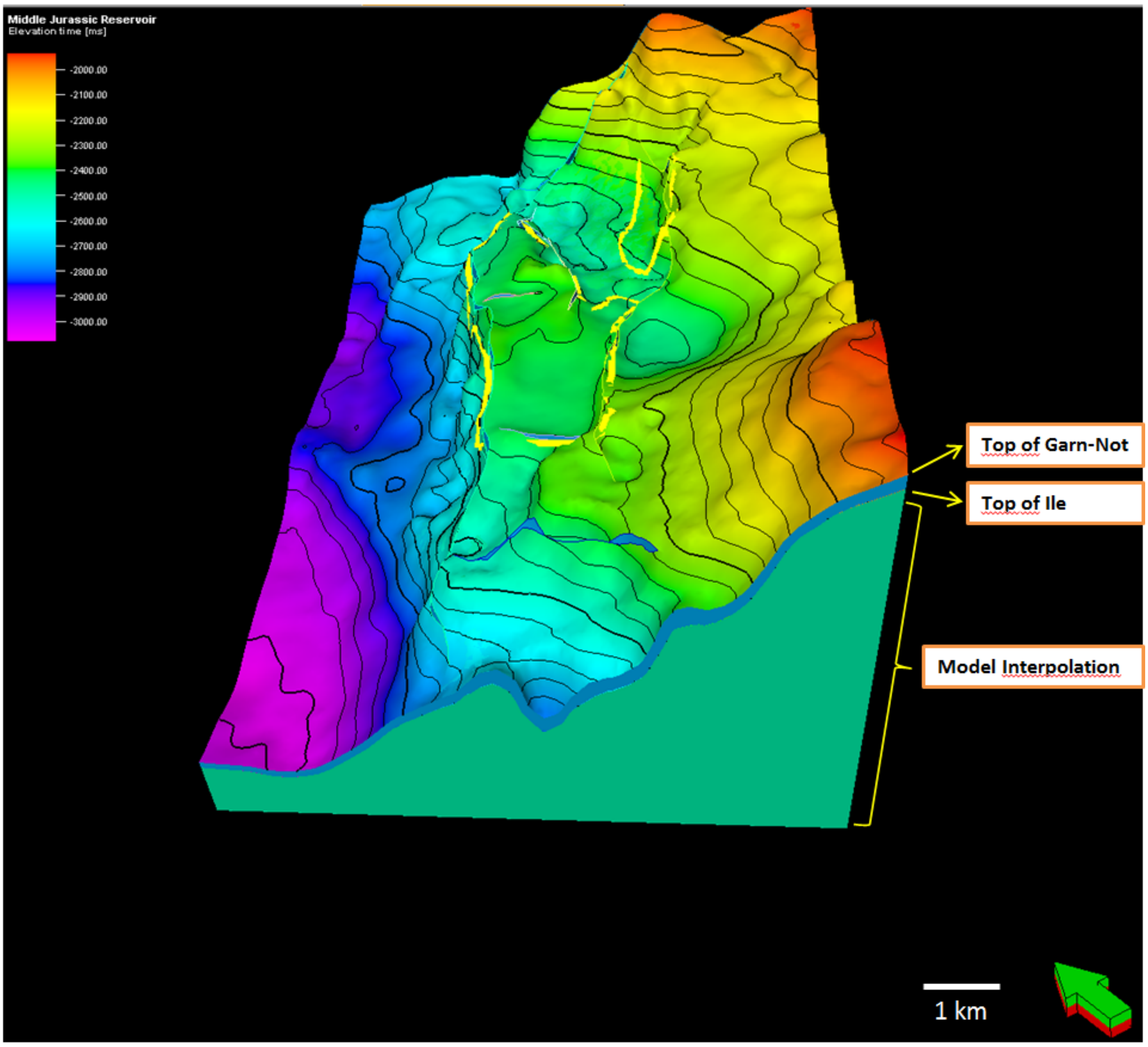

Figure 7.1: 3D Geological Model of the Middle Jurassic Not and Garn Formations. Norne field is outlined in yellow.

- In this 3D geological model, the yellow line is the field outline of the Norne field.

- The Norne field is located on upthrown block area of the seismic cube.

- The west fault compartment makes outline of this field.

- The Not-Garn horizon is homogeneous throughout the model.

- The 3D geo model gives a good layout of Norne's tectonic framework, i.e., normal faults with NE-SW orientation trends. This fault network coincides with the tectonic history of this area, where two rifting episodes occurred, first during the Permian, and second during the Late Jurassic – Late Cretaceous periods.

7.2 Paleogeography Model

The following is the interpretation of the paleogeography of the Norne field area during Middle Jurassic times, based on well log interpretation and correlation, as well as on seismic attribute analysis, and seismic facies analysis performed throughout this study.

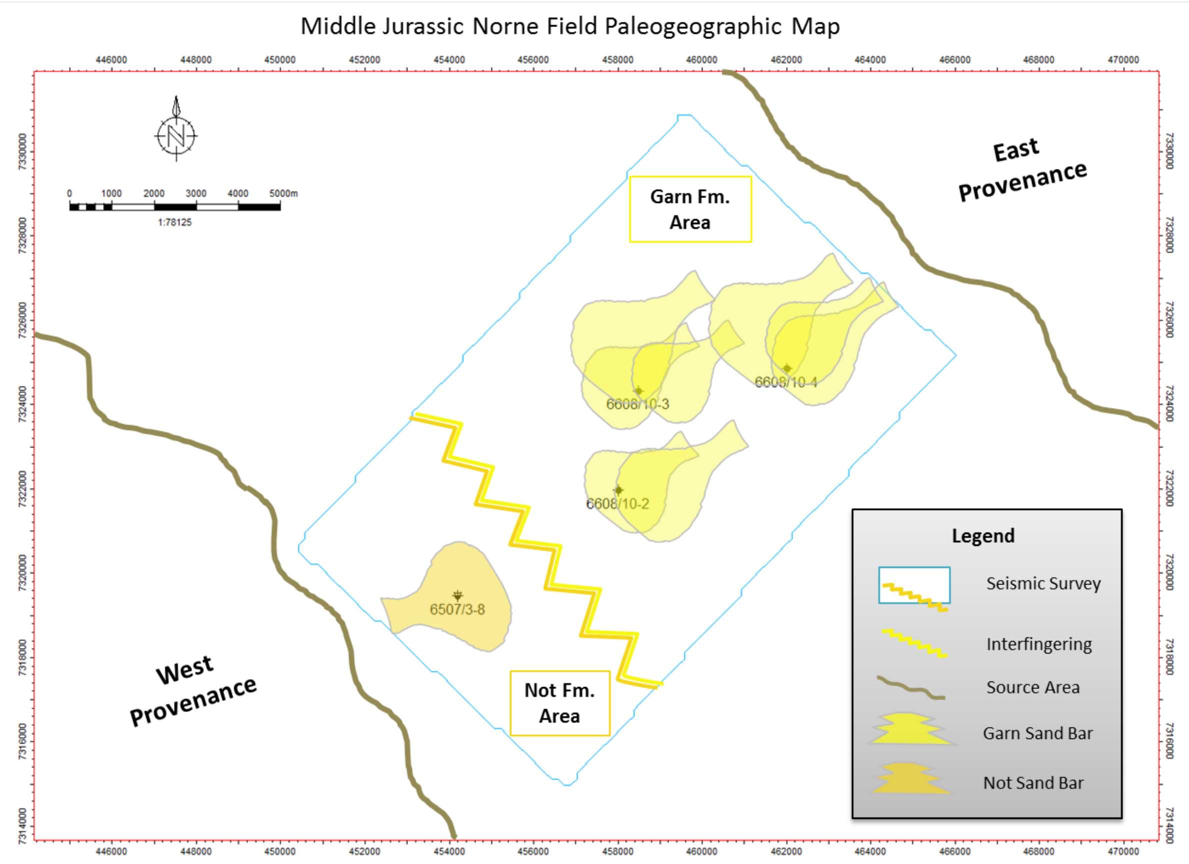

Figure 7.2: Paleogeography Model of the Norne Area.

Chapter 8

Discussion and Recommendations

8.1 Discussion

The results of this study revealed that the sand Middle Jurassic Not Formation changes in facies from the southwestern part of the field into the Garn Formation in the northeastern part. This was observed in the reflector amplitude of the Garn versus the Not, i.e., the Not presents a lower amplitude when compared to the Garn formation amplitude (Figure 6.1). An interesting aspect of the Not-Garn horizon came up when studying the well logs. The well logs revealed that the Not formation is present as a thick sand on well 6507/3-8 in the southwest of the field with out any Garn Formation sand at the top, and that it has a muddier response in the northeast part of the field. This mystery was resolved with seismic facies analysis, where, lenticular seismic configuration was observed near well 6507/3-8 in the form of a stratigraphic pinch out.

The 3D geological model represents the structural configuration of the area and thickness distribution of the interest zone (Garn – Not reservoir). The Not and the Garn formations were revealed to be deposited before the major tectonic rifting which occurred late Middle Jurassic. This was observed in the seismic fault interpretation of the Norne horst block where normal faults are mostly oriented towards northeast – southwest and cut the sediments until the Cretaceous age indicating that most likely the structure that composed the study area occurred or reactivated no later than Cretaceous. Since the Garn and the Not were deposited before the structural configuration, a paleogeography model was made to address the depositional characteristics of this formation.

According to literature (stratigraphy section in geologic background chapter), different provenances were proposed for this area. Based on well correlation interpretation and core photos interpretation, along with seismic attribute and seismic facies analysis, two source areas are proposed for the deposition of the Not and the Garn. The paleogeography intents to show the Not sand during Middle Jurassic prograding easterly from a western source, as proposed by Brekke et al. (2001) and Swiecicki et al. (1998). Moreover, it intends to show the Garn sand during the Middle Jurassic prograding westerly, from an eastern source area as proposed by Gage and Doré (1986) and Heum et al. (1986).

8.2 Recommendations

Although Halten terrace is the type area for the Not and Garn formation that is found on Norne, it is still located further south, and as literature suggests, there is controversy with the provenance of Fangst Group formation and overall agreement on the depositional environment for these formation. For example, some authors suggest that the Garn Formation is fluvial in the Halten ares, but the data from this study leans to shallow marine sedimentation. Whether this formation was part of a fluvial system feeding a shallow seaway and then it got reworked by tides and longshore currents, it is not clear in the Norne area. A recommendation to solve this would be to obtain access to the core storage facility that owns these cores, for a more thorough description (that from core photos alone) of the facies by obtaining details on the sedimentary structures, textures, possible trace fossils, and bed contacts. Also, access to the core data for petrophysical analysis helps enhance the well log interpretation and thus the correlation. Missing core photos on well 6507/3-8, although five cores were collected on this well. It would be recommended to study the sand interval of the Not this core photos, Integrating the above detailed information, can increase the paleogeography map quality, but since the numbers of exploration wells are limited, a recommendation would be to expand the area of study with a larger seismic survey and with more wells. Although the seismic data quality was good, the high presence of faults in the area, introduced uncertainty with potential errors on the horizon tracing. Moreover, the Not was too thin to be represented on seismic by a different horizon. Other than at the well 6507/3-8 where the Not was present without the Garn and the attribute map helped in obtaining a different seismic reflection response, seismic in other parts of the field was not able to differentiate the Not from the Garn. Better quality and better seismic resolution can be a recommendation for solving this problem.

Chapter 9

Conclusions

Based on the evaluation from the well logs, core photos, and 3D seismic survey of the Norne field, the following conclusion can be made:

- Garn and Not Formations are siliciclastic sediments deposited in the shallow marine environment.

-There is a facies change which was observed in the seismic as a pinchout in between the Not and Garn formation, due to the difference of the sediment provenance areas.

- The Garn formation is predicted to come from northeastern source area and prograded in the southwestern direction.

- The sediments in the Not Formation came from the southwestern source which prograded in the northeastern direction.

-The structural setting of the Norne Field is dominated by extensional structure mostly oriented NE-SW, which formed the horst block that outlines the field and most of these faults cuts the sediments until the Cretaceous age indicating that most likely the structure that composed the study area occurred or reactivated no later than Cretaceous.

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