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Detailed reservoir study of the Lower Jurassic Tilje Formation around the Noatun and Linnorm Discoveries, Halten Terrace, Norwegian Sea

by

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ABSTRACT

Tilje Formation in Halten Terrace is significantly affected by the strongly heterolithic nature of its component of lithofacies and the complicated reservoir architecture, which largely controlled by eustatic process of relative sea level fluctuations.

Sedimentological analysis from the core samples and log responses from 5 surrounding wells (6406/9-1, 6406/9-2, 6407/7-8, 6406/6-2 and 640774-1) were used to identify the variability of lithofacies, depositional element and depositional environment of Tilje Formation. Seven depositional elements was identified from the lithofacies and four main electrofacies classifications was characterized and combined into five generalized facies association classifications to reconstruct reliable facies models, which covers the wave-tide dominated delta to marine offshore environments.

Sequence stratigraphic analysis has allowed the recognition of three intervals of 4th order genetic sequences during the regressive-transgressive events. Sequence 1 consists of lower delta plain and wave-tide influenced delta, sequence is dominated by tide dominated delta deposits, which alternates with lower delta plain and estuarine deposits. Sequence 3 consists of tide dominated delta, estuarine and marine offshore deposits.

The integration analysis based on fault timing activity and stratigraphic interpretations indicates that Tilje Formation deposition was somehow affected by tectonic event in the early stage, and identified as early syn-rift deposits with SE-NW sedimentation trend within a NE-SW oriented half graben with local N-S normal fault trend.

The result of this study is an integrated data analysis and facies model which represents the paleoenvironment and tectonic evolution within the deposition of Tilje Formation.

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1 INTRODUCTION

The Halten Terrace area located in offshore mid-Norway has become a focus of hydrocarbon exploration since the early 1980s. Exploration started with the discovery of the Migrad Field in 1981, and continued with several major discoveries. The production of hydrocarbons is mainly from Lower and Middle Jurassic siliciclastic sequences deposited in shallow marine environments. These comprise either relatively homogeneous sands, or heterogeneous packages formed by an intercalation of mudstone, siltstone and sandstone.

This study focuses on the development of the non-marine through marginal marine to shallow marine deposits in the Lower Jurassic Båt Group (Norwegian name for boat) within the southern Halten Terrace, with emphasis on the Tilje Formation (Norwegian word for a boat's decking) around the Linnorm and Noatun Fields, offshore mid-Norway (**Figure 1.1**). The investigated interval is Pliensbachian in age (Dalland *et al.*, 1988).

Many challenges has been found in Tilje Formation which are significantly affected by the strongly heterolithic nature of its component of lithofacies and the complicated reservoir architecture. This lateral variability in reservoir architecture can be attributed to tectonic activity during deposition event. Therefore, this study was conducted to have a better understanding of heterogeneity in Tilje Formation.

Adequate data sets such as core samples, wireline logs and seismic surveys data was incorporated to make an integrated data analysis and build a reliable model to represents the paleoenvironment and tectonic evolution within the deposition of Tilje Formation.

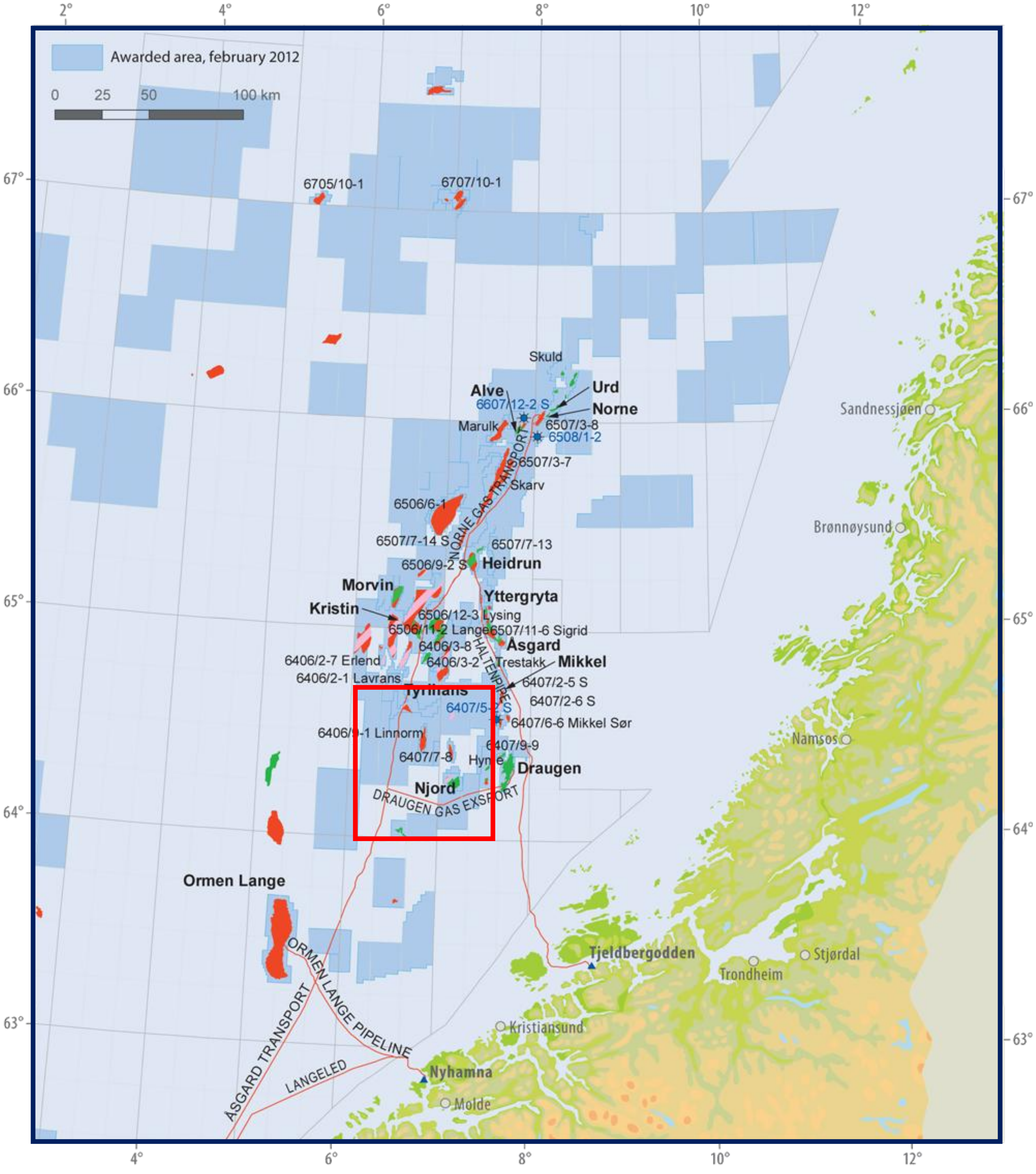


Figure 1.1 Location of study area in the Halten Terrace, Norwegian Sea

1.1 AIM OF STUDY

1.1.1 Objectives

The aim of this study was to provide a detail reservoir analysis of the Lower Jurassic Tilje Formation, and with emphasis on the stratigraphic subdivisions and lithofacies. The major focus was to provide an integrated and coherent conceptual geological model that can serve as a basis for a generic static model of Tilje Formation in the study area. This objective was achieved by:

- Provide a better understanding of sedimentological variation of Tilje Formation, including the depositional elements and depositional environments.
- Improve the understanding of dimension and architecture of facies within Tilje Formation and correlation with the influence of major eustatic and tectonic during the deposition.

1.1.2 Deliverables

- Sedimentological description of Tilje Formation from the core samples of 3 wells in Linnorm, Noatun and Spinel Field.
- Facies association for the entire cored section based on the sedimentological description and vertical stratigraphic variability observed from the core data.
- Identify log signature of defined facies association in order to calibrate the cored section interpretation and log response, and then apply the correlation result for the uncored section of Tilje Formation.
- Sequence stratigraphic correlation of the studied interval for further constrains the distribution of reservoir scale facies architecture and depositional environments of the Tilje Formation.
- Facies model map that represents the paleogeography for the area.

1.2 PREVIOUS WORK

The Halten Terrace was early recognized as part of a large sedimentary basin offshore Mid-Norway (Eldholm, 1970; Grønlie & Ramberg, 1970; Talwani & Eldholm, 1972; Åm, 1970; Gjelberg, J. et al, 1987).

The lithostratigraphy of the Mesozoic succession was formalized by Dalland et al (1988), and this publication established the nomenclature used to this day. Dalland et al (1988) defined the Tilje Formation as an interval consists of sub heterolithic and mudstones deposited on tidal to estuarine paleoenvironment. Lateral extent and variation for Tilje Formation is recognized on Haltenbanken and Trænabanken, whereas it is locally absent on the Nordland Ridge due to erosion. The formation is variably developed throughout the Halten Terrace where it is from 100 m to more than 250 m thick. It thins to the north to less than 100 m on the Trøndelag Platform. Typical depositional environment of the formation is near shore marine to intertidal environments, with delta plain and paralic environments present to the E-SE. Sub crops near the coast (Bugge et al., 1984) indicate a gradual transition to continental environments eastwards.

Another study from Gjelberg et al. (1987) suggested an overall tidally influenced setting for the marine parts of the Tilje Formation, while Dreyer (1992, 1993) subdivided the Tilje Formation on the Halten Terrace into a lower fan deltaic part and upper, thin bedded, tide-dominated part. Taylor and Gawthrope (1993) presented the first published sequence stratigraphic interpretation of the Tilje Formation in the Halten Terrace, where the development started from the shoreface in the lower part transitional into fluvial to tidal coastal plain in the upper part. More recently, Ichaso et al (1999) and Martinius et al. (2001) interpreted the Tilje Formation as a representation of a mixed tide and fluvial –dominated delta system, variably influenced by tidal processes.

1.3 METHODOLOGY

This subsurface study is based on the following data:

- Sedimentological core/lithofacies analysis of Tilje Formation from three wells with total 233,7 m of core length sections (**Table 3.1**)
- Electrofacies analysis of Tilje Formation from 5 surrounding wells exploration and appraisal wells which accommodate Gamma Ray, Neutron/Density , Sonic and Resistivity wireline logs from well 6406/9-1 and 6406/9-2 (Linnorm), 6407/7-8 (Noatun), 6406/6-2 (Onyx West Field), 6407/4-1 (Spinel). All of the wells reach depths greater than 4,2 km (~13,700 ft) into Tilje Formation. Well spacing is ranges from 3.3 km to 18.5 km.

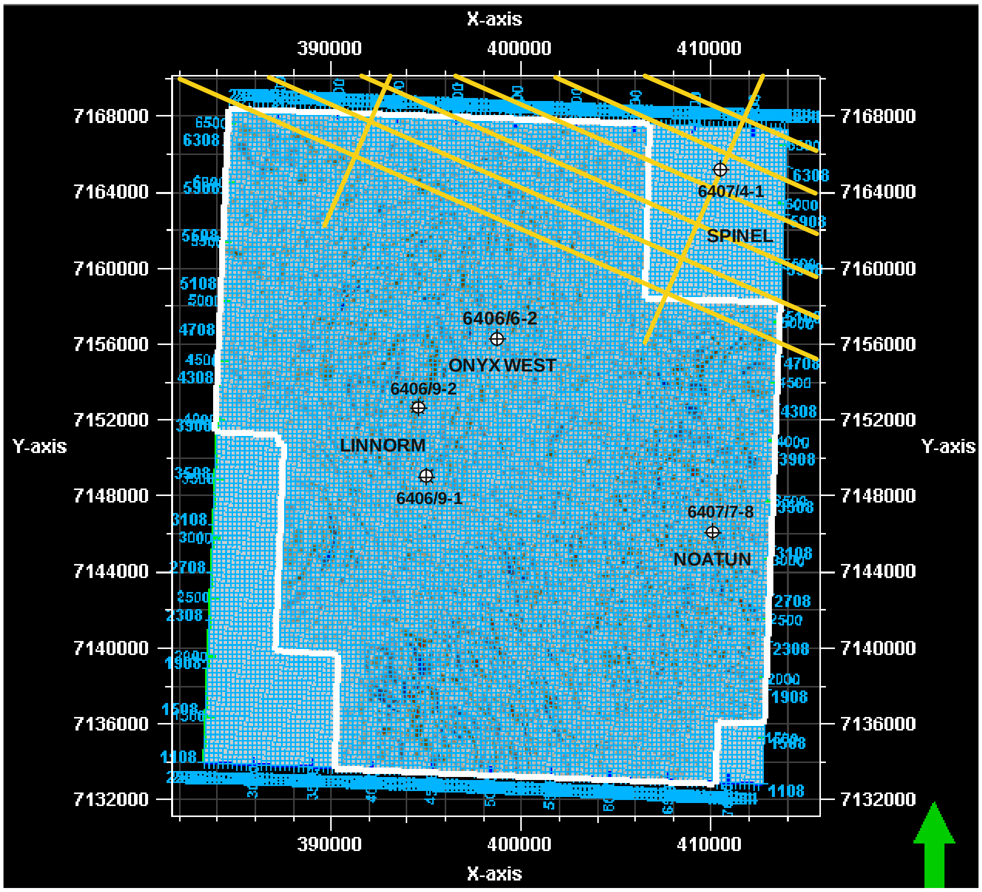


Figure 1.2 Seismic survey data around the study area. 3D merged seismic survey cube covers the Linnorm, Onyx and Noatun Field (white line), while the Spinel Field covered by eight 2D seismic survey lines (yellow lines).

- One merged 3D seismic survey cube (SH0902MZ10, reprocessed 2012) with total of 806,31 km² and two way travel time data recorded up to 6.1 s. the 3D seismic data set covers the Linnorm, Noatun and Onyx Field. For the Lower Jurassic, the dominant frequency is between 25 and 30 Hz, giving a minimum estimated vertical resolution of 30 m (95 ft). Since the 3D seismic survey does not cover the Spinel area, eight lines of 2D seismic survey (ST8409) was used, which consist of 6 NE-SE trend lines and 2 NE-SW trend lines. (**Figure 1.2**).

1.3.1 Core Analysis

The core descriptions are based on the core section data from Linnorm (6406/9-2), Noatun (6407/7-8) and Spinel Field (6407/4-1). The 59,8 m long core from Spinel Field only cover the upper part of Tilje formation, while the 62,5 m total core length in Linnorm represents the middle and lower part of TIlje Formation (**Table 3.1**). Noatun has the most complete sections of core data with 111,4 m length which covers the upper, middle and lower part of the Tilje Formation (**Table 3.1**)

The core description was logged at 1:50 scale detailed and included identification of the grain size, textures, sedimentary structures and trace fossils. This scale allowed sufficient resolution to resolve and differentiated between the identified lithofacies and depositional elements. Trace fossil interpretation from Jambo Geoconsultants Ltd (2007) was used as reference. The observation of these parameters gives leading information about the sedimentation processes. The results of this core analysis used as the reference to build the facies association and depositional environment framework.

1.3.2 Well Log Analysis

The core data was correlated with the wire line logs data from the five wells and used to identify the characteristic log motifs for the recognized depositional elements and facies associations. In order to successfully correlate core and well data, core shifts was performed by matching the response of specific log with the lithology observed from the core.

Well Name	CORE SECTION	Original depth		Shifted depth		Shift distance
		From	To	From	To	
		(m)		(m)		(m)
6406/9-2	2	5096	5100.3	5105.7	5110	9.7
	3	5103.3	5134.5	5113.3	5144.5	10
	4	5209.7	5237	5221.2	5248.5	11.5
6407/4-1	1	4278	4333.8	4282.9	4338.2	4.9
6407/7-8	1	4757	4772.2	4758	4773.2	1
	2	4806	4836	4807.1	4837.1	1.1
	3	4878	4910.9	4878.1	4910.9	0.1
	4	4937	4970.5	4944.1	4977.6	7.1

Table 1.1 Detail core - wireline log shifting

The mud-dominated sections of the core correlated with the high gamma ray log values and positive separation of neutron/density logs (high-high value), while the sand-dominated sections of the core correlated with low gamma ray log values and none or negative separation of neutron/density logs (low-low value).

Two neural network analysis methods were performed to interpret the facies association in un-cored well section in Tilje Formation. The first one is an un-supervised method, where the sections are divided into several classifications based on the value of gamma ray, neutron and density logs. The second is a supervised method, where the classifications were defined by the result of facies association in interpreted core sections. The result is the general log patterns which define a specific depositional event, depositional element, and depositional environment.

1.3.3 Sequence Stratigraphy

To investigate changes in architecture through depositional cycle, the hierarchy of depositional cyclicity was first identified, and the facies association assessed at the scale of smallest identifiable cycle using 4^{th} order of genetic sequence concept (0,1 – 1 My), which is defined by bounding surface such as flooding surfaces (FS) and Maximum Flooding Surface (MFS) (Galloway, 1989). This sequence stratigraphic approach incorporates the results of core and well log analysis to identify the stacking pattern and the main bounding surfaces by integration of all well data with variable resolutions. The resulting strata packages are all have a progradation-to-retrogradation timeline which defines a series of successive regressive-to-transgressive trends creating the form of the Tilje Formation. These transgressive and regressive trends are related to the balance between accommodation creation and sediment supply, which in turn control relative sea-level changes.

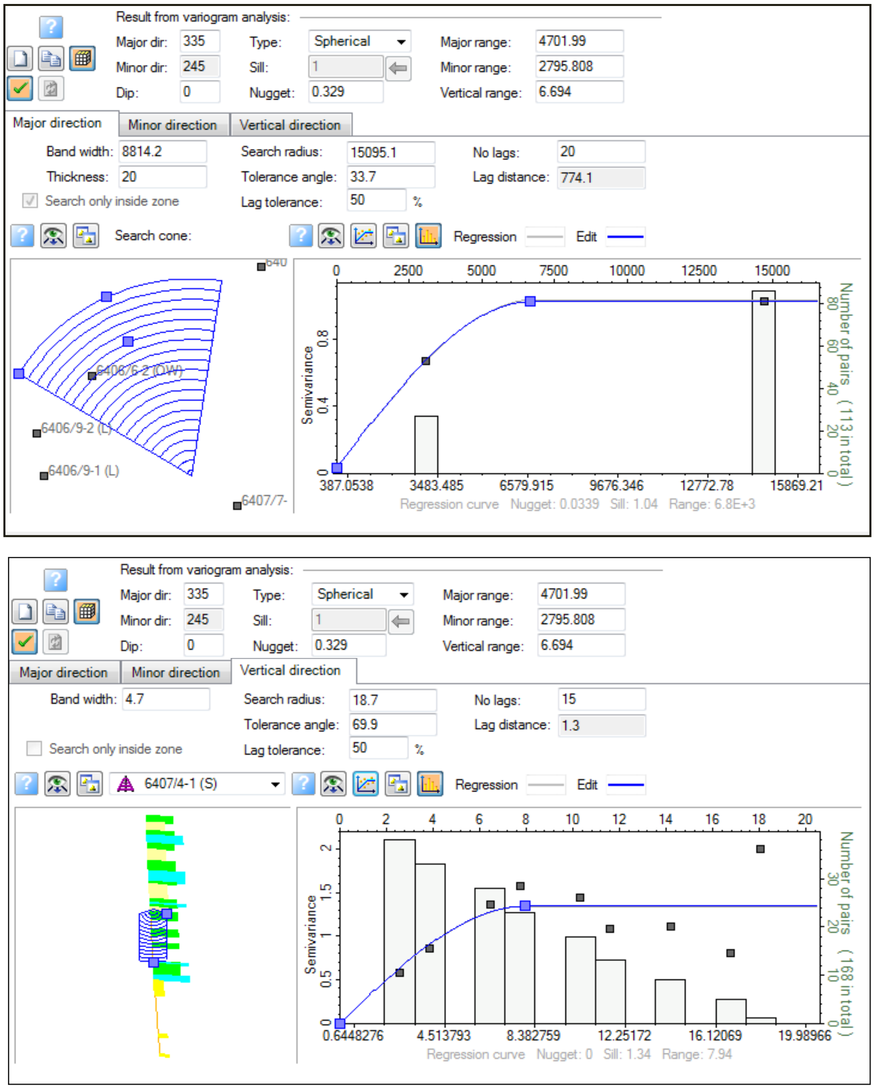
1.3.4 Seismic Interpretation

Seismic surveys data was provided in order to have a detail lateral distribution of the Tilje Formation sub environment within the Linnorm and Noatun area. Seismic-well tie process was performed to match between seismic survey and well data as they have difference in domain (time versus depth). Synthetic seismograms were constructed as a first step of seismic-well tie process by first calculating time-depth relation (TD charts) from the well log correlations and velocity data from sonic (DT) logs, and then compared with the trace extracted from the seismic volume. The correlation result provides the information of seismic amplitude and phase related to particular bounding surfaces used for seismic picking methods. This study focuses on the horizon and amplitude interpretations which represents lateral distribution of the Tilje Formation, while the fault interpretations were taken from SHELL in-house study. Seismic amplitude attribute extraction was performed to check if some trends or geological features could be provided from the seismic data, which likely to represents depositional architecture.

1.3.5 Facies Modeling

Facies modeling was performed in order to establish a coherence and comprehensive conceptual geological model of the facies association and the sequence stratigraphic results in the study area. Truncated Gaussian simulation (TGS; Galli et al.,1994; Journel and Ying, 2001) were used to reproduce depositional settings assuming highly ordered depositional models, for example like deltaic (Matheron et al., 1987; Rudikiewicz et al., 1990; Joseph et al., 1993) or fluvial (Mathieu et al., 1993; Eschard et al., 1998; Schlumberger, 2011). Some important input variables are:

- **Variogram.** This variable was done in data analysis, which decides the spatial continuity of the facies. It is basically a parameter to check the relationship of the variation in a property as a function of lateral separation distance between the data points. The input data for this variogram analysis is the upscaled log from the interpreted facies association. The analysis of the cell depends on the heterogeneity of the facies in the interval.



Result from variogram analysis:
Major dir: 335
Minor dir: 245
Dip: 0
Type: Spherical
Sill: 1
Nugget: 0.329
Major range: 4701.99
Minor range: 2795.808
Vertical range: 6.694

Major direction
Band width: 8814.2
Thickness: 20
☑ Search only inside zone
Search radius: 15095.1
Tolerance angle: 33.7
Lag tolerance: 50 %
No lags: 20
Lag distance: 774.1

Regression curve Nugget: 0.0339 Sill: 1.04 Range: 6.8E+3

Result from variogram analysis:
Major dir: 335
Minor dir: 245
Dip: 0
Type: Spherical
Sill: 1
Nugget: 0.329
Major range: 4701.99
Minor range: 2795.808
Vertical range: 6.694

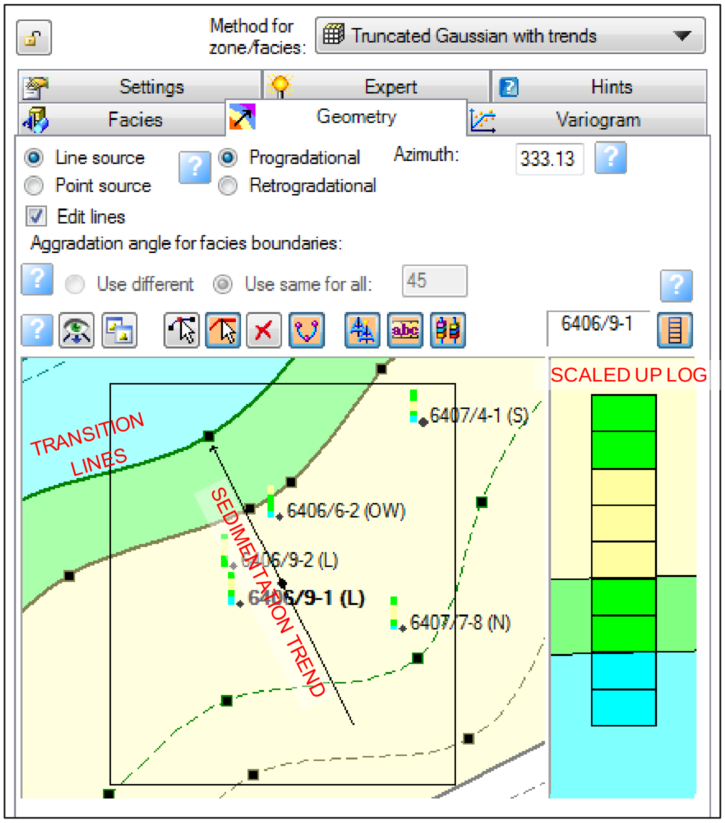
Vertical direction
Band width: 4.7
☐ Search only inside zone
Search radius: 18.7
Tolerance angle: 69.9
Lag tolerance: 50 %
No lags: 15
Lag distance: 1.3
6407/4-1 (S)

Regression curve Nugget: 0 Sill: 1.34 Range: 7.94

Figure 1.3 Illustration of major (above) and vertical direction (below).

In order to propagate the facies association, some input data needed to be defined, such as major direction which refer to the major sedimentation, minor direction which refers to the localized direction of sedimentation, and vertical direction which refers to the vertical heterogeneity of the sediments. The determination of sedimentation direction is strongly influenced by the observation of the geological history, well correlation trend and seismic attribute extraction. This data analysis was used together with variance to reconstruct the facies model.

- **Variance.** This variable decides the degree of interfingering along the transition (trend lines). If the variance increases, the detail of interfingering effect will increase.
- **Transition lines.** This variable represents the trend boundaries between the various facies, which were controlled by the result of up scaled well log for each interval (**Figure 1.4**).



Method for zone/facies: Truncated Gaussian with trends

● Line source
○ Point source
● Progradational
○ Retrogradational
Azimuth: 333.13
☑ Edit lines
Aggradation angle for facies boundaries:
○ Use different
● Use same for all: 45

Figure 1.4 Illustration of transition lines in Truncated Gaussian with Trends method.

1.3.6 Software Toolkit

In order to support the study, several software and toolkits were utilized for data processing:

- OPENWORKS (Geomodeling and Interpretation Software – Landmark) for data base and seismic interpretation
- PETREL 2011 – Geomodeling and Interpretation Software – Schlumberger) for seismic interpretation and facies modeling
    - Seismic Attribute Sculpture (Plug ins – SHELL) for seismic attribute extraction
- Arc GIS 10 – Map and Geographic Information Software – Esri) for map database
- Oilfield Data Manager (ODM) – Geological Well Data Software – Senergy) for core-well correlation.

2 GEOLOGICAL FRAMEWORK

2.1 STUDY AREA

The Halten Terrace is situated on the passive continental margin offshore mid-Norway (Blystad *et al.,* 1995), located on the Mid-Norway shelf and it forms the eastern margin and sub-platform area of the Mesozoic Norwegian – Greenland Sea Rift basin (**Figure 2.1**). It constitutes an area of approximately 10.400 km2 in total. It was formed as a part of a wide platform area, including the Trøndelag platform to the Late Jurassic rifting which established it as a separate structural element.

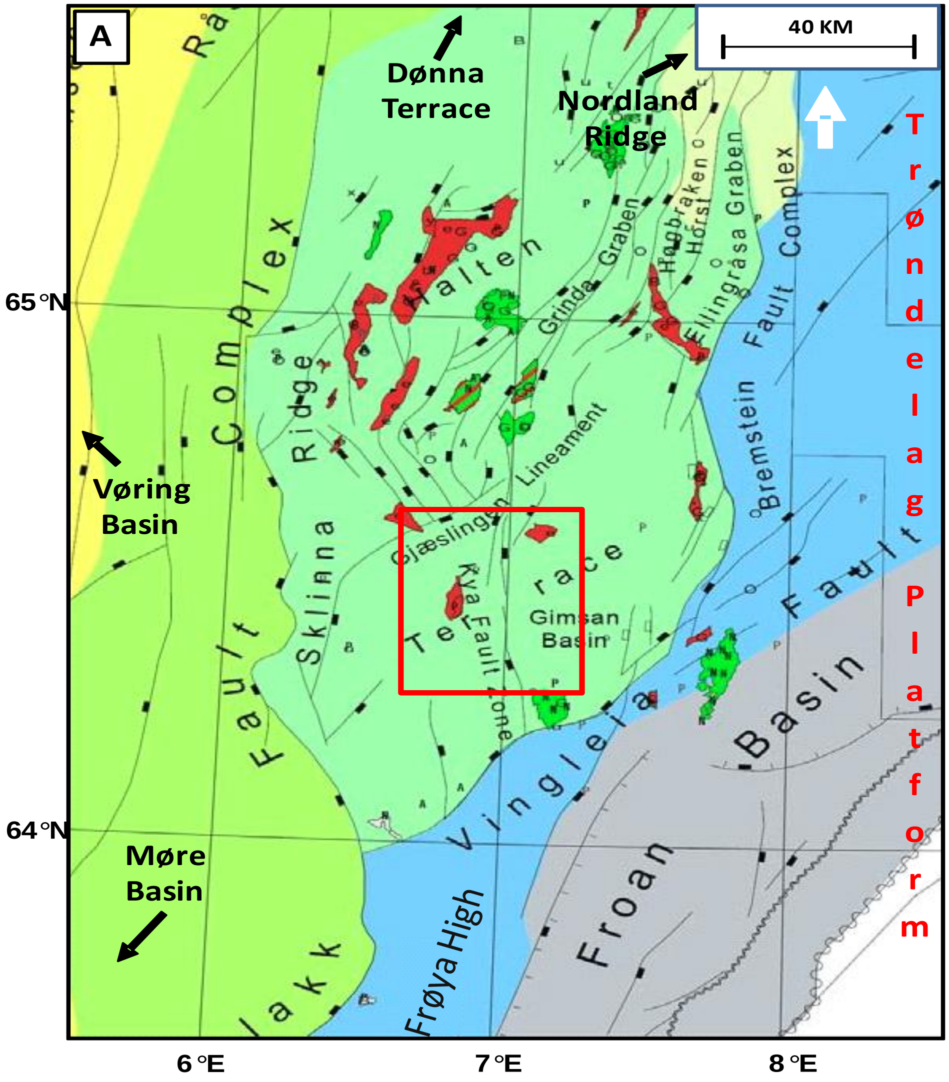


Figure 2.1 Structural elements of the Halten Terrace and surrounding area

The area of this study is around 1000 km2, and covers the southern part of Halten Terrace between 64° and 65° North and 6° and 8° East. Structurally, the study area is bordered by the uplifted western flank of Halten Terrace, the Sklinna Ridge to the west and the Vingleia Fault Complex to the south, which is the boundary between the Frøya High/Trøndelag Platform and the Halten Terrace. To the east, the study area is bordered by the N-S oriented structural depression of the Gimsan Basin, while in the north, the Gjæslingan Lineament limits the study area with NE-SW strike trend and southeasterly-dipping fault. This lineament controlled structural element during the tectonic phase in the Early to Middle Jurassic, and in the late Middle Jurassic – Early Cretaceous (Blystad et al., 1995).

2.2 GEOLOGICAL HISTORY

2.2.1 Structural and basin setting of Jurassic

Based on Nøttvedt *et al*., 2008, the development of the seaway between Greenland and Norway happened due to a gradual relative sea level rise through the Jurassic which connected the Boreal Sea with the Tethys Ocean in the Toarcian. Rifting stages was initiated in the Triassic with repeat in Jurassic. Rifting in cretaceous was culminating with break-up in the early Paleogene. Several previous studies have argued that the distribution of the earlier Permo-Triassic extensional structures controlled the geometry and location of Jurassic basin (Dorė et al., 1997; Brekke, 2000; Osmundsen et al., 2002). The presence of salt interval (alternates with mudstones in Halten Terrace) in the Upper Triassic was also exerted a strong control on structural styles on the Halten Terrace.

Most of the Jurassic faults, both planar and listric in geometry terminates within or detaching upon this interbedded Upper Triassic salt-mudstone package. Only the largest displacement faults at basement level offset the entire salt layer, which therefore effectively decouples much of the deformation from the basement (Withjack et al., 1989; Pascoe et al., 1999; Marsh et al., 2010).

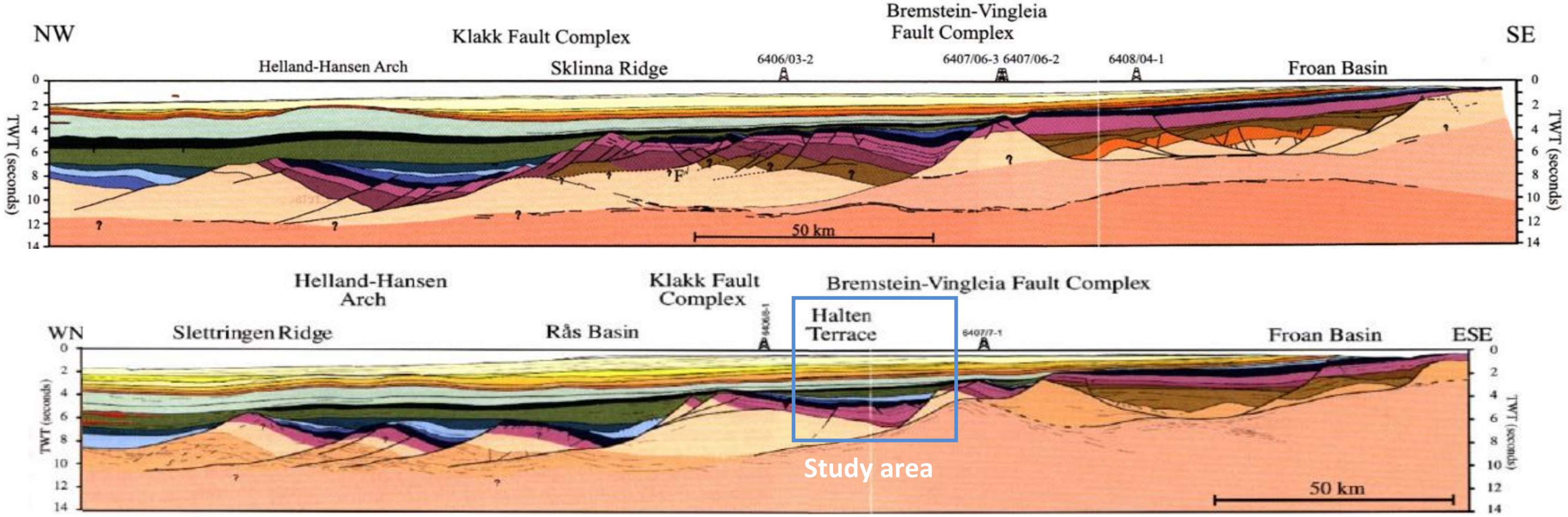


Figure 2.2 General regional cross section across the Halten Terrace (modified from Osmundsen et al., 2002).

The structural style related to the Early Jurassic rifting, was characterized by extensional system and dominated by NE – SW trend normal faults. Tectonic activity during this time was highly active, which is reflected by a relatively high subsidence rates. Faults trend changed into predominantly N-S during the Middle Jurassic and extension, while the tectonic event gradually decreased through the Middle Jurassic, and increased again in late Middle Jurassic due to the reactivated rifting and reached the climax event. The subsidence rate during this time was also changed in line with the tectonic event development.

The overall tectonic development activity during the Jurassic was increasing toward the westward (**Figure 2.3**). This trend was related to a narrowing of the existing rift basin and created a formation of a broad platform area along the eastern margin of the Norwegian – Greenland Sea rift basin, where Halten Terrace and Trøndelag Platform was formed.

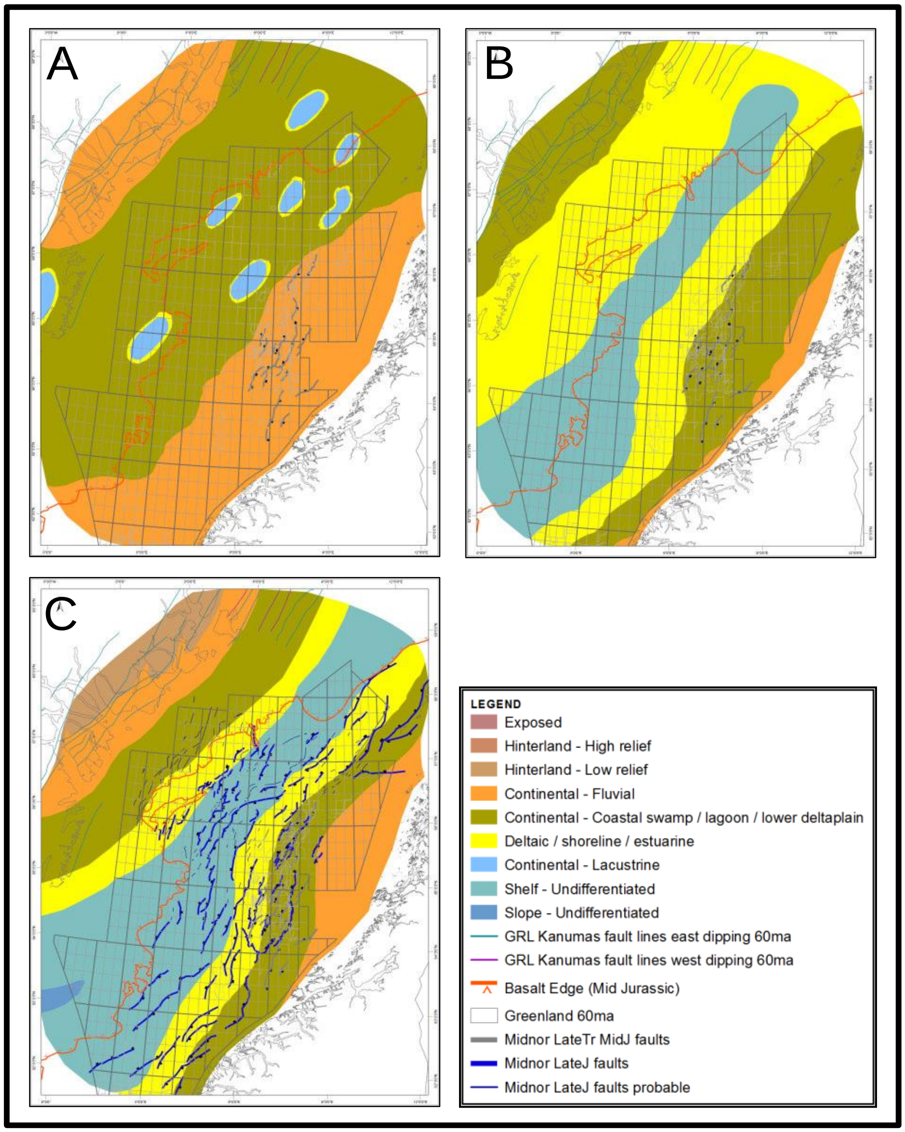


Figure 2.3 Early Jurassic Paleogeography of the Norwegian Greenland Sea rift system.

A) Hettangian to Sinemurian (Åre Formation) fluvial plain, B) Pliensbachian (uppermost Åre Formation and Tilje Formation) embayment, C) Toarcian to Aalenian (Ror – Tofte and Ile Formation) shelfal strait (Ravnas et al. 2000).

In Halten Terrace, sediment supply was very high during the Early Jurassic and gradually decreased throughout the Middle Jurassic, while the sea level generally increased during the Early Jurassic to Middle Jurassic. In turn, this resulted in a gross transgression (**Figure 2.4**). The Early-to-Middle Jurassic transgression was punctuated by repeated regressions represented by a series of fluviodeltaic to estuarine lithosome, namely the Tilje, the Tofte-Ile and the Garn Formations.

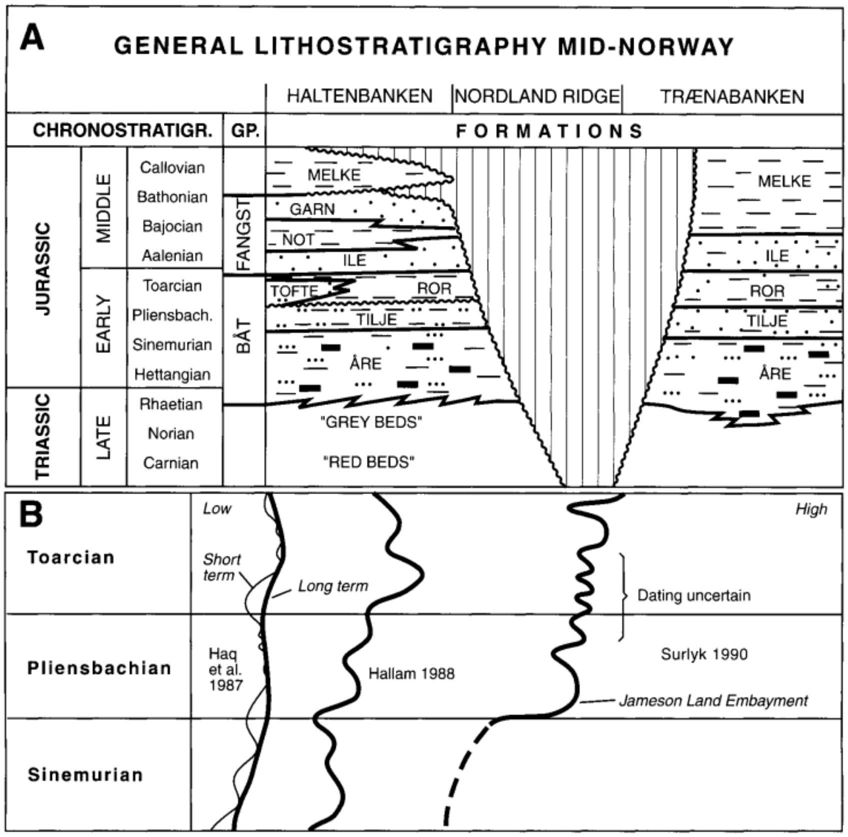


Figure 2.4 A). Generalized time and lithostratigraphic column of the Jurassic deposit on the Halten Terrace area, mid-Norway (modified from Dalland et al., 1998).

B). Sea level curve for the Early Jurassic (after Surlyk, 1990).

2.2.2 Stratigraphy and Paleogeography of Early Jurassic

The transgression event during the Early Jurassic generated an overall retrogradational sedimentation package starts from alluvial package until the shallow marine and shelfal strata. The lower Early Jurassic comprises of Rhaetian to Sinemurian age deposited an alluvial to fluvio-deltaic Åre Formation, while the Tilje Formation was deposited in mid Early Jurassic with Pliensbachian age. Tilje Formation comprises of fluvio-deltaic, estuarine and shallow marine sediments. The Toarcian to Aalenian age in the late Early Jurassic deposited Tofte and Ile Formation which formed fluvio-deltaic sand, estuarine and shallow marine units (Dalland *et al.*, 1988).

The sediments in Early Jurassic which dominated by Båt Group Member can be classified into two clastic wedges. The lower part consists of basin marginal clastic wedges separated by a mudstone interval which is the most pronounced on the Halten Terrace in between uppermost Åre and base of Tilje. Upper part of the Lower Jurassic consist of coarsening sand rich units which indicates a progradational sedimentation of basin marginal alluvial to fluvio-deltaic depositional system in a regressive event. The base of this part is an abrupt transition basal type from sandstones of the Tilje Formation into marine mudstone of the Ror Formation which is well defined in most Halten Terrace area. This break reflects a regional transgression, pronounced as marine flooding intervals. Locally on the Halten Terrace, the deposition of mudstone was interrupted by the coarse sands and conglomerates of the Tofte Fm, interpreted to result from local uplift and erosion near the Sklinna Ridge on the western Halten Terrace. This deposit commonly interpreted as fan-delta sediments (Ehrenberg et al., 1992; Gjelberg et al., 1987).

3 FACIES ASSOCIATIONS

3.1 INTRODUCTION

Lithofacies or facies is a rock unit with a distinctive set of characteristics, such as grain size and sedimentary structure, and is generally produced by a particular process or depositional environment. Based on Walker, 2006, facies is a term that can be used in both as a descriptive and interpretive sense. Basically it may highlight either a specific distinguishing feature of the deposits of a given facies, or may include interpretation as to the depositional environment from which the deposits originate.

In this study, the core data from the Lower Jurassic stratigraphic sequence was studied through the concepts of facies interpretation to have a better understanding of the origin and evolution of sedimentary facies and their distribution. The available core data are used from three surrounding wells with total length 233, 7 m length. Core description focused on lithology, sedimentary structures, bed contacts, textures and trace fossils. The different lithofacies were classified based on sand-mud ratio, bed thickness and bedding style, grain size and sedimentary structures, and degree of bioturbation.

Facies associations were built based on the characteristic of lithofacies definition. In this chapter, facies associations are given interpretative names and it is assigned to the facies describes the certain depositional element and lithology to make a clear classification.

Since the core sections only cover short intervals of the formation, electrofacies method was used to extend the interpretation defined from lithofacies analysis and facies associations to the entire well sections within the Tilje Formation. Serra and Abbot (1980) extended the concepts of lithofacies to geophysical logs and defined electrofacies as a set of log responses that characterize the sediments and differentiate it from the other sediments.

Seven depositional elements was identified from the lithofacies and four main electrofacies classifications was characterized based on the log responses and combined into five generalized facies association classifications to reconstruct reliable facies models.

3.2 LITHOFACIES ANALYSIS

3.2.1 Facies 1: Parallel-stratified sandstone

Description

Facies 1 consists of medium-to- coarse grained sandstone, sometimes with angular to round rip-up mudclasts. This facies interval commonly have erosive base and have a high sand-to-shale ratio. Some intervals contain low angle planar stratifications. There is no signs of any marine trace fossils (**Figure 3.1.A**).

Interpretation

This facies grain size profile suggests the presence of moderate-to-high energy flows. The coarse grains occurrence indicates a fluvial influx, while the rip up mudclasts was eroded and ripped up from the high mudstone content area in a near-bed suspension (Ichaso and Dalrymple, 2009) by the passing water flows. The absence of bioturbation in this facies suggests a stressed environment.

3.2.2 Facies 2: Inversely-graded Cross-stratified sandstone

Description

Facies 2 is dominated by fine-to-medium grained sandstones, occasionally with thin mudstone layers (**Figure 3.1.B**). This facies often has an overall coarsening upward trend with high sand-to-shale ratio. Cross stratification is common found in most of the sandstones, often in the form of herringbone cross stratification. Mudstone is sometimes presence as low amount of mudclast.

Interpretation

This facies is dominated by clean sandstone and low amount of mudstone layer which indicates an active and high energy environment with persistent currents to prevent mud to suspend. The complete absence of bioturbation supports a highly stressed environment, while the sedimentary structures with cross stratified sandstones and herringbone cross stratification indicate the strong currents and tidal influence (Darlymple and Choi, 2007).

3.2.3 Facies 3: Normally graded cross-stratified sandstone

Description

Facies 3 is characterized by normally graded fine-to-medium grained cross stratified sandstones. Mudstone layers are present as mudclasts or thin-to-thick alternations in the bottom sets of cross strata and decreases upward along each cross strata. Sometimes well preserved opposed ripple cross laminations are present, as well as planar-to-low angle lamination. No trace fossil was found in this high sand to shale ratio interval (**Figure 3.1.C**)

Interpretation

This clean sandstone interval indicates a moderate energy conditions. The thin-thick alternations of mudstone layers in bottom sets of cross beds are interpreted to represent tidal bundles, in turn as a suggestive of a tidal diurnal inequality (Visser, 1980). The dominance of trough cross beds over other sedimentary structures indicates deposition from a moderate to strong unidirectional currents within a tidal influenced settings. Complete absence of the trace fossil indicates a high energy and stressed environment.

3.2.4 Facies 4: Cross laminated with flaser bedded sandstone

Description

Facies 4 is dominated by a very fine-to-fine grain clean sandstone with an ungraded or fining upward appearance (**Figure 3.1.D**). Thin mudstone layers rarely occur, sometimes presents as a mudclast. The sandstones are dominated by asymmetrical ripple cross lamination which sometimes forms a herringbone structures. Climbing ripple cross lamination or tidal bundles are also present. Overall this facies has a high sand-to-shale ratio. The presence of bioturbation is only located at the top boundary of the facies.

Interpretation

This clean sandstones facies indicates an active but lower energy environmental setting, where the mudstone deposited as a thin layers. Climbing ripples suggest rapid changing of sedimentary, whereas cross lamination and herringbone suggests a tidal influence. The low presence of bioturbation suggests stressed conditions and also supports the active energy.

3.2.5 Facies 5: Wavy bedded sandstone

Description

Facies 5 characterized by fine- to medium grain sandstones, alternated with thin mudstone layers or mudclast and form a generally fining upward trend. Some well preserved sedimentary structures can be seen such as wavy lamination and planar – low angle climbing ripple lamination. Low amount of trace fossil was found in this moderate sand to shale ratio interval (**Figure 3.1.E**)

Interpretation

The grain size of sandstone in this facies is interpreted to be deposited by slow to moderate current energy settings. The dominance of wavy laminated beds and the alternation of thin mudstone layers imply a tidal influence (Baker et al., 1995; Darlymple and Choi, 2007, Van den Berg et al., 2007). The occasional occurrence of low angle climbing ripple sets indicates rapid deposition from decelerating flows, which associated with river floods event (Ashley et al., 1982). Low amount of trace fossils suggests brackish water conditions.

3.2.6 Facies 6: Hummocky-cross stratified sandstone

Description

This facies consists of fine-to-medium grain sandstone and interbedded mudstone layer (**Figure 3.2.F**). Locally, mudstone layers formed a thick fluid minor bed whereas other interval shows a normally graded parallel lamination. Sandstone beds with coarse grain occasionally present at the base and forms a gradually fining upward trend. Sedimentary structures of this facies consists of cross stratification, sometimes formed a hummocky cross stratification, wave ripple cross lamination and parallel lamination. . Bioturbation is moderately present in this high sand-to-shale ratio facies.

Interpretation

This facies was deposited in combined depositional environment energy. The fine-to-medium grain sandstone beds are interpreted to be deposited under the high energy setting with oscillary currents. This interpretation supported by the presence of hummocky-cross stratification structure, while the coarse grain indicates a fluvial/continental influx.

Wave ripples indicate that this facies was influenced by the presence of superimposed waves (Yang et al., 2005). The presence of fluid-mud deposits normally indicates a tidally influenced commonly deltaic setting (Hill et al., 2007). Fluid-mud layers can be distinguished from those that accumulated by slow settling over long periods of time by the absence of distinct lamination and bioturbation or structureless mudstone layers (Ichaso and Darlymple, 2009). The presence of moderate bioturbation is suitable with settings experiencing decreasing energy, which represent better habitats for living organisms.

3.2.7 Facies 7: Sand dominated heterolithic

Description

Facies 7 is comprises of fine-to-medium grain sandstone and interbedded mudstone layers (**Figure 3.2.G**). This facies present as a generally coarsening upward with moderate sand-to-shale ratio. The sedimentary structures consist of flaser bedded sandstone, climbing ripples (tidal bundle), current ripple cross lamination and some wavy laminated mudstone with low amount of bioturbation.

Interpretation

The alternating sandstone and mudstone in this facies indicates fluctuating energy regimes. Climbing ripples , herring bone cross lamination in sandstone intervals and current ripple cross laminated mudstones recognized as tidal influenced activity played an important role in deposition process, The low amount of bioturbation supports the active environment conditions and suggestive of brackish water conditions.

3.2.8 Facies 8: Wavy bedded-combined flow heterolithic

Description

This facies comprises of mixed fine-to-medium grain sandstone, interbedded with mudstone layers with moderate sand-to-shale ratio. The alternating intervals between sand and mud layers are in centimetre scale which sometimes alternate with mud drapes and mudclasts at some part (**Figure 3.2.H**). Sandstones are dominated by interbedded low angle planar as well as current ripple cross laminations. Bioturbation in this facies consists of alternation between high and low bioturbated intervals and increasing upward.

Interpretation

The mixed sand-mudstone heterolithic in this facies and the sediment structures such as wavy bedding and current ripple cross lamination are suggesting that they were formed by tidal currents with low to moderate current activity. The presence of fluid mud layers associated with the high suspended-sediment concentrations. The variation in bioturbation indicates potential alternations of times with low and high fluvial discharge (Ichaso and Dalrymple,2009).

3.2.9 Facies 9: Bioturbated heterolithic

Description

This facies consists of a very fine-to-fine grain sandstone and interbedded with mudstone layer (**Figure 3.2.I**). Current ripple cross lamination commonly appear with some mud drapes occasionally as double mud drapes as well as opposing paleocurrent directions. Wave ripple cross lamination and parallel laminations are sometimes present. This facies has moderate sand-to-shale ratio with high presence of bioturbation.

Interpretation

The high presence of bioturbation in this facies together with overall very fine-to-fine grain sandstone and mudstone layers indicates a low stressed marine and slow current depositional environment, where it is allow the organisms to develop and mudstone to deposits. However, the original bedding is still recognizable. The sediment structures such as wave ripple cross lamination suggests a low tidal influenced settings.

3.2.10Facies 10: Mud dominated heterolithic

Description

Facies 10 contains a wide range of lithological composition. The successions typically contain several set of very fine-to-fine sandstone and interbedded with mudstone layer content, which sometimes increasing relative to the other sets (**Appendix 1.J**). Various sedimentary structures are also observed where wave and current ripple cross lamination are commonly present, along with planar-low angle lamination. Climbing ripples appear in some particular section. Mostly this facies has low-moderate amount of bioturbation and some escape burrows.

Interpretation

The lithological composition of this facies represents various intensity of energy during the deposition. The active and high energy sedimentation settings allows sand to be transported and creates tidal influenced sediment structures such as cross lamination and climbing ripples, while the mudstone layer deposited during the low tidal activity. The low-to-moderate degree of bioturbation is also typical of intertidal flat formed near the low tidal activity, due active and unstable environment conditions. This facies represents a high and low tide activity levels, which creates a current influenced and suspension sedimentation.

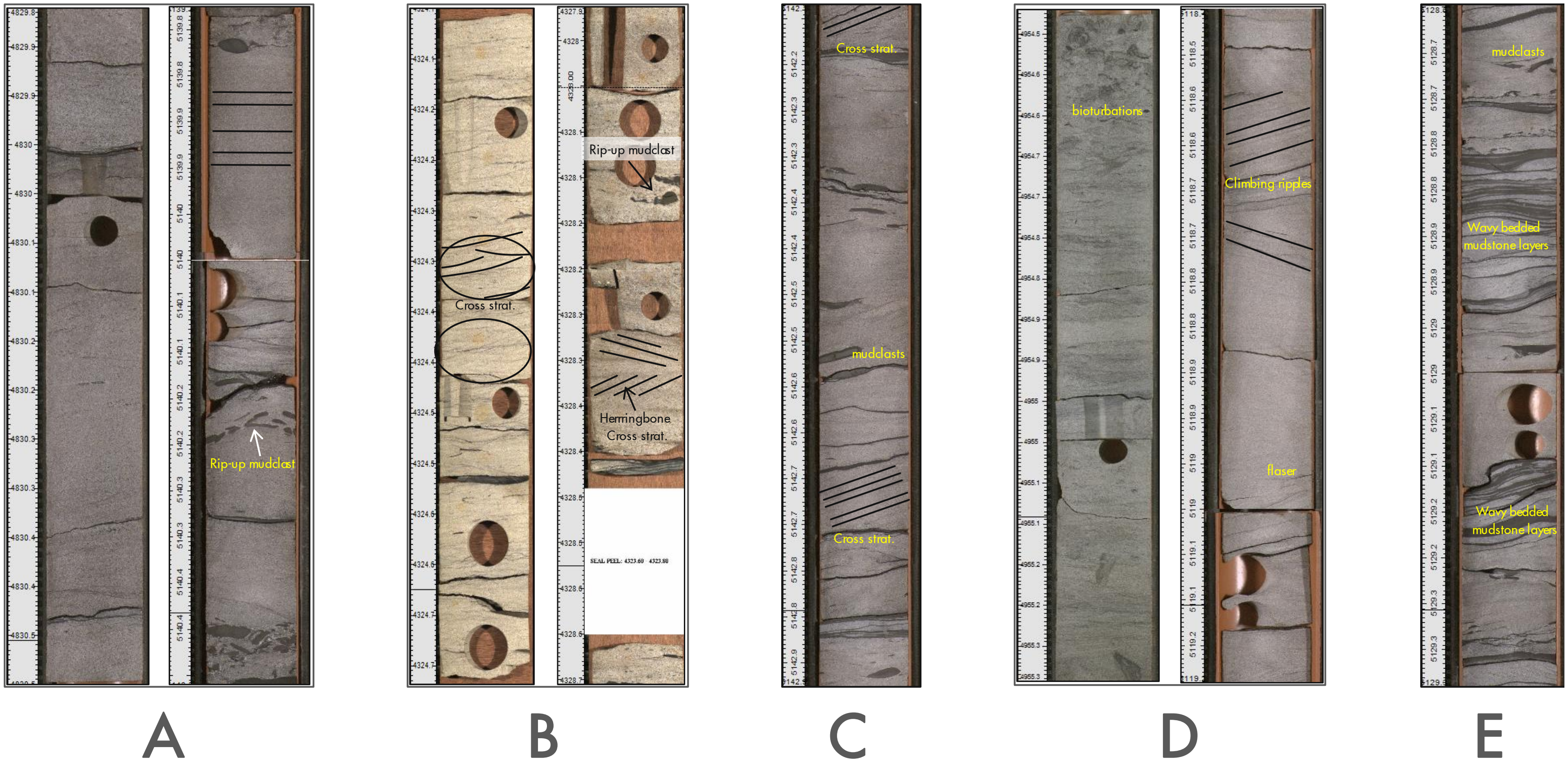


Figure 3.1 Core section pictures represents the lithofacies classification 1-5

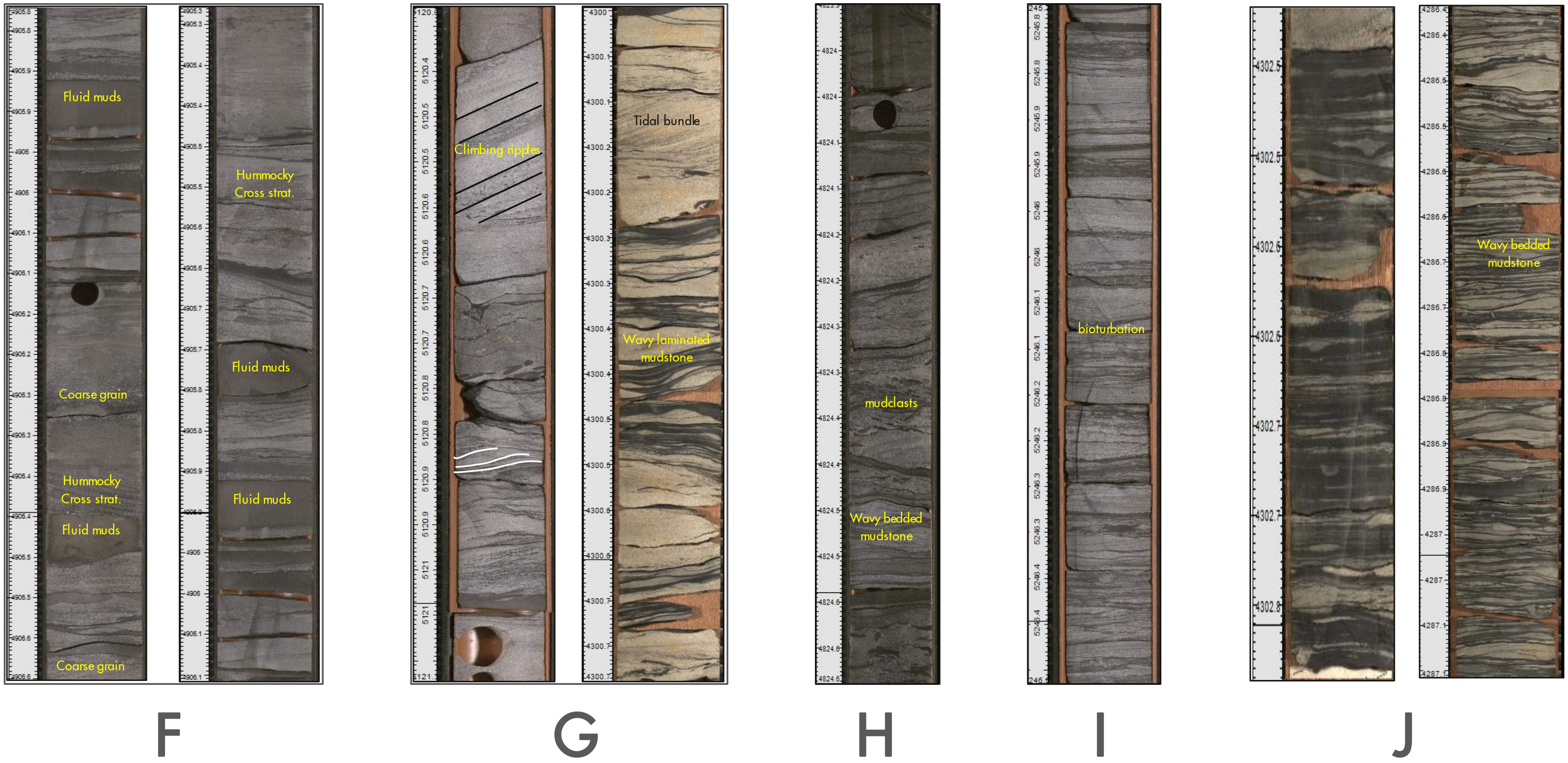


Figure 3.2 Core section pictures represents the lithofacies classification 6-10

3.3 DEPOSITIONAL ELEMENTS

3.3.1 Facies association 1 (FA 1): Tidal – fluvial channel

FA 1 is dominated by sand intervals with fining upward successions. This facies association consists of parallel stratified sandstones (Facies 1). The base of FA 1 succession sometimes is consists of erosionally based coarse grained normal graded cross stratified sandstones (Facies 3), containing large rip-up mudclasts or thick compound of fluid-mud layers. These deposits are overlain by fine-to-medium grain inversely graded cross stratified sandstone (Facies 2) and cross laminated sandstone (Facies 4). This facies association is alternating with sand dominated heterolithics (Facies 7). The mud layers commonly decrease and thin upward. This reflects an upward decrease in the amount of the suspended-sediment concentrations in water column (Ichaso and Darlymple, 2009). FA 1 shows dominantly high energy depositional setting sediment structures with local bidirectional ripple cross lamination and herringbone cross stratification, and abundant mudstones showing thick-thin alternations, which indicates a tidal influence. The relatively low amount of bioturbations suggests a stressed environment with brackish water conditions.

3.3.2 Facies Association 2 (FA 2): Distributary Mouth bar

FA 2 consists of sandy and mixed sandstone-mudstone deposits. The sand intervals have coarsening and sandier upward successions. Cross stratified sandstones (Facies 3) contain rip-up mud clasts and commonly alternate with fine–to-medium cross laminated sandstones (Facies 4). Hummocky cross stratified beds (Facies 6) are present locally. The high amount of cross bedding indicates a current dominated setting. Low amount of bioturbation together with the well preserved sedimentary structures suggest a relatively high energy environment. Tidal influence can be recognized by double mud drapes and ripple cross laminations. Sandier upward trend indicates a lower suspension process happened at the upper part. Another examples of FA 2 shows an overall upward fining cross bedded successions of fine grained sand dominated heterolithic (Facies 7) mouth bar deposits are interpreted as terminal distributary channels (Ichaso and Darlymple, 2009), where cross bedding was generated by migration of dunes and ripples. These deposits will be referred as sandy mouth bars and channelized mouth bar successions.

3.3.3 Facies Association 3 (FA 3): Tidal bar heterolithic

This facies association is dominated by thin-to-medium bedded mixed sandstone-mudstone heterolithic with thin to medium bedded. Overall units show a thinning upward of the interbedded sandstone and mudstone layers. Local sandier upward intervals are present with rare coarsening upward heterolithic successions. FA 3 is characterized by mixed sand dominated heterolithic (Facies 7) and wavy bedded combined flow heterolithic (Facies 8). These deposits are transitionally overlain by fine grain cross laminated sandstones (Facies 4) and wavy bedded sandstones (Facies 5). The mudstone layers decrease upward into thin lamination, which suggest vertical decrease in the suspended sediment concentration in the water column. Abundant of cross laminations and double mud drapes indicates a tidal influenced process. Rip-up mudclast that was brought into sandstone layers are represented minor erosional events. The relatively low amount of bioturbation suggests stressed conditions, probably due to high rates of sedimentation.

3.3.4 Facies Association 4 (FA 4): Tidally influenced delta front

FA 4 is dominated by mixture of sandstone-mudstone heterolithics. This facies association is comprised of sand dominated heterolithic (Facies 7) with abundant ripple cross laminated sits with double mud drapes, which alternate with wavy bedded combined flow heterolithics (Facies 8). The sandstone intervals tend to increasing upward in thickness, while the dominant sediment structures such as double mud drapes and ripple cross laminations indicates tidal current. The variation in degrees and diversity of bioturbation indicates the alternation of times of low and high fluvial discharge (Ichaso and Dalrymple, 2009), with times of lower discharge represents interval of higher marine influence.

3.3.5 Facies Association 5 (FA 5): Bayhead delta heterolithic

FA 5 is dominated by mixed sandstone –mudstone heterolithic. This facies association is comprised of hummocky cross stratified sandstones (Facies 6) alternate with thick fluid mud layers. Wavy bedded combined flow heterolithic intervals are also present (Facies 8) alternating with bioturbated heterolithics (Facies 9). The mixed sand-mudstone heterolithics in this facies association and the sediment structures such as wavy bedding and current ripple cross lamination are suggesting that they were formed by tidal currents with low to moderate speeds setting, while the coarse grain sandstones indicated a fluvial influence. Moderate presence of high diversity bioturbations in this facies association is suitable with the low to moderate energy environment, which represents better habitats for living organisms.

3.3.6 Facies Association 6 (FA 6): Tidal flat heterolithic

FA 6 is dominated by mudstone heterolithics, and is comprised by mud dominated heterolithic (Facies 10) and local sand dominated heterolithic (Facies 7). The high presence of mudstones suggests slow rates of sedimentation largely from suspension. Preserved sediment structure such as current /wave ripple cross lamination indicates both tidal and wave activity which occasionally increase and generate cross laminated sandstone intervals. Relatively low intensities and low diversity of bioturbation indicates the presence of brackish water conditions and high degree of instability of the sandy package.

3.3.7 Facies Association 7 (FA 7): Prodelta Heterolithic

FA 7 is overall dominated by mudstone. However, this facies still contains very fine-to-fine grained sandstones, alternating with mudstone layers. The mud dominated heterolithic (Facies 10) commonly alternate with wavy bedded combined flow heterolithics (Facies 8). This mud-dominated facies association shows internal lamination and low-to-moderate bioturbation suggests slow rates of sedimentation, largely from suspension. The sand intervals were brought by high energy event bends such as turbidity and geographic conditions. The low intensities of bioturbation indicate a stressed environment and somewhat represent of brackish water conditions. The mudstone dominated facies along with very fine grained sandstones suggests low energy environment settings.

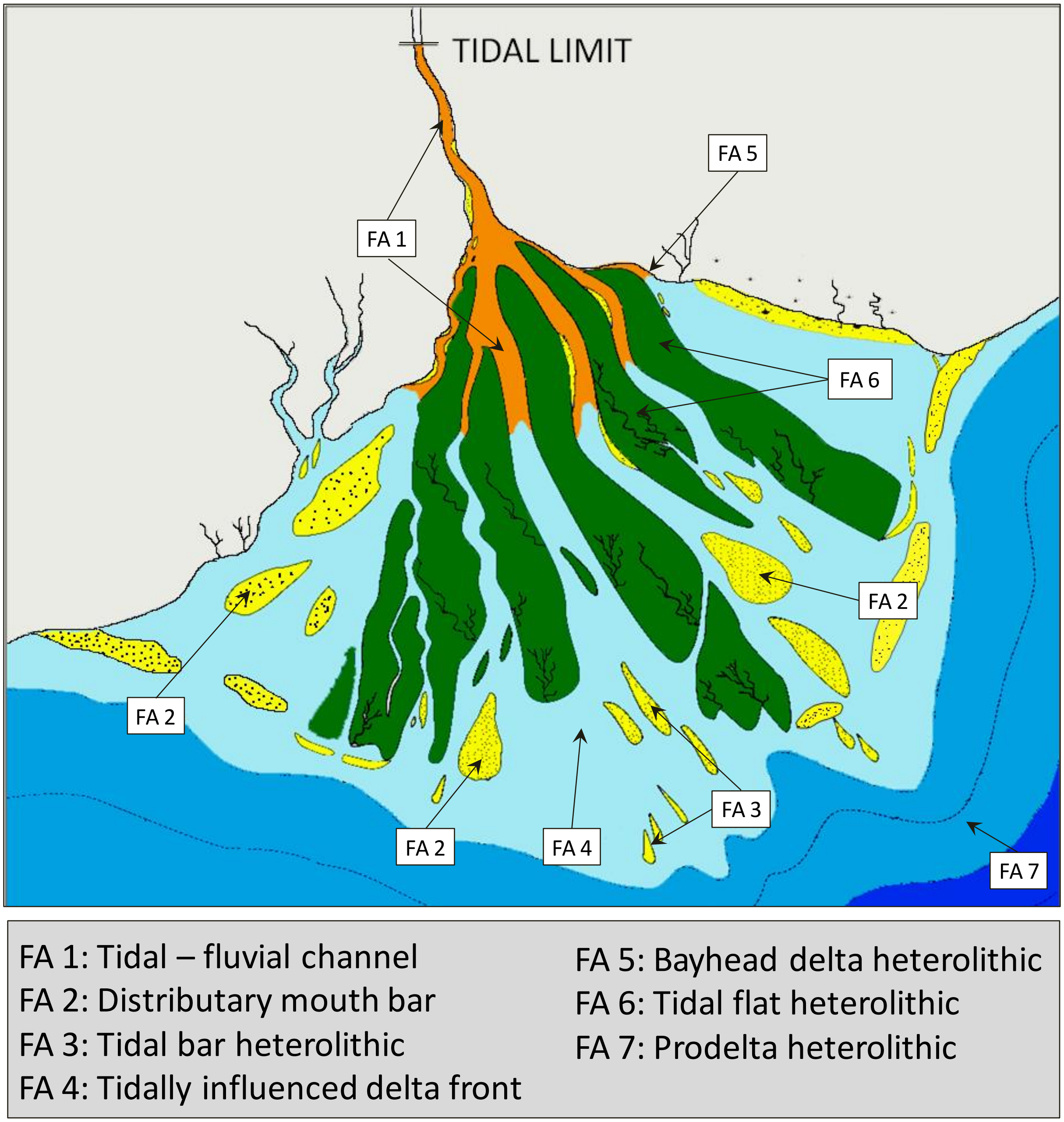


Figure 3.3 Conceptual model of the interpreted facies associations in the study area.

3.4 ELECTROFACIES ANALYSIS

The results of lithofacies analysis based on core description were correlated with the wire line log response to perform electrofacies analysis (**Figure 3.4**). Four main facies associations based on this correlation were established (**Table 3.**). They consist of:

1. Low Gamma Ray, blocky and fining upward trend
2. Low Gamma Ray, blocky and coarsening upward trend
3. Moderate Gamma Ray, spiky and coarsening upward trend
4. High Gamma Ray, erratic

These facies associations represent environments that range from fluvial to marine influenced environments in the Halten Terrace area.

Blocky, fining upward trend facies reflect the main sandy units in the Lower part of Tilje Formation and record the fluvial influx. This facies can be associated with fluvial/distributary channel, tide and wave influenced delta. This facies is related with a progradational or forestepping pattern with possible erosive surfaces.

Blocky and coarsening upward trend facies mostly appear in the middle and upper part of Tilje Formation, which can be associated with amalgamated fluvial, estuarine channel, or sand bar profile. This facies trend can be related either with progradation in regression event or in transgression event.

Spiky and coarsening upward facies trend are controlled by deposits that can be related with mouth bar, delta front or tidal bar facies. This profile is associated with either transgression or regression, and mostly appears in middle and upper Tilje Formation. Erratic facies reflect shallow marine environments with possible transgression event.

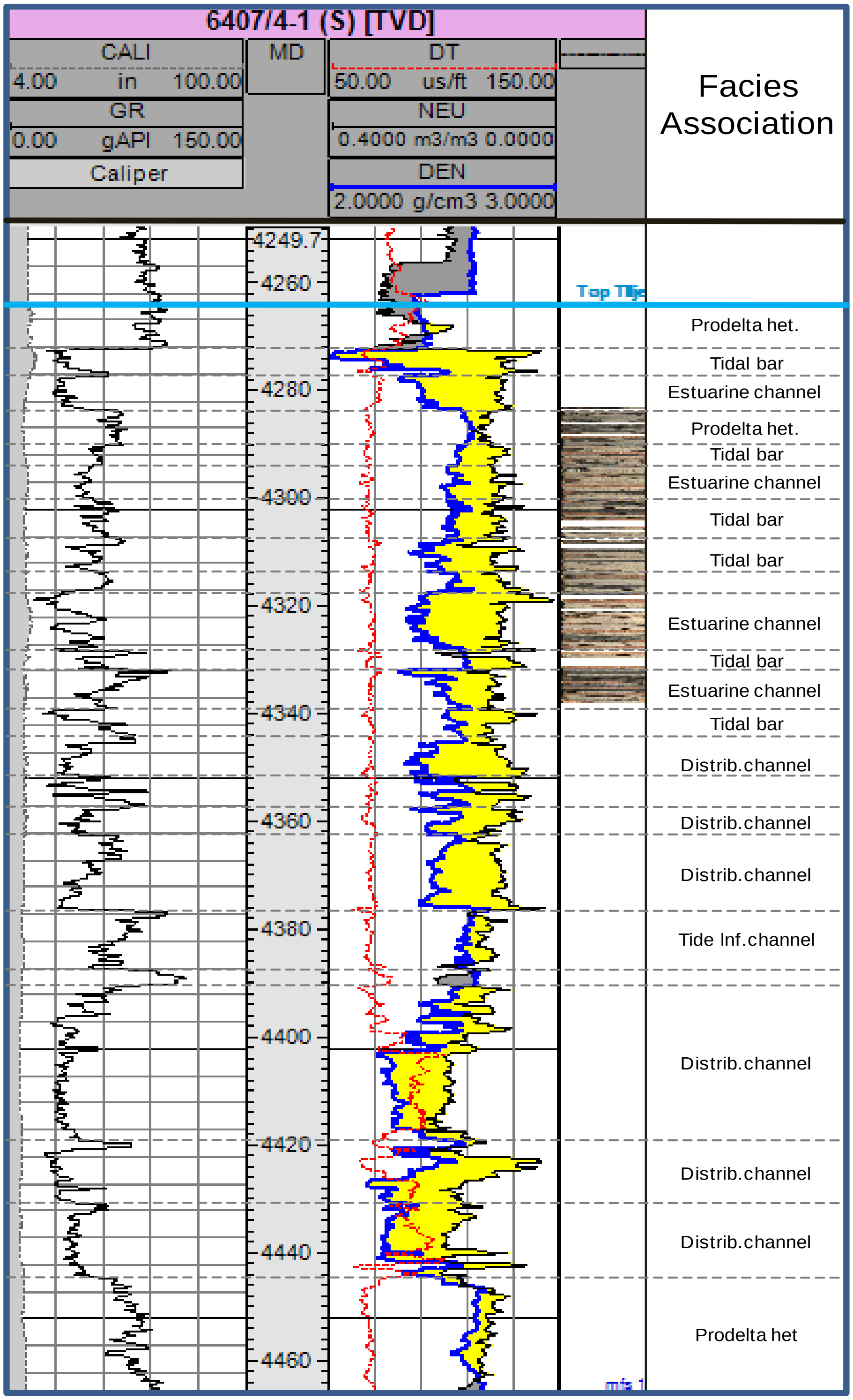


Figure 3.4 Example of facies association based on electrofacies from wireline log, core profile, in well 6407/4-1, Spinel Field

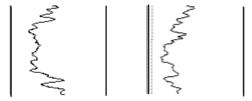
GR LOG RESPONSE	LOG SIGNATURE	FACIES ELEMENT	SEQUENCE STRATIRAPHIC FRAMEWORK
	Low GR, Blocky and fining upward	Fluvial/distributary channel, tide and wave influenced delta	Progradation with possible erosive surface
	Low GR, Blocky and coarsening upward	amalgamated fluvial, tidal sand bar or estuarine channel	Progradation and regression or transgression
	Moderate GR, Spiky and coarsening upward	Mouth bar, delta front or tidal bar	Transgression or Regression
	High GR, Erratic	Shallow marine/shelf, Tidal flat heterolithic, prodelta heterolithic	Transgression

Table 3.1 Facies association based on well log response and core description

3.5 GENERALIZED FACIES ASSOCIATIONS/DEPOSITIONAL ENVIRONMENTS

In order to build a relevant sequence stratigraphical model from lithofacies and electrofacies analysis, it is important to make general classification of identified facies associations and assure them to stack conformably both for vertical and lateral succession. The depositional element might be present in a different facies association. This general classification defines depositional systems, which allow recognizing of key surfaces in sequence stratigraphic framework and reconstructing paleogeographic changes trough time (Catuneanu, 2006). Walther's Law supports this fundamental principle as:

"The various deposits of the same facies areas and similarly the sum of rocks of different facies areas are formed beside each other in space, though in cross section we see them lying in top of each other…. It is a basic statement of far-reaching significance that only those facies and facies areas can be superimposed primarily which can be observed beside each other at the present time"(Walther, 1894), translated by Middleton (1973).

3.5.1 Facies association 1: Lower delta plain

Description

Facies association 1 is comprised by tidal-fluvial channel. The thickness of this facies association varies from 5 to 20 meters, and usually characterized by blocky and fining upward sequences. Log response for this facies shows a low gamma ray log reading, which slightly increasing and associated with fining upward succession, while the neutron and density log response show an overlapping curves with none or negative separation (low-low value).This facies association mostly appears in the lower part of Tilje Formation and thin layers in the middle part of Tilje.

Interpretation

This facies association was dominated by fluvial dominated environment, where most of the coarse grain deposited. The tidal influenced channel presents in the lower part of middle Tilje, which alternate with tide influenced delta. Compare to the others, this facies association is the most proximal from the sediment source, therefore the absence of bioturbation usually happen due to lack of marine influence.

3.5.2 Facies association 2: Mixed wave-tide influenced delta

Description

Facies association 2 consists of tidal-fluvial channel (FA 1), distributary mouth bar (FA 2), tidal bar heterolithics (FA 3), tidally influenced delta front (FA 4) and tidal flat heterolithic (FA 6). The thickness of this facies association varies from 5 to 18 meters, and characterized by blocky and coarsening upward motif. Since this facies is a mixture of several depositional elements, Gamma ray log response of this facies also varies from low to high values, mostly blocky or increasing upward, while the neutron and density log response show an overlapping curves with none or negative separation (low-low value). This facies association mostly appears in the lower part of Tilje Formation, sometimes interbedded with facies association 1.

Interpretation

This facies association consists of several depositional elements with including fluvial influenced to marine influenced units. The profile of this interval is showed by core section and log. The coarsening upward unit represents an outbuilding of the system. The variation of this facies is also quite stable, which indicates a less disturbance. This condition can be related with the protected environment by the sand barrier in front of the delta. High amount of bioturbation supports the stable condition and become a good habitat for organisms to develop.

3.5.3 Facies association 3: Estuarine

Description

Facies association 3 comprises of tidal-fluvial channel (FA 1), Bay head delta heterolithic (FA 5), tidal bar heterolithic (FA 3), and tidal flat heterolithic (FA 6). This facies mostly deposited in middle and upper part of TIlje Formation, and sometimes separated by facies association 4. The thickness of this facies association is from 3 to 10 meters and usually characterized by blocky to coarsening upward trend. The Gamma ray response shows a fairly low to moderate value, while the neutron and density log mostly shows a negative separation (low-low value).

Interpretation

This facies association consists of mostly sandy sediments and contains features indicative of both tidal and wave influence. The profile shown by core and log is quite stable, which can be related with fewer disturbances happened during the deposition. Low amount of bioturbation represents minor marine influence.

3.5.4 Facies association 4: Tide dominated delta

Description

Facies association 4 consists of tidal – fluvial channel (FA 1), distributary mouth bar (FA 2), tidal bar heterolithic (FA 3), tidally influenced delta front (FA 4), and tidal flat heterolithic (FA 6). This facies mostly deposited in middle and upper part of Tilje Formation with various thicknesses from 3 to 10 meters, characterized by serrated coarsening upward succession. The gamma ray log response of this facies is moderate to high value with intense variations. The neutron and density log response shows overlapping-to-negative separation (low-low value).

Interpretation

This facies comprises of various type of depositional elements, from fluvial to marine influenced sediments. Therefore, the profile shown by both core and well logs are unstable and have high variations, which can be related with high and active energy fluctuations from tidal influence. The coarsening upward trend indicates a building out successions. The low average of bioturbation is also represents the active and unstable condition, where organisms rarely developed.

3.5.5 Facies association 5: Marine offshore

Description

Facies association 5 consists of prodelta heterolithic. The thickness of this facies varies from 4 to 14 meters. Gamma ray log response of this facies shows high value with erratic profile, while the neutron and density log response show positive separation (high-high value). This facies appear in almost all the part of Tilje Formation as thin intervals and increasing upward.

Interpretation

This facies association is dominated by mudstones, which can be interpreted as the most distal from the sediment source. The bioturbation in this facies is low to moderate, which is typical of moderate energy shallow marine settings. This could probably happen due to a high fluvial sediments supply typical of distal muddy prodelta areas.

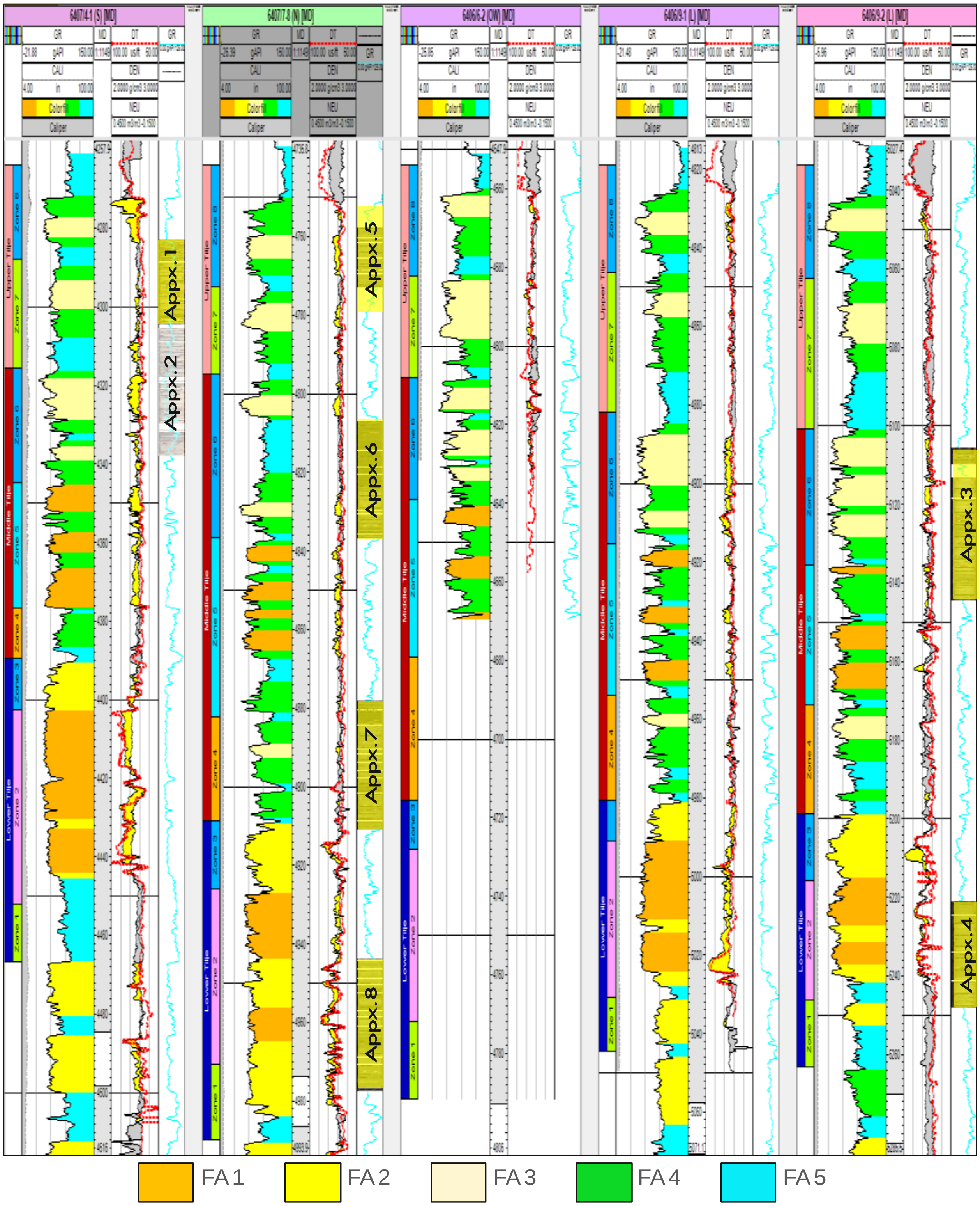


Figure 3.5 Summary of facies associations defined for entire intervals in study area.

4 SEQUENCE STRATIGRAPHY

4.1 INTRODUCTION

Sequence stratigraphy analysis was performed to correlate the facies association that has been defined in the previous chapter within a time stratigraphic framework, and defines the sedimentation trends relevant to relative sea level movement.

The facies associations and their vertical stacking pattern in wells has been used to define the bounding surfaces in the well, and thereby the framework of the sequence stratigraphical development. This has then been used to identify the evolution trends for the Tilje Formation depositional system.

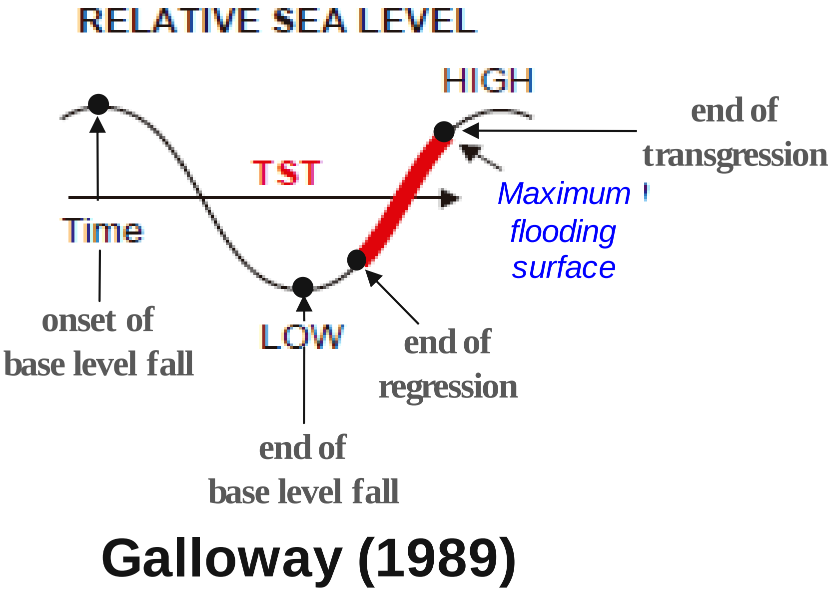


Figure 4.1 Illustration of genetic sequence method by Galloway, 1989.

The analysis and subdivision into component sequence for Tilje Formation was performed using 4th order genetic stratigraphic sequences. Genetic sequence was defined by Galloway (1989) as "a type of sequence bounded by maximum flooding surface (MFS)" (**Figure 4.1**). Three genetic sequences were defined based on the stacking patterns of parasequences or higher order sequences.

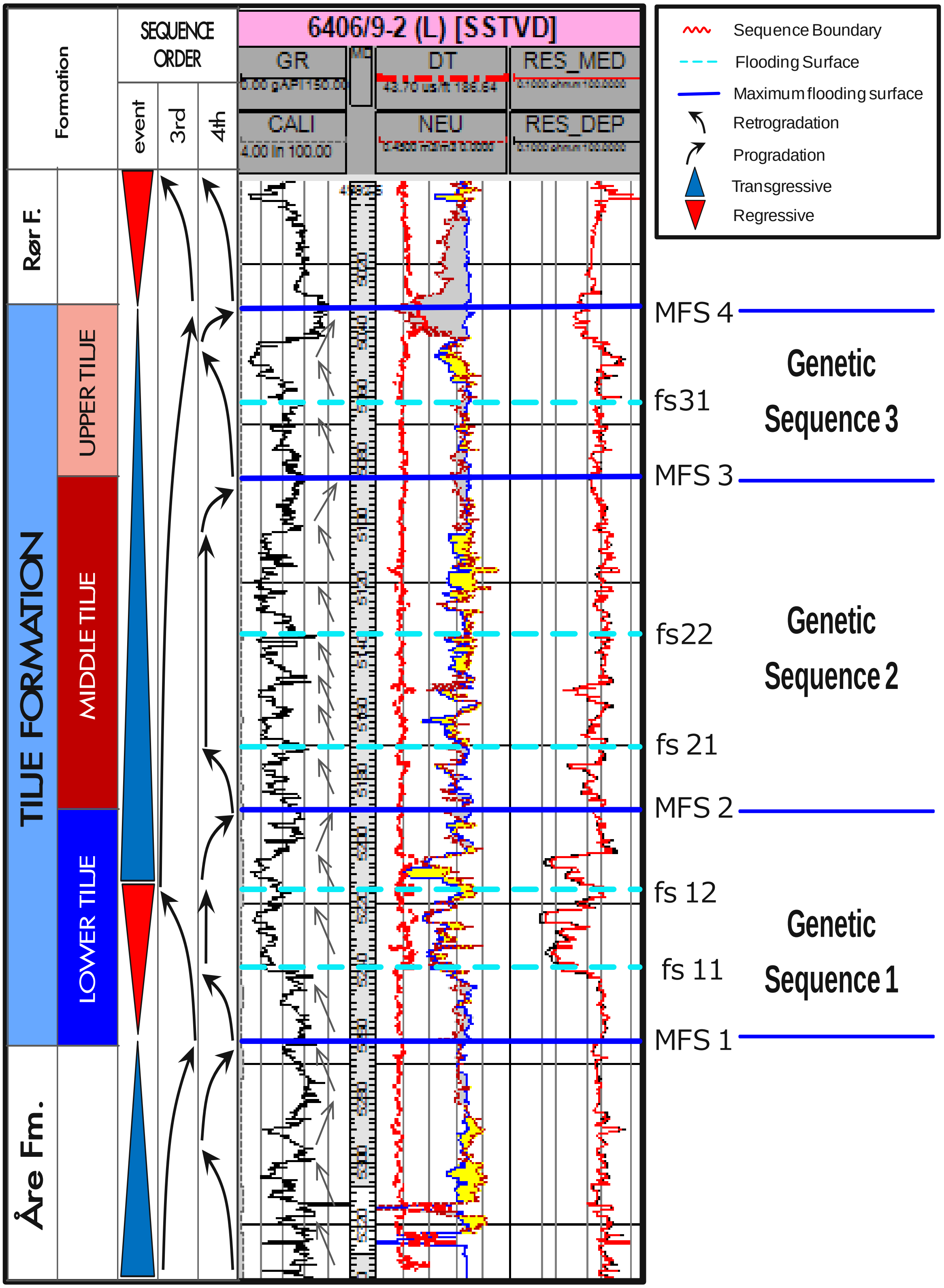


Figure 4.2 Sequence stratigraphy analysis based on genetic sequence, using MFS as surface boundary (Galloway, 1989)

4.2 SEQUENCE STRATIGRAPHY of TILJE FORMATION

Sequence stratigraphy of Tilje Formation in the study area was built based on 5 wells with thickness approximately 200 – 250 meters. **Figure 4.2** show an example of the well log response from well 6406/9-2 through the TIlje Formation including the uppermost Åre containing the sequences and parasequences interpretation which was supported by facies interpretations from cores. Based on genetic sequence definition, three main depositional patterns interpreted. They are:

- **Genetic sequence 1** thickness ranges from 60-80 m. It is bounded by MFS 1 and MFS 2, with two flooding surfaces (fs 11 and fs 12) in between (**Figure 4.2**). This interval consists of two progradation parasequences on the lower part, which alternates into aggradation parasequences in Linnorm and Spinel well, while retrogradation parasequence present on the upper part. MFS 1 and MFS 2 in this sequence are located in the muddiest part, where the retrogradation vertically turns into progradation pattern.

  The facies in this sequence is dominated by lower delta plain (FA 1) and wave-tide influenced delta (FA 2). Sequence 1 is generally thicker on the eastern part (Noatun), which dominated by lower delta plain deposit and slightly thinning westward (**Figure 4.3**) and northward (**Figure 4.5**), which consists of coarsening upward succession from marine mudstones (FA 5) to wave-tide influenced delta deposits.

- **Genetic sequence 2** thickness ranges from 70-110m. It is located stratigraphically between MFS 2 and MFS 3 with two flooding surfaces (fs 21 and fs 22) in between (**Figure 4.2**). This interval considered as heterogeneous sequence with high intensity of lithology alternations, which generally showing a local progradation parasequences with sandier and thickening upward succession. MFS 3 is located in the muddiest part, which is a turning point from retrogradation into progradation pattern.

  This sequence dominated by tide dominated delta deposits (FA 4), which alternates with lower delta plain (FA 1) on the lower part, and estuarine deposits (FA 3) on the upper part. Thicker interval package of this sequence presents on the east part (Noatun), however it is slightly thinning westward (Linnorm), and even more towards the north (Spinel) (**Figure 4.5**).

- **Genetic sequence 3** thickness ranges in thickness from 50-60m. This sequence is bounded by MFS 3 and MFS 4, with one flooding surface (fs 31) in between (**Figure 4.2**). This interval consists of local progradation parasequences, with thickening and sandier upward succession. MFS 4 is located in the muddiest part, which also become an MFS for regional event (3rd order).

  The thickness of this sequence interval is higher on the west part (Linnorm) and thinning towards the east (**Figure 4.3**) and north (**Figure 4.4**). This sequence is dominated by tide influenced delta deposits (FA 4), which alternates with estuary (FA 3) and marine mudstone deposits (FA 5). The marine mudstone deposit thickness is increasing towards the west.

Sequence 1. The general progradation trend of sequence 1, which is dominated by lower delta plain (FA 1) and wave dominated delta sandstones (FA 2) and represents the outbuilding of mixed wave-tidal influenced delta, which happened due to sea level fall and create less accommodation space (regressive event).

The higher marine mudstone deposits (FA 5) in Linnorm and Spinel compared to Noatun area indicates the seaward sedimentation trend from SE to NW. This interpretation is supported by the thickness of the sequence, which is higher in the eastern part and thinning towards the west (**Figure 4.3**) and north (**Figure 4.5**). The relatively uniform thickness of this sequence is attributed to uniform subsidence and low tectonic activity, which allowed the sediments to laterally well-distributed. The comparison between the thickness of the sand and mud packages (net-to-gross) (**Figure 4.6**) in this sequence shows a thinning and fining trend from SE towards the NW, reflecting a change from more proximal to distal fluviodeltaic setting. As results, the FA 1 and FA 2 distribution interpretation shows a continuous correlation from the east and thinning towards the west (**Figure 4.7**), similar with the trend from the NE towards the SW (**Figure 4.8**).

Sequence 2 has more heterogeneous architecture, as is also evidenced from the dominance of lower delta plain (FA 1), estuarine (FA 3), and tide dominated delta deposits (FA

4). Compared to sequence 1, mud contents in this sequence are higher, which interbedded with the sandstone packages. The bulk part of sequence 2 shows an overall retrogradation with local progradation patterns. This profile represents the backstepping process relative to sequence 1 due to transgressive event, where the sea level was rising and accommodation space was increased. The sequence is thicker on the east and thins towards the west (**Figure 4.3**) and north (**Figure 4.5**). However with a random net-to-gross distribution. The high thickness change can also be attributed to the increased tectonic activity during the deposition combined with lateral delta migration and shifting alternation, represents a change to a series of small laterally separated delta. The variety of the facies in this sequence suggests a laterally shifting movement during the deposition process. The comparison between the thickness of the sand and mud packages (net-to-gross) (**Figure 4.6**) in this sequence needs more data to capture the detail of high variability and to represents the actual trend of the sedimentation. This variability is shown in the **Figure 4.7** and **Figure 4.8**, where the interpretation distributions of the FA 1 and FA 4 in lower part are fairly connected, while in the upper part, the facies distributions of FA 3 and FA 4 are poorly connected.

Sequence 3 is the thinnest interval compared to the other sequences, and is dominated by estuarine (FA 3), tide dominated delta (FA 4) and marine offshore deposits (FA 5). Increasing amount of mud contents compared to sequence 2 represents an overall retrogradation. However, this sequence is still consists of local progradation patterns. This profile indicates a backstepping process due to transgressive event, where the sea level was rising and increase in accommodation space. The marine mudstone deposits (FA 5) is increased on the west and north part, which represents the sedimentation trend is going seaward from SE to NW. The minor thickness variability of this sequence indicates a decrease in tectonic activity during the deposition, which allows the sediments to laterally well distributed. The comparison between the thickness of the sand and mud packages (net-to-gross) (**Figure 4.6**) in this sequence shows a thinning trend from E-SE towards the W-NW, inline with the sedimentation trend. Tide dominated delta deposits (FA 4) is well distributed in this sequence from E to W (**Figure 4.7**), similar with the distribution from NW to SW (**Figure 4.8**), while the estuarine deposits (FA 3) is poorly connected.

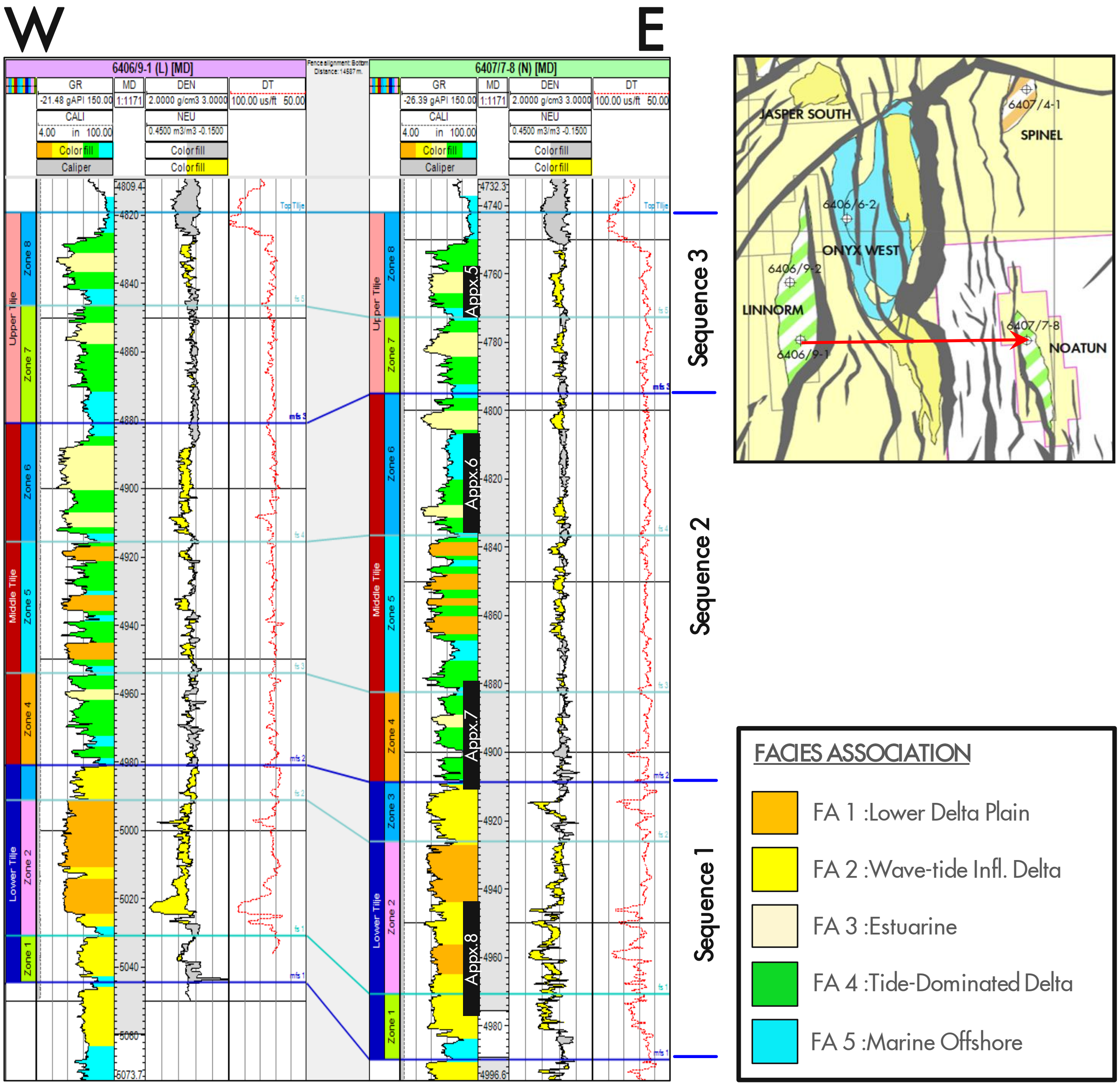


Figure 4.3 Well cross section and sequence stratigraphic correlation from Linnorm (W) to Noatun Field (E). Gamma ray log overlay with facies association classification.

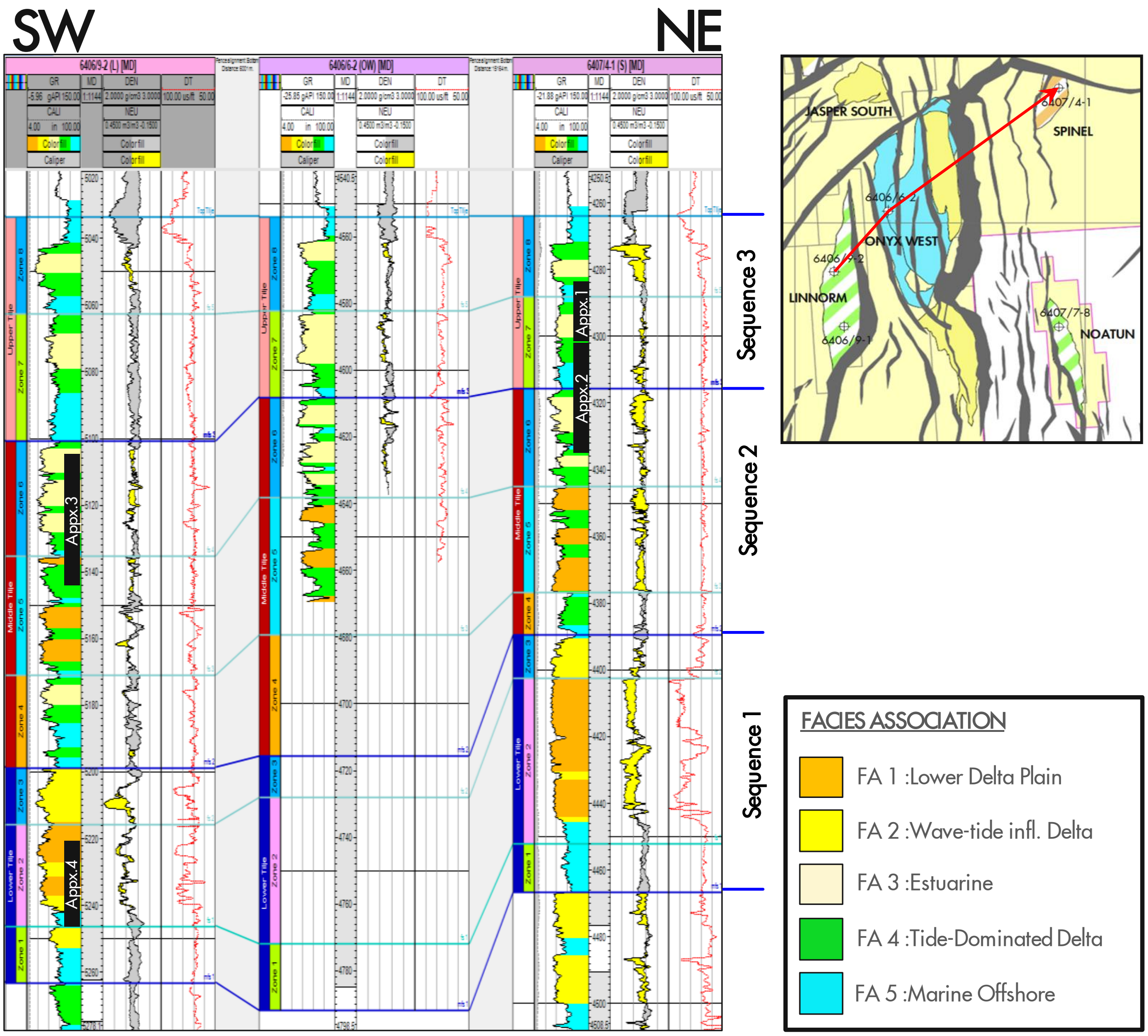


Figure 4.4 Well cross section and sequence stratigraphic correlation from Linnorm (SW) to Spinel Field (NE). Gamma ray log overlay with facies association classification.

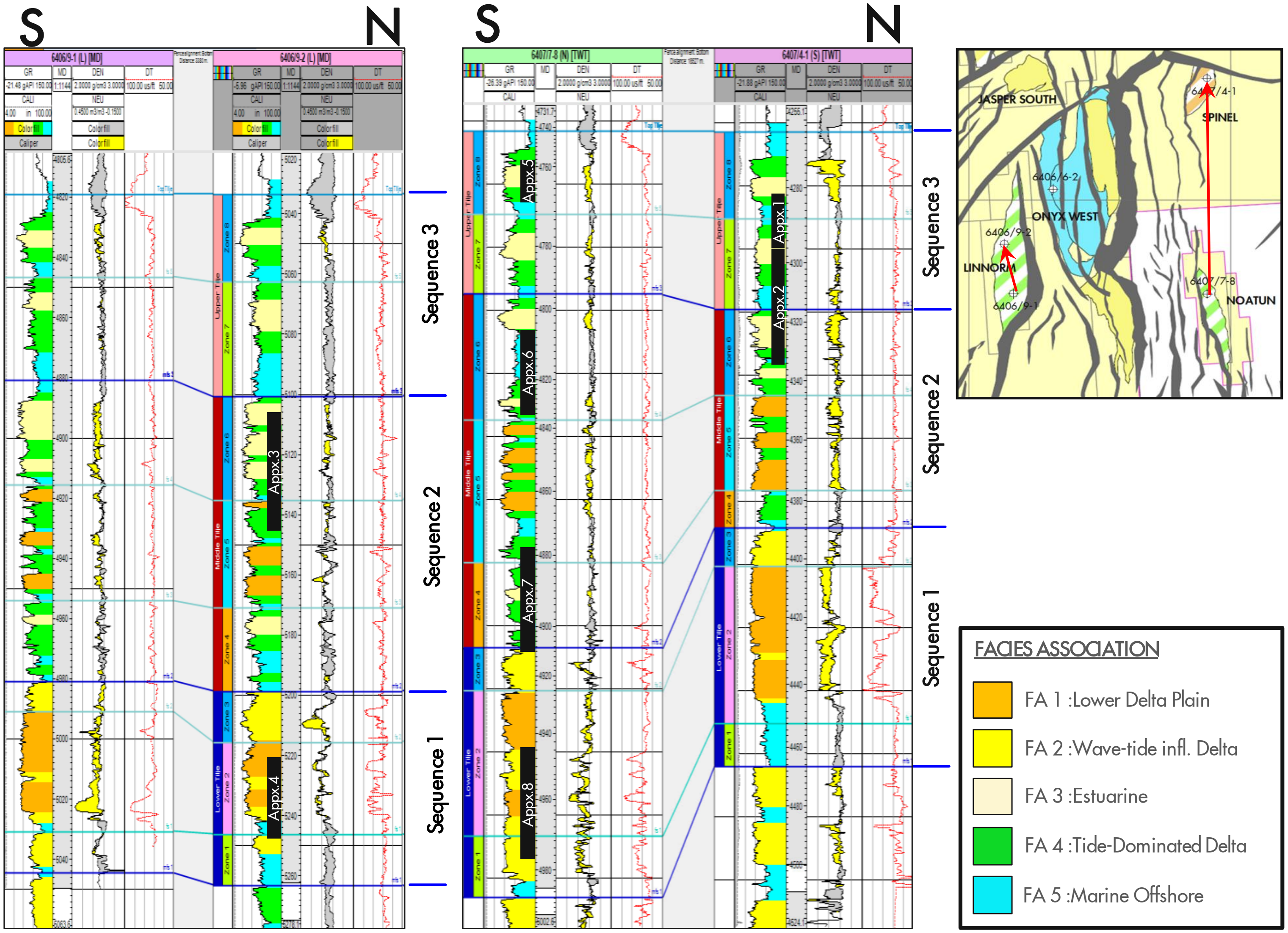


Figure 4.5 Well cross section and sequence stratigraphic correlation on Linnorm (left), and from Noatun (S) to Spinel (N) (right). Gamma ray log overlay with facies association classification.

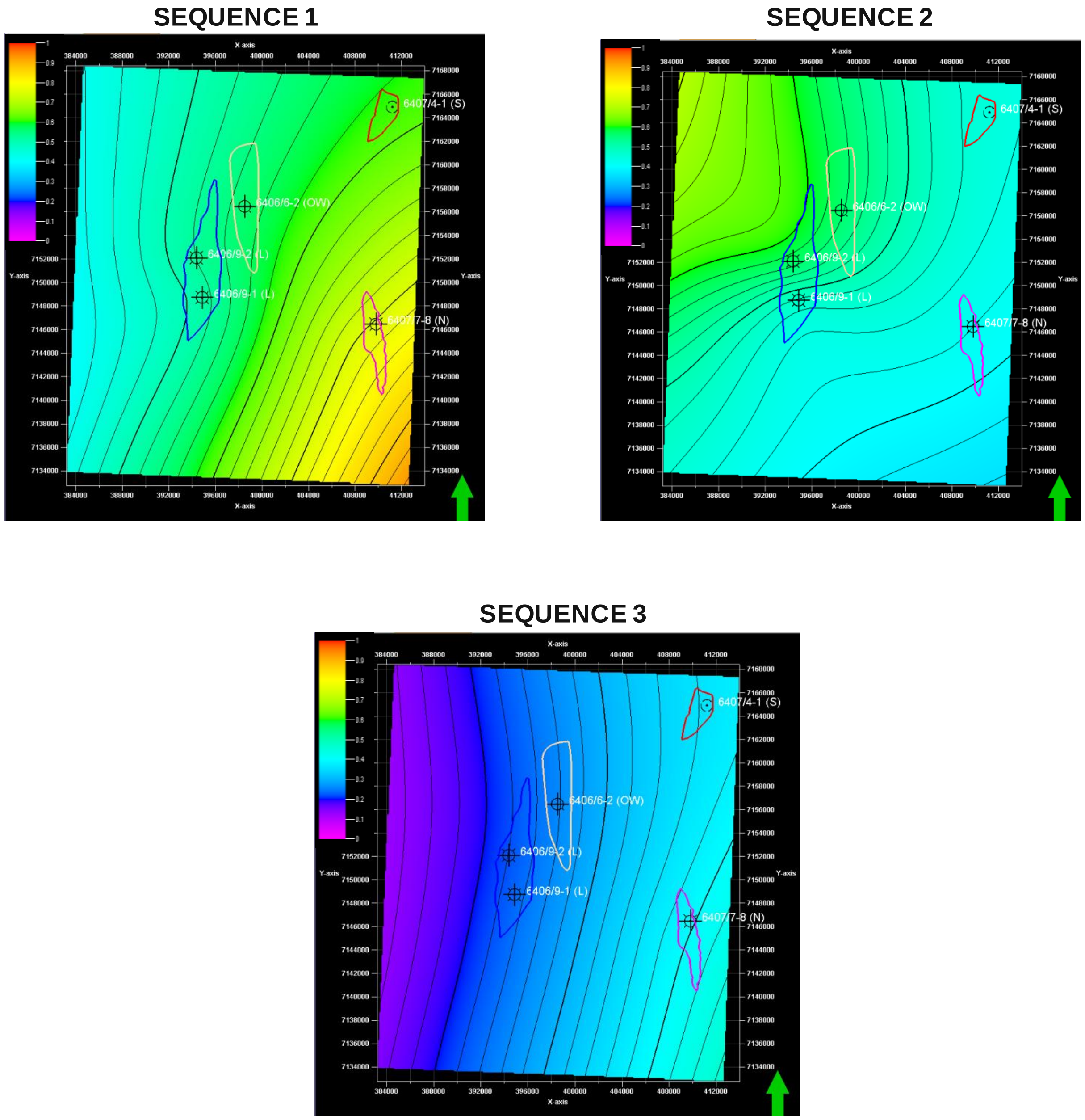


Figure 4.6 Net-to-Gross distribution map of sequences in Tilje Formation.

Sequence 1 shows high value (appx. 80%) of net to gross in S-SE and decreased toward N-NW down to 30%. Sequence 2 has 40%-60% net-to-gross with SE-E to NW-W. Due to high variability, the trend of this sequence does not represent the actual trend. Low net-to-gross value in sequence 3 (10%-40%) shows SE-E to NW-W trend.

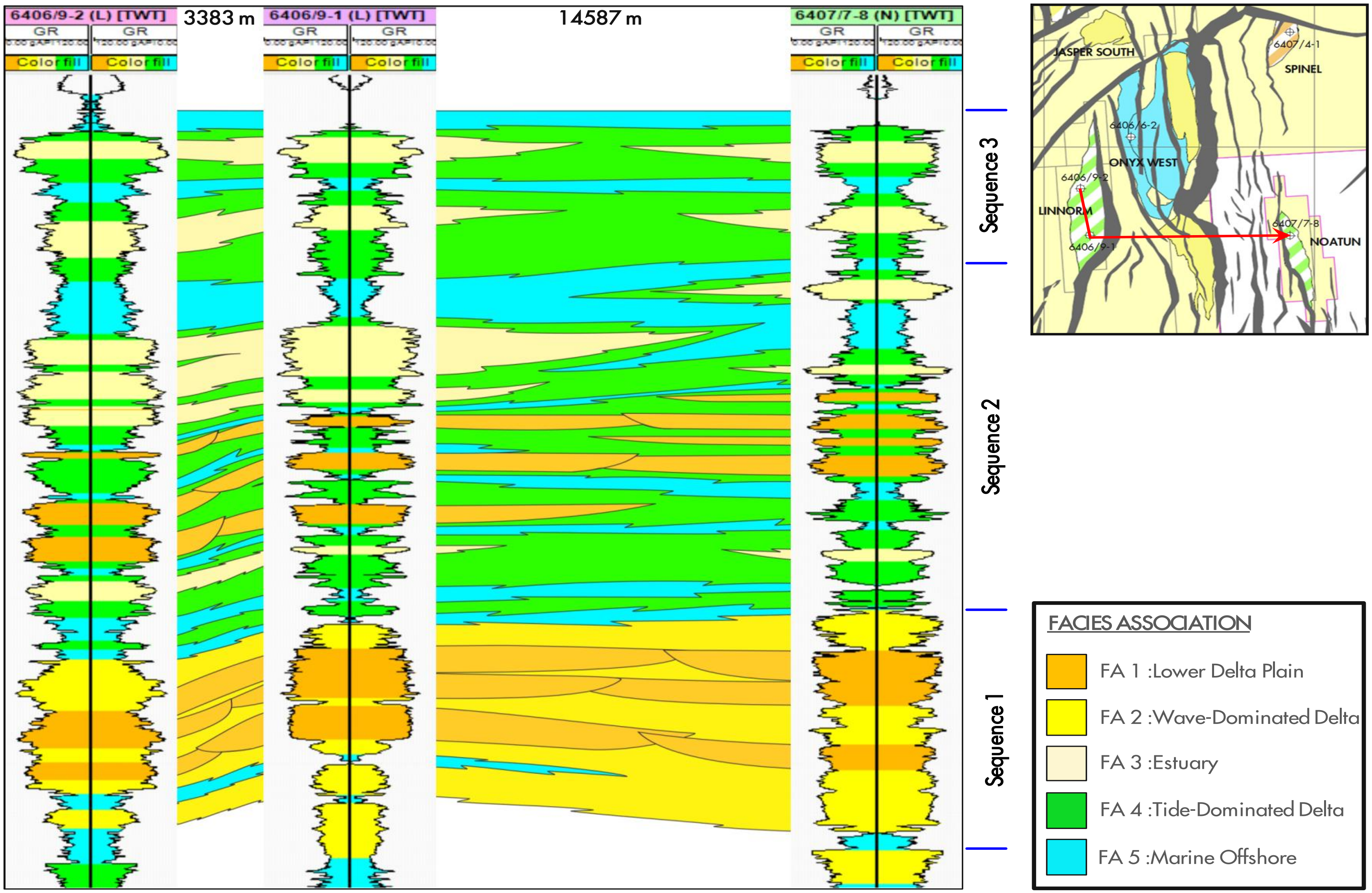


Figure 4.7 Interpretation of facies lateral distribution from Linnorm to Noatun

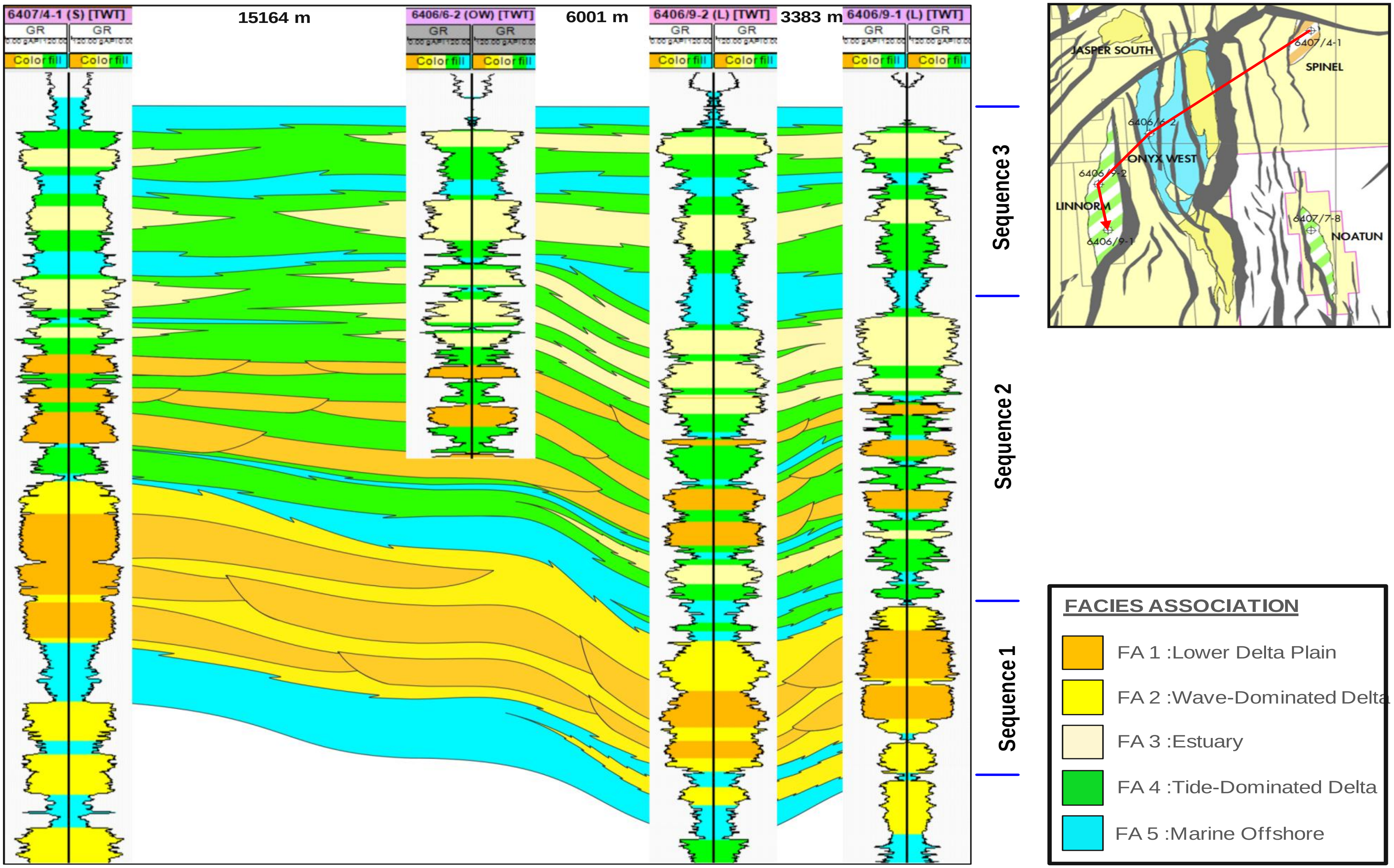


Figure 4.8 Interpretation of facies lateral distribution from Spinel to Linnorm

5 SEISMIC INTERPRETATION

The well data are only representative for a certain point with limited range. Therefore seismic interpretation was conducted by incorporating the 3D merged seismic survey cube (SH0902MZ10, reprocessed 2012) and eight lines of 2D seismic lines to cover Spinel area. Seismic interpretation provides valuable information by precisely mapping a lateral variation of subsurface structures and continuity of horizons and layers. The result from seismic interpretation was used as input data to guide the orientation of depositional features and paleogeographies, thereby provide some constraints on the resultant.

5.1 WELL-to-SEISMIC TIE

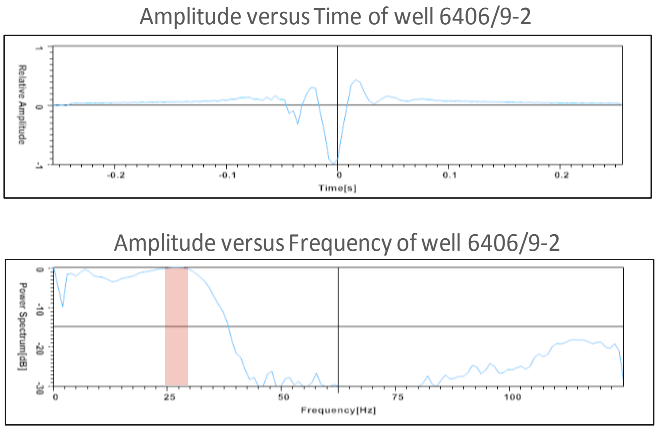


Figure 5.1 Extracted wavelet from well 6406/9-2, with zero phase and average frequency of 25-30 Hz

In order to integrate well information with reflection signal interpreted on seismic, well-to-seismic tie was performed in for all the wells. Synthetic seismogram was produced to illustrate the seismic response that resembles the well log data. The result is illustrated by well 6406/9-2 in Linnorm field, since this well gives the best correlation result between log response and seismic reflection. In this well, the synthetic seismogram was made along the borehole from 4000 ms to 4270 ms (near end of borehole), which correspond with Tilje Formation in interval range 5000 m – 5300 m.

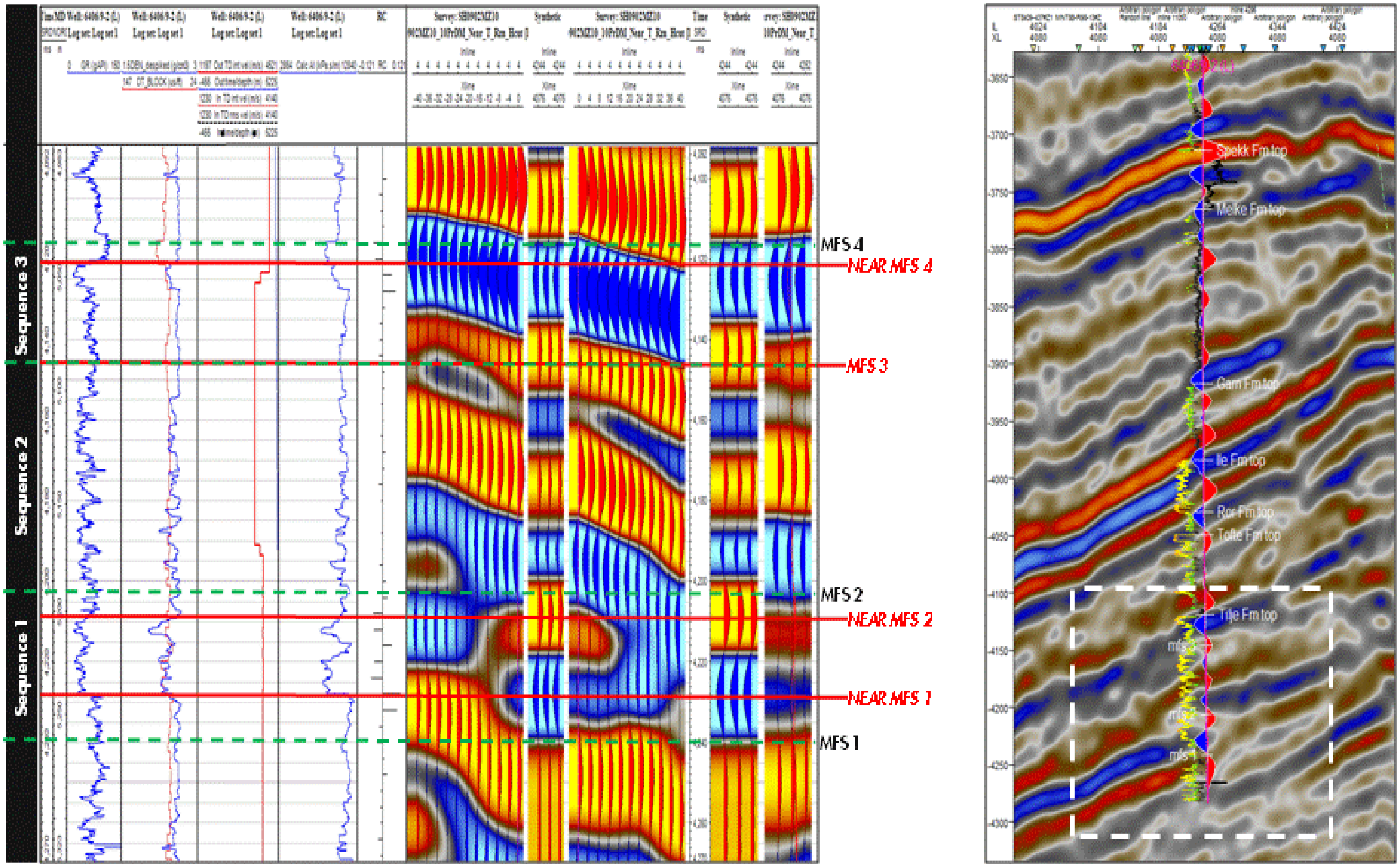


Figure 5.2 Well-to-seismic tie panel with extracted wavelet from 4000 ms to 4270 ms in well 6406/9-2. Red lines represent the new interpreted horizon markers. These are named according to the closest MFS (Left). Seismic section around well 6406/9-2 overlaid with generated synthetic seismogram (Right).

The extracted wavelet from well 6406/9-2 shows a reversed polarity with frequency range from 25 -30 Hz and near zero phase (**Figure 5.1**). Interval velocity of Tilje Formation ranges between 3527, 5 m/s – 3878 m/s, giving a minimum estimated vertical resolution of 30 m (95ft).

The result from well-to-seismic tie correlation in well 6406/9-2 shows a good match between the synthetic seismic and the original seismic (**Figure 5.2**). However, the identified log markers from the sequence stratigraphic analysis needed to be adjusted to match with the seismic response. Therefore, to be able to determine the continuity of seismic reflection, some markers have been redefined by correlating the well logs response with AI contrast, to see the closest horizon responsible for the high amplitude pattern in the seismic data.

Horizon	New interpreted horizon	AI	Amplitude	Seismic reflector
MFS 1	Near MFS 1	Positive	negative	hard (blue)
MFS 2	Near MFS 2	Negative	positive	soft (red)
MFS 3	-	Negative	positive	soft (red)
MFS 4	Near MFS 4	Positive	negative	hard (blue)

Table 5.1 Summary of horizons and seismic responses from well-to-seismic tie.

On **Figure 5.2**, MFS 1 is represented by *Near MFS 1,* which is located few milliseconds above the MFS 1. This reflection marks the boundary between the base of sandstones above the lower Tilje Formation and marine mudstone below. Acoustic Impedance (AI) log shows a positive response (increasing value). This is reasonable since the density and the velocity in mudstone is higher compared to sandstone. This AI correlated with a trough (hard) in seismic response. *Near MFS 2* is located few milliseconds below the MFS2, and represents the top sandstones of Lower Tilje in sequence 1. This boundary corresponds to decreased acoustic impedance, due to transition from mudstone to sandstone (decreasing in density and velocity value), providing a peak response in the seismic response (soft). MFS 3 is interpreted on a peak (soft), and coincides with the interval of highest mud content between sequence 2 and 3. MFS 4 is represented by *Near MFS 4*, which is located few milliseconds below the MFS 4, at the top sandstones of sequence 3. Near MFS 4 is the boundary between marine mudstone on top and sandstone interval below, or the Ror and Tilje Formation, providing a trough (hard) response as the AI increasing.

5.2 STRUCTURAL INTERPRETATION

This study incorporates the fault interpretations of Tilje Formation from the in-house study conducted by SHELL. Seismic structural variance volume attribute and structural smoothing process was performed and overlaid with the fault interpretations to clarify the continuity and consistency of the previous interpretations (**Figure 5.3** C).

Generally, structural configuration of Tilje Formation in the study area is dominated by NE – SW trending faults and as well as local N-S faults trend. According to the strike, dip direction and faulting age, the faults can be classified into two families (**Figure 5.3 C**). Fault family one comprises of NE-SW faults trend and consist of a few large and regularly spaced faults, with an average spacing of approximately 0.5-1 km. These major faults have more than 400 ms displacement. The dip direction of fault family one suggests two subsets of classification, one with southeastward and the other with a northwestward dipping trend.

Most faults of this family consists of planar and listric fault, which sometimes terminating within or detaching towards the older layers, most likely the Triassic salt (**Figure 5.3** A). In many cases, these faults extend above the BCU. Thickness variations within the Lower Jurassic interval (Åre Formation) show a clear pattern of thickening and thinning pattern suggesting a growth pattern into the fault plane. Cross sections through these structures typically show divergent reflectors, wedge-shaped packages (**Figure 5.3** LEFT) and thicker intervals in the hanging walls of active faults relative to the footwall, which indicates a growth strata. This observation suggests that this fault family were active during the deposition of the Lower Jurassic.

Fault family two consists of N-S faults trend with mostly planar geometry. This fault family developed during the widening of depocenters in the hanging walls of previous major Early Jurassic's faults of fault family one. The initiation of this fault family is recorded by thickness change. Dipping direction of this fault family suggest two subsets of classification, one eastward and another westward dipping set. Some growth strata and divergence of sediments into the fault plane can also be seen (**Figure 5.3** LEFT). This family is related to Middle to Late Jurassic rifting.

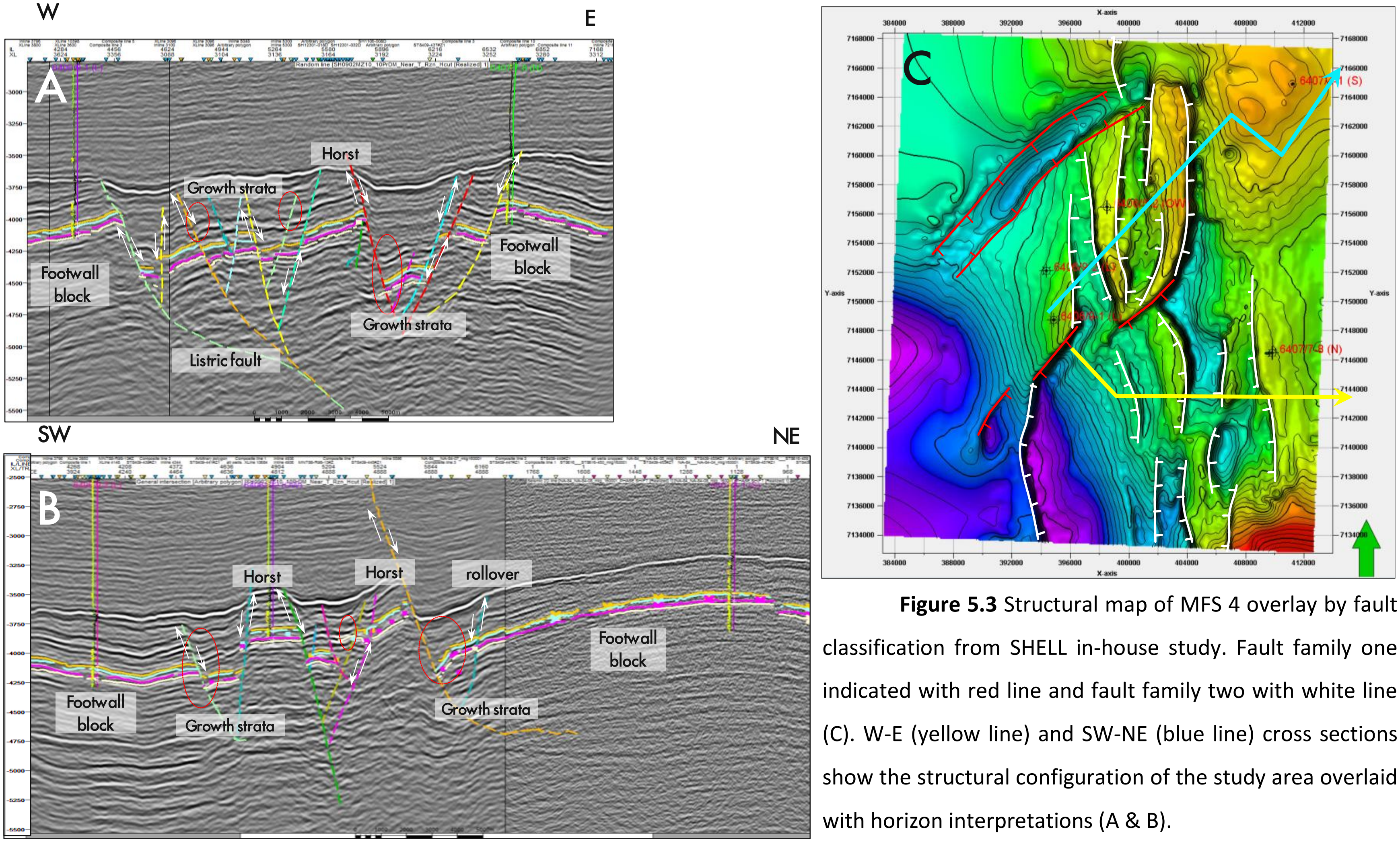
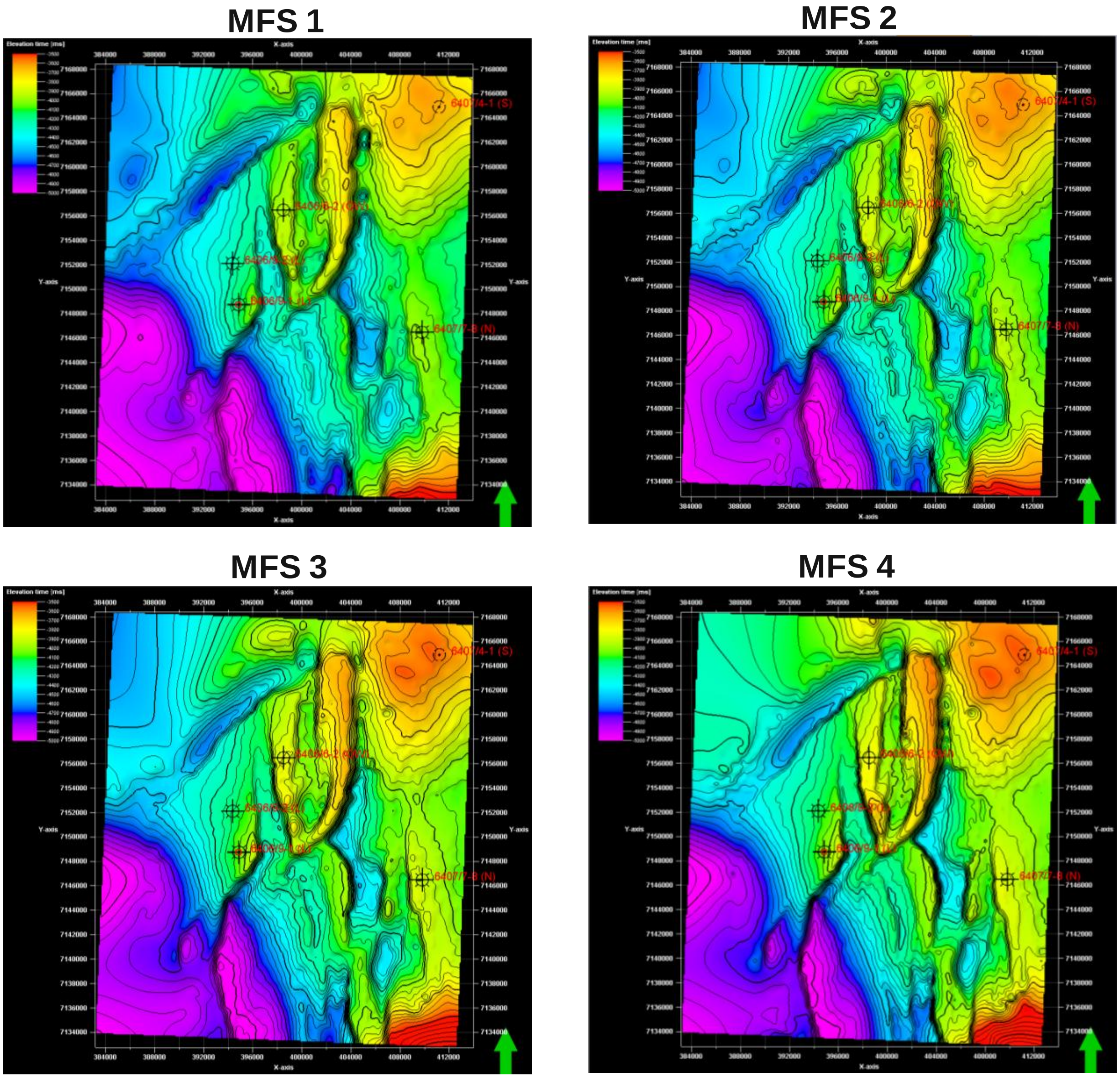


Figure 5.3 Structural map of MFS 4 overlay by fault classification from SHELL in-house study. Fault family one indicated with red line and fault family two with white line (C). W-E (yellow line) and SW-NE (blue line) cross sections show the structural configuration of the study area overlaid with horizon interpretations (A & B).


MFS 1

MFS 2

MFS 3

MFS 4

Figure 5.4 Structural map of interpreted horizons. The red to yellow represents the high structures, and purple to blue represents the low structures.

Based on the observation, the structural configuration at the time of Tilje Formation deposition suggests a dominance of NE-SW trend of horst and graben system. The west foot wall block formed the Linnorm Field which is bounded by major N –S fault with E-SE dipping trend, while the east foot wall block formed the Noatun Field which is bounded by N-S fault with W-SW dip. Two horsts on the northern part formed Onyx West and East, and one horst on the southern part were formed as Onyx South with N-S trend (**Figure 5.4**). Further discussion about structural interpretation dos not covered in this study.

5.3 STRATIGRAPHIC INTERPRETATION

Isochore map from the seismic interpretation was generated to see the distribution and continuity of the sequences. Generally, there is no significance change in terms of lateral distribution between sequences.

Sequence 1 has relatively homogenous and thin isochore, around 25 – 40 ms. Thicker sediments accumulated on the S-SE part of the area, and thinning towards the N-NW. The depocenter is located between the Linnorm and Noatun Field with a NE to SW orientation. This sequence has fairly constant thickness distribution and extends further towards the NW.

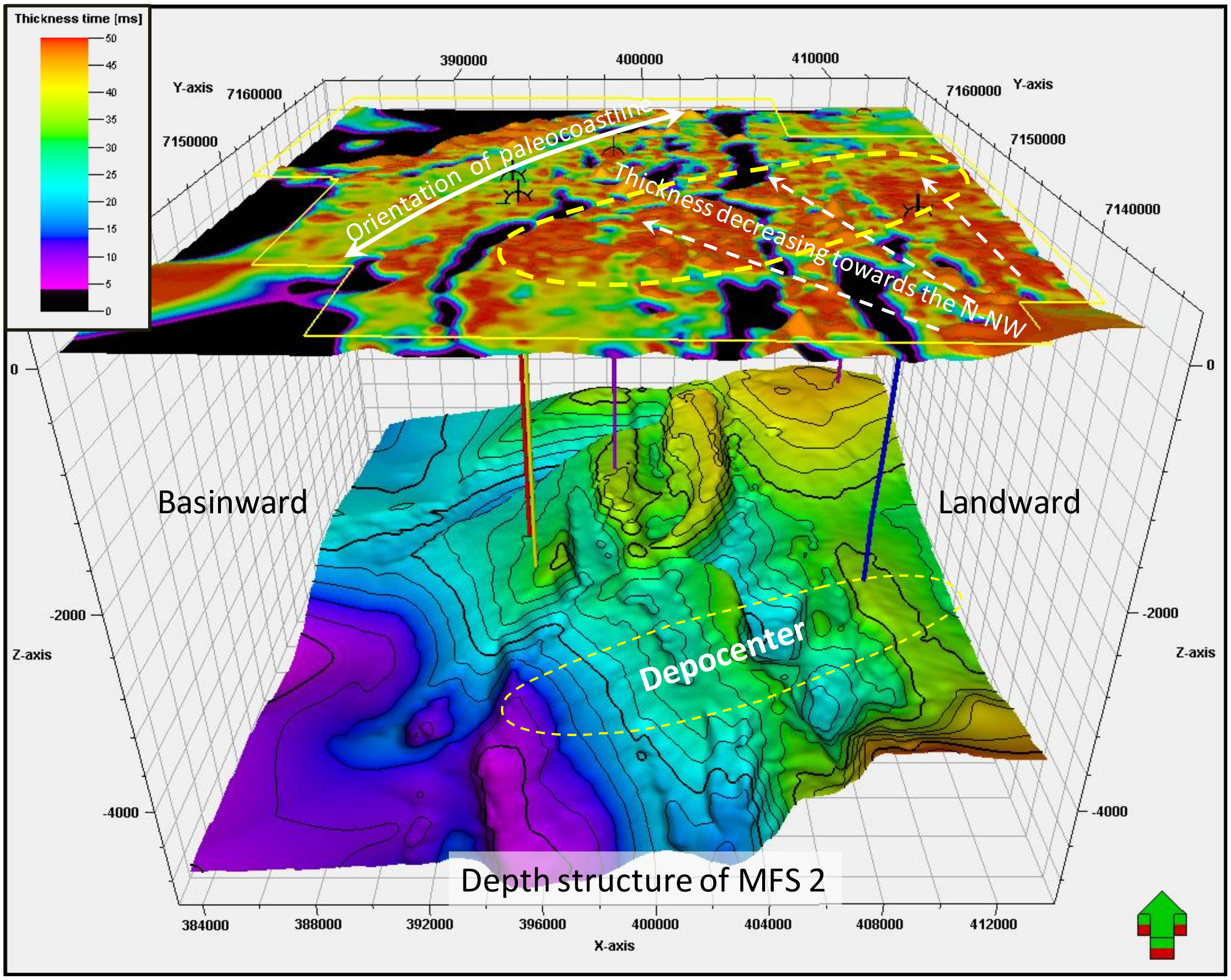


Figure 5.5 Example of overlay between the isochore map of sequence 2 with the depth structure map of MFS 2. These maps derived from the seismic interpretation.

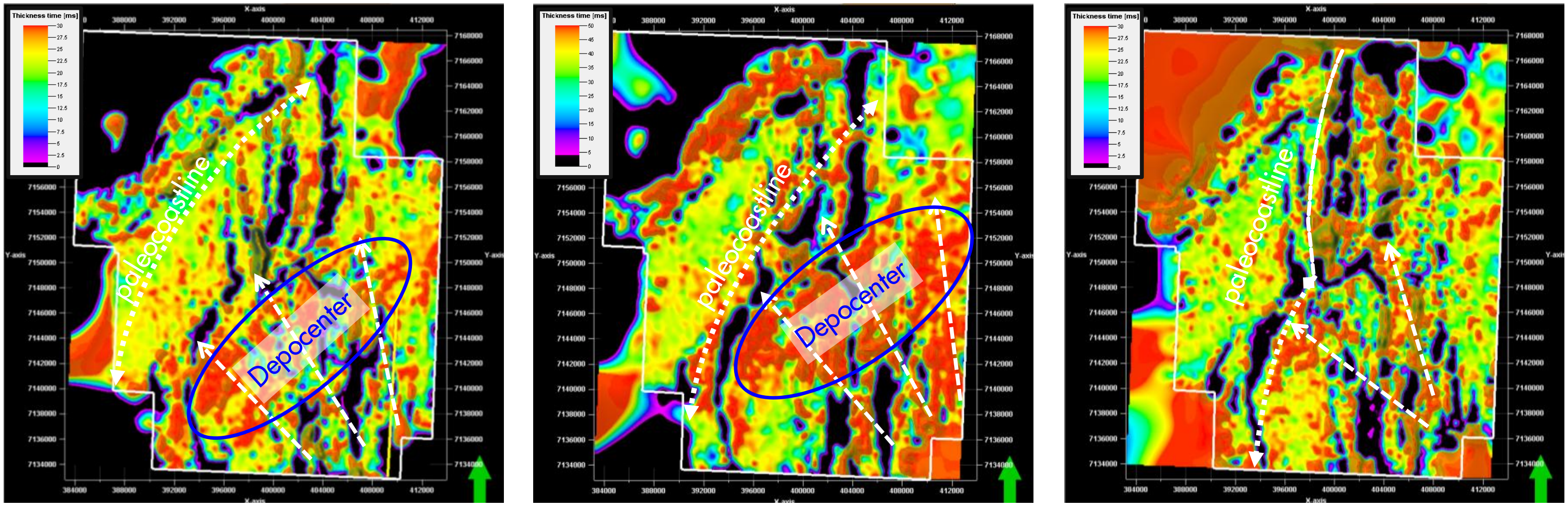
Sequence 2 has approximately 40-60 ms of isochore thickness. Similar to sequence 1, sequence 2 also shows the SE-NW trend of sedimentation. Thicker sediments accumulated on the SE, with the NE-SW depocenter in the middle of Linnorm and Noatun Field. Sediment distribution has fairly constant thickness until the major NE-SW fault in the middle (fault family one) and then thinning towards the NW.

Sequence 3 has the lowest isochore value (20 – 30 ms). The distribution of the thickness is fairly homogenous, with slightly thicker sediments on the S-SE and thinner sediments on the N-NW.

The trend of sedimentation from every sequence represents the source of sediment that was coming from the SE to NW. The sediment thickness and further extension of thick sediments towards NW in sequence 1 represents moderate sediment supply and low accommodation space, which allows the sediments to building out and creates progradation pattern. This was happened due to sea level fall during the regressive event. Constant thickness of sediments in sequence 1 suggests low tectonic activity happened during the deposition.

Sequence 2 has relatively thick isochore, and the thick sediments that represent the paleo coastline are limited by the major NE-SW fault. This pattern indicates a back stepping trend towards the SE, which can be related with increasing accommodation space due to sea level rise during the transgressive event. The high variety of the sediment thickness in sequence 2 suggests increasing tectonic activity happened during the deposition, which become an indication of synrift deposit.

Thickness in sequence 3 was decreased and relatively homogenous. The thicker sediment distribution is limited by the major N-NE to S-SW faults. This trend can be related to the increasing accommodation space due to sea level rise during the transgressive event, while the low thickness variety suggests low tectonic activity during the deposition.



SEQUENCE 1 SEQUENCE 2 SEQUENCE 3

Figure 5.6 Isochore map results of Tilje Formation from the seismic interpretation.

Sediment distribution of sequence 1 relatively homogenous in the study area compared to sequence 2, and sequence 3, which is related with the SE-NW outbuilding regressive sedimentation trend during the deposition and then backstepping towards the SE during sequence 2 and 3 due to transgressive event. The thicker interval package in sequence 2 implies the high sedimentation rate, while the heterogeneity of sequence 2 compared to the other sequence suggests an increased tectonic activity during the sequence 2 deposition event. This information indicates that Tilje Formation is considered as synrit deposit. This interpretation also supported by the presence of growth strata observed in seismic, which shows the thickness change due to fault activity.

5.4 ATTRIBUTE EXTRACTION and INTERPRETATION

Seismic attribute amplitude map has been made directly from survey SH0902MZ10 on the Tilje Formation. These attribute maps was extracted at the interpreted seismic horizons defined in well-to-seismic correlation result (**Figure 5.2**). The challenges lies in the ability to use the extracted amplitudes to predict distribution of facies and depositional that are thinner or below than the seismic resolution. However, the sand intervals are still in the range of visible resolution. Accordingly, seismic amplitude attributes has only been used as a support to define the facies lateral distribution trends. There are several suggestion solutions to explain the presence of amplitude contrast such as the presence of hydrocarbons to lithological features (**Figure 5.7**). However, lithological features are more preferable since the anomalies are also present in the downthrown or graben area.

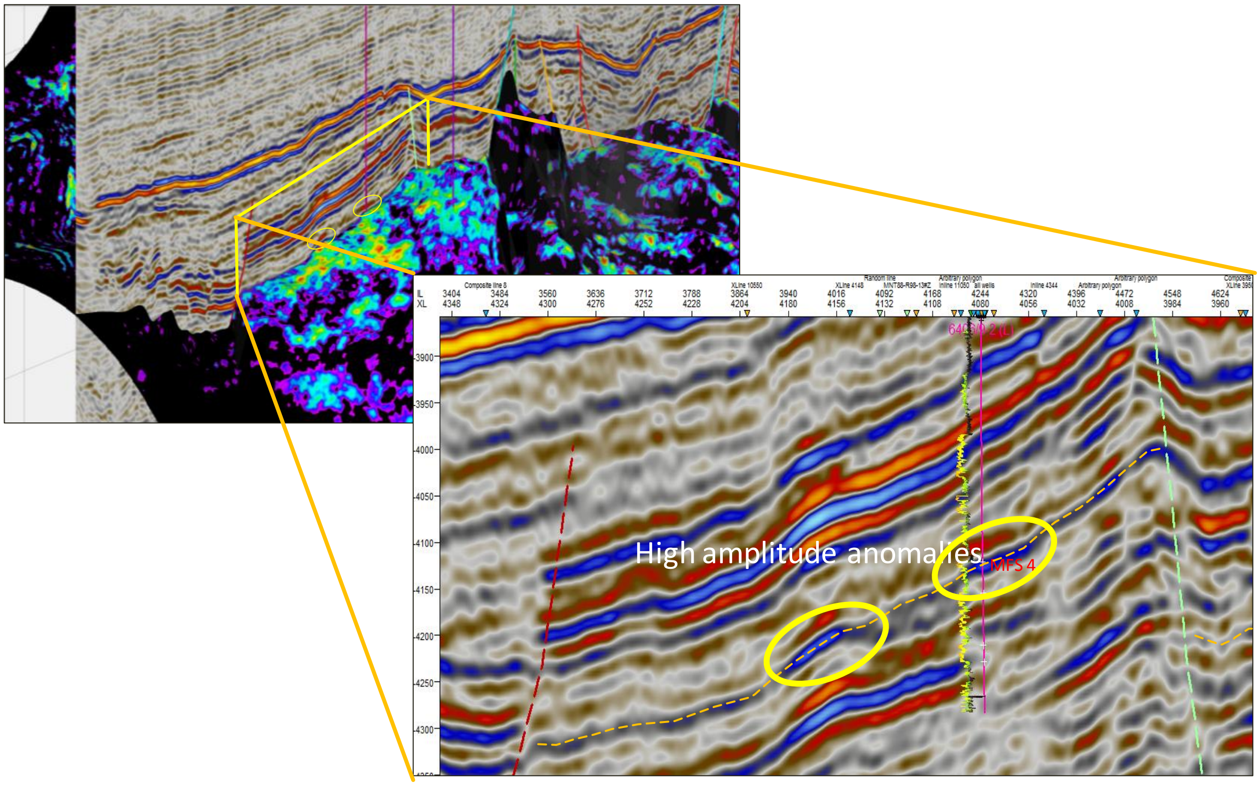
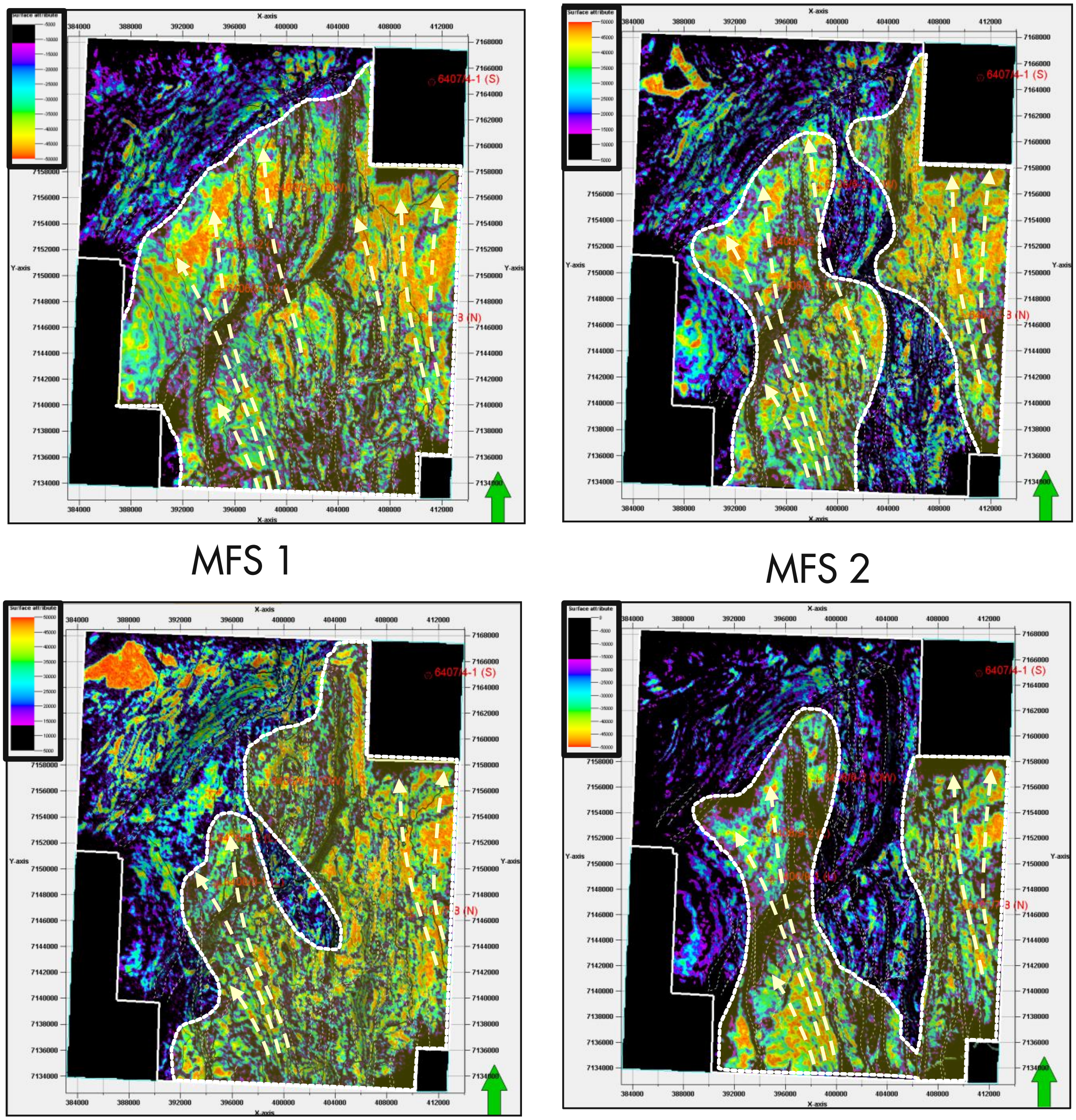


Figure 5.7 Illustration of seismic amplitude attribute observed from the cross section and map in Linnorm Field.



MFS 1

MFS 2

MFS 3

MFS 4

Figure 5.8 Amplitude attribute map of TIlje Formation based on assigned horizons.

Amplitude attribute map of MFS 1 represents the minimum amplitude (hard) (**Figure 5.8**). The high minimum amplitude value is indicated by warm colors (red and yellow) and the orientation of the stronger amplitude reflector roughly indicates a SE-NW to S-N trend with triangular shape. The high minimum amplitudes are really clear in the Noatun area, which obviously shows the SE-NW to S-N trend. It is similar with Linnorm and Onyx West area, where the high minimum amplitudes show a clear contrast. Southern part of the area does not show an obvious reflector due to highly faulted area.

Amplitude attribute map of MFS 2 represents the extracted maximum amplitude (soft) (**Figure 5.8**), where the high maximum amplitude value is indicated by warm colors (red and yellow). The orientation of the reflector is still showing a rough SE-NW to S-N trend with triangular shape. The high maximum amplitude mostly presents in Linnorm, Onyx West, Onyx South and Noatun area.

Amplitude attribute map extracted from the MFS 3 represents the maximum amplitude (soft) (**Figure 5.8**), where the high maximum amplitude value is indicated by warm colors (red and yellow). Overall reflection in MFS 3 does not show a clear trend, except for the area around Noatun which shows a good contrast of high maximum amplitude with roughly SE-NW to S-N trend.

Amplitude attribute map of MFS 4 represents the minimum amplitude (hard) (**Figure 5.8**). The warm colors (red and yellow) indicate the high minimum amplitude. Trend of the reflection is showing a roughly SE-NW to S-N trend with triangular shape. The high contrast mostly present in the Linnorm, Noatun, Onyx West and the southern part of the area.

In general, the amplitude attribute maps of each horizons display contrasts with a SE-NW to S-N trend (**Figure 5.8**). Some of the parts are however more dominated by faults, complicating the seismic reflector and disturbing the attribute maps. However, the anomalies are most prominent in the Linnorm, Onyx West and Noatun structure, of which both the Linnorm and Noatun are two relatively large undeformed structure, leading some credence to the interpret of these amplitude as lithological feature. The intensity of the anomalies and trends in MFS 1 and MFS 2 are relatively obvious, since the interval between these surfaces is relatively thick and can be captured in the seismic. This is supported by the uniform distribution of this sequence, which allows the sediments to deposits in less disturbance condition.

Amplitude attribute map in MFS 3 shows some amplitude contrast at some part of the area, however, it does not reveal any obvious trend. This response can be correlated with the gross strata architecture of sequence 2, which represented by MFS 3. The sparse and chaotic reflection pattern was caused by the lateral and stratigraphic heterogeneity of the package thickness, which is lower than the minimum thickness resolution. MFS 4 has a fairly low amplitude contrast compared to the other amplitude attribute maps. This is caused by the low thickness of sequence 3, which is below resolution. The continuity of the amplitude reflection is also relatively poor, due to marked interval variability in facies tracts and gross sequence thickness distribution.

6 GEOLOGICAL MODELING

6.1 TILJE FORMATION CONCEPTUAL GEOLOGICAL MODEL

Trough the observations of sedimentological analysis from the core samples, electrofacies and sequence stratigraphy analysis from the wireline logs, seismic interpretations and seismic amplitude attribute analysis from the seismic surveys, the conceptual geological model of Tilje Formation was built to reconstruct the depositional environment evolution as a basis for facies model.

Sequence 1 is dominated by tidal-fluvial channel in lower delta plain (FA 1) and wave-tide influenced delta deposits (FA 2). This sequence represents the outbuilding pattern, which happened during the regressive event. The thickness of sequence 1 is relatively homogenous with SE to NW trend sedimentation. The fairly constant thickness of sequence 1 represents the low tectonic activity during the deposition. Seismic amplitude attribute shows a strong contrast and suggests S-SE to N-NW trend, which is inline with the sedimentation trend.

Sequence 2 is considered as a heterogeneous architecture with dominance of lower delta plain (FA 1), estuarine (FA 3) and tide dominated delta deposits (FA 3). This sequence is deposited in overall transgressive event, with generally backstepping process relative to sequence 1 with local progradation. The lower part of sequence 2 consists of dominantly tide dominated delta deposits, which alternate with lower delta plain deposits. Where the upper part of sequence 2 consists of tide dominated delta and alternate with estuarine deposits. The thickness of sequence 2 is various across the study area, where the thicker interval deposited in the SE, and thins towards the NW. this high thickness is attributed to the increased tectonic activity during the deposition, which combined with lateral delta migration and shifting alternation. Due to this high variability, the amplitude attribute map for sequence 2 does not reveal any obvious trend, however still shows slightly S-SE to N-NW direction.

Sequence 3 consists of tide dominated delta (FA 4), estuarine (FA 3) and marine offshore deposits (FA 5). This sequence is deposited in overall transgressive event, with generally backstepping process relative to sequence 1, with local progradation. The thickness in this sequence is relatively homogenous with SE-NW sedimentation trend. The minor thickness variability of this sequence indicates a decrease in tectonic activity during the deposition. The seismic amplitude attribute map for sequence 3 suggests a S-SE to N-NW trend, which is inline with the sedimentation trend.

6.2 FACIES MODEL

Facies model for each sequence was built to give information about the sediment geometry and represent the gross depositional environment evolution in Tilje Formation. The following pages represent several maps which aimed at the reconstruction of the facies models. The facies models were reconstructed based on the facies association/facies tract distribution and thickness that has been defined from the five wells, correlations of sequence stratigraphy analysis and zonation from the seismic interpretation.

Truncated Gaussian Simulation with Trend analysis was used based on three variables in the following table:

	Major dir	Minor dir	Vertical dir	Variance
Sequence 1	5303	2500	4.5	0.1
Sequence 2 L	7100	3100	11	3
Sequence 2 U	6000	2400	8	1
Sequence 3	4701	2795	7	1

Table 6.1 Variogram data analysis and variance inputs for facies modeling in Tilje Formation

Facies model of sequence one represents the early and peak regressive conditions and consists of equal proportion between facies association 1 and facies association 2 (**Table 6.2**) in lower Tilje. Based on the previous chapters, the trend of sedimentation suggests a progradation pattern from SE to NW. Facies association 1 and 2 which dominated by sandstones has well distribution within the area and thinning towards the NW.

Facies model of sequence two was deposited during the transgressive event and it is divided into two intervals in order to capture details of the stratigraphic evolution. Overall trend of sedimentation in this sequence is SE to NW, with local progradation. The lower interval is dominated by facies association 1 and 4. It is represents the condition of the interval was still highly affected by fluvial deposits. The elongated geometry triggered by tidal influence, which separates the continuity of the sandier packages in facies association 1 and 4 with marine mudstones in facies association 5.

The upper interval has a high proportion of facies association 3 and 5. The domination of facies association 3, which represents the estuarine deposits reflect a backstepping deltas of the middle Tilje. It is inline with an overall transgressive evolution. This is also supported by high proportion of facies association 5, which represents the marine offshore deposits, interbedded with and capping the parasequence of estuarine to delta deposits. This interval still has a strong tidal influence, which is suggestive of elongated geometries, separating the sandier packages in facies association 3 and 4 with marine mudstones in facies association 5.

	FA 1	**FA 2**	**FA 3**	**FA 4**	**FA 5**
	in %				
Sequence 1	50	50			
Sequence 2 Lower	31,46			43,82	17,98
Sequence 2 Upper			54,17	29,17	51,67
Sequence 3			37,21	46,51	16,28

Table 6.2 Percentage of upscaled facies association log for each sequence

Sequence three is dominated by facies association 3 and 4, which deposits during the transgressive events with local progradation. The sedimentation trend from the previous chapters suggest SE to NW direction with local progradation. High proportion of facies 4 which represents the tide dominated delta confirmed the elongated geometry of the facies that was influenced by tidal activity.

6.3 PALEOGEOGRAPHY

Figure 6.1 shows the development of sequence one, which consists of fluvial-lower delta plain (FA 1) sediments and wave dominated delta (FA 2). From the proximal to distal perspective, this sequence has been interpreted as progradation from SE to NW. The reconstruction demonstrates how the depositional environments of the facies are expanding further basinward during the sea level fall and the paleo coast line reach the maximum extension. This well distributed facies happened during the minimal or low tectonic activity.

Figure 6.2 and **Figure 6.3** shows the setting for deposition in sequence 2. As has been explained in the previous chapters, the development in sequence two is quite complex, It is interpreted as a roughly SE to NW landward oriented during the transgression event with local progradation trend. This lower part of the sequence is dominated by tide dominated delta (FA 4), which alternates with fluvial-lower delta plain (FA 1) (**Figure 6.2**) with a local building out pattern. The elongated deposits shape happened due to high tidal influence, which separated by the marine offshore deposits (FA 5). The upper part is dominated by tide dominated delta plain (FA 4), which alternates into estuarine deposits (FA 3) (**Figure 6.3**). The elongated shape of the deposits trend represents the dominant tidal influence. The high variation of the facies was also affected by the minor tectonic activity during the deposition.

Figure 6.4 shows the development stage in sequence 3. This sequence consists of tide dominated delta (FA 4) and estuarine deposits (FA 3) which developed after the marine offshore deposits during the maximum flooding event. In general, sequence 3 deposited during the transgression event with local progradation trend. The depositional environment of the facies was relatively well distributed compared to sequence 2. This is happened due to less tectonic activity during the deposition. The elongated shape of the facies indicates a tidal influence activity.

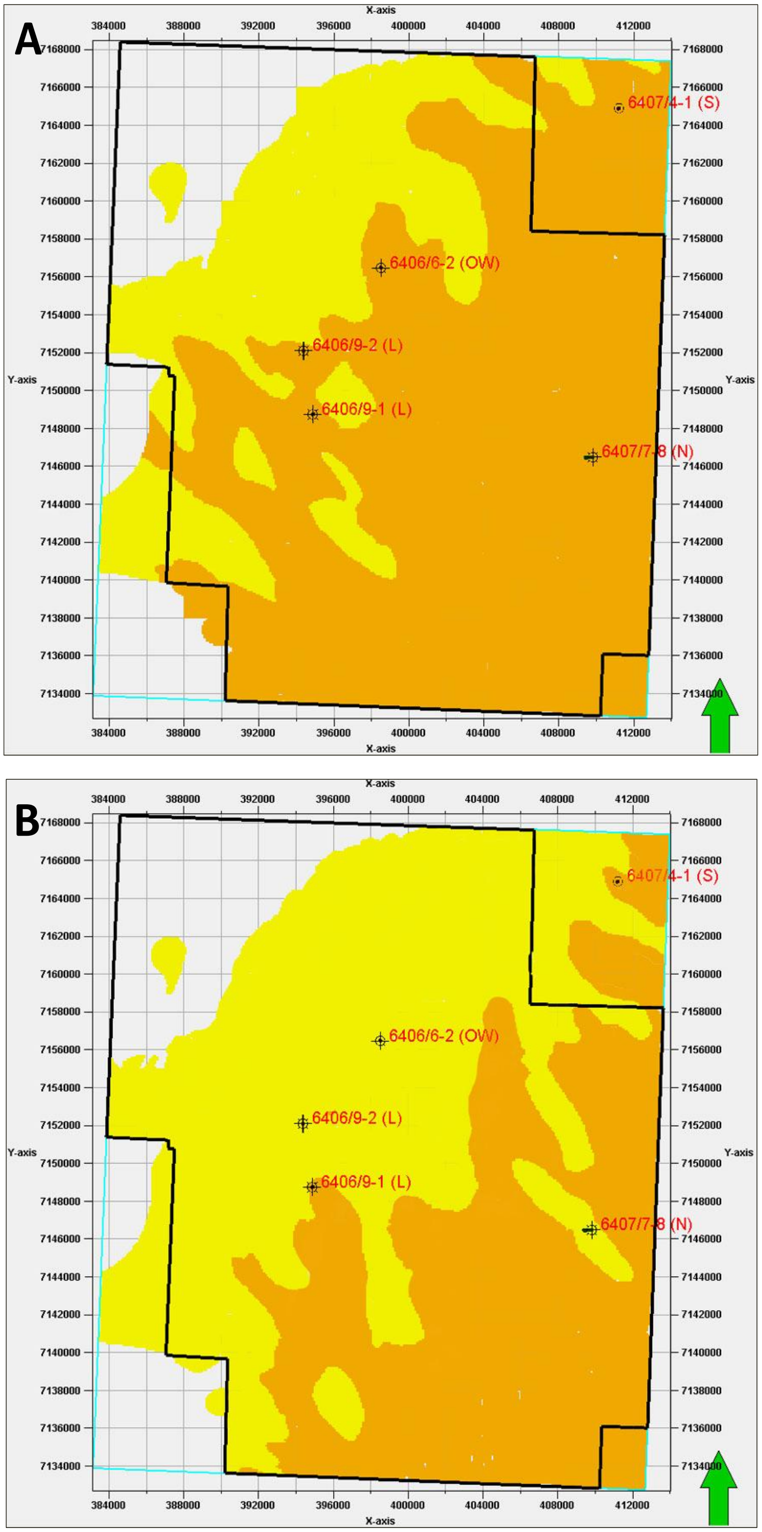


Figure 6.1 Facies model of sequence 1 in Tilje Formation. This picture reconstructs the regressive event and progradation trend from the lower (B) to the upper part (A).

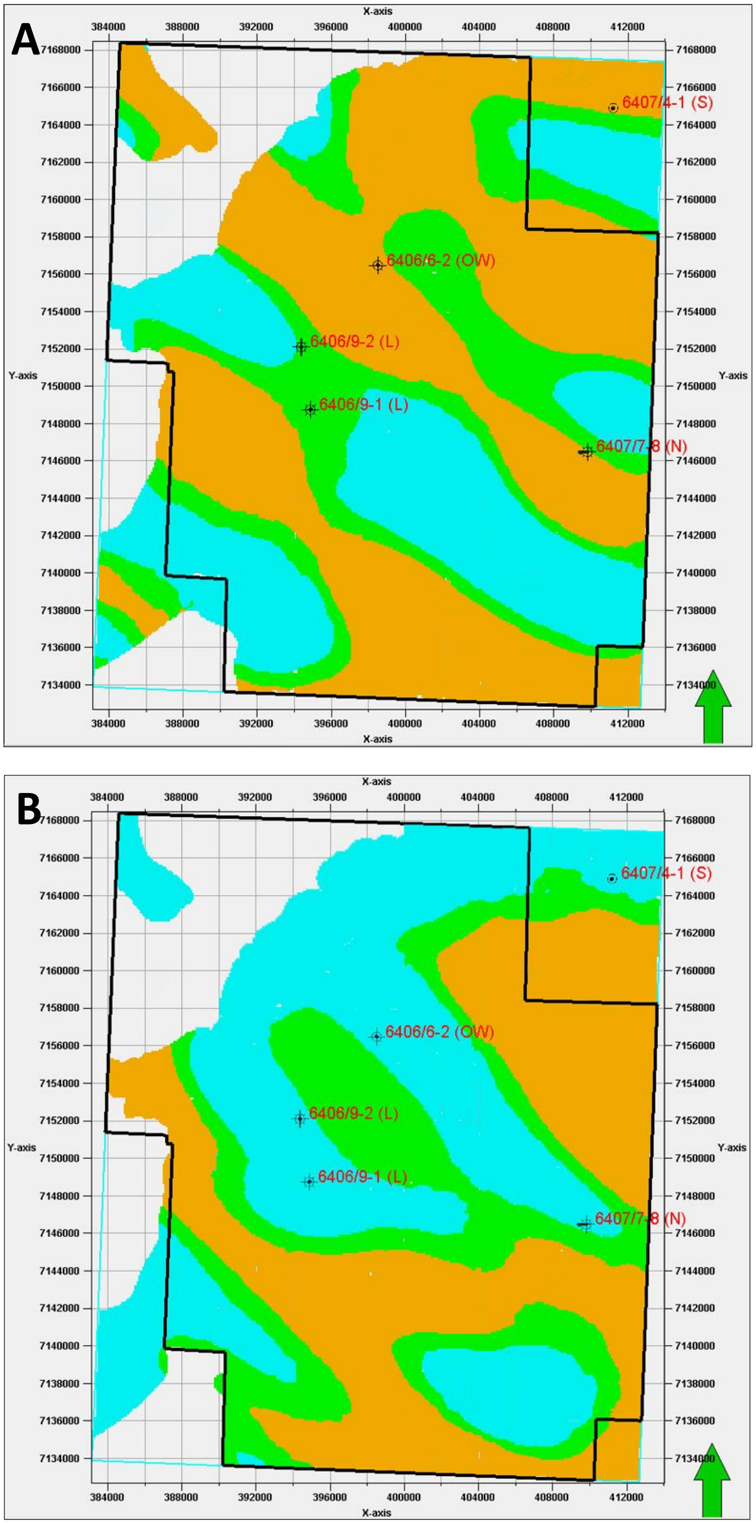


Figure 6.2 Facies model of lower sequence 2 in Tilje Formation. This picture reconstructs the transgressive event with local progradation trend from the lower (B) to the upper part (A).

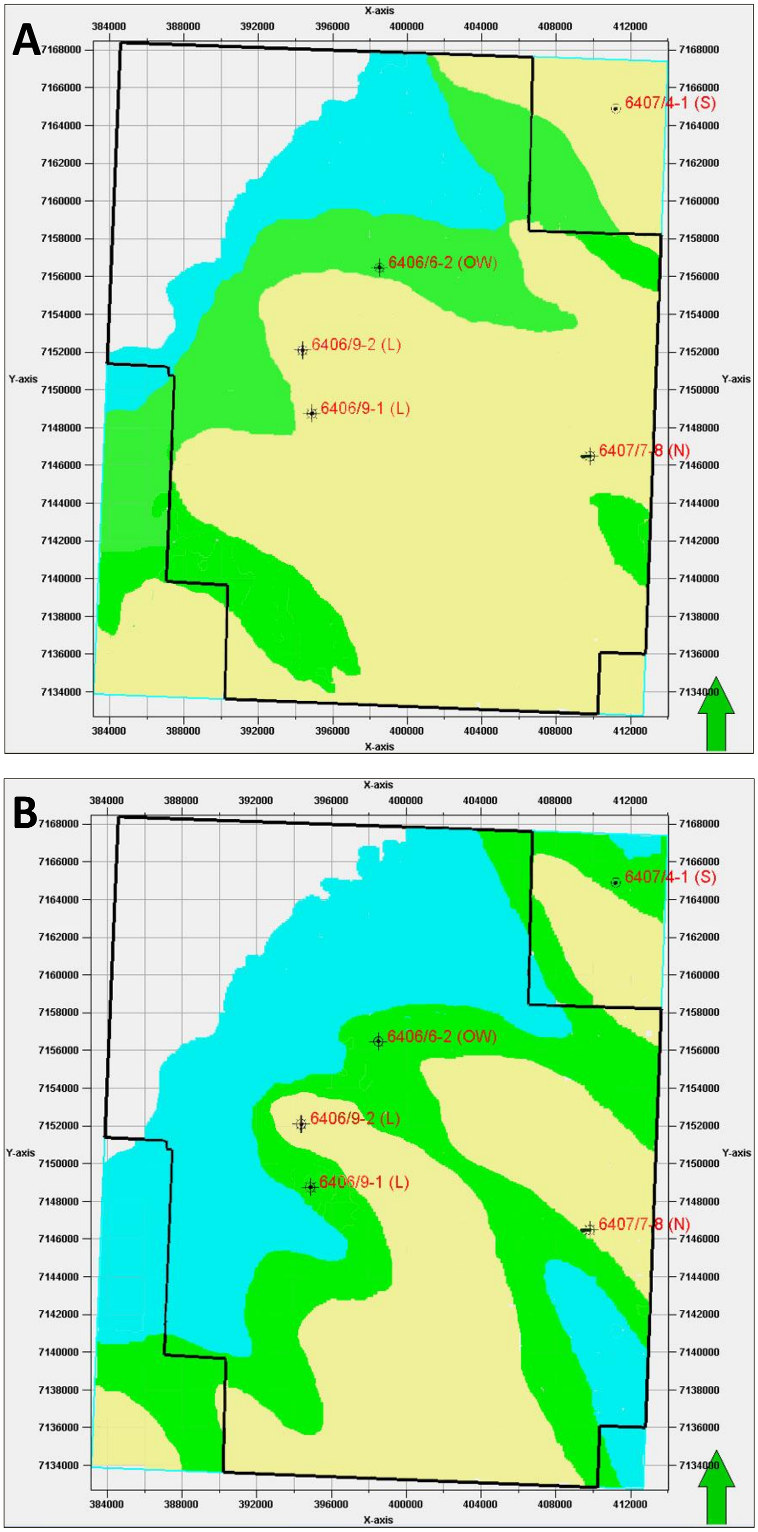


Figure 6.3 Facies model of upper sequence 2 in Tilje Formation. This picture reconstructs the transgressive event with local progradation trend from the lower (B) to the upper part (A).

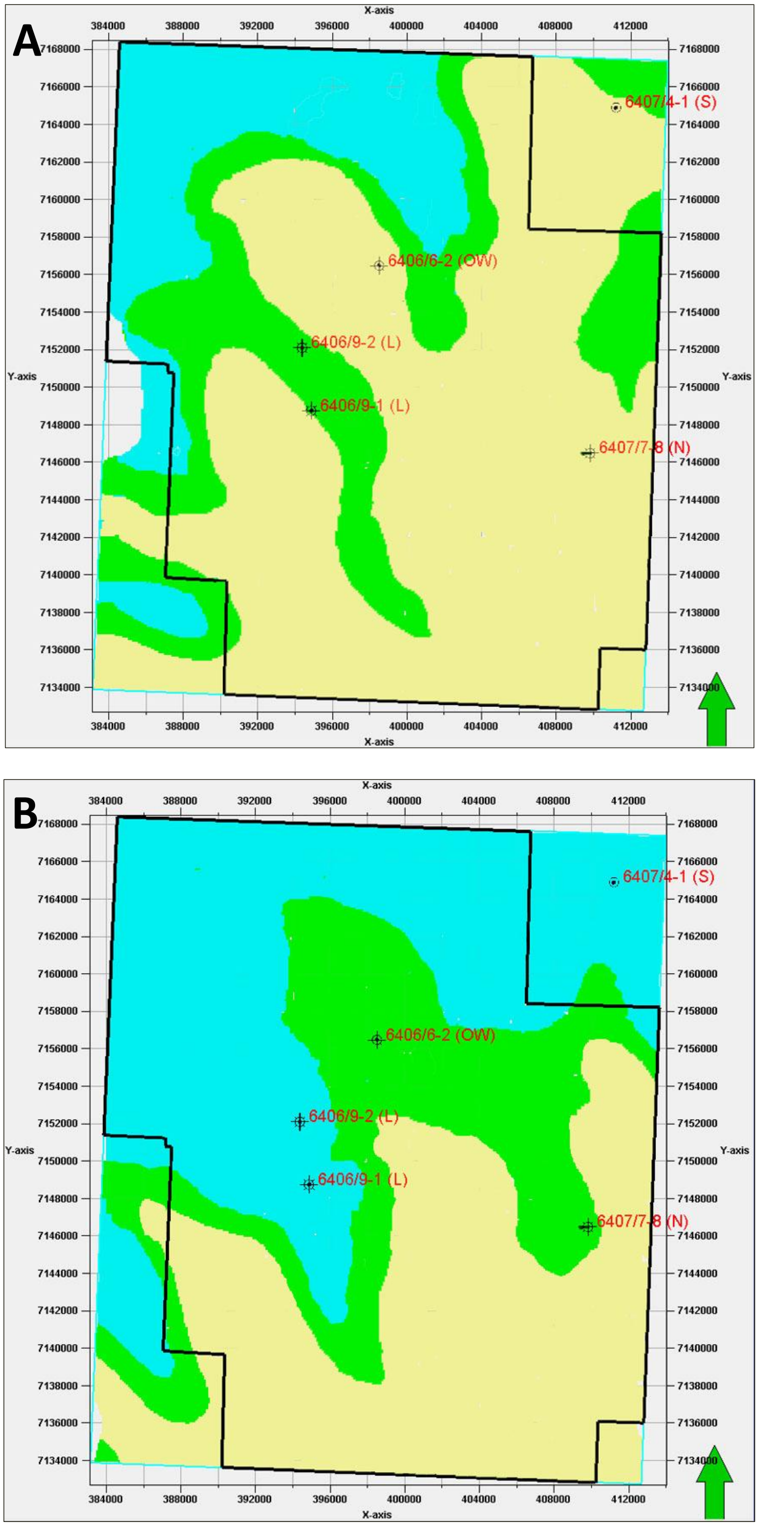


Figure 6.4 Facies model of lower sequence 3 in Tilje Formation. This picture reconstructs the transgressive event with local progradation from the lower (B) to the upper part (A).

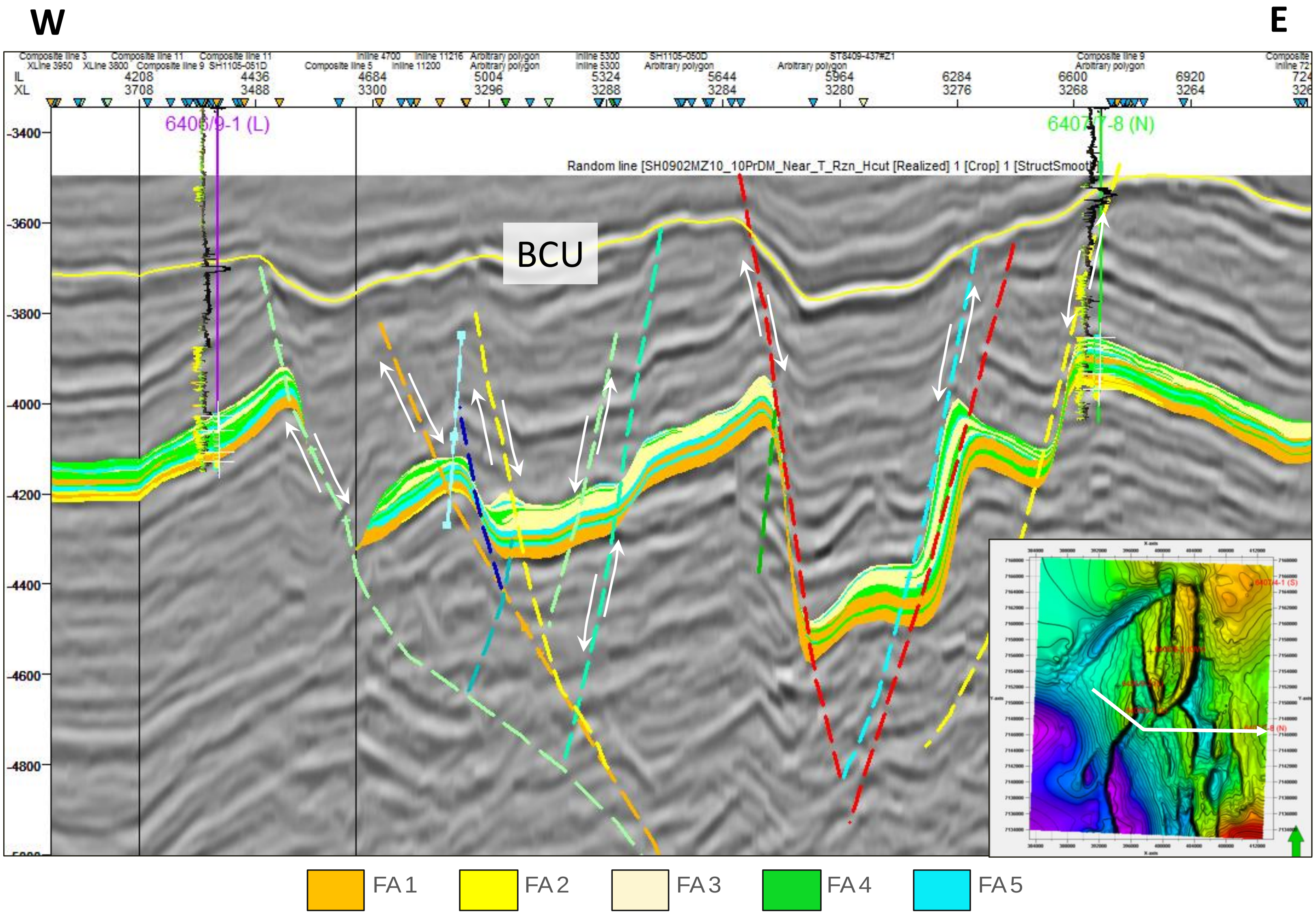


Figure 6.5 W to E cross section overlay with facies association lateral distribution in TIlje Formation

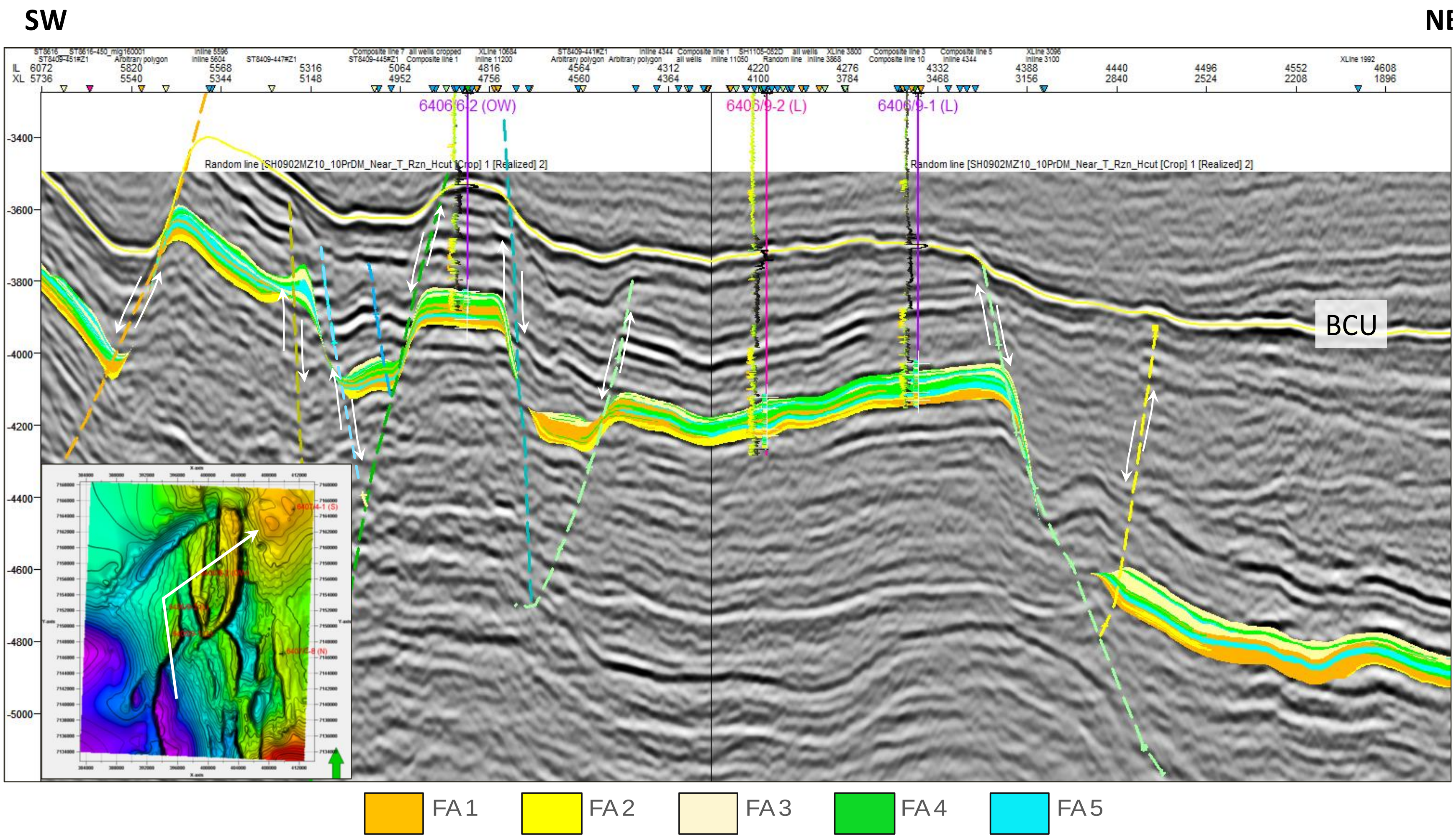


Figure 6.6 SW to NE cross section overlay with facies association lateral distribution in TIlje Formation

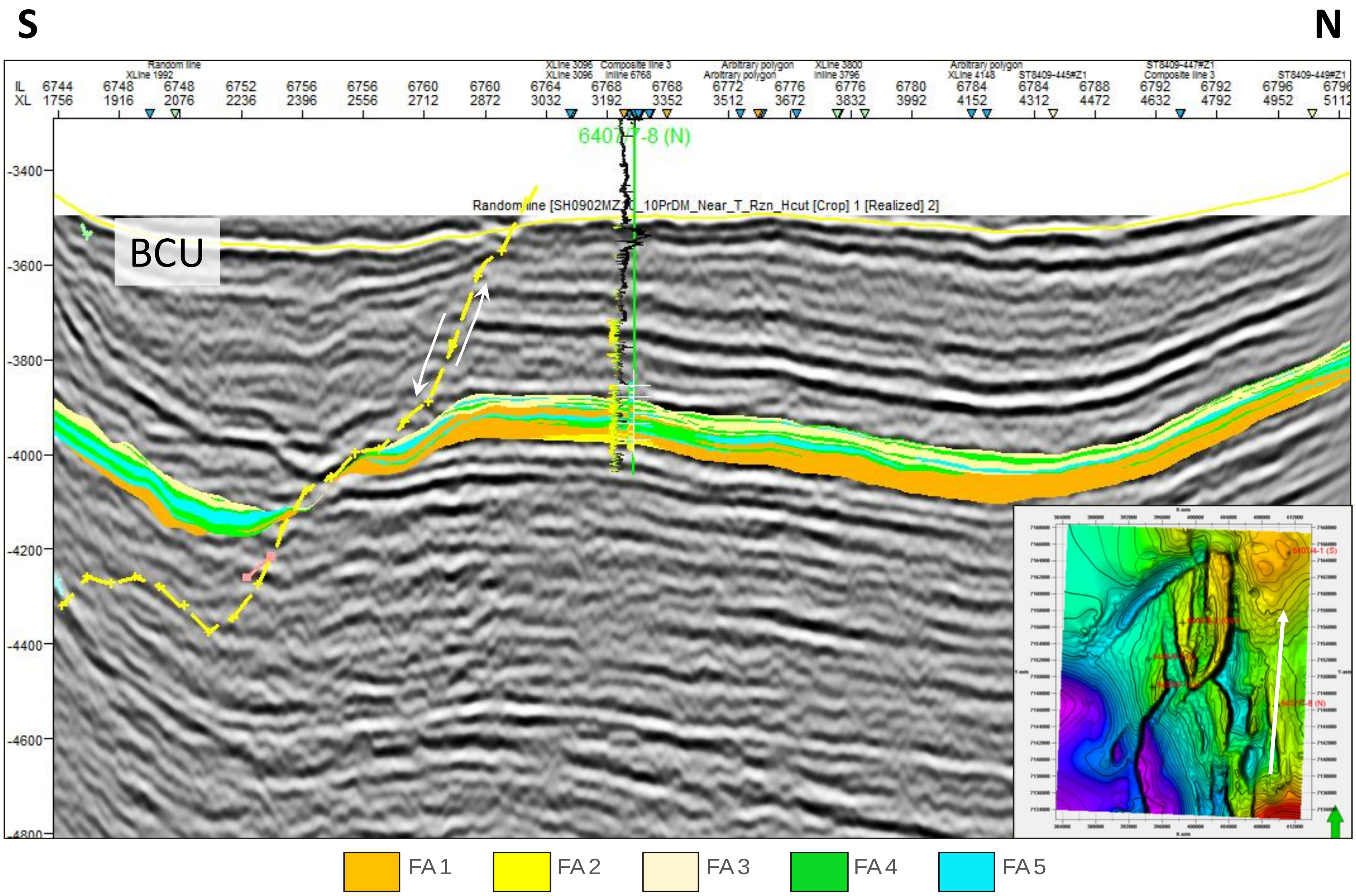


Figure 6.7 S to N cross section overlay with facies association lateral distribution in TIlje Formation

7 CONCLUSION

Ten lithofacies were indentified in the Tilje Formation stratigraphic interval in the southern Halten Terrace based on the sedimentological characteristic, including the grain size, textures, sedimentary structures, bed contacts, trace fossils and sand/shale ratio. Depositional elements association was built from the lithofacies analysis to represents the depositional elements. The results were combined with four electrofacies classifications to produce 5 general facies associations as an input to reconstruct the facies evolution within Tilje Formation which cover the delta to marine offshore deposits.

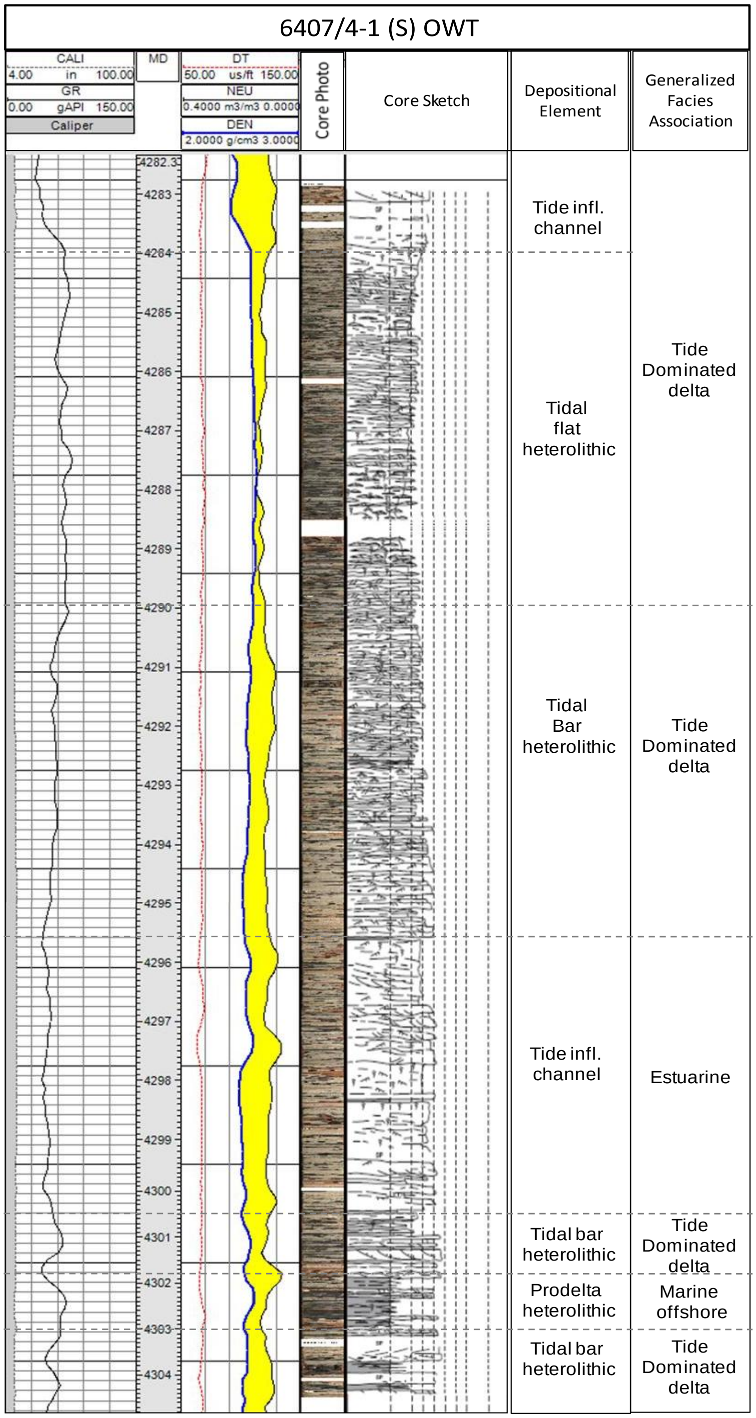
TIlje Formation consists of diverse range of facies and depositional environments. Based on sequence stratigraphy, Tilje Formation is divided into three main genetic sequences, bounded by Maximum Flooding Surfaces (MFS). Sequence 1 is dominated by broadly developed lower delta plain (FA 1) and mixed wave-tide influenced delta (FA 2) which represents in regressive event with SE-NW progradation trend. The architectural motives comprises of sandier upward packages into sand rich units. Sequence 2 was deposited during the transgressive event and shows a complex vertical tide dominated delta deposits, which alternates into lower delta plain on the lower part and estuarine on the upper part. This sequence facies distribution suggests overall SE-NW retrogradation with some local progradations. High tidal influence during the deposition affected the elongated shape of the sediments, separated by marine offshore deposits. Sequence 3 consists of tide dominated delta, estuarine and marine offshore deposits, which deposited during the transgressive event. The facies distribution in this sequence shows a general SE-NW retrogradation with two local progradations. The elongated shape of the deposits indicates high tidal activity during the deposition.

The integration analysis based on fault timing activity and stratigraphic interpretations indicates that Tilje Formation deposition was somehow affected by tectonic event in the early stage, and identified as early syn-rift deposits with SE-NW sedimentation trend within a NE-SW oriented half graben with local N-S normal fault trend. Together with relative sea level fluctuation, depositional styles, and sediment supply, the minor tectonic activity during the deposition built the complex sedimentological variation of Tilje Formation.

APPENDIX

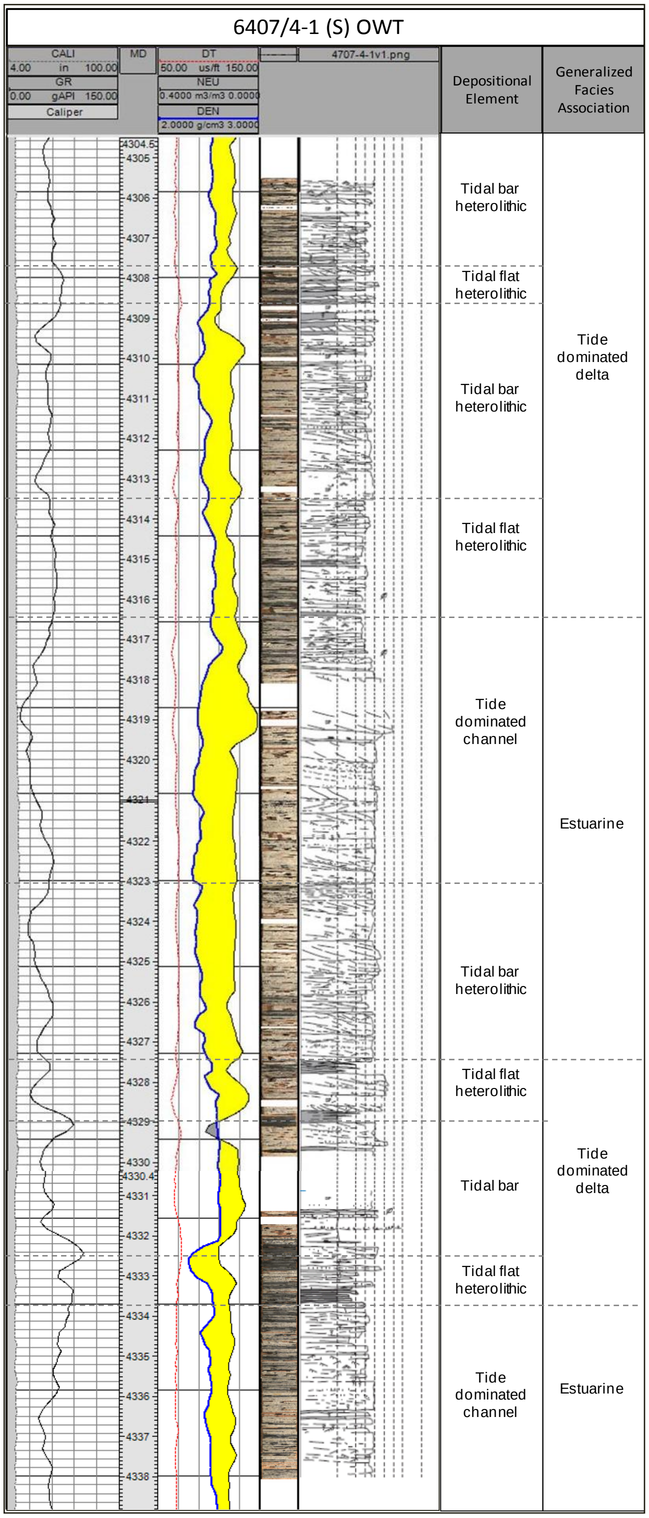
Appendix 1

Core description and facies association in well 6407/4-1 #1-1.



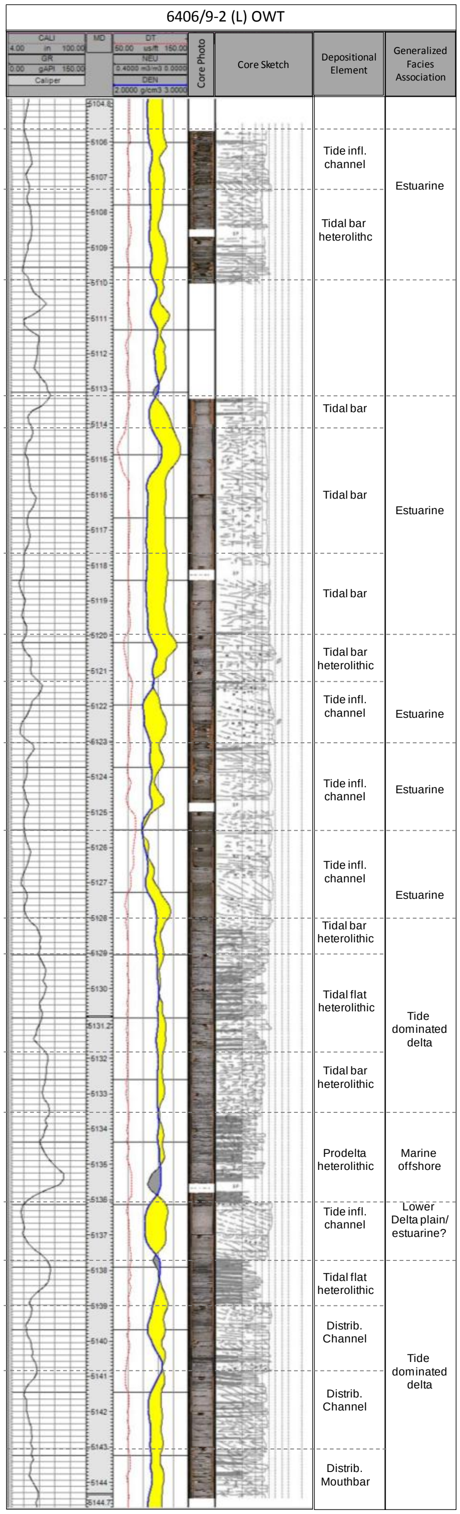
Appendix 2

Core description and facies association in well 6407/4-1 #1-2



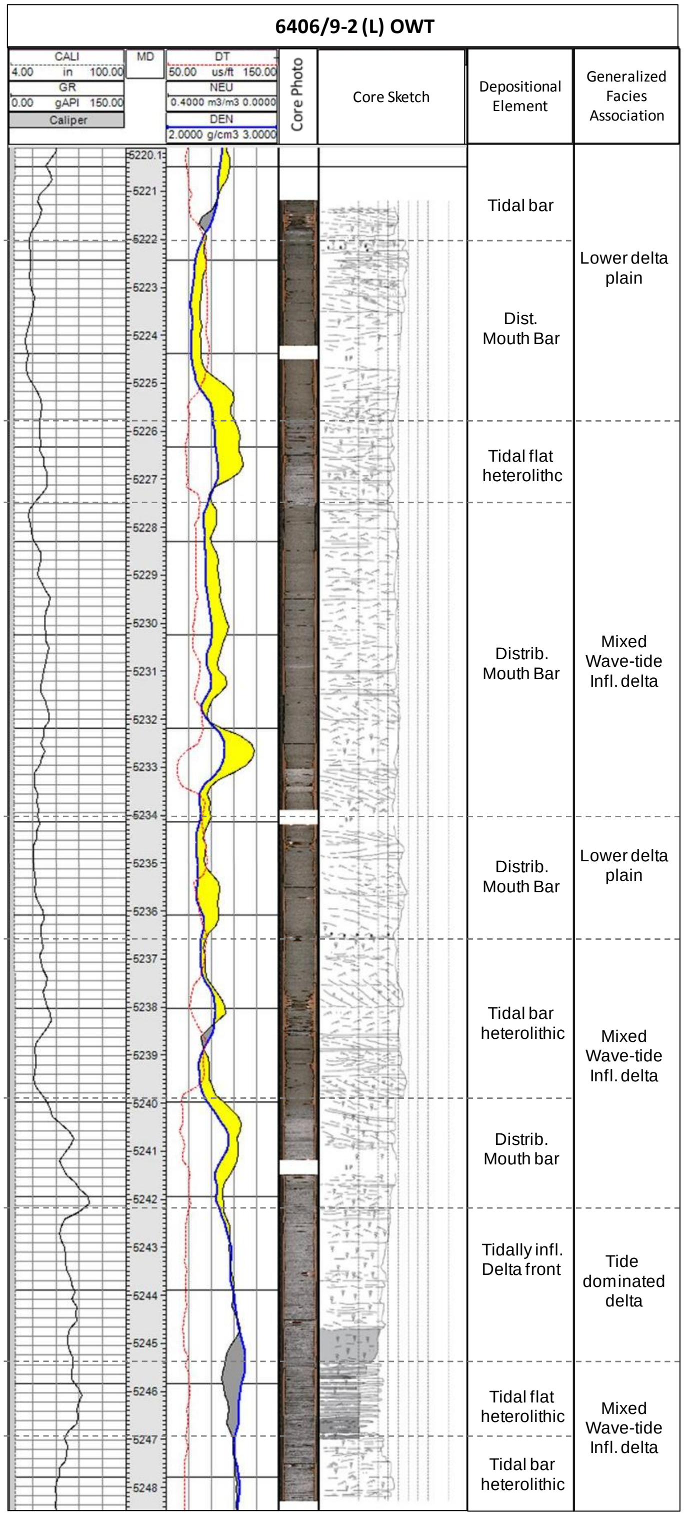
Appendix 3

Core description and facies association in well 6406/9-2 #2 & #3.



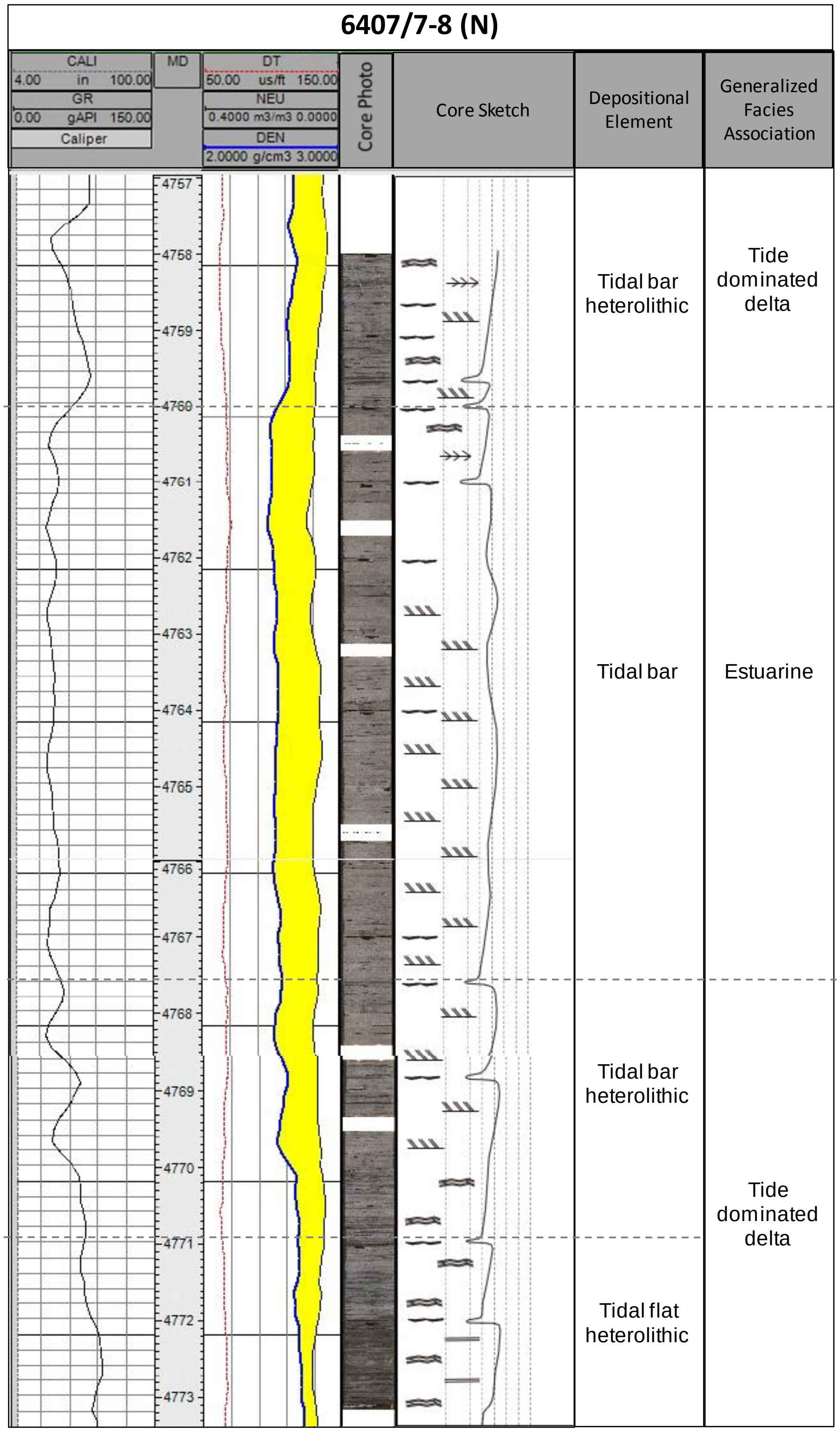
Appendix 4

Core description and facies association in well 6406/9-2 #4



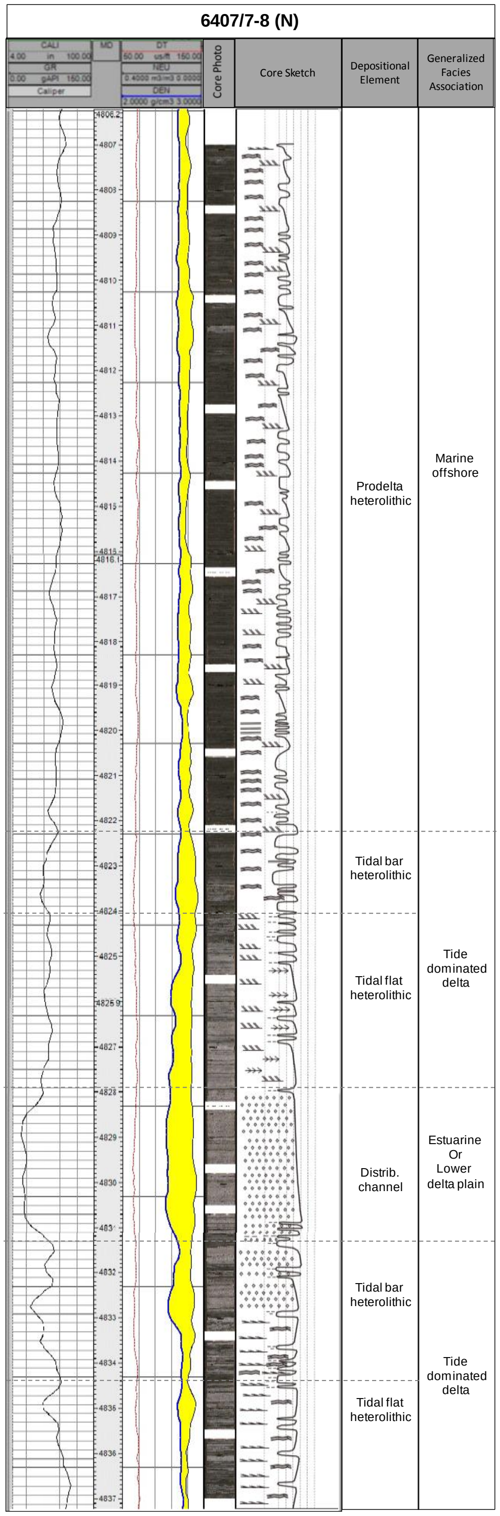
Appendix 5

Core description and facies association in well 6407/7-8 #1



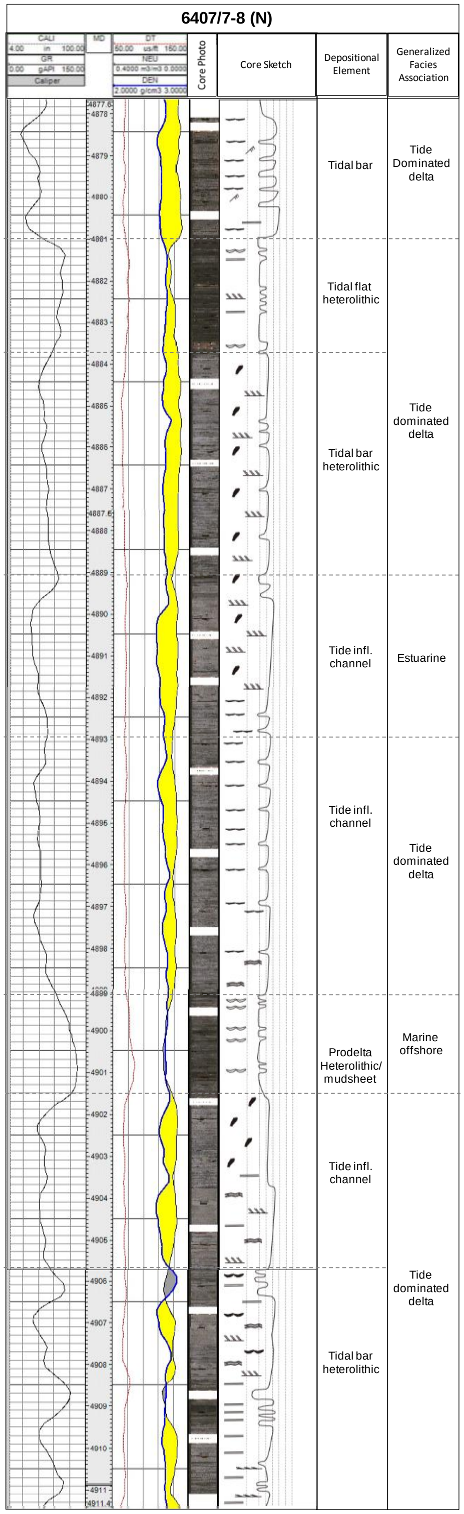
Appendix 6

Core description and facies association in well 6407/7-8 #2



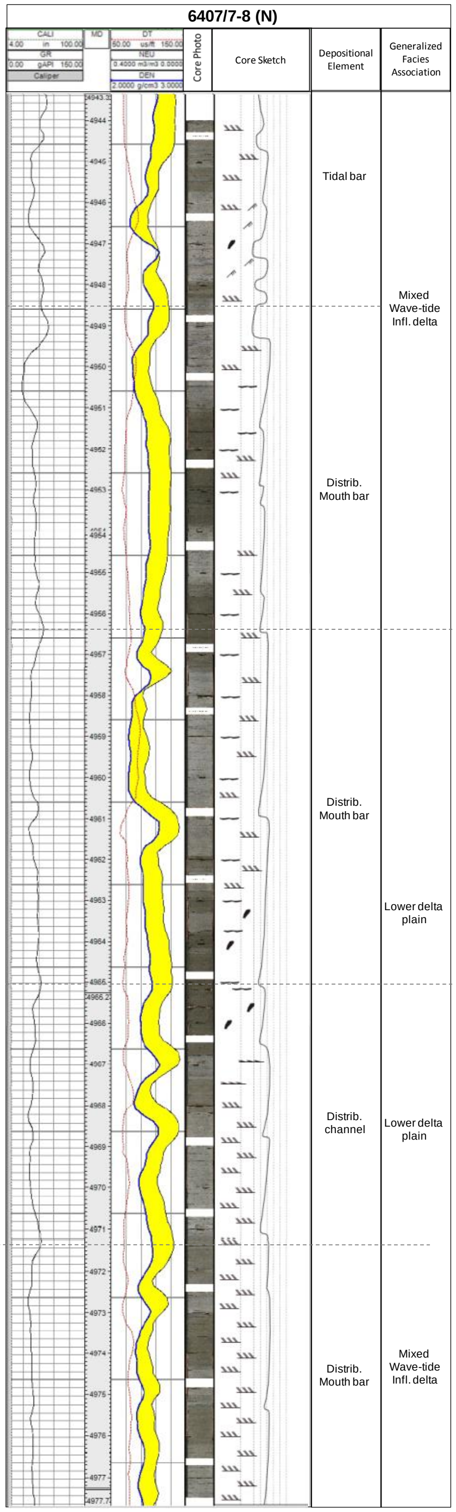
Appendix 7

Core description and facies association in well 6407/7-8 #3



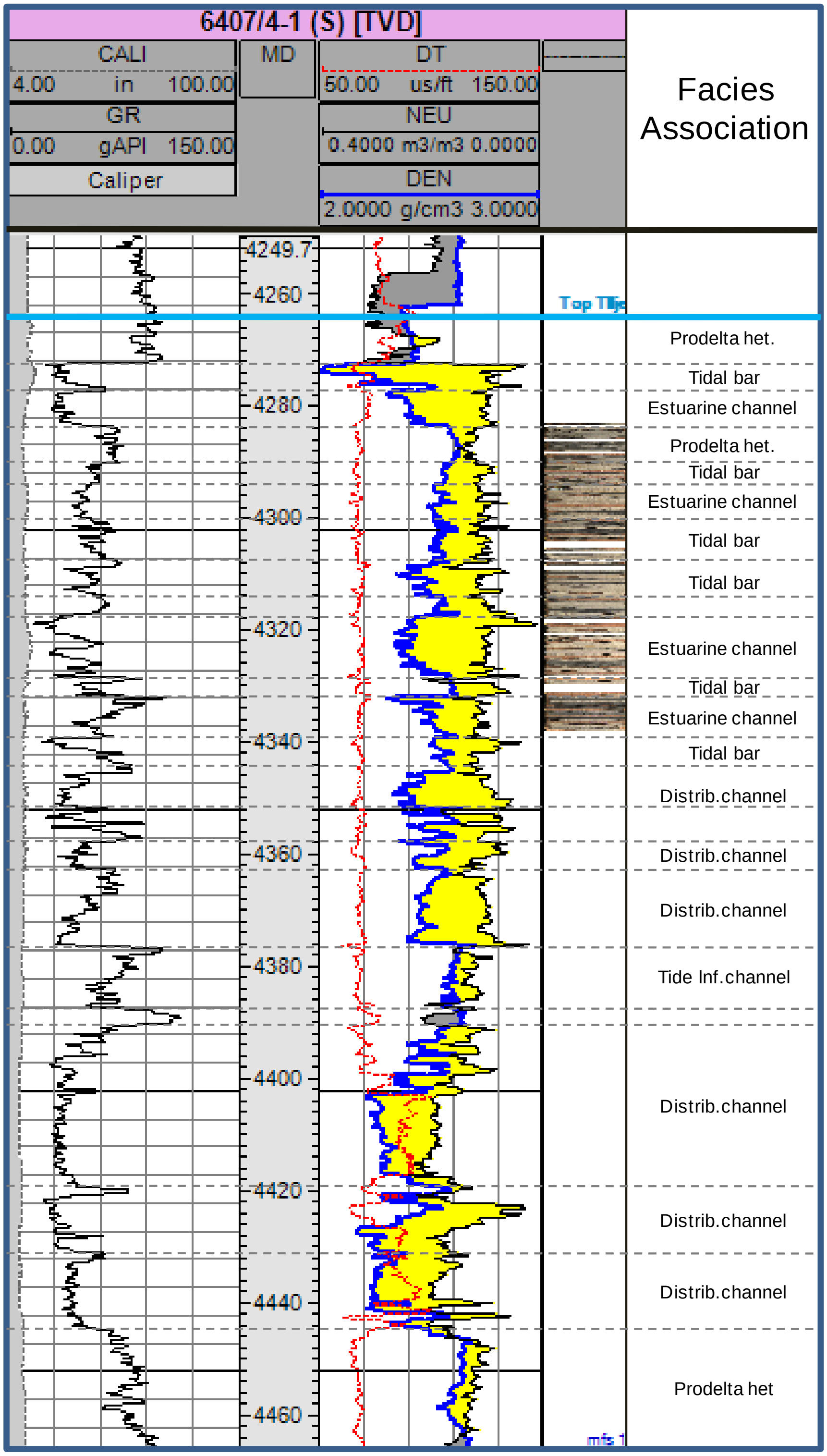
Appendix 8

Core description and facies association in well 6407/7-8 #4



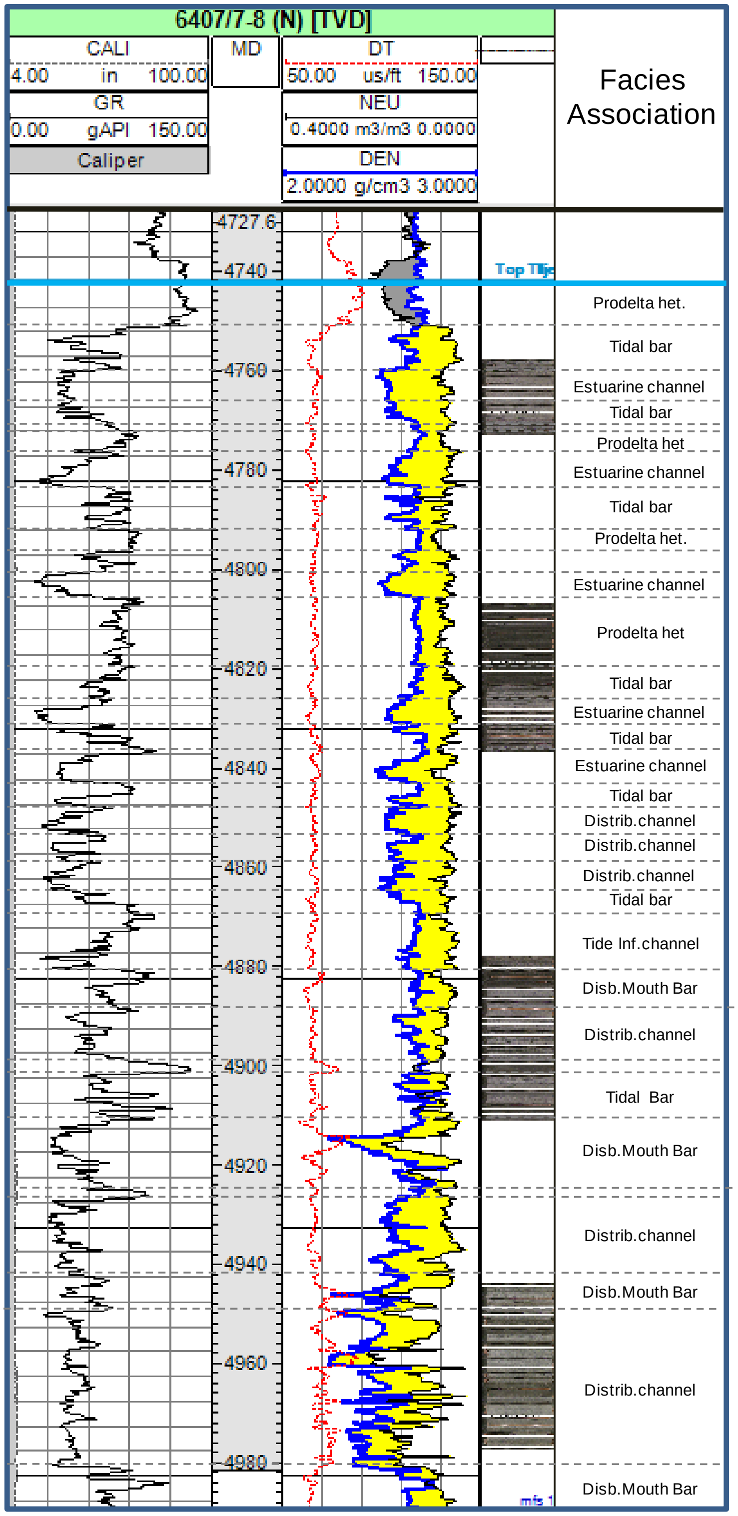
Appendix 9

Electrofacies classification in Tilje Formation in well 6407/4-1.



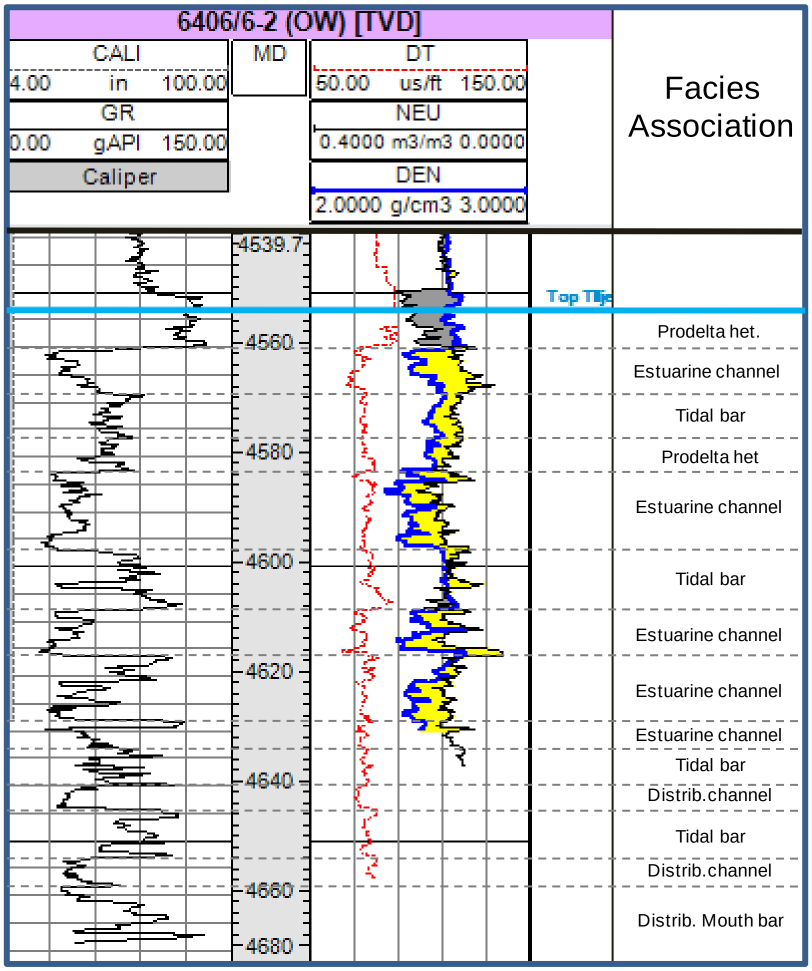
Appendix 10

Electrofacies classification of Tilje Formation in well 6407/7-8



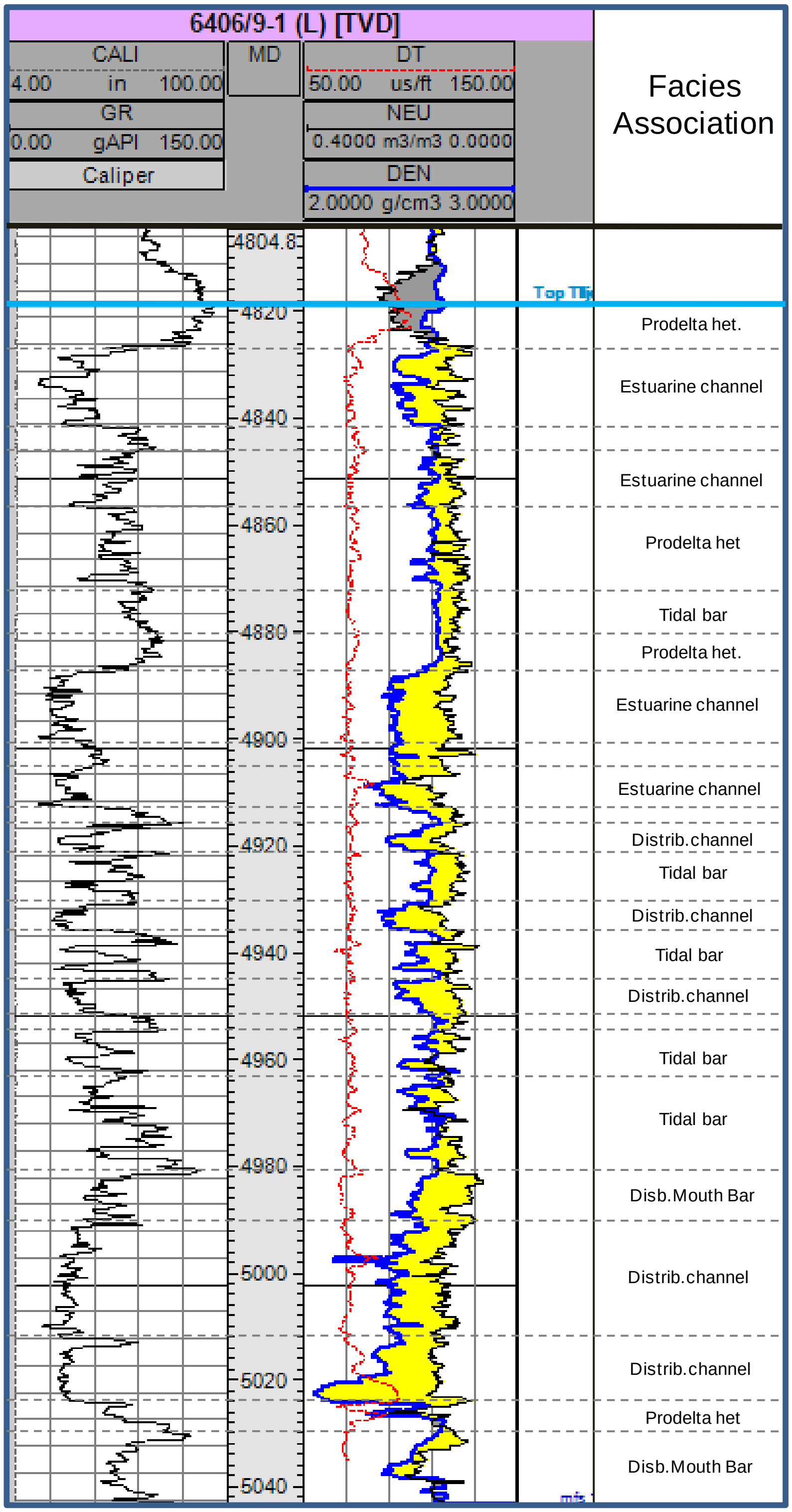
Appendix 11

Electrofacies classification of Tilje Formation in well 6406/6-2



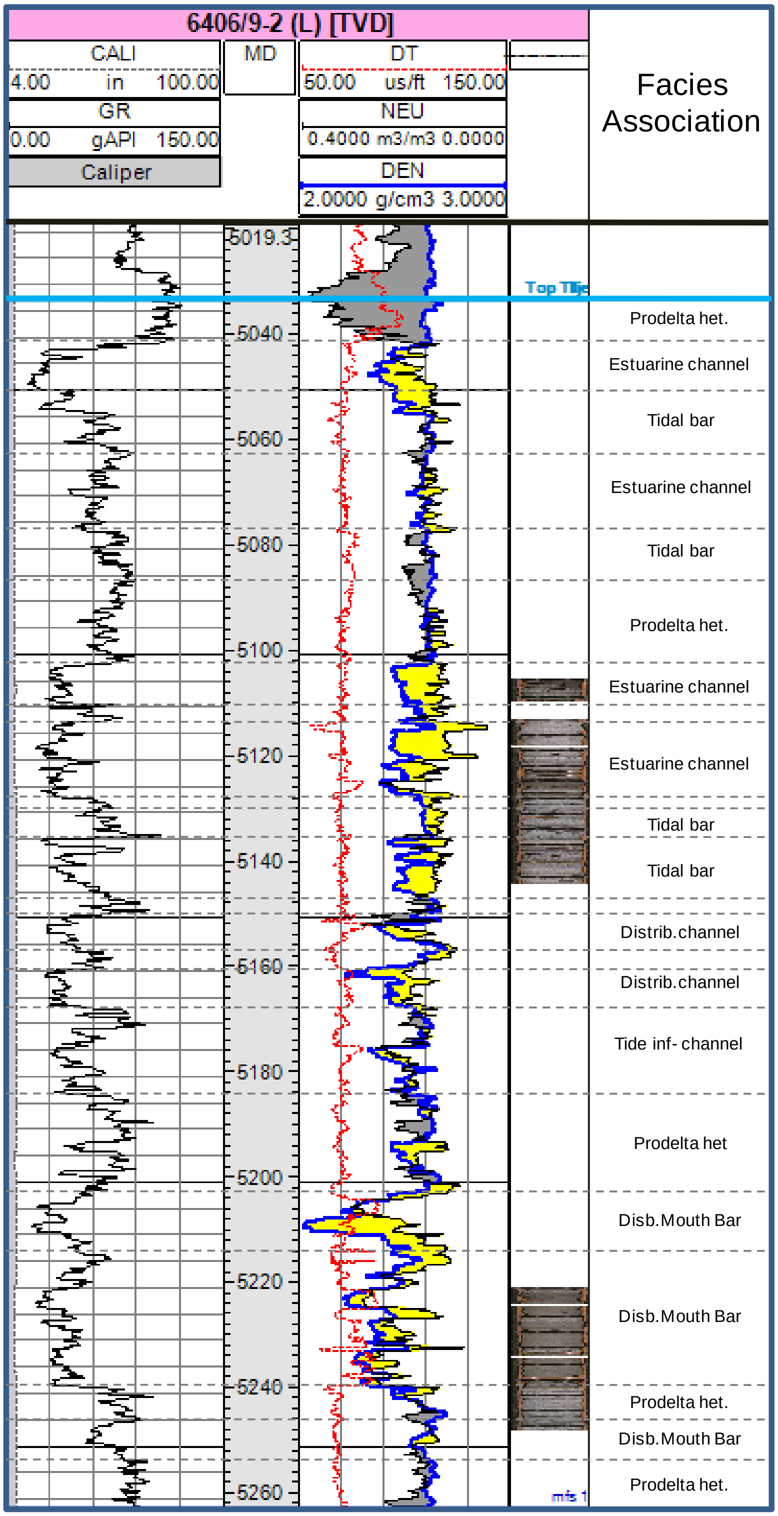
Appendix 12

Electrofacies classification of Tilje Formation in well 6406/9-1



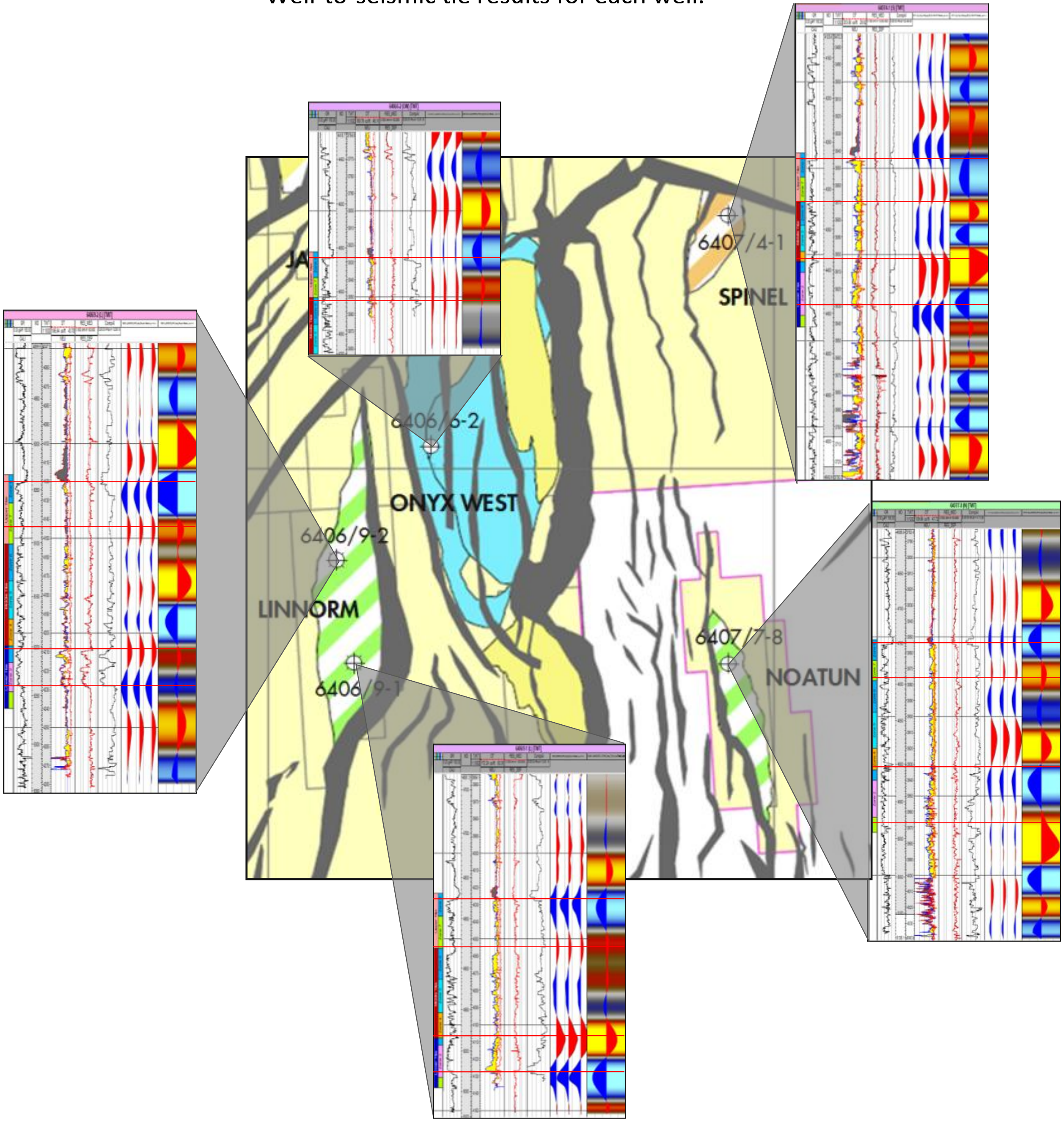
Appendix 13

Electrofacies classification of Tilje Formation in well 6406/9-2



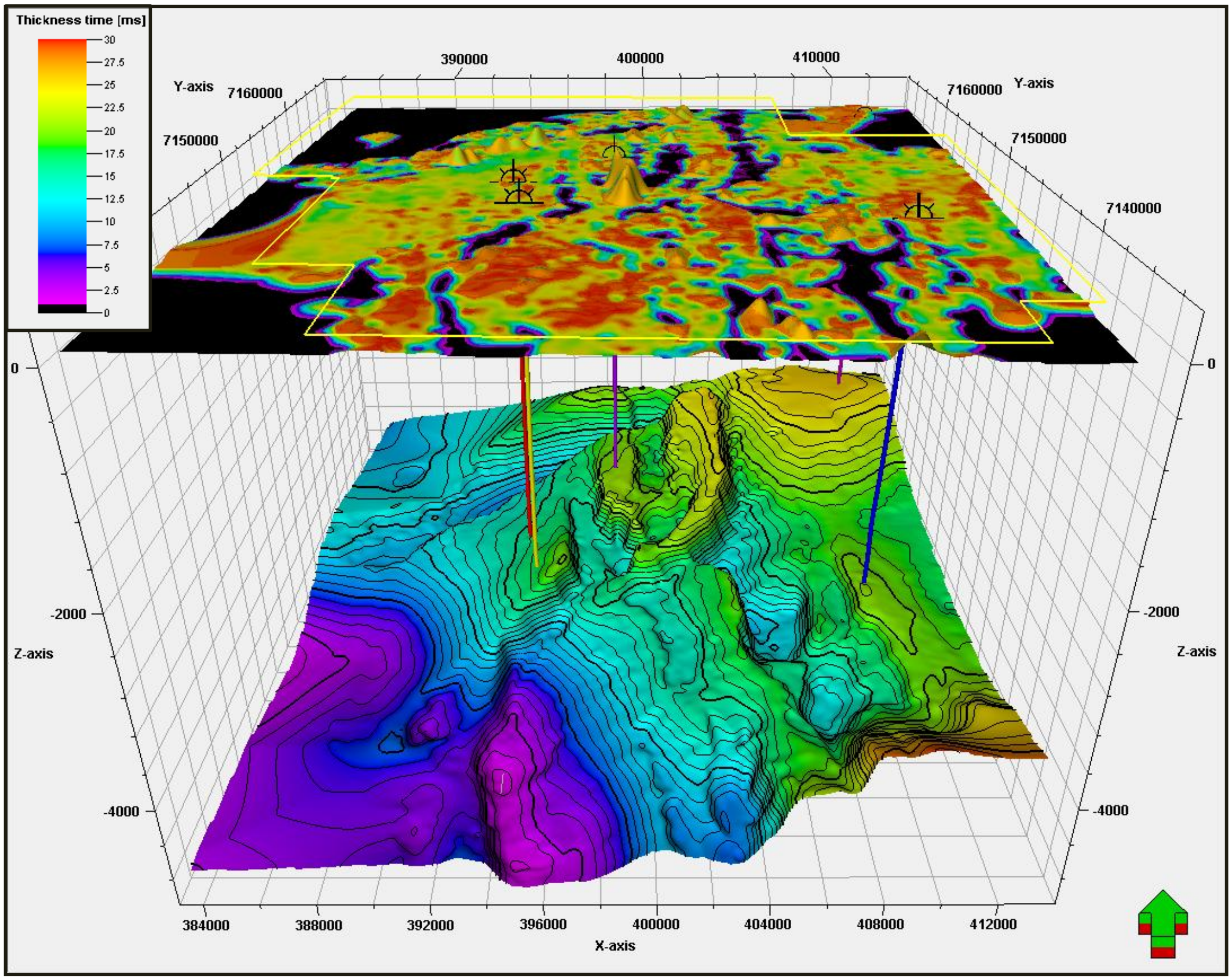
Appendix 14

Well-to-seismic tie results for each well.



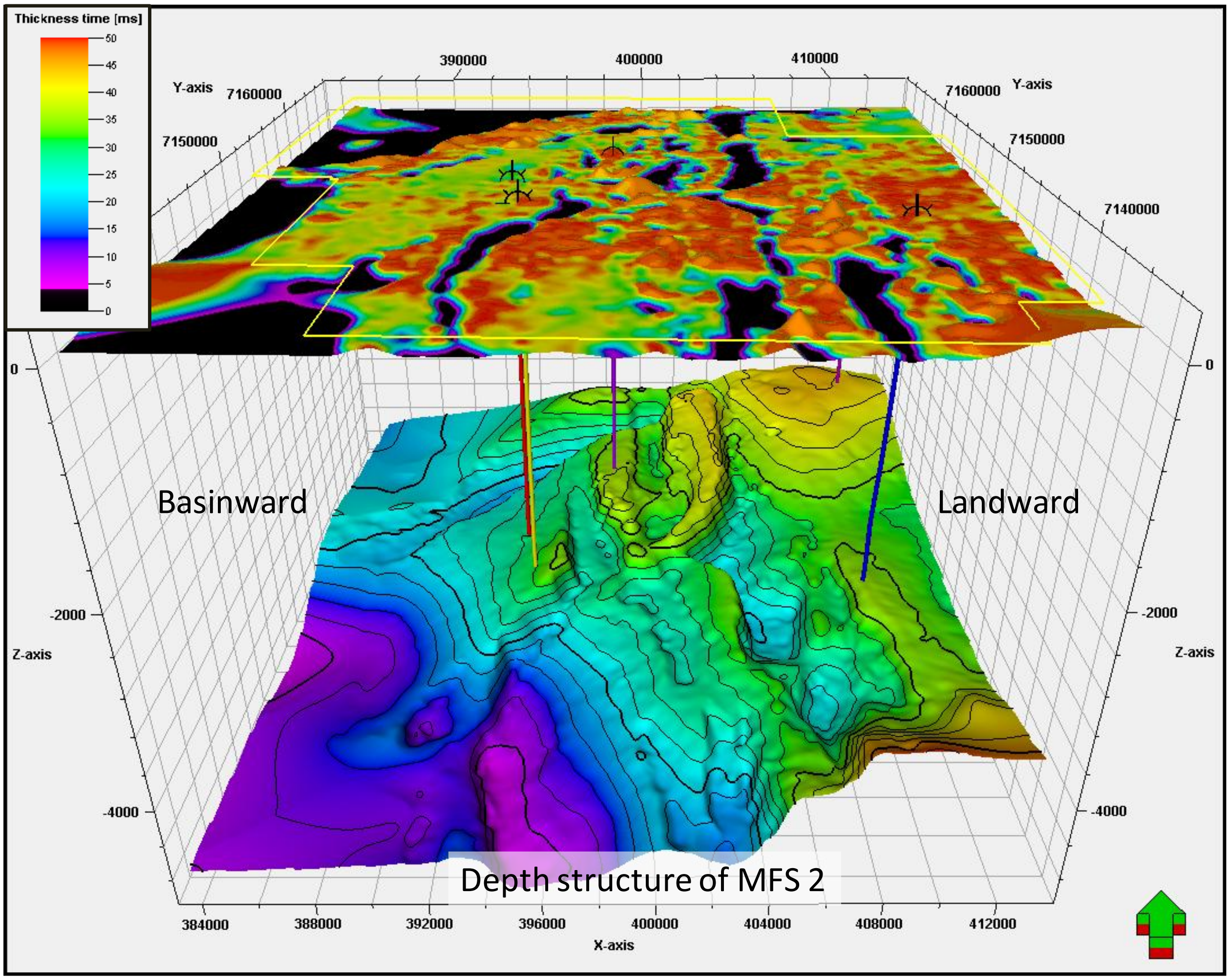
Appendix 15

Overlay between the isochore map of sequence 1 with the depth structure map of MFS 1. These maps derived from the seismic interpretation



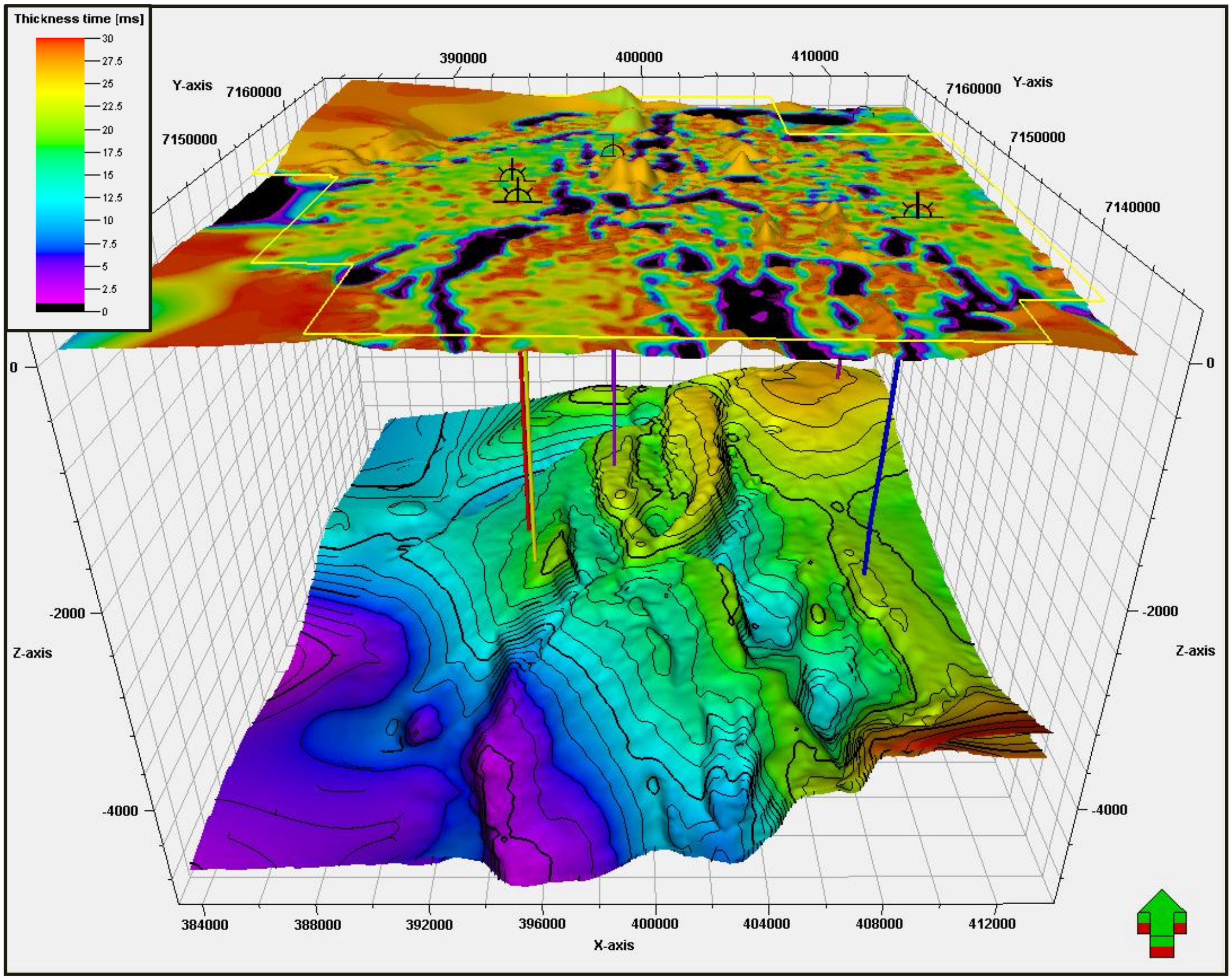
Appendix 16

Overlay between the isochore map of sequence 2 with the depth structure map of MFS 2. These maps derived from the seismic interpretation



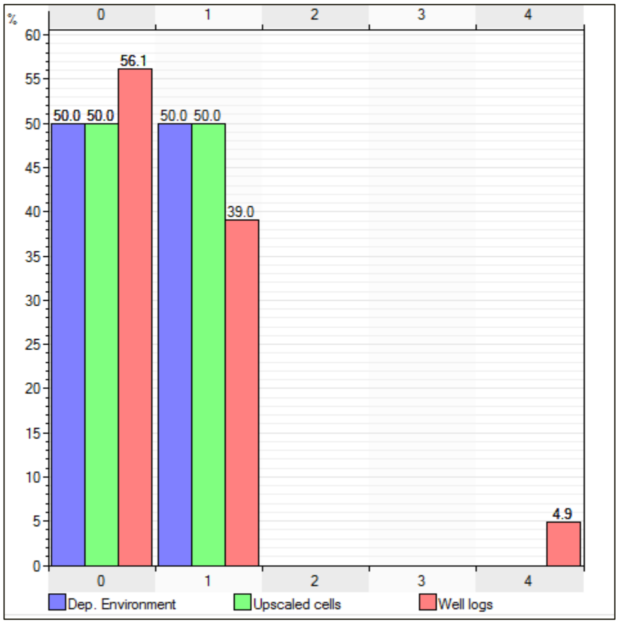
Appendix 17

Overlay between the isochore map of sequence 3 with the depth structure map of MFS 3. These maps derived from the seismic interpretation

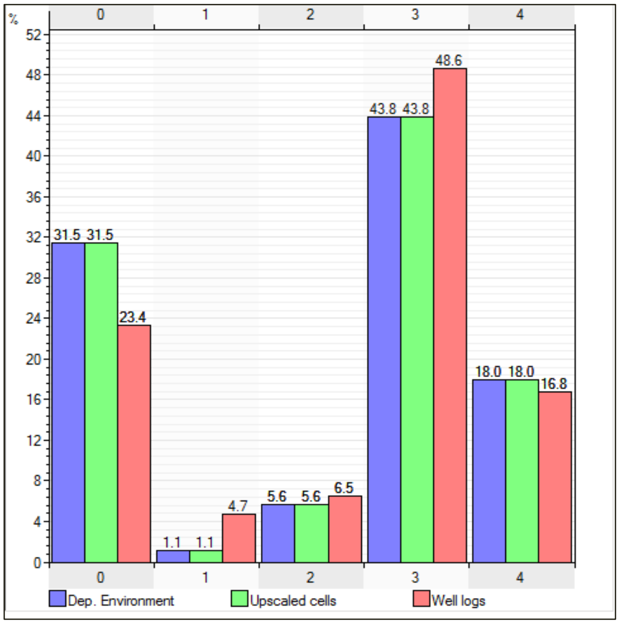


Appendix 18

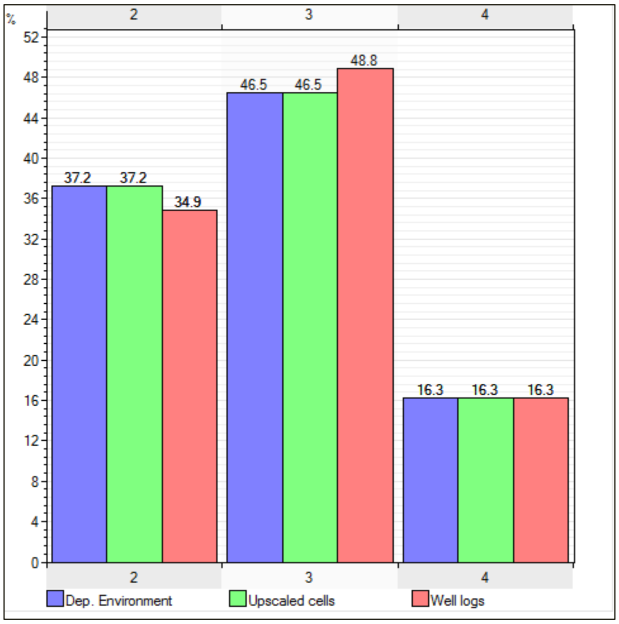
Histogram plots of percentage of facies association for the original well logs data compared with the upscaled well logs data



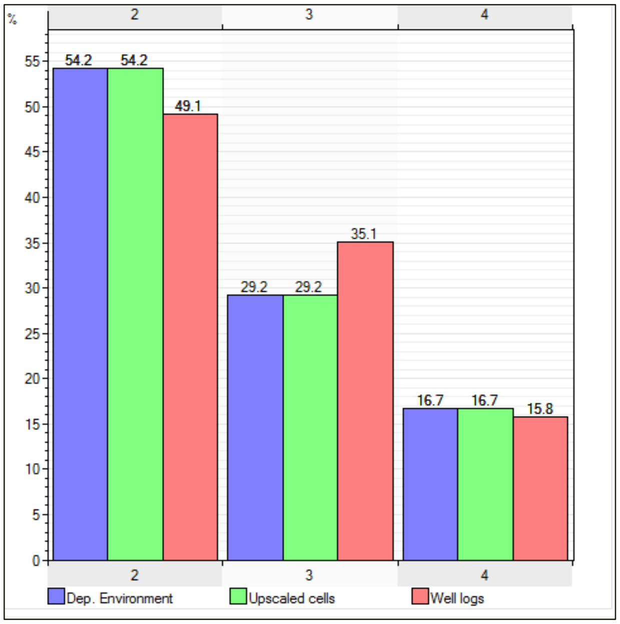
SEQUENCE 1



SEQUENCE 2 LOWER



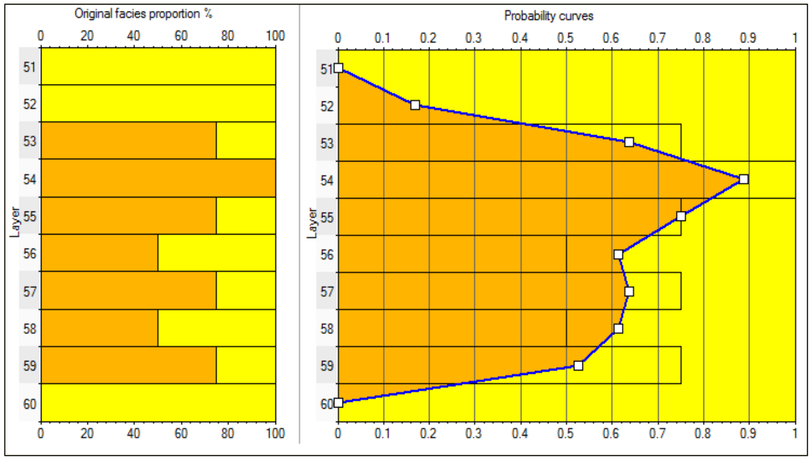
SEQUENCE 2 UPPER



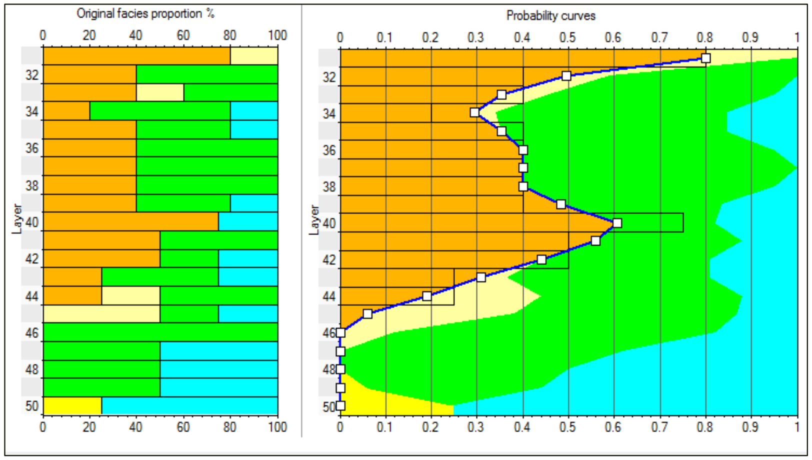
SEQUENCE 3

Appendix 19

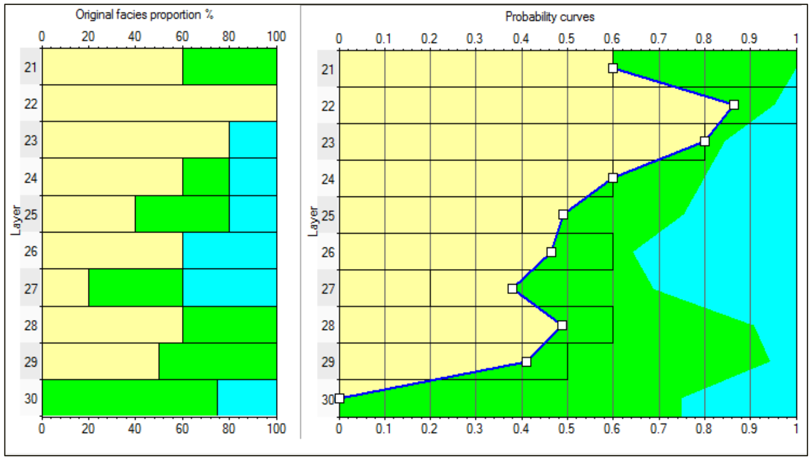
Original facies proportion and probability curves of every sequence



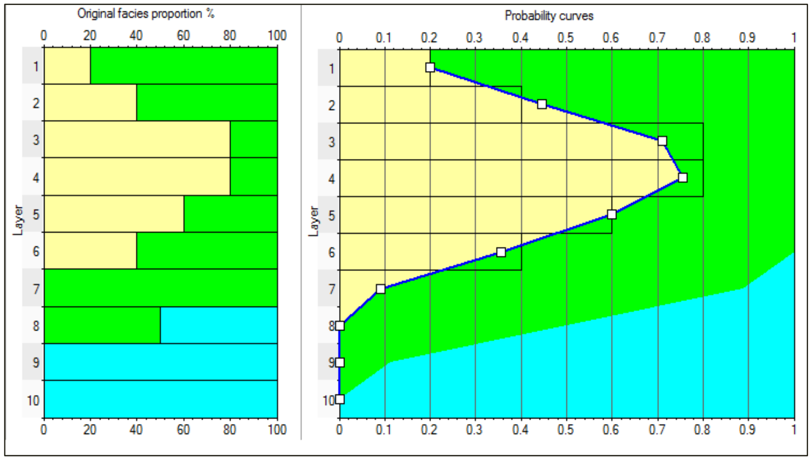
SEQUENCE 1



SEQUENCE 2 LOWER



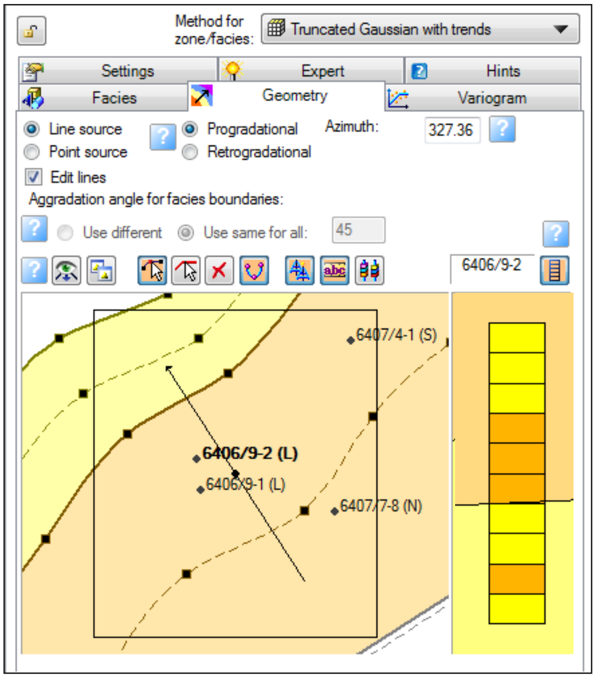
SEQUENCE 2 UPPER



SEQUENCE 3

Appendix 20

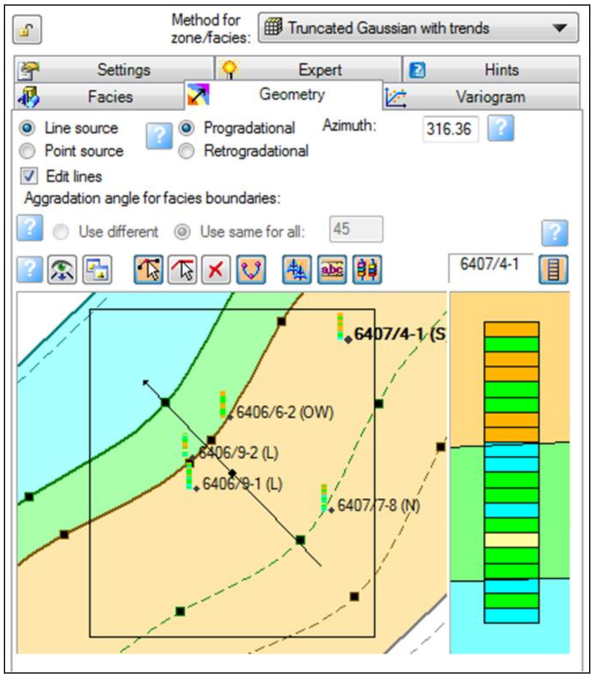
Geometry settings of each sequence, including the transition lines, trend geometry and stacking patterns.


Method for zone/facies: Truncated Gaussian with trends

● Line source
○ Point source
● Progradational
○ Retrogradational
Azimuth: 327.36
☑ Edit lines
Aggradation angle for facies boundaries:
○ Use different
● Use same for all: 45

6406/9-2

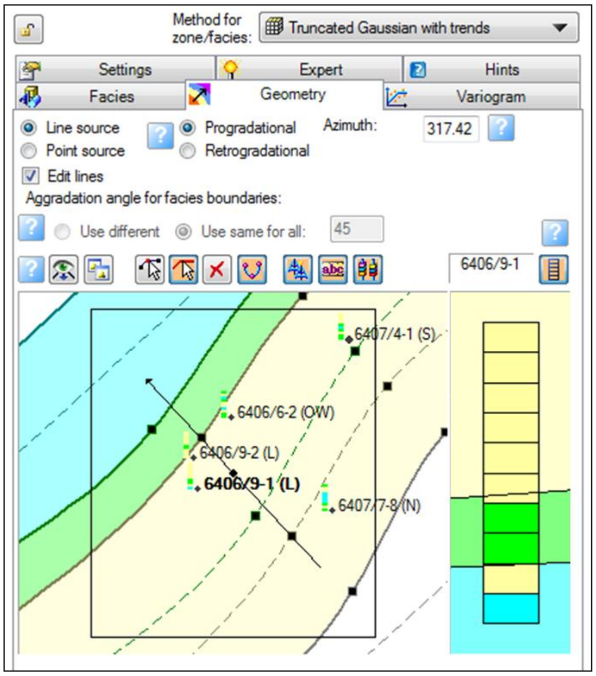
SEQUENCE 1


Method for zone/facies: Truncated Gaussian with trends

● Line source
○ Point source
● Progradational
○ Retrogradational
Azimuth: 316.36
☑ Edit lines
Aggradation angle for facies boundaries:
○ Use different
● Use same for all: 45

6407/4-1

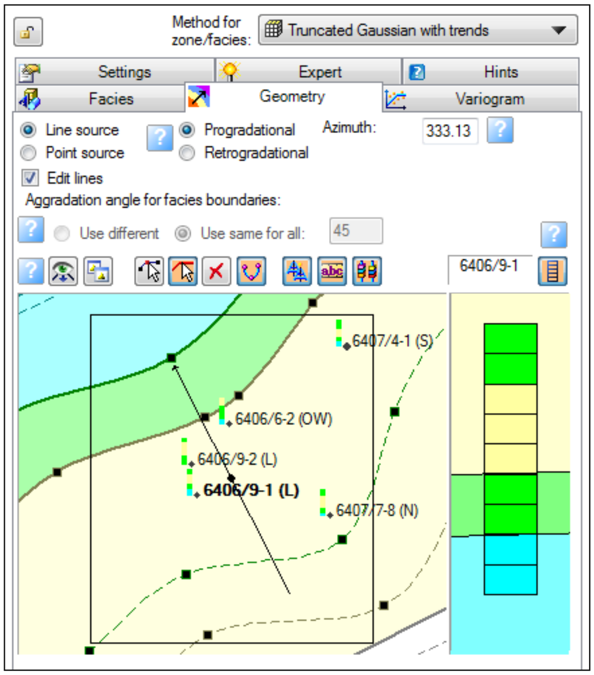
SEQUENCE 2 LOWER


Method for zone/facies: Truncated Gaussian with trends

● Line source
○ Point source
● Progradational
○ Retrogradational
Azimuth: 317.42
☑ Edit lines
Aggradation angle for facies boundaries:
○ Use different
● Use same for all: 45

6406/9-1

SEQUENCE 2 UPPER


Method for zone/facies: Truncated Gaussian with trends

● Line source
○ Point source
● Progradational
○ Retrogradational
Azimuth: 333.13
☑ Edit lines
Aggradation angle for facies boundaries:
○ Use different
● Use same for all: 45

6406/9-1

SEQUENCE 3

REFERENCES

- **Baker, E. K., Harris, P. T., Keene, J. B.** and **Short, S.A.** (1995) Patterns of sedimentation in the macrotidal Fly River delta, Papua New Guinea. In: *Tidal Signatures in Modern and Ancient Sediments* (Eds B. W. Flemming and A. Bartholoma), *IAS Spec. Publ*., 24, 193-211.
- **Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J.** and **Tørudbakken, B.** (1995) Structural Elements of the Norwegian Continental Shelf – Part II: the Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin*, **8**, 44 pp.
- **Catuneanu, O. (2006).** *Principles of sequence stratigraphy*: Elsevier Science Ltd.
- **Dalland, A., Worsley, D.,** and **Ofstad, K.** (1988) A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *Norwegian Petroleum Directorate Bulletin*, **4**, pp. 65.
- **Dalrymple, R. W.** and **Choi, K**. (2007) Morphologic and Facies trends through the fluvial-marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation: *Earth-Sci. Rev*., 81, 135–174.
- **Galli, A., Beucher, H., Le Loc'h, G., Doliguez, Group, H., 1994. The pros and cons of** the truncated Gaussian method. In: *Armstrong, M., Dowd, P.A. (eds.). Geostatistical Simulations. The Netherlands, Kluwer Academic Publishers,* 217-233
- **Gjelberg, J., Dreyer, T., Høie, A., Tjelland, T.** and **Lilleng, T.** (1987) Late Triassic to Mid-Jurassic development of the Barents and Mid-Norwegian Shelf. In: *Petreoleum geology of Northwest Europe* (Eds. J. Brooks & K. Glennie). Graham & Trotman, London, 1105-1129.
- **Heidar Malki and Jeffrey Baldwin**, "Determination of Lithofacies from Well-Logs Using Neural Networks," Journal of Engineering Technology, pp. 33-35, 1994.
- **Hill, P. R., Meulé, S.** and **Longuépée, H.** (2003) Combined flow processes and sedimentary structures on the shoreface of the wave-dominated Grande-Rivière-de-la-Baleine-delta. *J. Sed. Res*., 73, 217-226.
- **Ichaso, A.A.** and **Dalrymple, R.W.** (this volume) Eustatic, tectonic and climatic controls on anearly syn-rift mixed-energy delta, Tilje Formation (Early Jurassic, Smørbukk Field, offshore Mid-Norway).

- **Kjærefjord, J.M.** (1999) Bayfill successions in the Lower Jurassic Åre Formation, offshore Norway: sedimentology and heterogeneity based on subsurface data from the Heidrun Field and analog data from the Upper Cretaceous Neslen Formation, eastern Book Cliffs. In: *Advanced Reservoir Characterisation for the 21st Century* (Ed. T.F. Hentz), *Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Special Publication*, 19th AnnualResearch Conference, 149–157.
- **Jambo Geoconsultants, 2007.** An Ichnological-Sedimentological Assessment of the Onyx 6406/9-2 Core.
- **Journel, A.G., Ying, Z., 2001.** The theoretical links between Sequential Gaussian Simulation, Gaussian Truncated Simulation, and Probability Field Simulation. *Mathematical Geology,* 33, 31-39.
- **Marsh, N., Imber, J., Holdsworth, R.E., Brockbank, P.** and **Ringrose, P.** (2010). The structural evolution of the Halten Terrace, offshore mid-Norway: extensional fault growth and strain localization in a multi-layer brittle–ductile system. *Basin Research*, **22**, 195-214.
- **Martinius, A.W., Kaas, I., Næss, A.,Helgesen, G., Kjærefjord, J.** And **Leith., D.A.** (2001) Sedimentology of the heterolithic and tide-dominated Tilje Formation (Early Jurassic, Halten Terrace, offshore mid-Norway. In: *Sedimentary Environments Offshore Norway – Paleozoic to Recent* (Eds. O.J. Martinsen and T. Dreyer), *NPF Special Publication*, 10, 103-144.
- **Nøttvedt, A., Johannessen, E.P** and **Surlyk, F.** 2008. The Mesozoic of western Scandinavia and eastern Greenland. *Episodes*, **31**, 59-65.
- **Pascoe, R., Hooper, R., Storhaug, K.** and **Harper, H**., (1999) Evolution of extensional styles at the southern termination of the Nordaland Ridge, Mid-Norway: A response to variations in coupling above Triassic salt. In: Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference (Eds A.J. Fleet and S.A.R. Boldy), Geological Society, London, 83-90
- **Ravnås, R., Nøttvedt, A., Steel, R.J., and Windelstad, J. (2000)** Syn-rift sedimentary architectures in the northern North Sea. In: Dynamics of the Norwegian Margin (Eds.A).
- **Schlumberger, 2011**. Property Modeling Manual of Petrel 2011.

- **Serra, O., 1989,** Sedimentary environments from wireline logs, 2nd ed., Schlumberger, Dallas, Texas.
- **Serra, O. & Abbot, H. T., 1980,** The contribution of logging data to sedimentology and stratigraphy, *55th Annual Fall Meeting of AIME* (SPE 9270), Dallas, Texas.
- **Van den Berg, J. H., Boersma, J. R.** and **Van Gelder, A.** (2007) Diagnostic sedimentary structures of the fluvial-tidal transition zone – Evidence from deposits of the Rhine and Meuse. *Geol. Mijnbouw*, 86, 287-306.
- **Visser, M. J.** (1980) Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: a preliminary note. *Geology*, 8, 543-546.
- **Whitjack, M.O., Meisling, K.E.U. and Russell, L.R. (1989)** Forced folding and basement detached normal faulting in the Haltenbanken area, offshore Norway. In: *Extensional Tectonics and Stratigraphy of the North Atlantic Margins* (Eds. A.J. Tankard, A.J. and H.R. Balkwill), *AAPG Memoir*, **46**, 567-575.
- **Walker, R.G. (2006).** Facies Models Revisited: Introduction. In H.W. Posamentier & R.G. Walker (Eds.), *Facies Models Revisited*. Tulsa, Oklahoma, USA; Society for Sedimentary Geology.
- **Walther,J. (1984).** Einleitung in die Geologie als historische Wissenschaft. 3. Lithogenesis der Gegenwart: Fischer
- **Watnet, W.L., *et al*.,** Petrofacies Analysis – A petrophysical tool for geologic/engineering reservoir characterization, 1999, in R.Schatzinger and J.Jordan, eds., *Reservoir Characterization – Recent Advances, AAPG Memoir* 71, p 73-90.
- **Yang, B. C., Dalrymple, R. W.** and **Chun, S. S**. (2005) Sedimentation on a wave-dominated, open-coast tidal flat, south western Korea: summer tidal flat – winter shoreface. *Sedimentology*, 52, 235-252.