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MASTER'S THESIS

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Abstract

Norsel High is located in the southeastern part of the Bjarmeland Platform area, close to the southwestern margin of the Nordkapp Basin. There is one well located on Norsel High, exploration well 7226/11-1. The Lower Triassic, the Havert Formation, is very deeply buried and seems to be a prograding tide – dominated delta system, which very often have poor or challenging reservoir qualities, and therefore has been a bit challenging.

The Havert Formation has been interpreted to be dominated by mixed – influenced delta systems with impacts from fluvial input, tidal action and drift currents. This interpretation is based on different sets of data. These different dataset are core description, detailed well interpretation, 2D – and 3D seismic interpretation. The first dataset is the core description of the Havert Formation from three core samples, combined with the second dataset, a detailed well interpretation, which has been interpreted in sequences and depositional environments. The third dataset is seismic interpretation, comprising of both 2D and 3D seismic interpretation. Integrating these datasets gives the Havert Formation a thorough interpretation.

The main goal for this study is to provide a better understanding of the Lower Triassic on Norsel High, focusing on the stratigraphic and tectonostratigraphic evolution of the Lower Triassic basin-fill.

Acknowledgments

I would like to thank my supervisor Rodmar Ravnås. This thesis would not have been possible without his knowledge and excellent guidance. Writing this thesis has been a great experience, and I thank Rodmar for all he has taught me throughout this challenge.

Furthermore I would like to thank A/S Norske Shell for providing me access to core data and 2D seismic needed for this thesis. I would also like to thank the University of Stavanger for providing me with 3D data and facilities throughout the thesis period.

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1. Introduction

1.1 Aim of study

The aim of this study will focus on resolving the stratigraphic and tectonostratigraphic evolution of the Lower Triassic basin-fill on the Norsel High and northeastern margin of the Nordkapp Basin. The Lower Triassic is an interesting section of the Norsel High, where there is located a gas-discovery in the Havert Formation. The Havert Formation has been a bit challenging because of it is so deeply buried. The Formation has seems to be prograding tide-dominated deltas, which very often have challenging reservoir qualities. The aim of this study will be to reveal a better understanding over this area, by interpreting and integrating different set of data, such as core, well and seismic data.

1.2 Objectives

The datasets that will be used for this thesis will be core data, well data, 2D – and 3D – seismic. The integration of these datasets that are available for the westward area of the Norsel High location, this will be an approach to achieve a better understanding of the stratigraphic and tectonostratigraphic evolution of the Lower Triassic basin-fill on the Norsel High and northeastern margin of the Nordkapp Basin.

1.3 Previous Work

There have been no previously studies about the Lower Triassic of the Barents Sea.

1.4 Deliverables

- A core description of the Havert Formation from three core samples of the Norsel Well 7226/11-1 on Norsel High
- Detailed well interpretation, interpreted in sequences and depositional environments
- 2D seismic interpretation giving a seismic semi – regional 2D grid
- 3D seismic interpretation used for the structural identification giving a seismic facies classification of Havert Formation clinoform system and a amplitude analysis of depositional – geometries
- Integrated conceptual geological model for the evolution of the Havert Formation on the Norsel High.

2. Geological framework

2.1 Study area

Norsel High is located in the southeastern part of the Bjarmeland Platform area, close to the southwestern margin of the Nordkapp Basin (Directorate), see Figure 1. Norsel is a high, a quite long extensive high, which was formed pre – Triassic, from late Carboniferous, possibly older and developed through time. Norsel High lies next to the Nordkapp Basin and therefore may be developed as a response to the basin. Norsel High is the study area for this thesis with one well located on the area, exploration well 7226/11-1. The Triassic package on Norsel High is very thick and the reservoir has been located in the Upper Triassic. The Lower Triassic has been a bit challenging; because of it is very deeply buried and it seems to be prograding tide-dominated deltas, which very often have poor or challenging reservoir qualities. Therefore the Lower Triassic will be the main focus. Norsel High is located in a deltaic environment, going from a pro-delta to the main delta environment in the Lower Triassic. The Havert Formation, which has the age of Lower Triassic, will therefore be the main attention area. The Havert Formation has been interpreted as wave-dominated deposits, but by looking at the core data it seems to be more like gravity flow deposits. East of Norsel High the area is different. Here the Lower Triassic packages are thick and the basin seems to have been filled in the Early Triassic, because of these thick Lower Triassic packages. Middle and Upper Triassic are thin and therefore this will be a part of a system that seems to be mainly deltaic further west and move in a more fluvial environment towards the east.

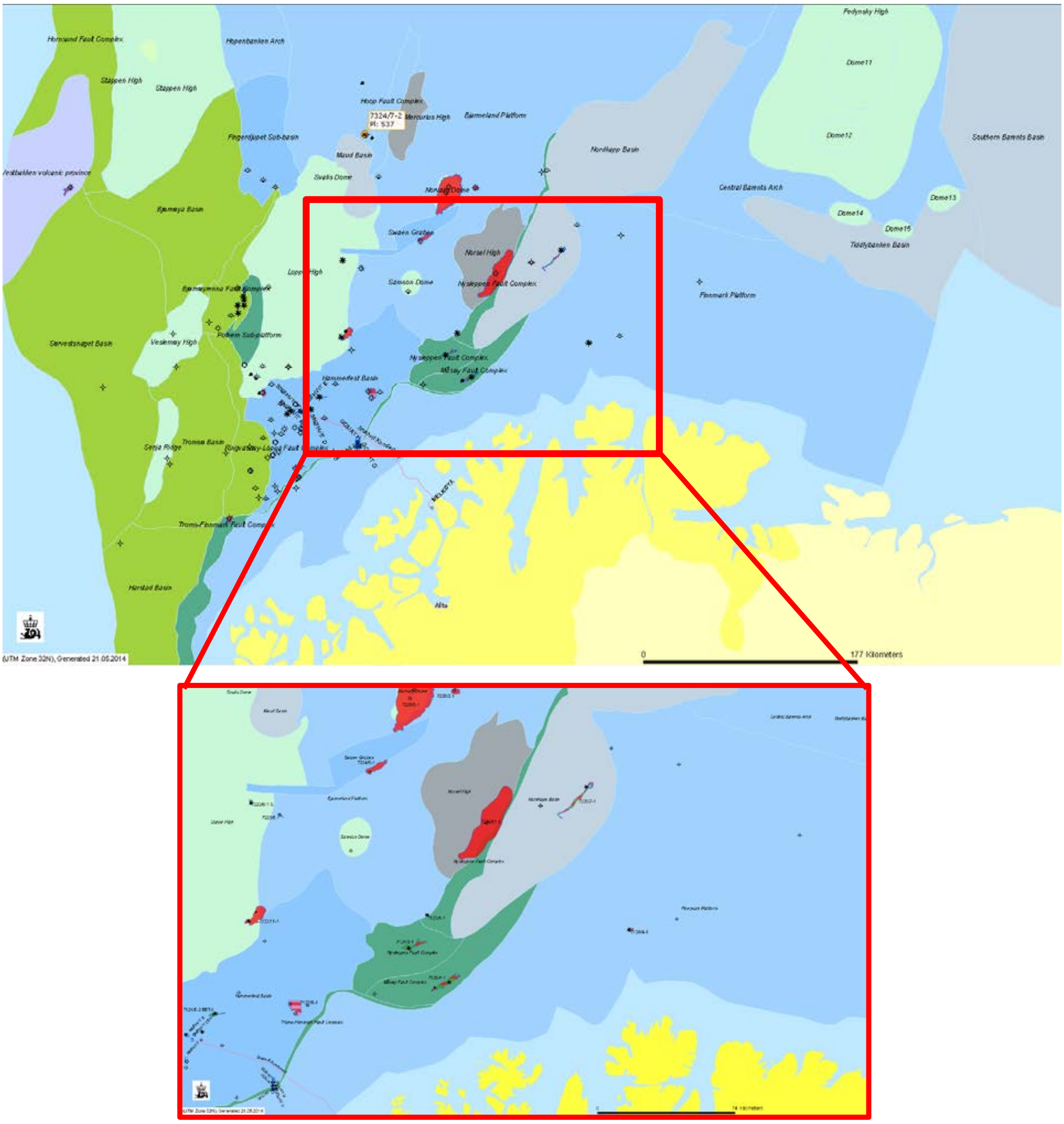


Figure 1 Location map, with structural elements, of the Barents Sea and zoomed in on Norsel High, (Directorate)

2.2 Regional geology

2.2.1 The greater Barents Sea

The greater Barents Sea has its boundaries comprises the shelf area between Norway and Svalbard in the west and the eastern boundary is defined by Novaya Zelma (Henriksen, Ryseth et al. 2011). The Barents Sea today, located in the north, a large flat shelf, which through time has gone through an intra-cratonic basin, which is composed of rift basin in the west, Svalbard, and Novaya Zelma in the east and the Barents Sea in the deep located in between. Crustal extension in the Late Paleozoic let to the developments of half grabens and, later, a regional sag basin which covers a major part of the current Barents Shelf (Henriksen, Ryseth et al. 2011). The Barents Sea is located there as a basin, where is post – Caledonian the Barents sea have been a platform shelf/passive margin to a part of a intra – cratonic foreland basin in the east and a platform which seems to have been uplifted in late Triassic to early Jurassic, which again sinks in and some more rifting in late Jurassic. During the Devonian a subsequent uplift took place to the east, included by the onset of the Uralide Orogeny, and the Carboniferous – Permian plate collision let to a pronounced change in basin physiography in late Paleozoic to Early Triassic times (Henriksen, Ryseth et al. 2011). Throughout time, the focus of extensional tectonics has shifted westward towards the Atlantic rift system, so that in the Hammerfest Basin and generally along the western margin the Middle to Late Jurassic rifting is prominent (Henriksen, Ryseth et al. 2011). From late Devonian to Middle Jurassic times paleogeographic reconstruction can be related to two main phases of orogenic uplift and denudation: first, the Paleozoic Caledonian orogeny created topography to the west, and drainage into marine environments to the east during Devonian – Carboniferous times; and second, Late Permian – Early Triassic uplift to the east (Uralides) combined with the development of an Atlantic rift system to the west reserved the sediment distribution pattern, with a strong sediment flux from the east particularly during the Triassic times (Henriksen, Ryseth et al. 2011).

2.2.2 The Triassic period

As mentioned above, throughout time the Barents Sea has gone through an intra-cratonic basin complex of rift basin, Svalbard, in the west and Novaya Zelma in the east, where the Barents Sea is the deep in between, located there as a big basin. Post-Caledonian the Barents Sea have gone from being a platform shelf /passive margin to being a part of an intra-cratonic foreland basin in the east and a platform development which seems to have been uplifted in late Triassic. During the Triassic the Barents Sea area was a wide epicontinental seaway covering the continental shelf of northwestern Eurasion and the northwest Barents Sea was a part of the regional basin (Glørstad-Clark, Faleide et al. 2010). Marking the Late Permian – Early Triassic is a significant extensional event, contributing to Triassic subsidence, with deposition of approximately 4-7 km of Triassic strata (Henriksen, Ryseth et al. 2011).

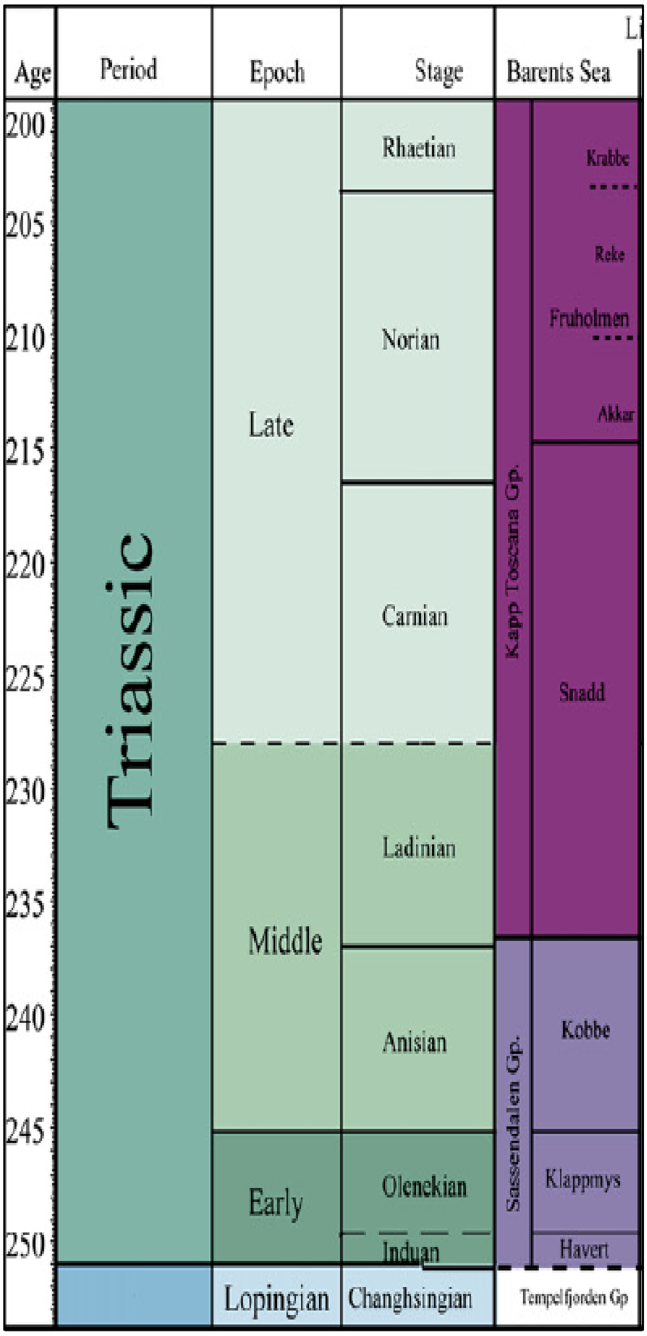


Figure 2 Geological time scale of the Triassic Period (Glørstad-Clark, Faleide et al. 2010)

Triassic deposition was hugely influenced by the erosion of sediment source areas to the southeast, assumed to be primarily from the Uralian Mountains (Glørstad-Clark, Faleide et al. 2010). According to Glørstad-Clark, resent work in the northern Barents Sea demonstrated the development of seismic prograding clinoforms from the east and southeast throughout the Triassic, indicating a continuous shallow shelf area with shelfal to paralic deposition from main Svalbard Archipelago in the north to the southern Barents Sea.

The Induan – Early Norian succession shows a total thickness in excess of 2500 m, which comprises of the four lithostratigraphic formations, Havert, Klappmyss, Kobbe and Snadd. With the formation boundaries picked at inferred maximum flooding events, each of these formations can be related to regional regressive – transgressive cycles. As such they can be seen as genetic stratigraphic units (Henriksen, Ryseth et al. 2011). The Triassic intervals is characterized by large – scale clinoforms on seismic data and the oldest clinothems from the Norwegian sector, and show several phases of northwards progradation. Throughout the Early – Late Triassic the predominant progradation path is from southeast to northwest (Henriksen, Ryseth et al. 2011). The Havert Formation constitutes the first of these large – scale clinoform systems of the Triassic interval.

2.2.3 The Havert Formation

Post-Caledonian the Barents Sea have gone from being a platform shelf /passive margin to being a part of an intra-cratonic foreland basin in the east and a platform development which seems to have been uplifted in late Triassic. The Triassic intervals is characterized by large – scale clinoforms on seismic data and the oldest clinothems from the Norwegian sector, and show several phases of northwards progradation. The Havert Formation constitutes the first of these large – scale clinoform systems of the Triassic interval. The Havert Formation ranges from base with the age of Early Induan to the top of the Havert Formation with the age of Olenekian (Henriksen, Ryseth et al. 2011). According to the Norwegian petroleum directorate the Havert formation in the well 7226/11-1 located on Norsel High is located at the depth 2913 m – 3877 m, a 964 m thick formation (Directorate). According to the article Henriksen, Ryseth et al. 2011, the cored section of the Havert Formation comprises fine-grained, micaceous sandstone and associated mudrock that are related to deposition in the offshore to marginal marine environments of a wave-dominated shoreline and in associated distributary channel and/or inlets (Henriksen, Ryseth et al. 2011). The Havert Formation has been interpreted to belong to a broad costal embayment, which passed offshore into more of a shelfal sub-environment as its depositional environment, and has been divided into four recurring facies associations, bay margin sands, bay margin heteroliths, bay floor muds and heterolithic shelf. The bay margin sandstone is dominated by planar stratification and hummocky – cross-stratification were deposited in areas subject to high wave-energy in a shallow mater, marginal part of this embayment. Whilst in marginal areas with slightly lower wave-energy bay margin heteroliths were deposited. Within slightly deeper, central parts of the embayment, below fair-weather wave base, bay floor muds were deposited. These deposits mostly comprise pinstriped to lenticular-bedded and rippled siltstones with a low diversity, marginal marine trace fossil assemblage. The Havert Formation displays more of a shelfal signature in distal settings of cored intervals with storm-emplaced sandstone beds. This is how the Havert Formation has previously been interpreted, following in chapter 4 Facies association and description, there will be discussed the possibility of an alternative interpretation.

3. Dataset and methodology

This thesis is based on the following data:

- Core data
- Well data
- Seismic data, consisting of 2D and 3D seismic data.

The dataset was provided by A/S Norske Shell and consists of core data, well data and 2D seismic data. 3D seismic data was provided by the University of Stavanger.

3.1 Core data

Core data comprises of three cores taken from the Norsel well 7226/11-1. The cores are; core #5, core #6 and core #7, which are all cores representing the Havert Formation with the age of Lower Triassic. Core #5 is taken from the depth interval 2951.0 m – 2958.0 m. Core #6 is taken from the depth interval 3057.0 m – 3084.0 m and is the longest core interval. Core #7 is taken from the depth interval 3236.0 m – 3240.0 m.

3.2 Well data

Well data comprises of the Norsel well (7226/11-1) that was used for detailed reservoir study. Norsel well is located on the Norsel High, close to the southwestern margin of the Nordkapp Basin, in the southeastern part of the Bjarmeland Platform area (Directorate). For a more regional study two more wells (7225/3-1 and 7128/4-1) were added.

3.3 Seismic data

Seismic data provided for this thesis consists of both 2D and 3D seismic data. The 2D projects consist of interpretation of four lines. These lines stretch from north to south and east to west. Line 1 is 201.7 km and goes from NE to SW and crosses the Norsel well. Line 2 stretches from E to W, and is 116.5 km long. The third line is 108 km long and has its orientation from north to south. The fourth line is 176 km long and goes from N to S. The 2D seismic interpretation is mainly for the regional setting. The 3D seismic interpretation will be used for the structural identification, giving a seismic facies classification of the Havert Formation clinoform system and an amplitude analysis of the depositional – geometries. The 3D seismic consists of a 227 km^2 large survey (ST0828).

3.4 Sequence stratigraphy and clinoform analysis

Sequence stratigraphy analysis of the Havert Formation was conducted to ensure a more solid correlation of depositional package to develop a more detailed framework for the depositional environment within the formation. The interpretation is based on tectonic sequences, genetic sequences and para-sequences. Hierarchical subdivision based on duration of the cycle. The sedimentary record throughout all of the geologic history is characterized by stratigraphic cycles of different orders of magnitude, both in terms of thickness, duration and regional extent. For this interpretation third, fourth and fifth order of Hierarchical subdivision is used. Third order eustatic cycles, this is the change in volume of ocean basins also known as tectono-eustasy. Tectono-eustasy is unable to account for all of the 3^{rd} order cycles in the stratigraphic record, because these cycles demand faster rate. Thus, the origin and control of 3^{rd} order cycles remain problematic. The relative sea level 4^{th} order is the genetic sequence. Genetic sequence was defined by Galloway as “A type of sequence bounded by maximum flooding surface (MFS)” (Galloway 1989). Parasequence which is the 5^{th} order sequence is defined as “a relatively conformable succession of genetically related beds or bedsets bounded by marine – flooding surfaces or their correlative surfaces” (Van Wagoner, Mitchum et al. 1990). The conventional sequence stratigraphic analysis is done in the well data, combined with a clinoform analysis on the seismic stratigraphic analysis.

3.5 Methodology

As the first step core interpretation was conducted. The three cores representing the Lower Triassic of the Norsel well have been interpreted to identify and characterize reservoir scale depositional elements and facies associations within the Norsel well 7226/11-1. The second step was a detailed well interpretation, where the well will be interpreted in sequences, and depositional environments. The interpretation of the sequence development, the recognition of sequence stratigraphic surfaces is based on gamma-ray log, and the combination of neutron and density log. The third and final step was the seismic interpretation. 2D seismic interpretation giving a seismic semi-regional 2D-grip by interpreting four 2D lines and on each line the five horizons Kobbe FM, Klappmyss FM, Havert FM, Ørret FM and Røye FM. 2D seismic interpretation was also concentrated to the Havert FM, interpreting the Havert FM clinoform system. 3D seismic interpretation used for the structural identification giving a seismic facies classification of Havert FM clinoform system and an amplitude analysis of depositional – geometries. The final step also consists of creating geological models of the clinoform system and depositional – geometries using the amplitude analysis. Integration of the different data sets, conventional sequence stratigraphy, seismic stratigraphy, seismic facies analysis, seismic amplitude, clinoform analysis tied up to the well, by the use of local data, 3D and regional data, 2D and wells to place Norsel High in a regional context. Creating integrated conceptual geological models.

4. Facies description and interpretation

4.1 Introduction

The Havert Formation consists of a 964m thick formation, with a gross depositional setting of mixed influenced delta system. Where on the log, several appearances of this depositional setting is located, GR log response 3 with facies element fluvial/distributary channel, tide and wave influenced delta, see table 4, and a sequence stratigraphic framework of progradation with possible erosive surfaces. The core intervals are divided in three cores, core #5 5 is taken from the depth interval 2951.0 m – 2958.0 m. Core #6 is taken from the depth interval 3057.0 m – 3084.0 m and is the longest core interval. Core #7 is taken from the depth interval 3236.0 m – 3240.0 m. The main approaches for this chapter are to define facies associations based on the three cores, generalized classification of facies associations based on well log response and log interpretation, which will give an overall gross depositional environment and trends in cores of the Havert Formation.

4.2 Core description

The core description is a detailed interpretation of the three cores taken for the Norsel exploration well, 7226/11-1. The interpretation consists of a column displaying which meter of the core is being interpreted, a second column with lithology and a third column with a log description based on grain size. Some of the cores representing the main facies associations have been enlarged from the lithology column and the core picture are presented.

Figure 3 to Figure 7 displays a log description of the three cores taken from the Norsel well, where pictures of cores representing different facies associations are dragged out. Figure 8, Figure 9 and Figure 10 are the hand-drawn core description, also with pictures of cores representing different facies associations are dragged out, The pictures are taken from the NPD’s webpages (Directorate). Figure 11, Figure 12 and Figure 13 are the core pictures taken from the NPD’s webpage, where the red boxes indicate which core has been dragged out from the core descriptions.

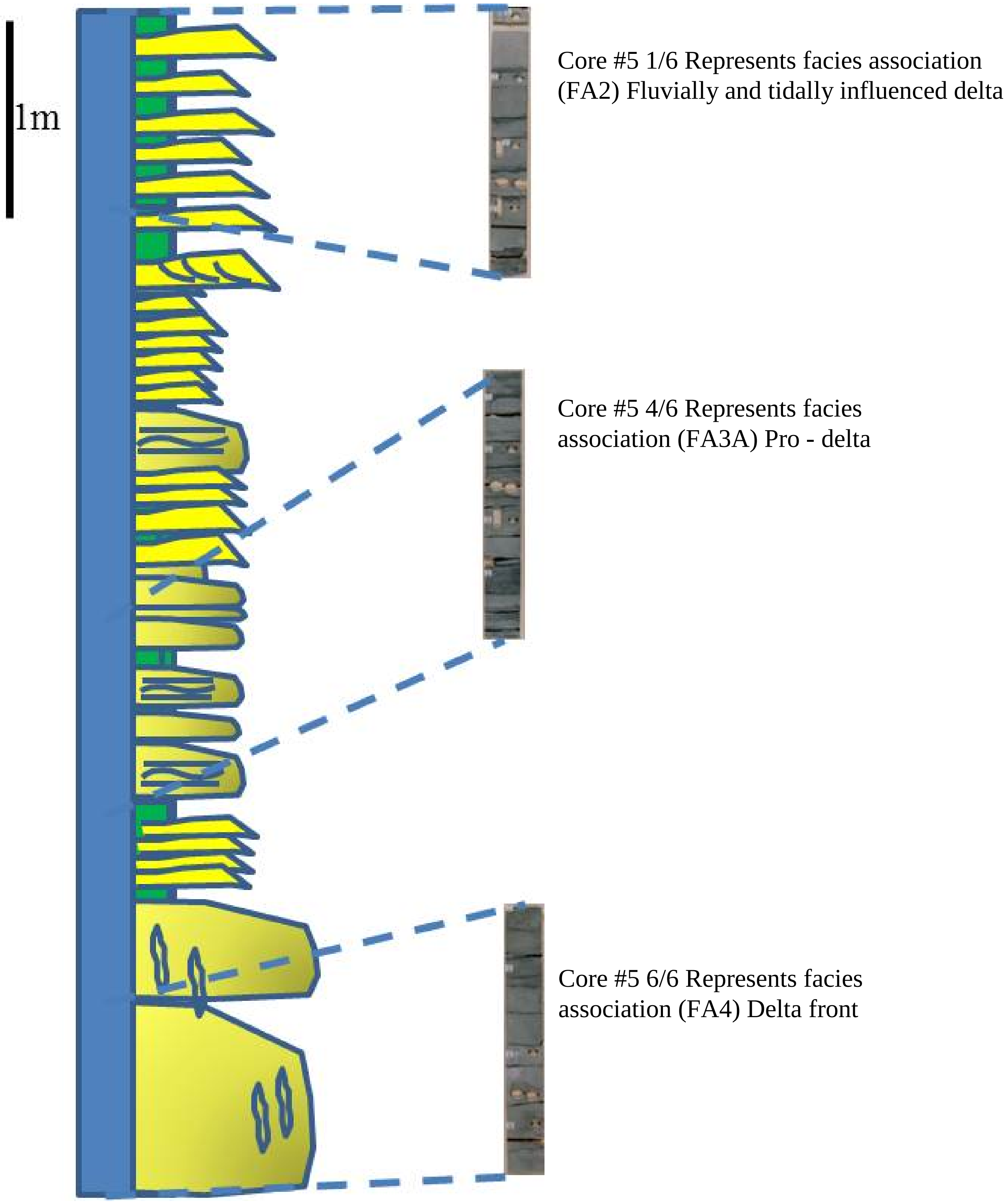


Figure 3 Core description of core #5

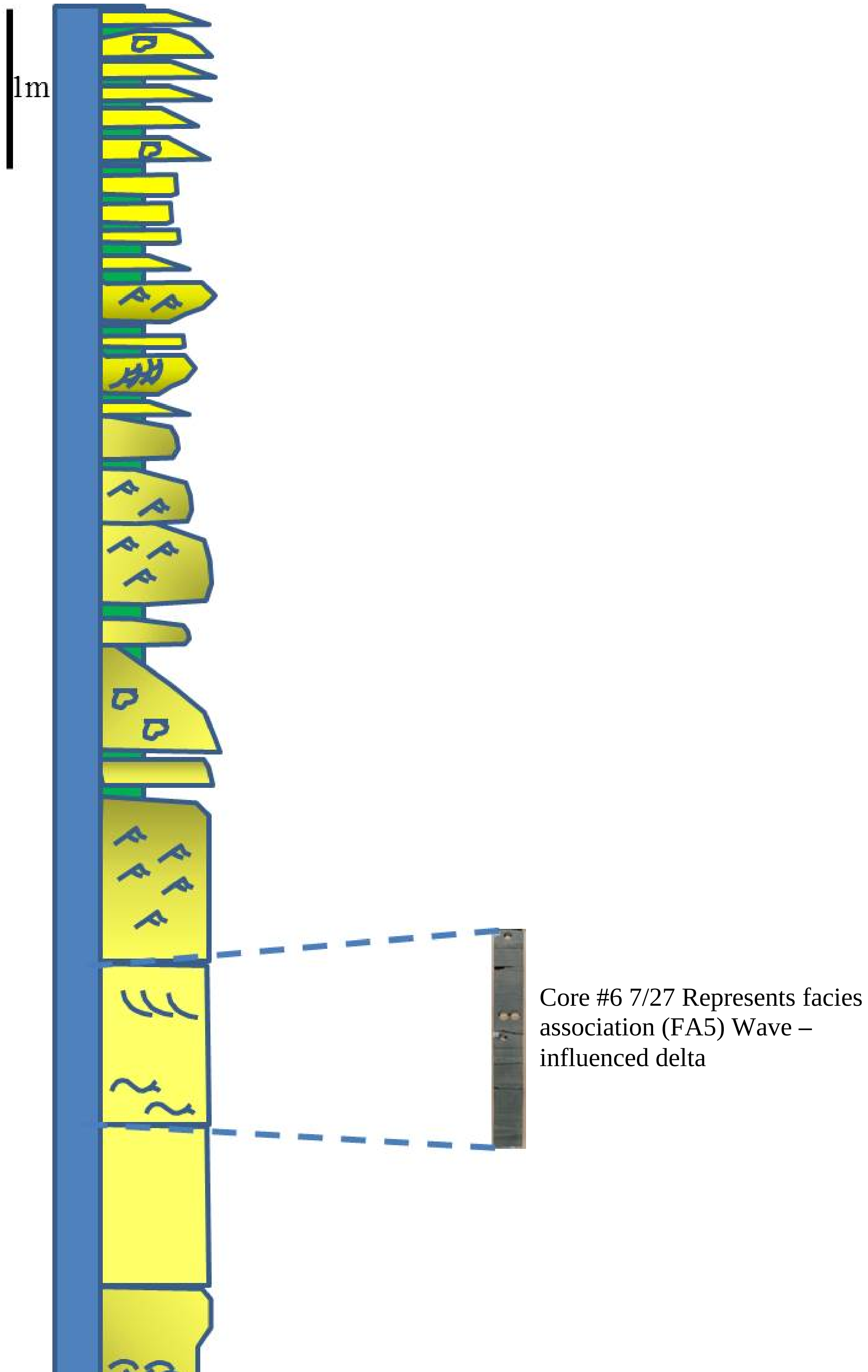


Figure 4 Core description of core #6 – part 1

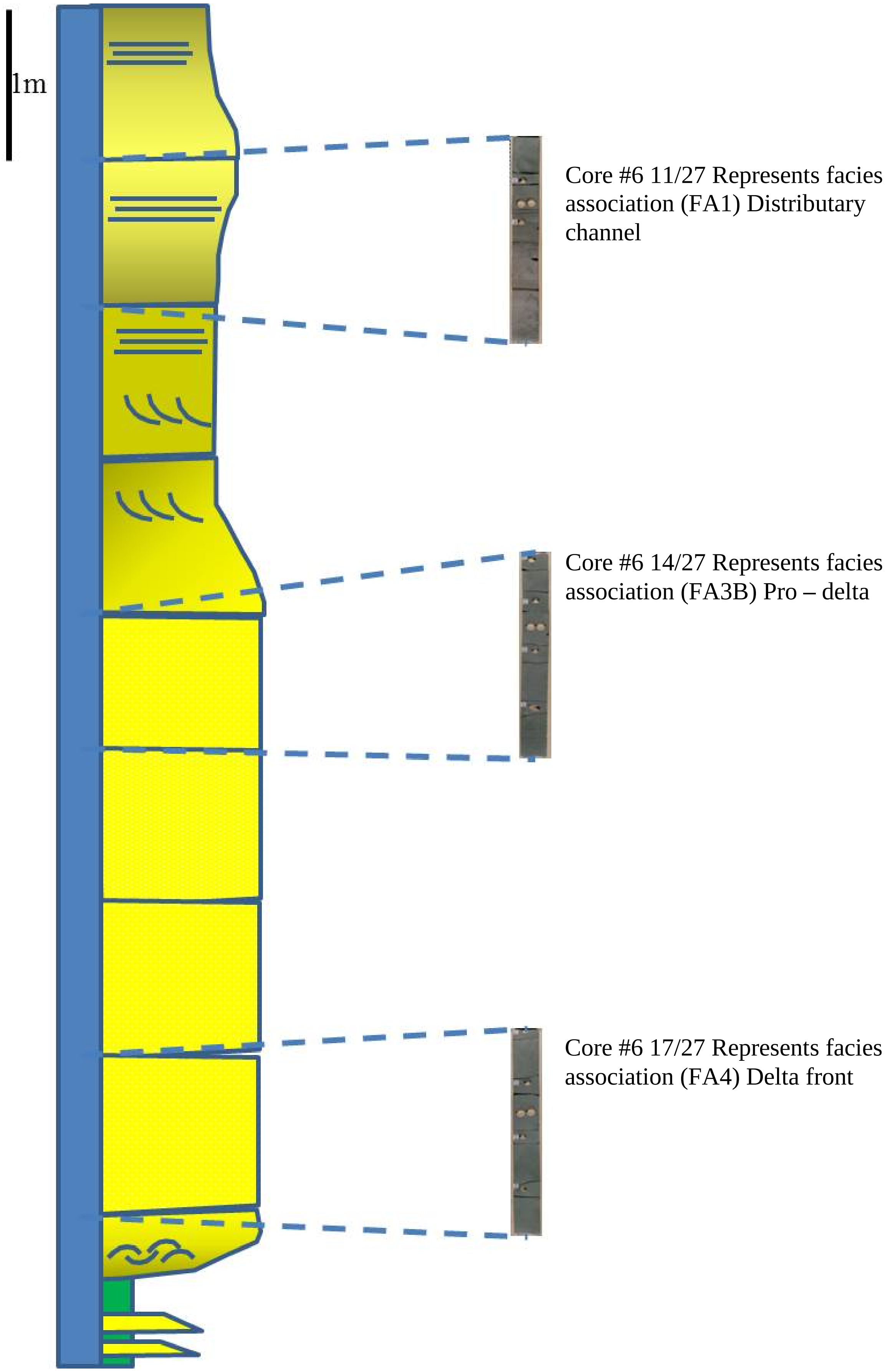


Figure 5 Core description of core #6 – part 2

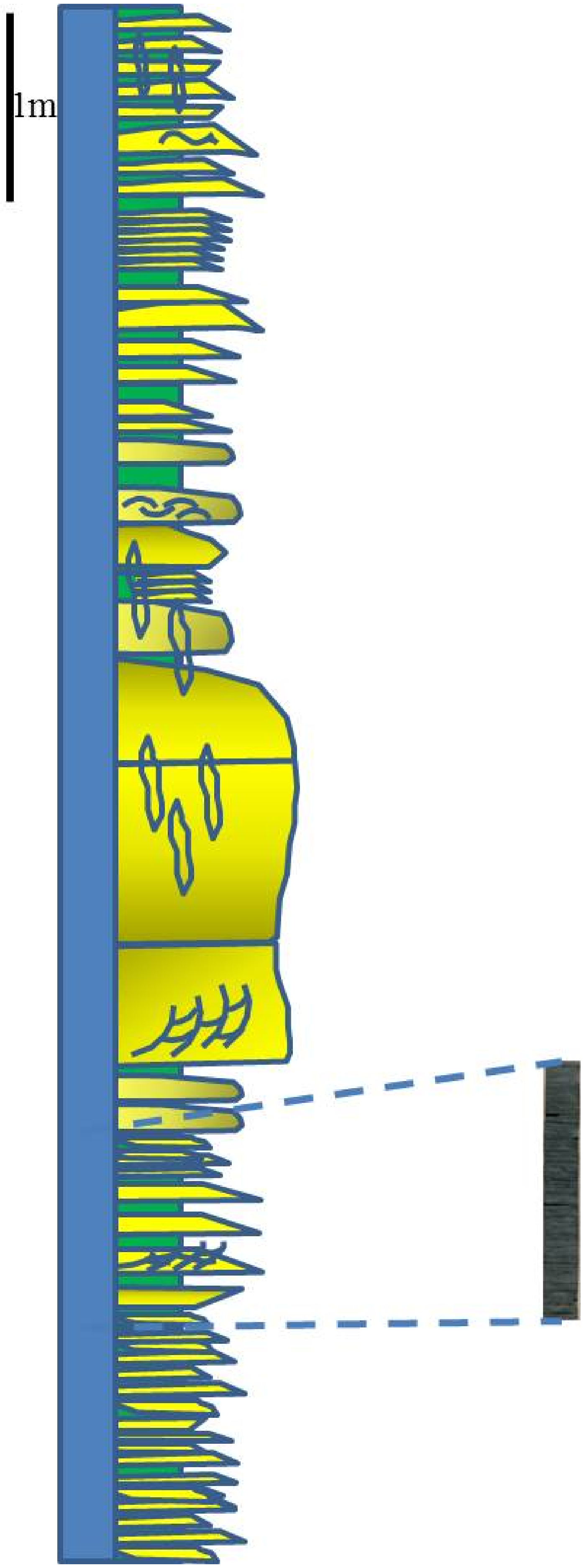
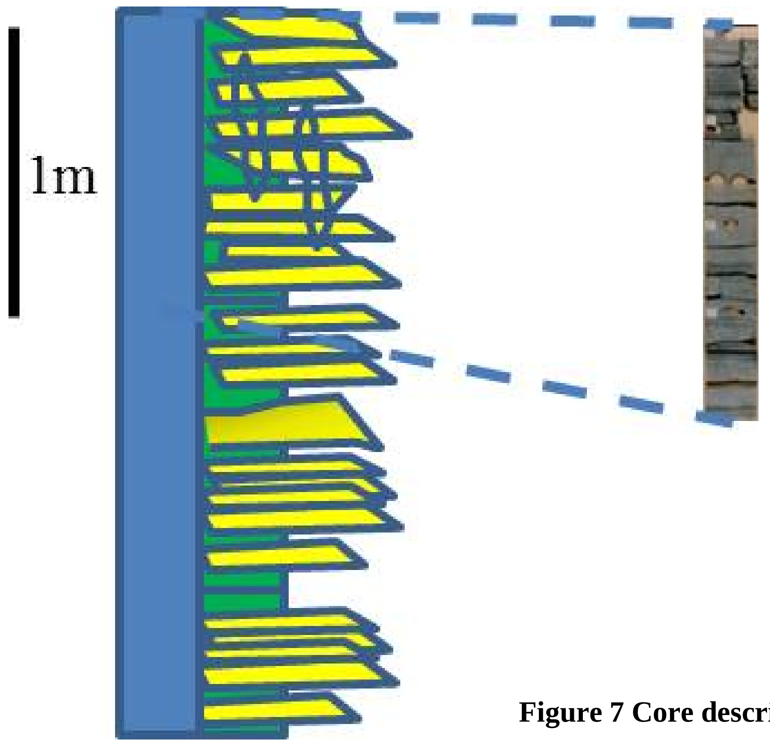


Figure 6 Core description of core #6 – part 3



Core #7 2/3 Represents facies association (FA2) Fluvially and tidally influenced delta

Figure 7 Core description of core #7

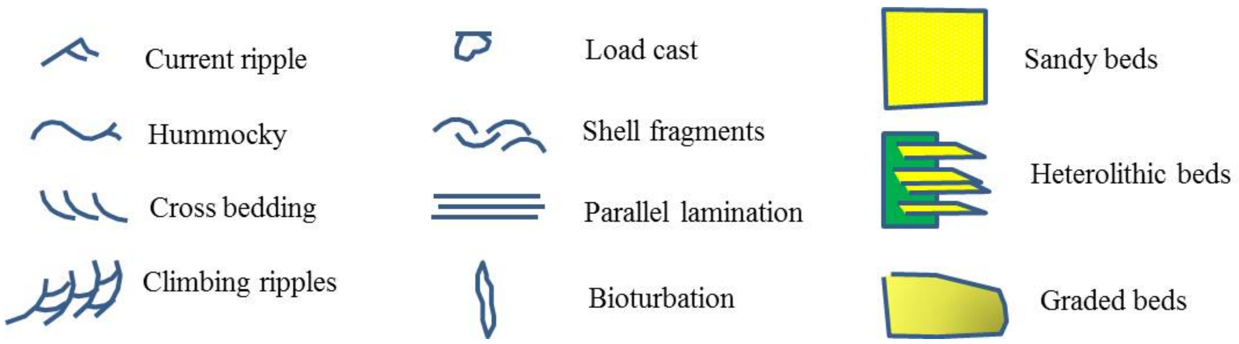


Figure 8 Legend for the core description

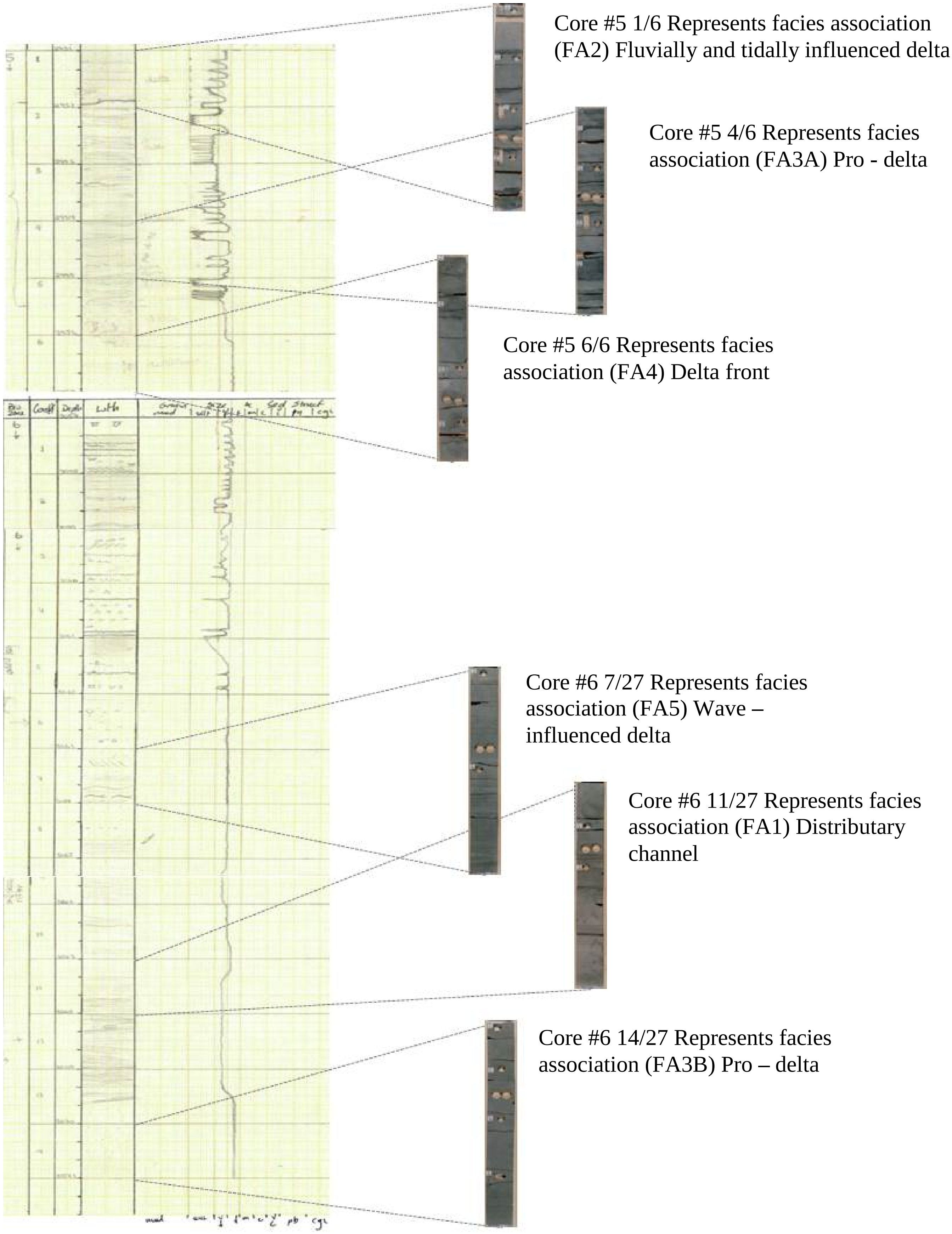


Figure 9 Hand-drawn core descriptions

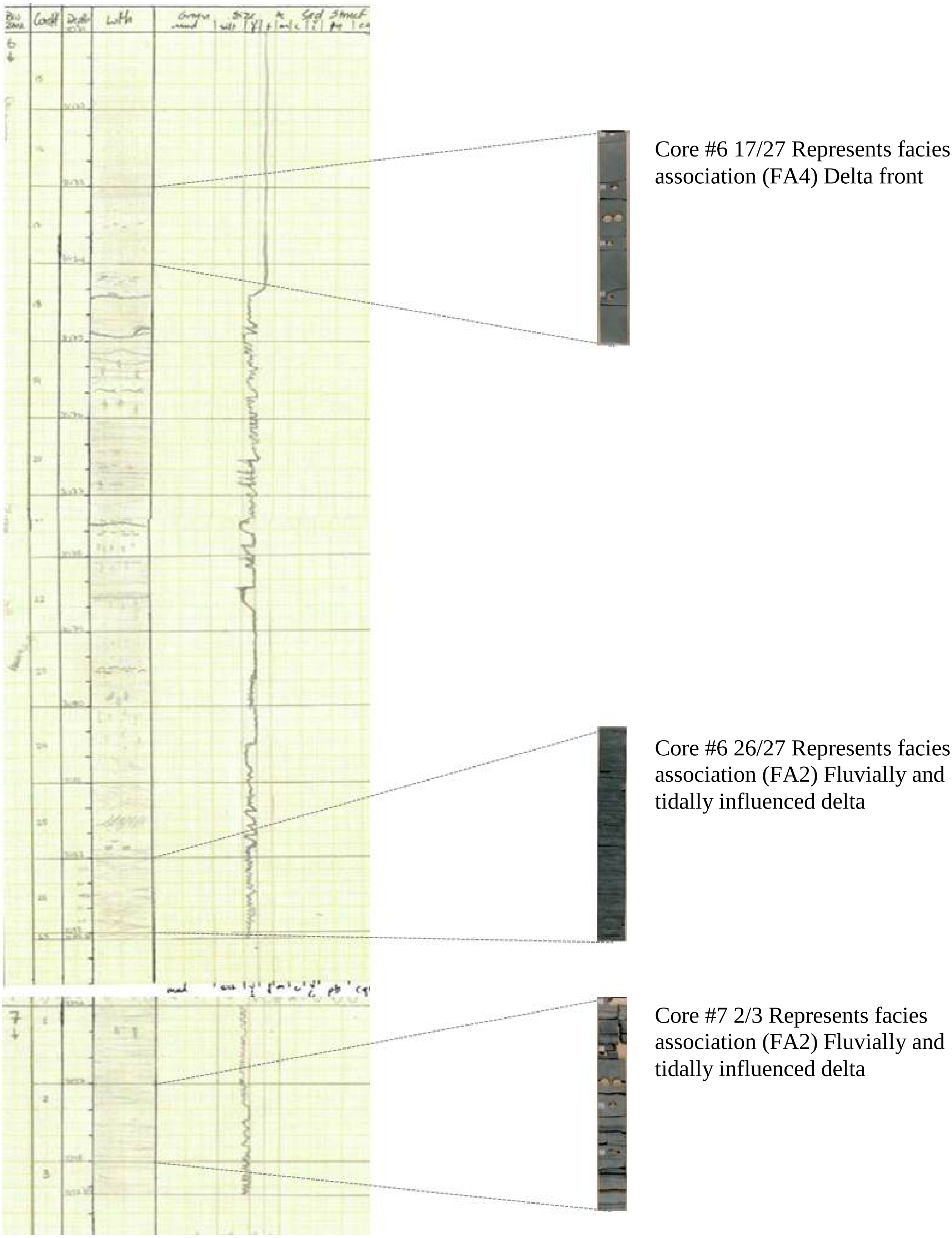


Figure 10 Hand-drawn core descriptions

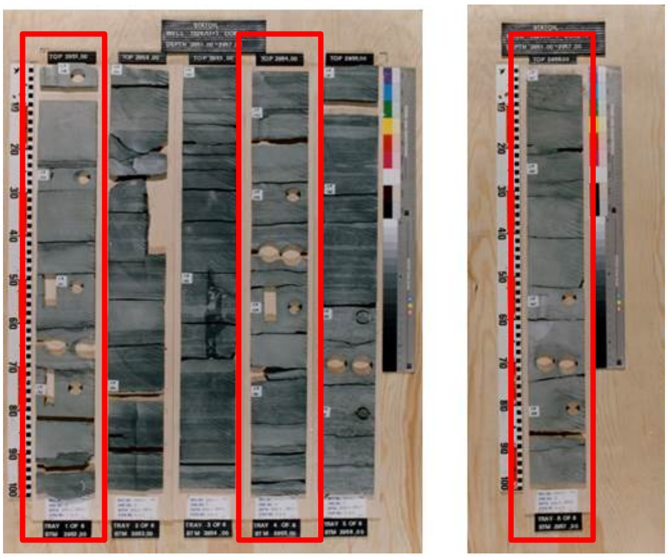


Figure 11 Core #5

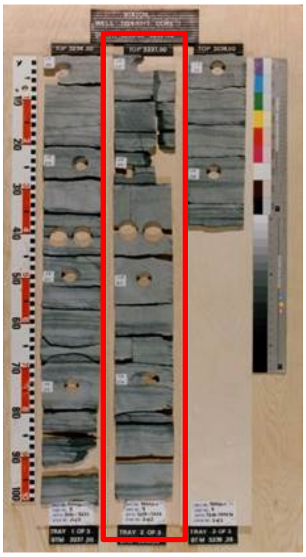


Figure 12 Core #7

Figure 13 Core #6

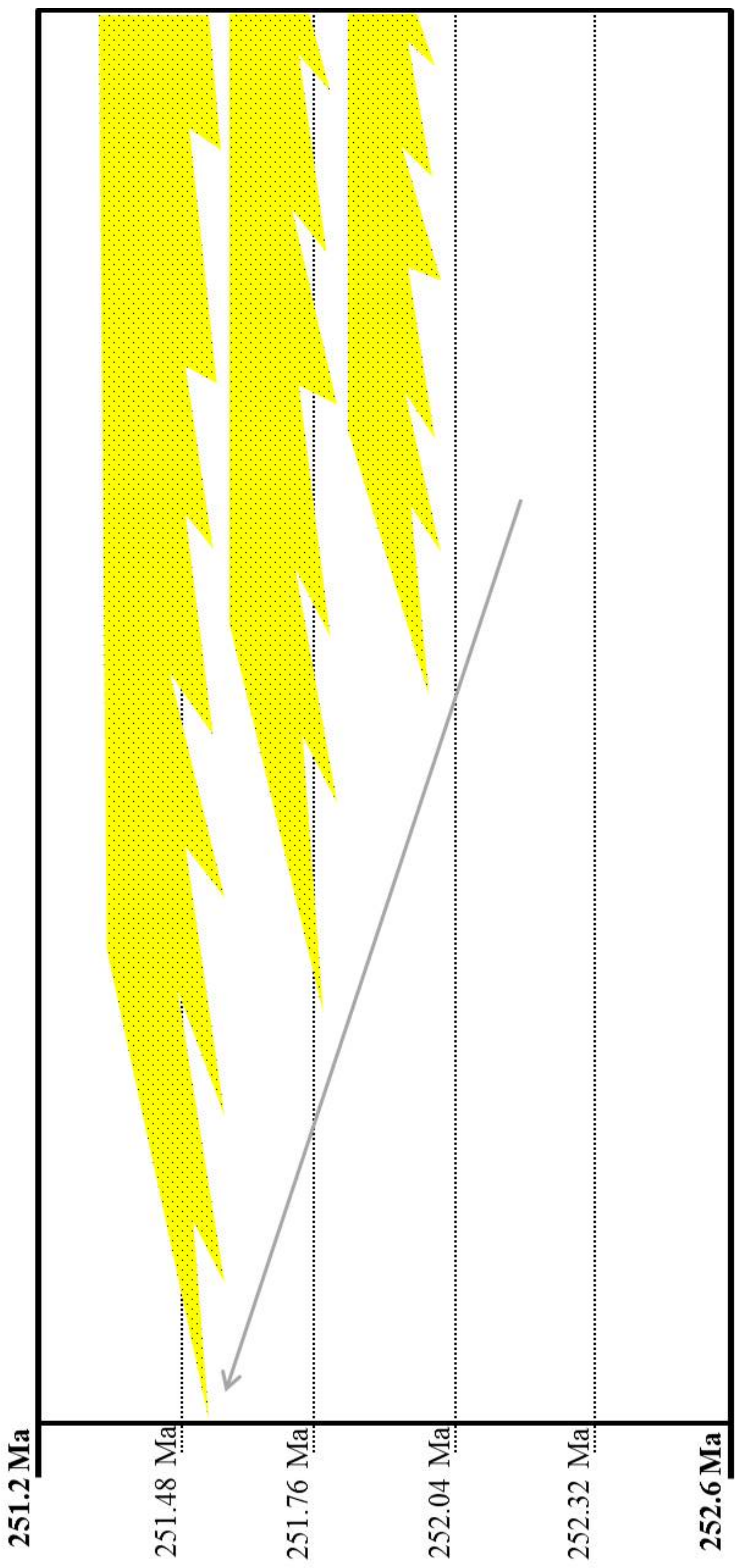


Figure 14 Stages of the deposition

Figure 14 represent the stages of deposition of the Havert formation, the prograding clinoform system within the scale of Ma.

4.3 Facies associations

Facies is defined as a body of rock characterized by a particular combination of lithology, physical and biological structures that bestow an aspect different from the bodies of rock above, below and laterally adjacent (Walker and James 1992). Facies can be defines on a variety of different scales. In a study specifically devoted to the interpretation of depositional environments, there is usually a deliberate attempt to subdivide a rock of body into constituent facies (Walker and James 1992). This is a classification procedure, and the degree of subdivision is governed by the objective of the study, therefore if the objective is routine description and interpretation on a large scale, a fairly broad facies subdivision may suffice (Walker and James 1992). If the objective is more detailed, perhaps involving the refinement of an existing model or the definition of a new one, the facies subdivision must be more detailed (Walker and James 1992). For this study the objective is more detailed, therefore it has been made two tables for the description of the cores, the first table, Table 1: Havert Formation facies association, is divided into facies associations, description, log motive which includes an example of the core, lithology and grain size log., and depositional sub – environment. The second table, Table 2: Havert Formation facies description and interpretation, is divided into facies types, description, bed thickness and interpretation. "Groups of facies genetically related to one another and which have some environmental significance" (Collinson 1969) is the definition of facies associations.

4.3.1 FA1 Distributary channel

Description

Rippled siltstone representing centimeter to decimeter thick beds bioturbated siltstone with low angle ripples. Centimeter to decimeter thick very fine sandstone beds with climbing ripples with moderate angle.

Interpretation

Deposits formed and developed in low energy conditions by currents with one-way direction. And deposits formed in a moderate to high energy conditions, quick deposition, most likely at the front of a distributary channel.

4.3.2 FA2 Fluvially and tidally influenced delta

Description

Tide – influenced bioturbated heterolithic millimeter to centimeter very fine – to – fine grained sandstone with interbedded siltstone layers. Bioturbation is observed within these layers.

Interpretation

Alternating paleo – current, deposit in a low to moderate energy condition. A delta, which is dominated by a river system and tide.

4.3.3 FA3A Pro - delta

Description

Gravity – flow dominated centimeter to decimeter silt to very fine grained sandstone beds, with repeated upwards sections. Event beds, fine to medium grained light grey sandstone with sharp base in centimeter to decimeter thick beds. Parallel laminated decimeter to meter thick sandstone, fine grained sandstone, and plane parallel laminate, with sharp base and sharp top.

Interpretation

Indication of turbidites, deposit formed in a moderate to high energy condition. Deposits formed due to gravity flow or during storm events and deposits formed by gravity underflows and variable flow speed. Pro – delta turbidite lobes.

4.3.4 FA3B Pro – delta

Description

Parallel laminated sandstone, decimeter to meter thick fine grained parallel laminated sandstone beds with sharp base and top. Flood/storm mud dominated heterolithic millimeter to centimeter thick siltstone – mudstone beds. Grain size mixture of mud – to very fine mudstone to siltstone, with sharp – based graded beds.

Interpretation

Deposits formed by gravity underflows with variable flow speed and deposits formed due to flooding events or during storm events indicating gravity flow dominated pro – delta.

4.3.5 FA4 Delta – front

Description

Cross stratified light grey sandstone with some light brown beds, fine grained and well sorted decimeter to meter thick beds. There are no bioturbation observed.

Interpretation

Deposits formed currents with one-way direction indicating depositional sub – environment to be delta – front outer distributary channel.

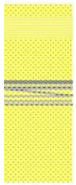
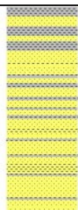
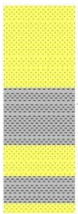
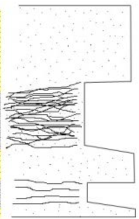
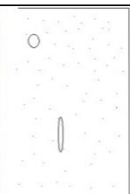
4.3.6 FA5 Wave – influenced delta

Description

Wave – influenced very fine grained sandstone with some indication of wave – ripples, slumping, and pseudo – hummocky and hummocky structures in centimeter to decimeter thick beds. Sandy event beds, fine to medium grained light grey sandstone with sharp base in centimeter to decimeter thick beds.

Interpretation

Deposits formed by waves, or high energy alternating pale – currents and deposits formed due to gravity flow or during storm events, representing the depositional sub – environment delta, influenced by waves.

Facies association	Description	Log motive					Depositional sub-environment
		Core	Lithology	Grain size			
				silt	vf	f	
FA1 Distributary channel	Comprised with bioturbated siltstone with low angle rippled structure (Facies 7) and fine grained sandstone with internal climbing – ripple structures (Facies 8), which is very well sorted.						Distributary channel deposits
FA2 Fluvially and tidally influenced delta	Alternated silt/sand layers with various thicknesses. Alternating paleo-current (Facies 3) Bioturbation is observed.						Delta, dominated by river system and tide
FA3A Pro – delta	Generally comprised of packages of sandy event beds (Facies 6) The package display sharp bases and sharp tops with fining upwards sections (Facies 1) with parallel laminated sandstone (Facies 9), which is very well sorted.						Pro – delta turbidite lobes
FA3B Pro – delta	Parallel laminated sandstone (Facies 9). Sharp bases and sharp tops on siltstone – mudstone beds (Facies 2) Slumping, which an indication of a possible slope.						Gravity flow dominated pro – delta
FA4 Delta – front	Fine grained cross stratified sandstone (Facies 5) which is well sorted. Some bioturbation is observed. Some indication of slumping, transition to pro-delta.						Delta – front outer distributary channel

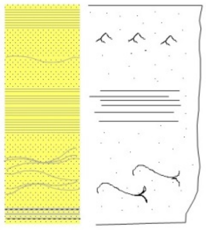
FA5 Wave – influenced delta	Very fine to fine grained, light grey colored sandstone with some indication of wave – ripples in the form of pseudo – hummocky and hummocky structures (Facies 4). There are also some event beds (Facies 6) present within the wave – influenced delta.			Delta, influenced by waves

Table 1: Havert Formation facies association

Facies type		Description	Bed thickness	Interpretation
1.	Turbidites, gravity-flow dominated sandstone	Silt to very fine grained sandstone, with repeated fining upwards section	Centimeter to decimeter	The mixed silt – to – very fine grained sandstone with repeated fining upward sections indicated turbidites. Deposit formed in a moderate to high energy condition
2.	Flood/storm mud dominated heterolithic	Siltstone – mudstone beds with sharp – based graded beds. Bioturbation is present in this facies. The grain size of this facies is a mixture of mud – to – very fine mudstone to siltstone.	Millimeter to centimeter	Deposits formed due to flooding events or during storm events
3.	Tide–influenced bioturbated heterolithic	Very fine – to – fine grained sandstone with interbedded siltstone layers. Bioturbation is observed.	Millimeter to centimeter	Alternating paleo-current. Deposit in a low to moderate energy condition
4.	Wave–influenced sandstone	This facies consist of very fine grained sandstone with some indication of wave – ripples, slumping, pseudo – hummocky and hummocky structure	Centimeter to decimeter	Deposits formed by waves, or high energy alternating paleo-currents
5.	Cross stratified sandstone	Light grey, with some light brown beds, fine grained, and well sorted sandstone. Erosive based. Bioturbation is not observed	Decimeter to meter	Deposits formed by currents with one-way direction
6.	Sandy event beds	Fine to medium grained light grey sandstone with sharp base.	Centimeter to decimeter	Deposits formed due to gravity flow or during storm events
7.	Rippled siltstone	Siltstone, low angle ripple forms. Bioturbation is observed.	Millimeter to	Deposit formed and developed in low energy conditions by

			centimeter	currents with one-way direction
8.	Climbing – rippled sandstone	Very fine sandstone with climbing ripples with moderate to high angle	Centimeter to decimeter	Deposits formed in a moderate to high energy conditions, quick deposition, most likely at the front of a distributary channel
9.	Parallel laminated sandstone	Fine grained sandstone, plane parallel laminate, with sharp base and sharp top.	Decimeter to meter	Deposits formed by gravity underflows with variable flow speed

Table 2: Havert Formation facies description and interpretation

4.4 Havert Formation

The core data from the Lower Early Triassic stratigraphic sequence was studied through the concept of facies interpretation to achieve a better understanding of the depositional environment within the Havert Formation. The cores taken for the Havert Formation is concentrated in the upper part of the formation. The Havert Formation within the Norsel well is a formation dominated by mixed – influenced delta systems, illustrated in Figure 3. The three cores taken from the Norsel well have by definition the same facies association comprises the cores, though there are different structures within the same associations that differentiate the cores. The lowest core taken from the Havert Formation is core #7. Core # 7 represents fluvially and tidally influenced delta, with alternated silt/sand with various thicknesses. The tide – influenced bioturbated heterolithic were deposited in a low to moderate energy condition, showing alternating paleo-current ripples. Moving upwards the middle core taken form the Havert Formation is core #6. The main facies associations within core #6 are fluvially and tidally influenced delta, wave influenced delta, pro – delta, delta – front and distributary channel. The fluvially and tidally influenced delta is characterized by alternated silt/sand layers, with the facies type of tide – influenced bioturbated heterolithic in millimeter to centimeter thick beds. Interpreted to be alternating paleo – current, deposits formed in a low to moderate energy conditions. The wave – influenced delta comprises of very fine to fine grained, light grey colored sandstone with indication of wave – ripples, in the forms of pseudo – hummocky and hummocky structures. Event beds are also present within this facies association, deposits formed due to gravity flow or during storm events. The pro – delta facies association belongs to the pro – delta turbidite lobe depositional sub – environment, which is generally comprised of packages of sandy event beds, with fine to medium grained light gray sandstone with sharp base. Fining upwards sections are also elements defining this facies association and an indication of turbidites, gravity – flow dominated sandstone and parallel laminated sandstone where the deposits are formed by gravity underflow with variable flow speed. Delta – front in this core description consists of bioturbated fine grained cross stratified sandstone in decimeter to meter thick beds. Where the depositional sub – environment is delta – front outer distributary channel. The cross stratified sandstone is light grey, with some light brown beds, fine grained and well sorted sandstone, formed by currents with one – way direction. The upper part of the core #6 represents distributary channel, comprised with bioturbated siltstone with low angle rippled structure and fine grained sandstone with internal climbing – ripple structures. The rippled siltstone have low angle ripples, deposits formed and developed in low energy conditions by currents with one – way direction. The climbing – rippled sandstone is very fine sandstone with moderate to high angle climbing ripples in centimeter to decimeter thick beds. These climbing – ripples were formed in a moderate to high energy conditions with quick deposition and most likely at the front of a distributary channel. The uppermost core of the Havert Formation is core #5. The core comprises of delta – front, wave – influenced delta and pro – delta facies associations. Delta – front with a depositional sub – environment of the delta – front outer distributary channel. Some slumping, which is indication of a slope, transition zone from the wave – influenced delta to the delta – front. The delta is influenced by waves with deposits formed by waves or high energy alternating paleo – currents within centimeter to decimeter bed thicknesses. Pro – delta consisting of parallel laminated sandstone in decimeter to meter thick beds and sharp bases and sharp tops on siltstone – mudstone beds. The sharp bases and tops on siltstone – mudstone beds indicate flood/storm mud dominated heterolithc facies type, where bioturbation is observed. These deposits were formed due to flooding events or during storm events, and possibly belong to a gravity flow dominated pro – delta depositional sub – environment.

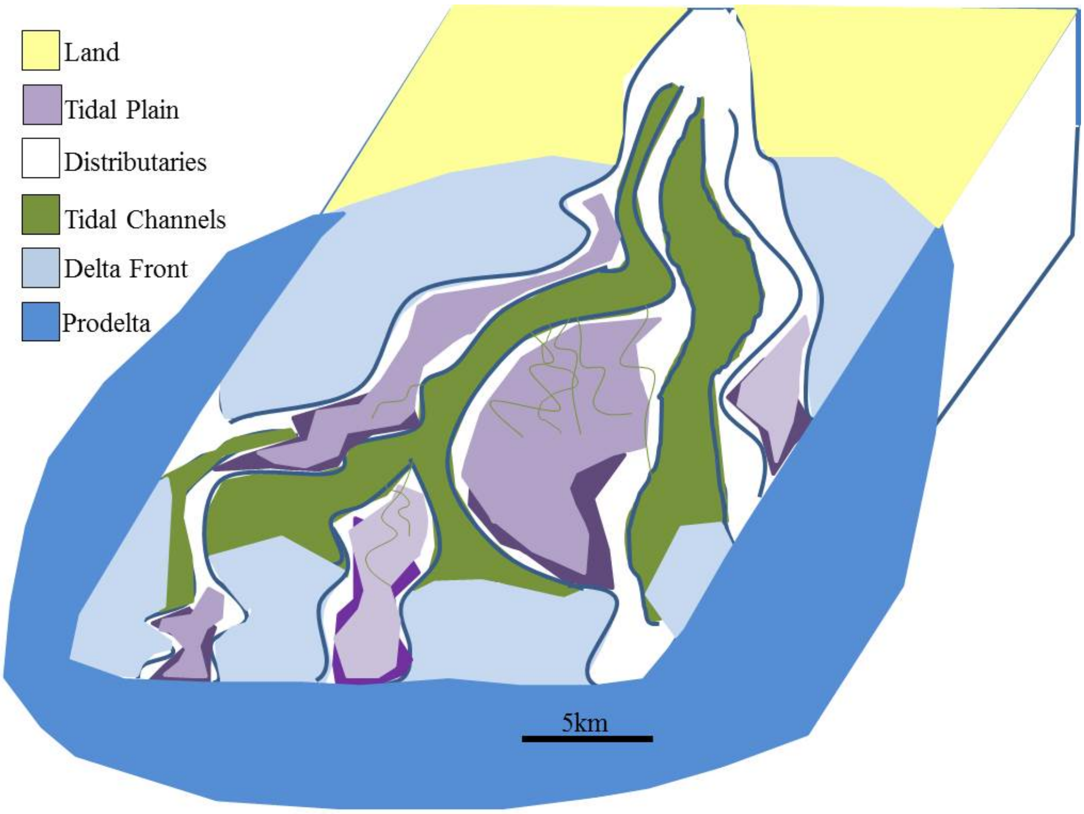


Figure 15 Gross depositional environment and depositional elements of the Havert Formation

4.5 Generalized classification of facies association based on well log response.

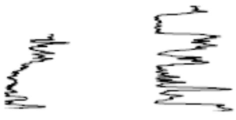
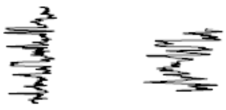
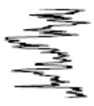
Eocene gamma-ray (GR) log pattern	Well-log signature	Facies interpretation based on core description	Sequence-stratigraphic framework
	Blocky and fining upward	Fluvial channel, distributary channel. Fluvially and tidally influenced delta	Progradation with possible erosive surface and sandstones at the base of regressive ravinement surface
	Spiky or mixed	Crevasse splay, tidal bar. Middle to lower delta plain	Transgression with possible ravinement surface at the base of main sandstone bodies
	Spiky and coarsening upward	Mouth bar, delta front, or tidal bar	Progradation or transgression
	Erratic	Lower delta plain to shallow marine/shelf	Transgression
	Blocky and coarsening upward	Amalgamated fluvial or estuarine channel	Progradation and transgression

Table 3: Facies association based on well log response and core description (Escalona and Mann 2006)

In order to build a relevant sequence stratigraphic model based on core description and facies associations, it is important to make a general classification of identified associations based on well log response, Figure 16, and core description. With this general classification, it defines depositional systems, which allow recognizing of key surfaces in sequence stratigraphic framework. The target area for this generalized classification of facies association is the upper part of the Havert Formation. This Generalized classification of facies associations if based on the Table 3: Facies association based on well log response and core description (Escalona and Mann 2006) and Table 4: Facies association based on well log response and core description, taken from the Havert Formation of the Norsel well. The well log response is based on the Gamma Ray log. At the base of the target area the log signature displays moderate to high gamma ray (GRLR 4) with a coarsening upwards section implying facies elements as delta front, mouth bar or tidal bar and reflects on a progradational and regression or transgression sequence stratigraphic framework. Moving upwards, the GR log response shows a moderate gamma ray and erratic log signature (GRLR 5). The erratic log signature reflects on a lower delta plain to a shallow marine/shelf facies, which acts transgressive. Above the delta plain to shallow marine/shelf facies the low gamma ray and fining upwards log signature (GRLR 3), with progradation and possible erosive surfaces, indicate fluvial/distributary, tide and wave influenced delta. Then there is a second section of moderate GR (GRLR 5), erratic log signature, a transgressive lower delta plain of shallow marine/shelf facies. The upper part of the Havert Formation display a low gamma ray, blocky log signature (GRLR 2), implying progradation with possible erosive surfaces and sandstone at the base of regressive ravinement surface. This sequence stratigraphic framework indicated facies elements like fluvial channel, distributary channel or fluvial and tidally influenced delta. At the top of the well moderate GR, spiky and mixed log signature with transgressive or regressive sequence stratigraphic framework implies mouth bar, delta front or tidal bar facies elements. This generalized classification of facies associations based on well log response is tied up to sequence stratigraphic analysis, which is the main subject in the next chapter.

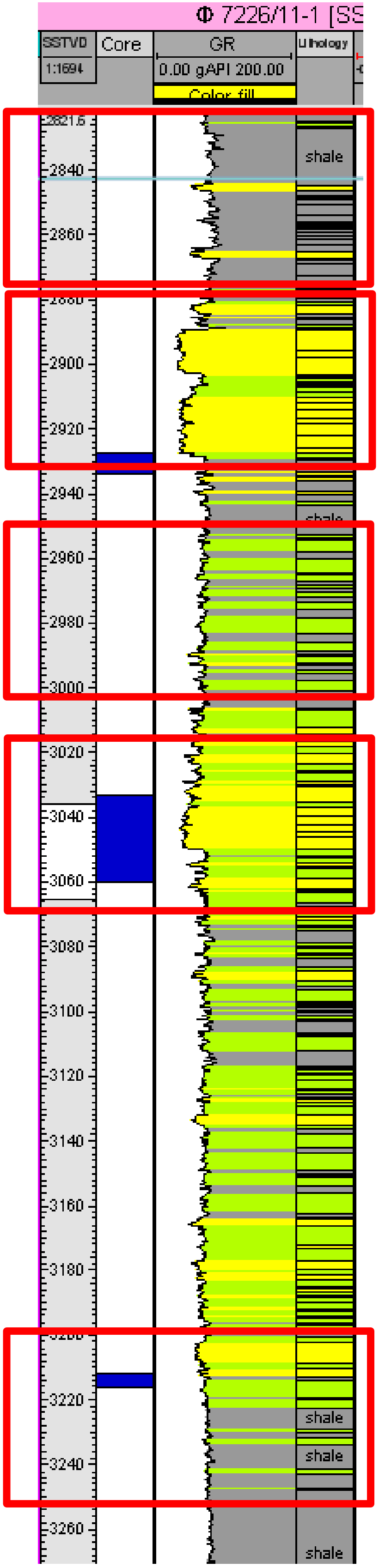


Figure 16 Well log response form well 7226/11-1 of the upper part of the Havert Formation, representing the location of the cores.

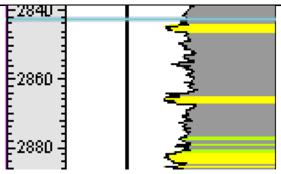
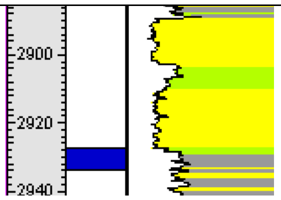
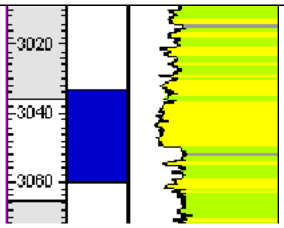
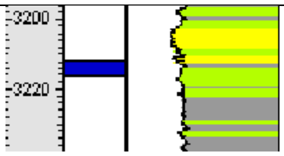
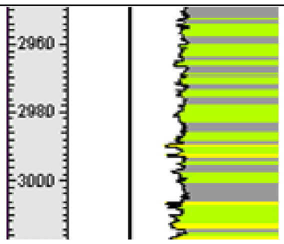
GR LOG RESPONSE (GRLR)		LOG SIGNATURE	FACIES ELEMENT	SEQUENCE STRATIGRAPHIC FRAMEWORK
1.		Moderate GR, spiky and mixed.	Mouth bar, delta front or tidal bar	Transgression or regression
2.		Low GR, blocky	Fluvial channel, distributary channel. Fluvial and tidally influenced delta	Progradation with possible erosive surface and sandstone at the base of regressive ravinement surface
3.		Low GR, fining upward	Fluvial/distributary channel, tide and wave influenced delta	Progradation with possible erosive surface
4.		Moderate to high GR, coarsening upward	Delta front, mouth bar or tidal bar	Progradation and regression or transgression
5.		Moderate GR, Erratic	Lower delta plain to shallow marine/shelf	Transgression

Table 4: Facies association based on well log response and core description taken from the Havert Formation of the Norsel well, red boxes in figure 4 indicate where the GR log response are taken from

5. Seismic interpretation

5.1 Introduction

The seismic interpretation has its intention to give a seismic semi-regional 2D grid with the interpretation of four 2D seismic lines and structural identification giving a seismic facies classification of Havert Formation clinoform system and an amplitude analysis of depositional-geometries. The 2D seismic supports the 3D seismic interpretation – regional context. The 2D seismic comprises of four 2D seismic lines and the 3D survey is a 227km^2 large survey. Based on the 2D and 3D interpretation, amplitude maps has been generated and combined with the interpretation, horizons and structures, this will be the basis for conceptual geological models generated in chapter 6.

5.2 2D seismic interpretation

The purpose of the 2D seismic interpretation is to understand the regional setting around the Norsel High area. To achieve this understanding, four 2D seismic lines were interpreted. Within each of these four seismic lines, five horizons were interpreted based on the well tops of the Norsel well. These five horizons are picked on hard, strong reflections and each horizon represent a regional maximum flooding surface. These five horizons are Kobbe FM, Klappmyss FM, Havert FM, Ørret FM and Røye FM, where each formation representing a mega-sequence. The seismic lines have orientation stretching in every direction, north, south, east and west, see Figure 17. Several other 2D seismic lines were interpreted to make the intersection between the interpretations of these four 2D seismic lines as accurate as possible. To represent the regional framework these four 2D seismic lines were the ones that covered the broadest framework and are connected with each other.

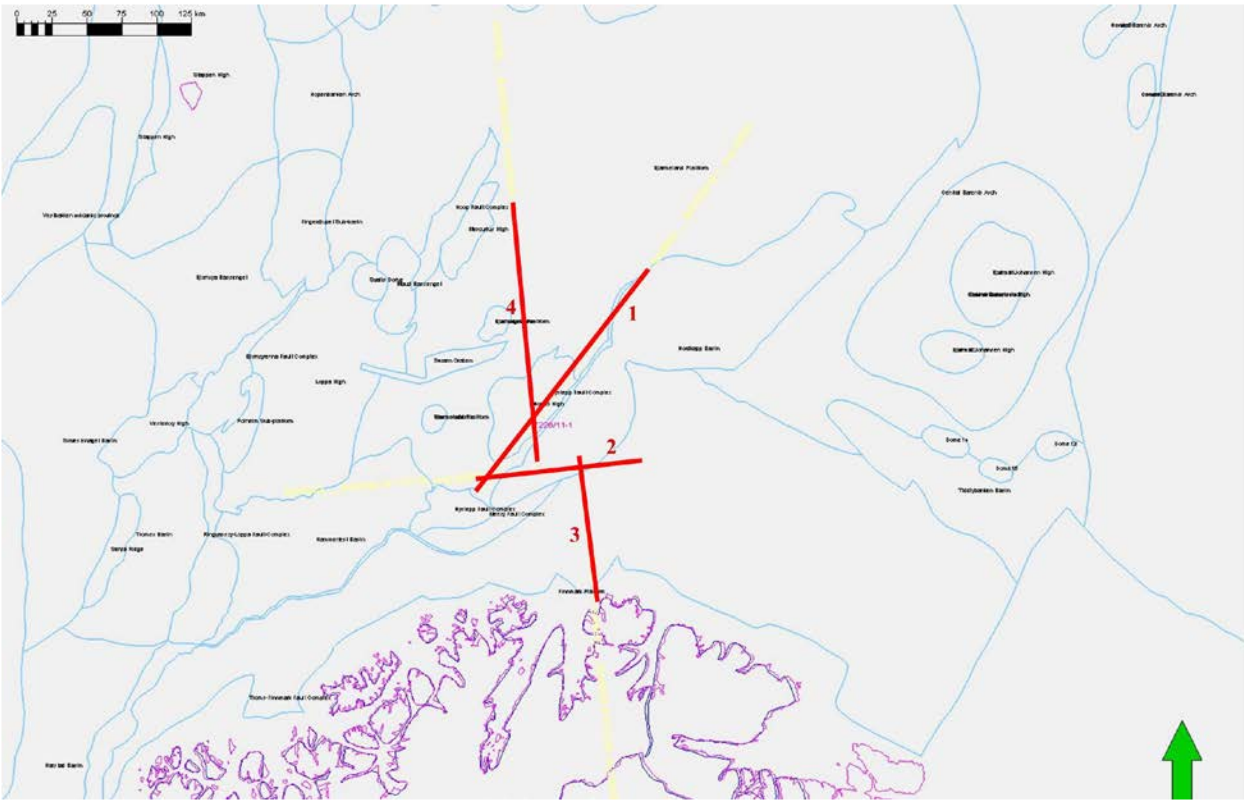


Figure 17 Location map displaying structural elements and the location of the four 2D seismic lines

The first 2D line, Figure 18 goes from northeast to southwest and the well is located on this seismic lines. The horizons follow a constant thickness almost throughout the entire seismic line. Located to the northeast there is a possible salt dome which is forcing the horizons upwards. The possible salt dome does most likely belong to the Nordkapp basin. The first 2D seismic line crosses line 2 and 4. The second 2D line, Figure 19 goes from east to west, and crosses line 1 and 3. There are two possible salt domes, relative to the Nordkapp Basin, located in the western part of the seismic line. The salt domes forcing the horizons direction to move upwards and because of the development of the salt dome, the thickness of the layers are affected. See clearly change in thickness in the Kobbe Formation located between the two possible salt domes. The third 2D line, Figure 20 has the direction from north to south. This 2D seismic line is the one that is located nearest to onshore land and shares the intersection with the second 2D seismic lines in the northern part of the seismic line. From south to north the formation grow in thickness towards the north. In the northern part of the seismic line the formations seem to move down, most likely into a basin. The fourth 2D line, Figure 21 stretches from north to south and crosses only the first 2D seismic line. The formations have a constant thickness throughout the entire line. In the southern part of the 2D seismic line is seem like the formations are sinking down, probably in to a basin. This will be the same basin as the basin in the northern part of the third 2D seismic line. This basin is most likely the Nordkapp Basin. The combination of these four seismic sections gives a regional geologic framework around the Norsel High area.

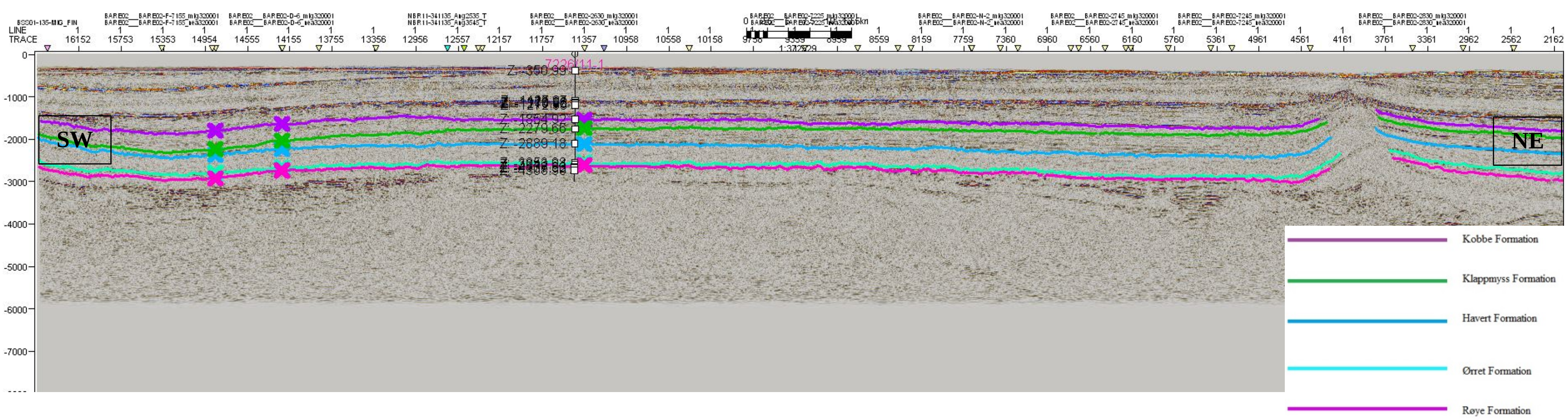


Figure 18 The first seismic section displaying the five interpreted horizons and the location of the well 7226/11-1.

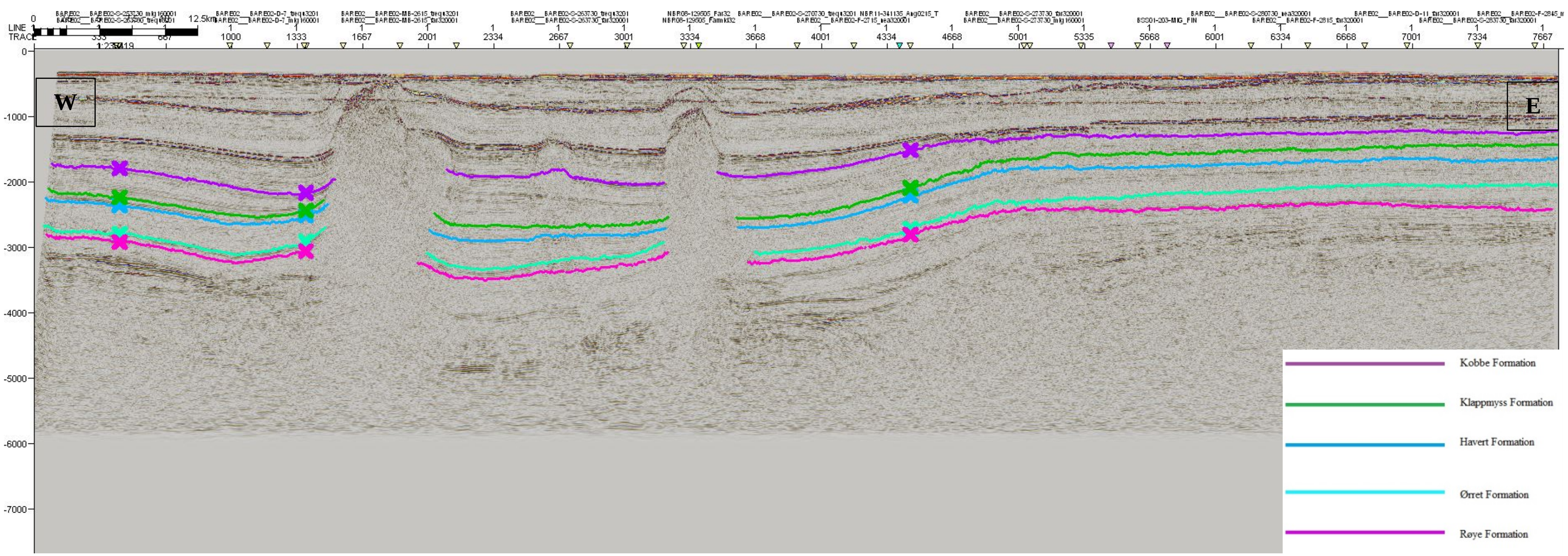


Figure 19 The second seismic section displaying the five interpreted horizons

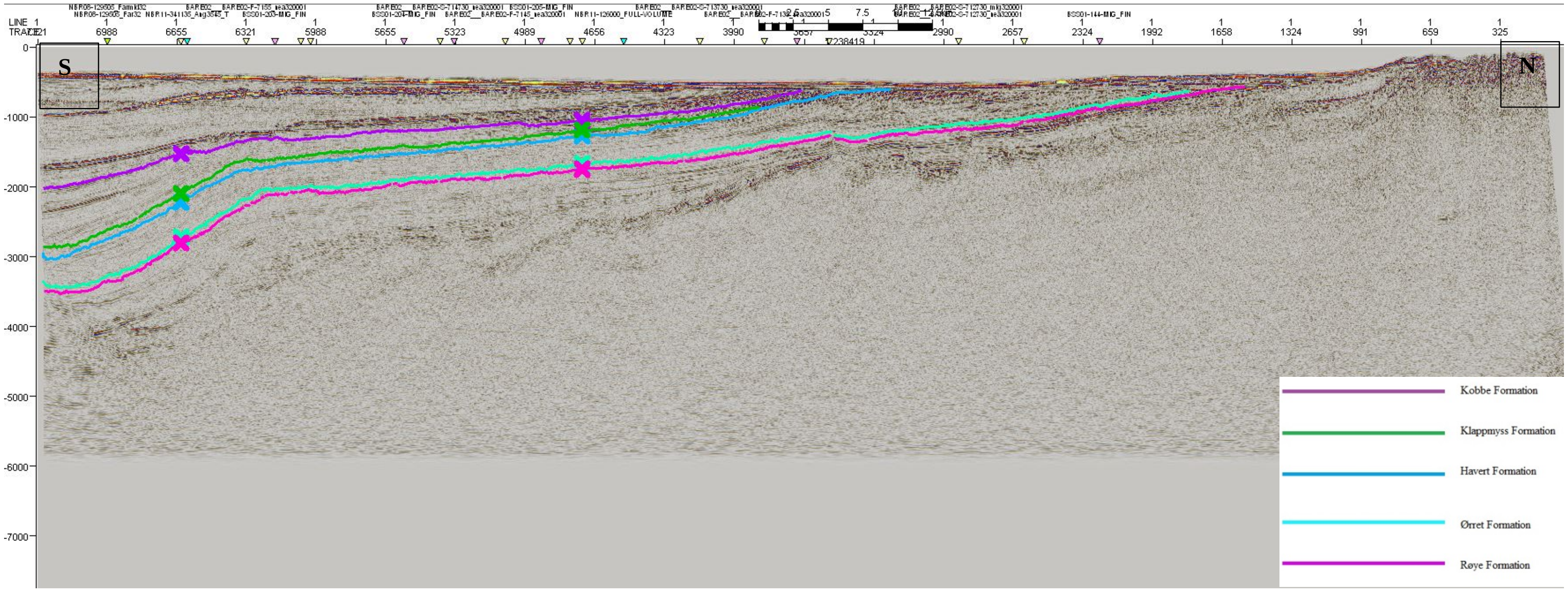


Figure 20 The three seismic section displaying the five interpreted horizons

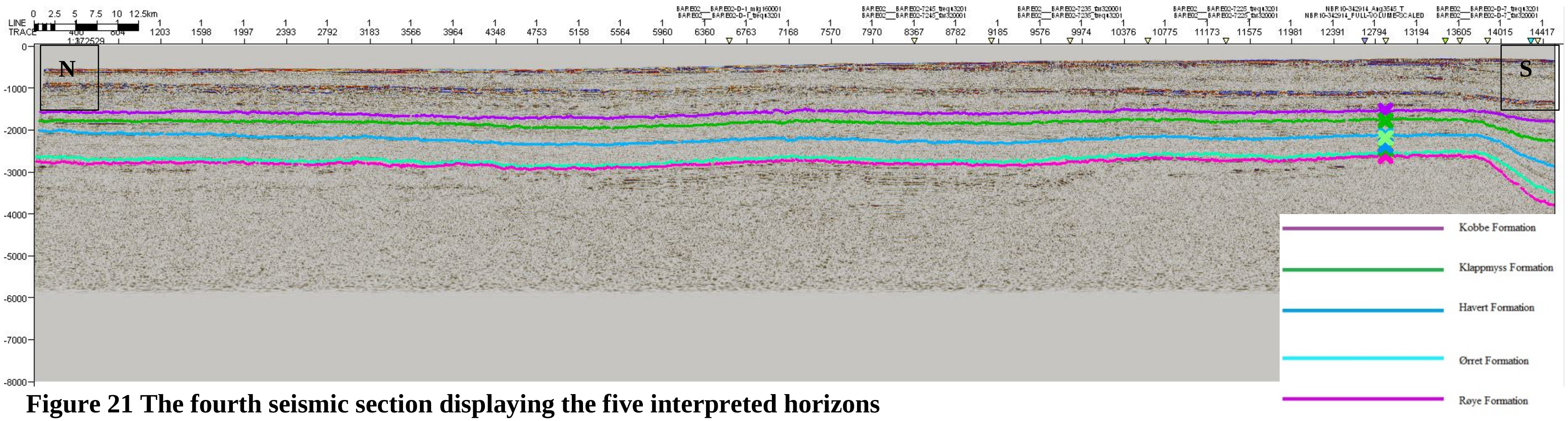


Figure 21 The fourth seismic section displaying the five interpreted horizons

Zooming in on the first line, a seismic section, where the well is located a step – by – step interpretation process has been applied. The step – by – step interpretation is more of a learning process, with the purpose to get a better understanding of the seismic in each section. Starting with the first section, see Figure 22, displays only the seismic and the well with the well tops. No interpretation has been done. The next section, the second section, is showing the interpretation of the horizons. The purple line represents the top Kobbe Formation, the green line represents top Klappmyss Formation, the blue line represent the top Havert Formation, the turquoise line represent the top Ørret Formation and the deepest line, the pink line, represent the top Røye Formation, see Figure 23. The third section displays the interpreted horizons and colored infill between the interpreted horizons indicating the age of the formations. The Kobbe Formation with the age of Middle Triassic, the Klappmyss Formation with Upper Early Triassic age, the Havert Formation with the age of Lower Triassic and the Ørret Formation with Late Permian age, see Figure 24.

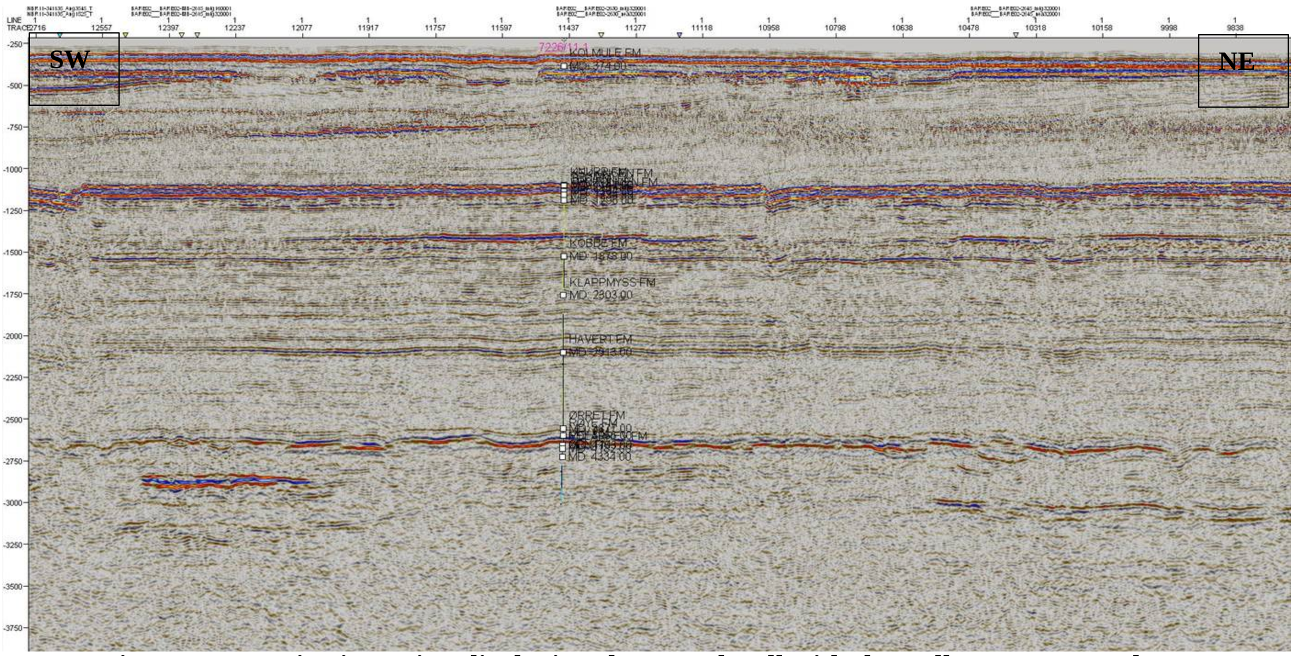


Figure 22 2D seismic section displaying the Norsel well with the well tops presented

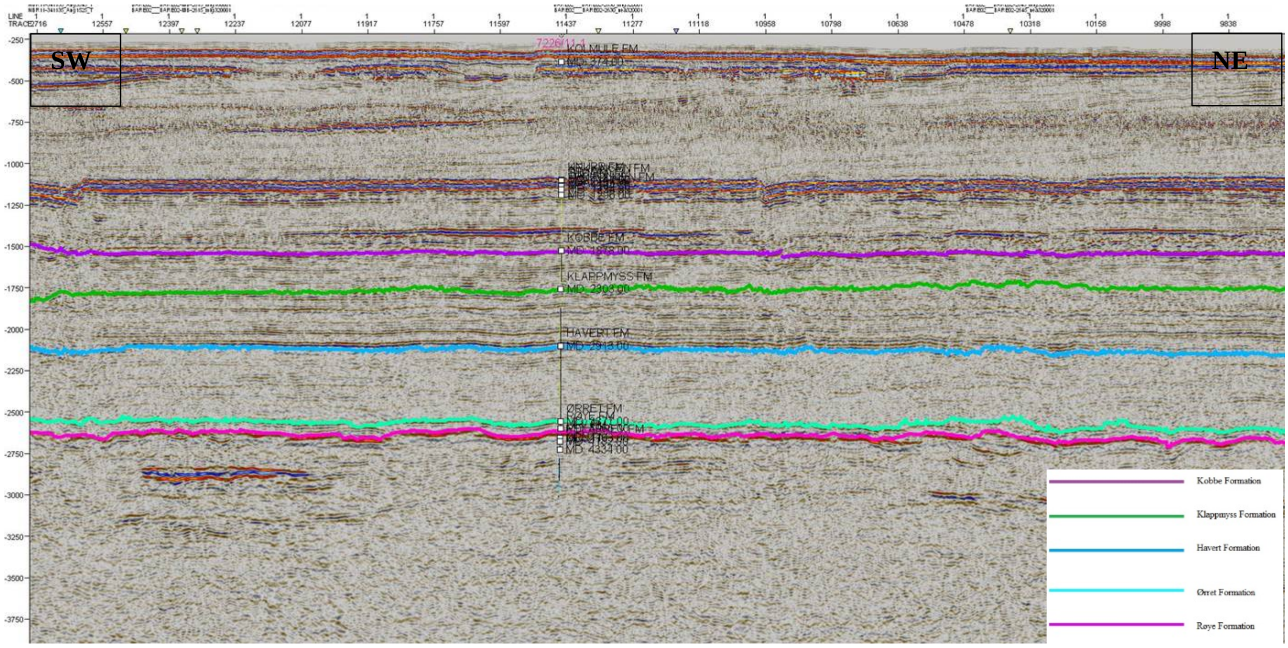


Figure 23 2D seismic section displaying the Norsel well with horizon interpretation of top Kobbe FM, top Klappmyss FM, top Havert FM, top Ørret FM and top Røye FM.

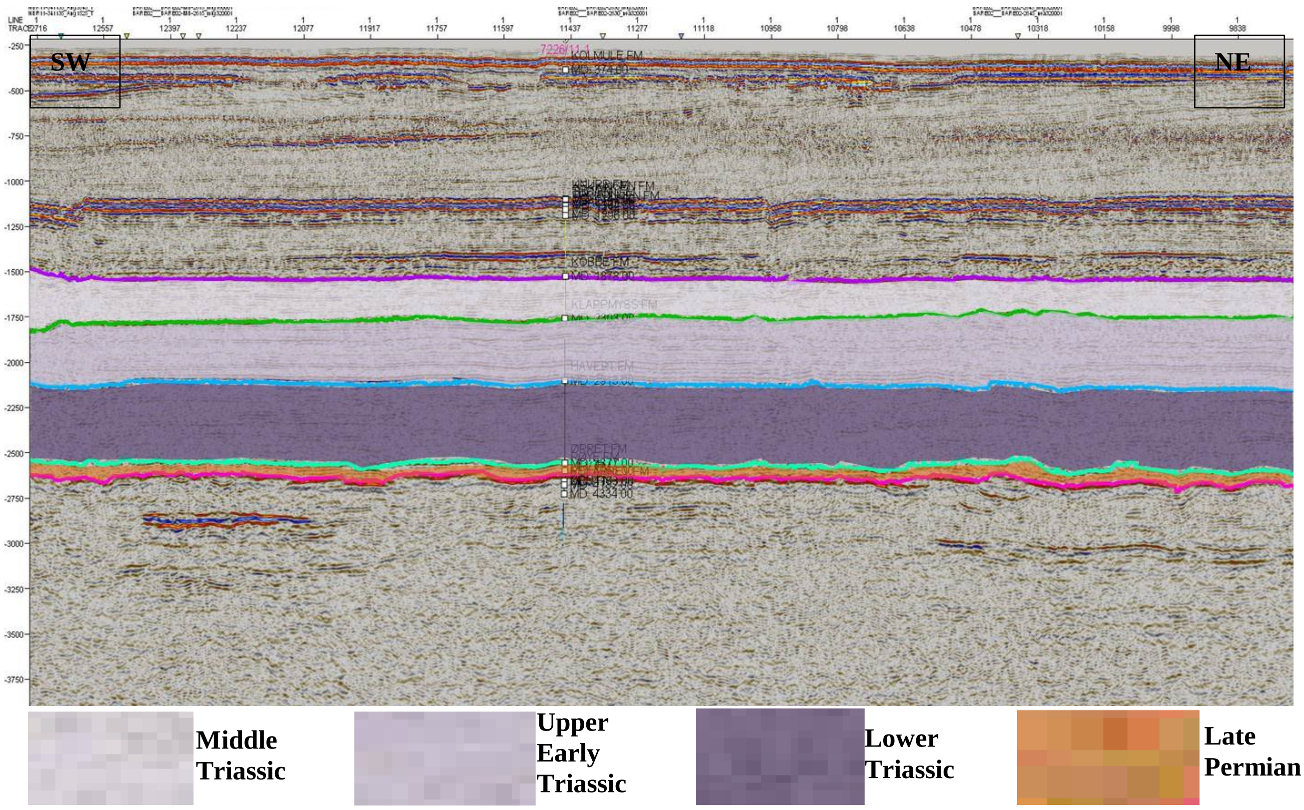


Figure 24 2D seismic section displaying the Norsel well with horizon interpretation and color infill representing the geological time scale for each formation

The fourth section, see Figure 25, has the combined interpretation and age display of section one and two. The interpretation of the different horizons and the colored infill age representation, only here the colors are more transparent. The further step for this section is the interpretation of the clinoform systems within the Havert Formation. Clinoforms are developed in response to transgressive deepening followed by the re-establishment of laterally prograding sedimentary layers (Walker and James 1992). There are both small – scale and large – scale prograding clinoforms present in the formation. Small – scale clinoforms in the front of the large – scale clinoforms. The clinoform system is prograding from the northeast to the southwest. The clinoforms in the middle of the formation, are low – angle clinoforms with small – scale clinoforms prograding in the front. In the upper part of the Formation the clinoforms are of large – scale systems. The final seismic section, the fifth section, see Figure 26, is a zoomed in from the fourth section. The final section is displaying the entire interpretation process, with added lithology within the clinoform systems.

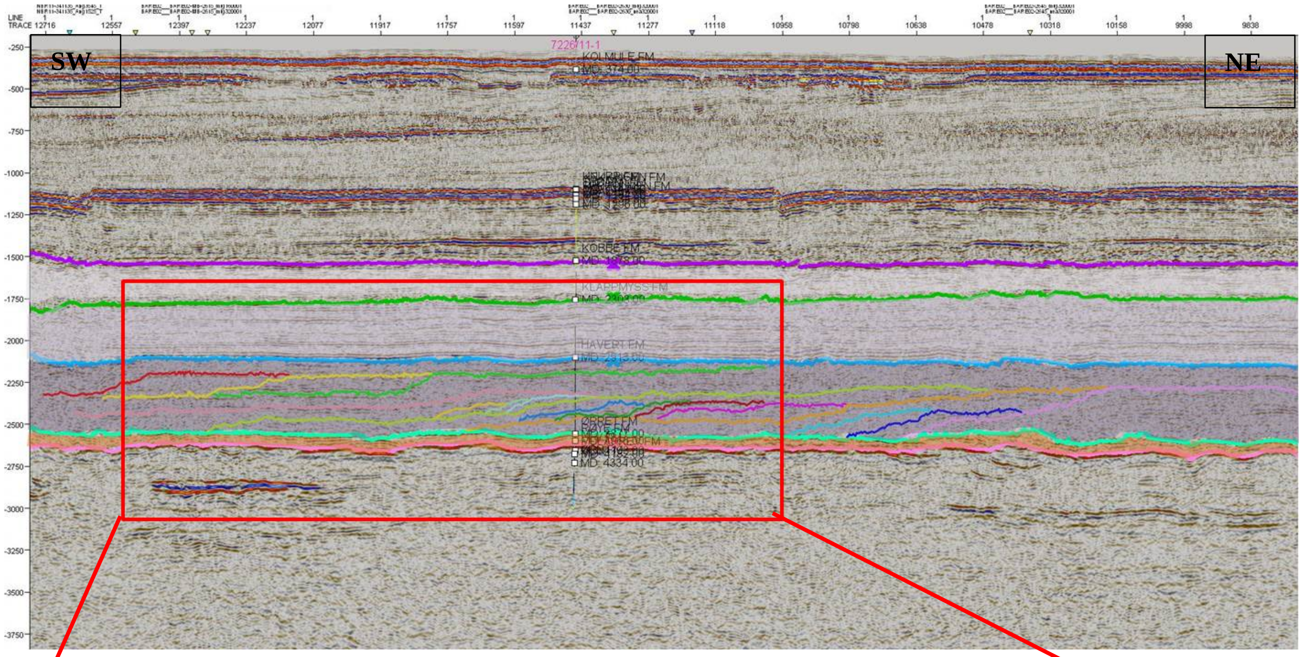


Figure 25 2D seismic section displaying the Norsel well with the horizon interpretation and structural interpretation of the clinoform system

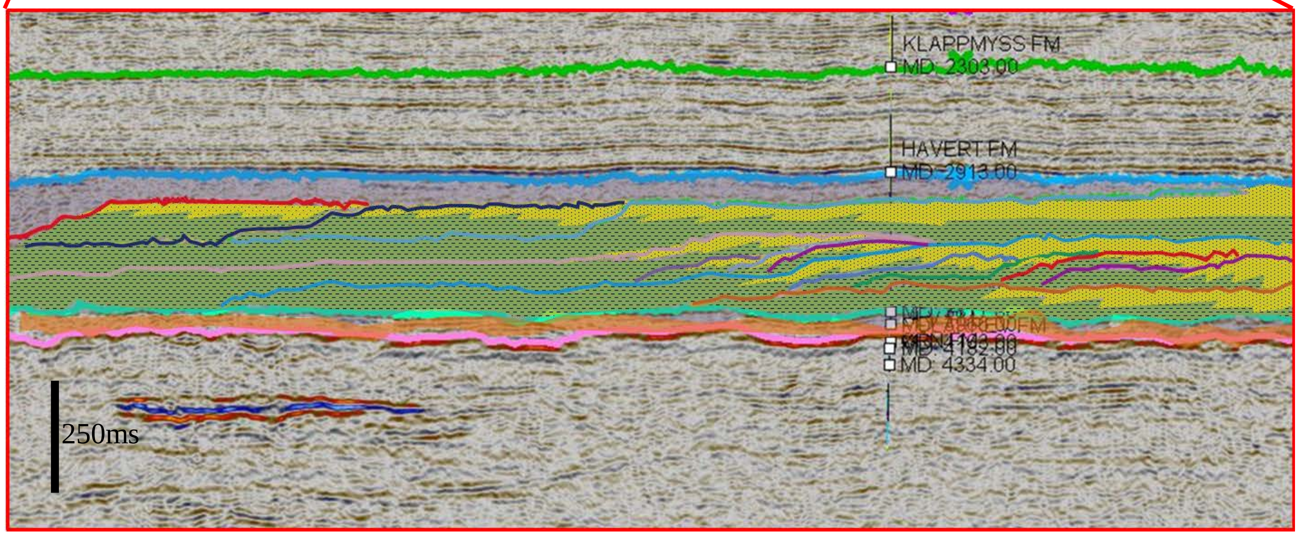
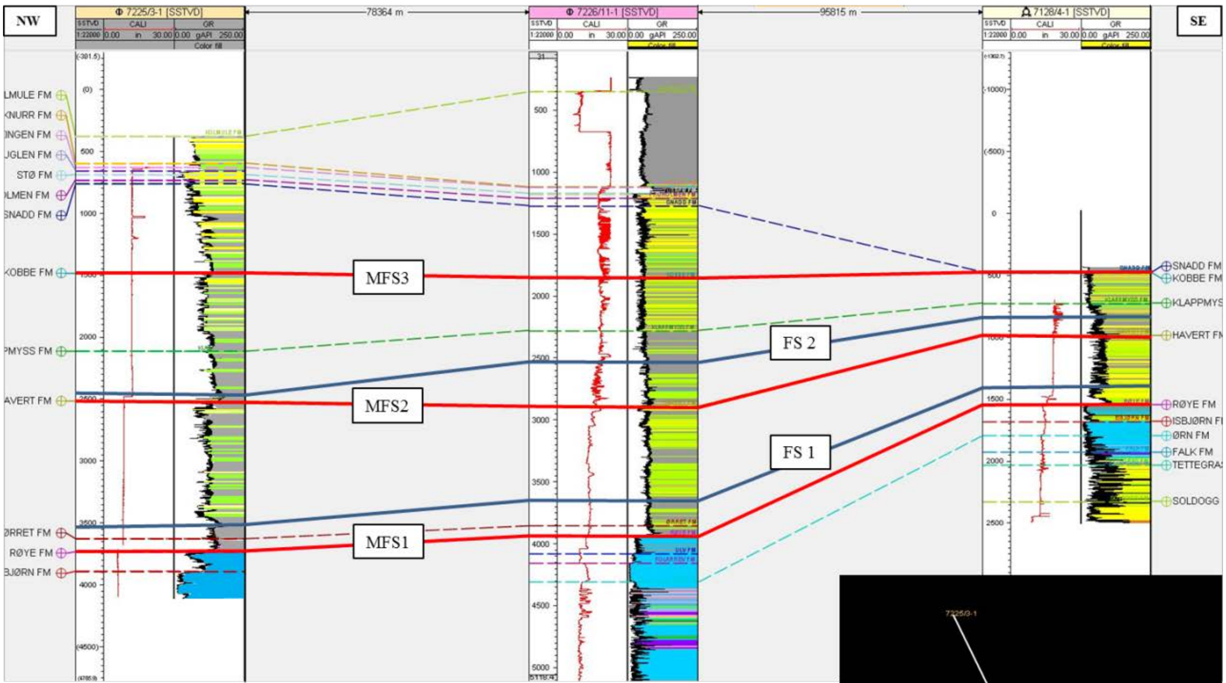


Figure 26 Zoomed in section from the 2D seismic section in Figure, displaying the lithology within the structural interpretation of the clinoform system

5.3 Well correlation

The well correlation is to develop a regional framework of the area around Norsel High, see Figure 27. For the regional framework two wells has been added, next to the Norsel well. These wells are 7128/4-1 Finnmark East located to the northwest relative to the Norsel well, the Norsel well 7226/11-1 in the middle and the Norvarg well, 7225/3-1 southeast relative to the Norsel well. Therefore, in the direction landward to basinward; the first is 7128/4-1, the middle well is 7226/11-1 and the third is 7225/3-1. There was no lithology available for the well 7128/4-1, therefore the colored lithology in the figure is based on information according to the NPD’s webpage (Directorate), interpreted based on the gamma-ray log and by comparing 7128/4-1 to the nearby wells, mostly the Norsel well. The regional framework displays the three seismic scale mega-sequences based on the three maximum flooding sequences interpreted on the three wells and with two flooding surfaces interpreted, one within two of the three mega-sequences. The well correlation stretches from the southeast to the northwest, where the southeast is the most landward positioned well.



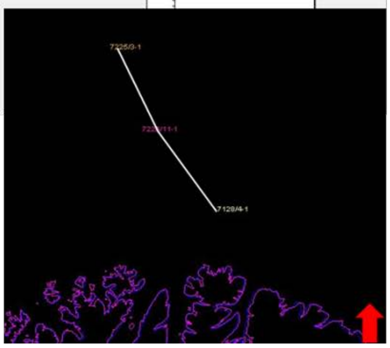


Figure 27 Well correlations comprising of the wells 7225/3-1, 7226/11-1 and 7128/4-1 and a location map displaying the orientation of the three wells.

In a zoomed in section of the Havert formation, Figure 28, it is observed that the thickness of the formation gets thicker towards the northwest. In the figure there is illustrated a clinoform system. These interpretations of clinoforms are based on seismic interpretation. On seismic data, the Triassic interval is characterized by large scale clinothems (Henriksen, Ryseth et al. 2011). From the Norwegian sector the oldest clinothems recorded are of Induan age and show several phases of northward progradation. Well data from these clinothems show development of a thick, sandstone dominated succession, most likely representing delta systems which have its source from the Fennoscandian hinterland (Henriksen, Ryseth et al. 2011). However, the predominant progradation path throughout the Early – Late Triassic is from SE to NW (Henriksen, Ryseth et al. 2011). Provenance studies (Mørk, Elvebakk et al. 1999) and palaeogeographic considerations (Riis, Lundschien et al. 2008, Smelror, Petrov et al. 2009) suggest that Triassic sandstones across the entire Norwegian Barents Sea region were derived from source areas to the east, with a more limited supply from the Fennoscandian hinterland to the south (Henriksen, Ryseth et al. 2011).

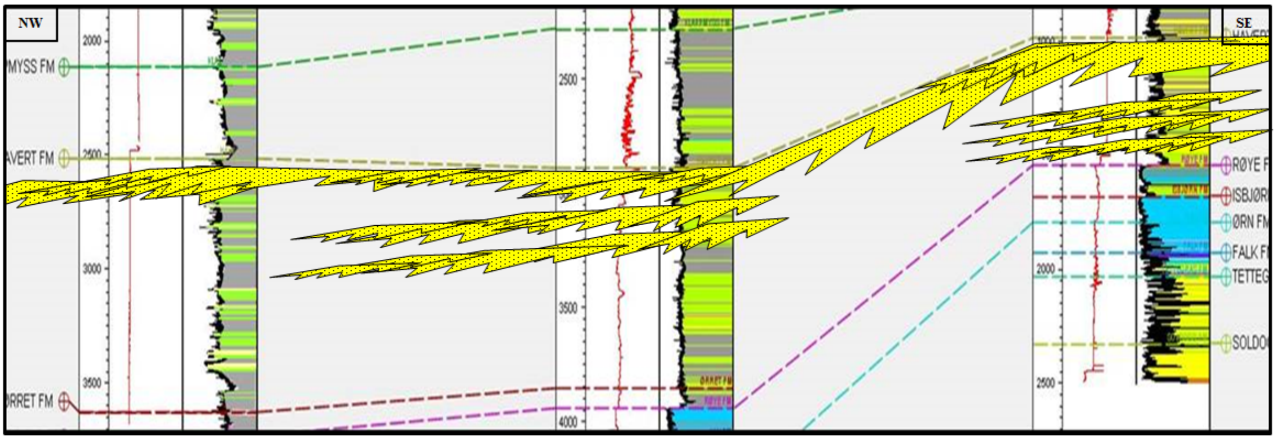


Figure 28 Zoomed in section of the well correlation, representing the Havert Formation of the three wells, with an illustration of the clinoform systems.

5.4 3D seismic interpretation

The 3D seismic interpretation is used for structural identification, which implies the interpretation of the clinoform system, giving a facies classification of the Havert Formation clinoform system. The 3D seismic interpretation will provide an amplitude analysis of the depositional – geometries, with the interpretation of amplitude maps extracted from both the top Havert Formation and the bottom Havert formation. The interpretation on the 3D seismic is tied to the 2D interpretation, with the prograding clinoforms systems within Havert on Norsel.

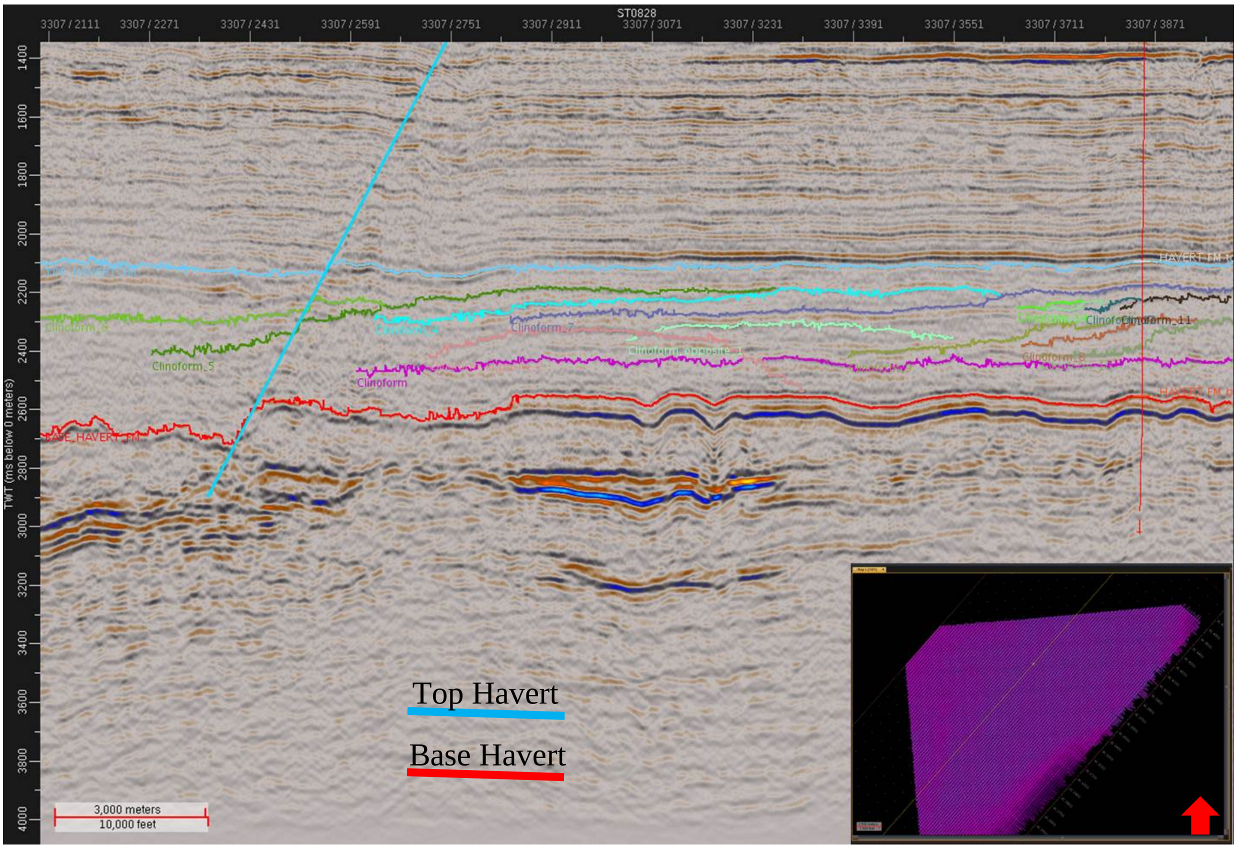


Figure 29 3D seismic section of the inline interpretation of top and base Havert Formation and structural elements, the clinoform systems and fault

First seismic section, Figure 29, displays the inline interpretation of the 3D survey. The interpretation comprises of top and base of the Havert Formation, big – scale and small – scale clinoform systems, and within this inline there is one fault crossing the Havert Formation. The small – scale clinoforms located in the front of the big – scaled clinoforms. These clinoform systems are prograding from northeast to southwest.

There are also clinoforms with opposite direction, in the middle part of the Havert Formation with the direction southeast to northwest. This is displayed in the second seismic section, Figure 30, which represents the crossline interpretation of the 3D survey. The interpretation of this crossline comprises of top and base of the Havert Formation, along with prograding clinoform system from the southeast to northwest and five interpreted faults which affects the Havert Formation.

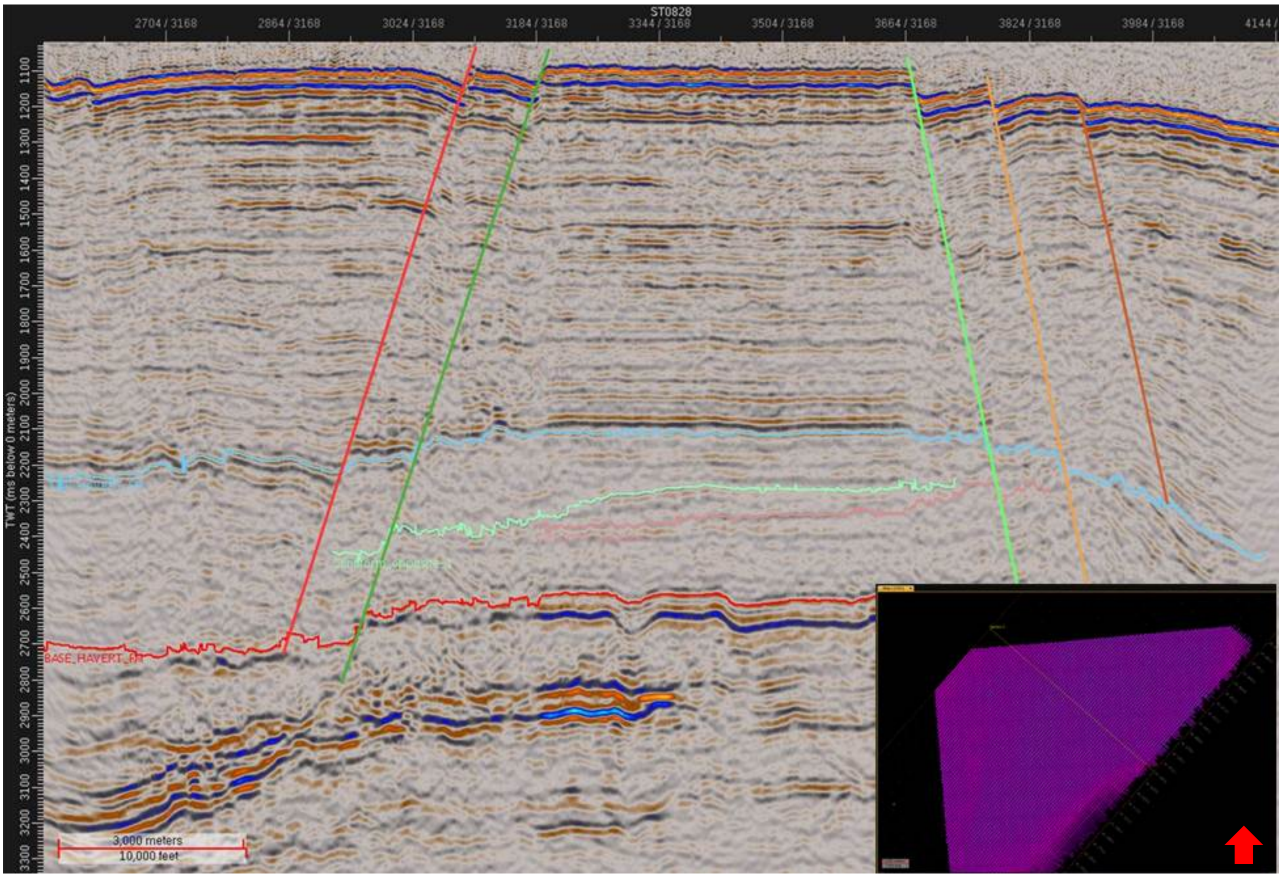


Figure 30 3D seismic section of the cross-line inline interpretation of top and base Havert Formation and structural elements, the clinoform systems and faults

The Havert Formation has been divided into three systems. System 1 is the lower part of the Havert Formation, system 2 represents the middle part of the Havert Formation and the upper part represents the third system. The Havert has been divided into these three systems according to the three main sequences based on the well – interpretation of the Havert Formation; see Figure 31, for the sequence stratigraphic interpretation of the Havert Formation and based on the seismic interpretation with the clinoform systems. The three systems also represent the three main stages of deposition, where the sources of sediment supply vary for each system. The source of sediment supply is based on the interpretation of the amplitude maps and displayed in the following chapter 6. Havert FM on Norsel – Integrated well and seismic.

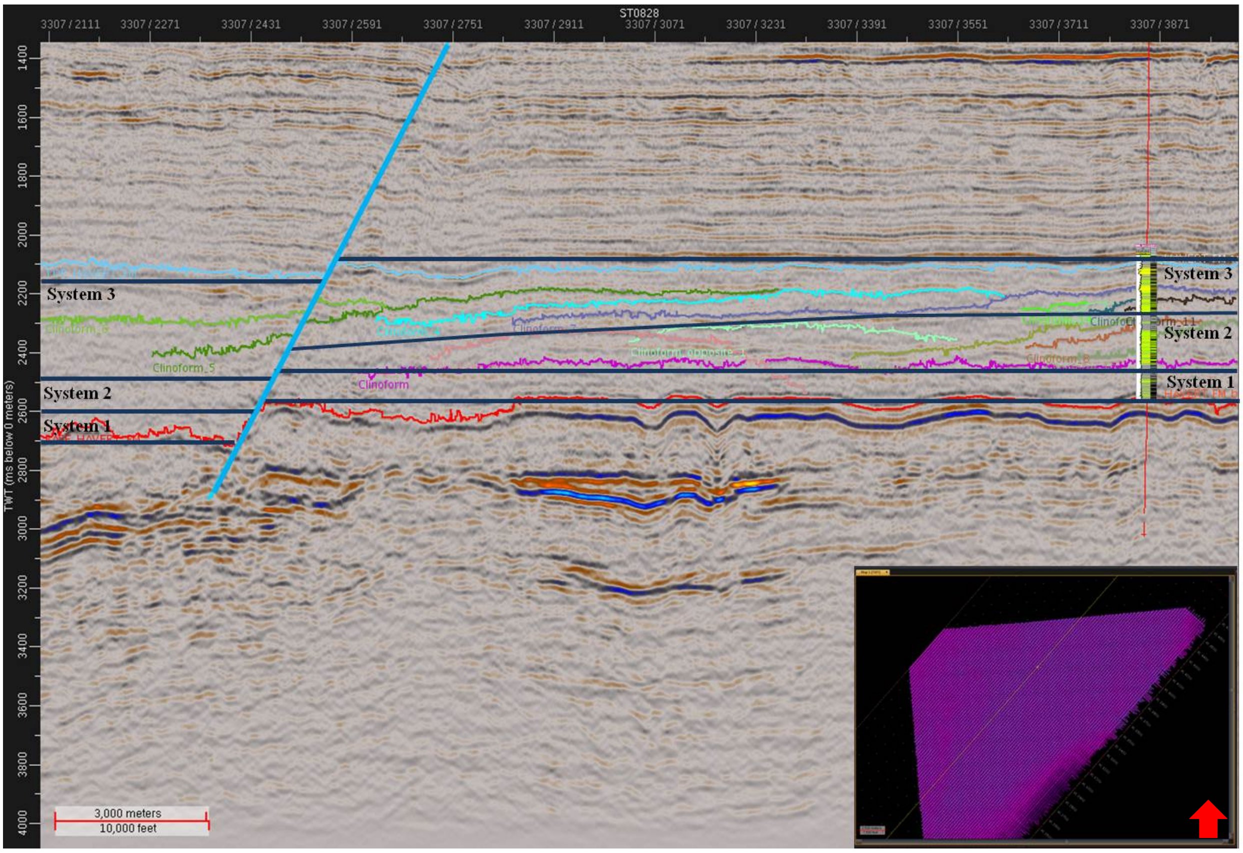


Figure 31 3D seismic section of the inline, displaying the three systems the Havert Formation can be divided in

The amplitude maps are extracted from both the top and base of the Havert Formation 3D seismic. There are three sets on amplitude maps. Each set consists of two identical amplitude maps, where the first in each set is an amplitude map without interpretation and the second one contains interpretation. The interpretation in each set represents a possible river system, the yellow lines, interpreted to be distributary channels based on the previous interpreted datasets, the well interpretation and seismic interpretation. The white dashed curved lines represent the knickpoint position of the clinoforms. The red area on the amplitude map represent the highest amplitude, and therefore most likely the best sedimentary quality, more sandy areas. The green area represent possibly the channels, channel – levees or overbanks/sandbanks. The channel – belts are green out at the edges and red in the middle. These clinoform systems are of large – scale systems, it's a large system, where the channels are fairly small and therefore referred to channel complex, not individual channels. The first set represents the upper part of system 3, see Figure 32 and Figure 33, the flooding event, where some channels reflecting from the lower part of system 3. The second set represents the lower part of system 3, see Figure 34 and Figure 35, displaying the prograding clinoform system with three knickpoints and with southwest direction. The channel complex have a fairly straight direction, possibly some meandering structures and with levee belts located around the channel complex. The third set represents system 2, with the opposite directed, direction towards the northwest, clinoforms containing two knickpoints, see Figure 36 and Figure 37. System 1 has no amplitude map because of any clinoform system interpreted within this system.

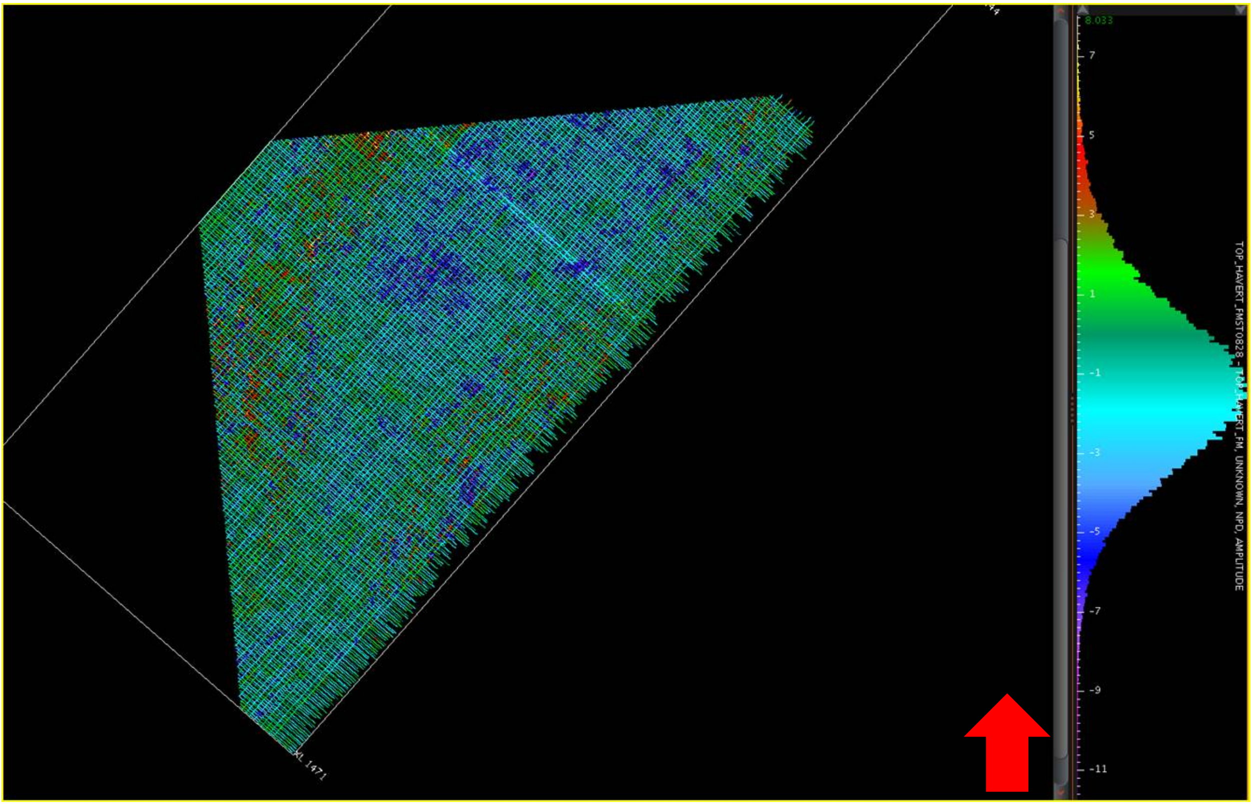


Figure 32 Amplitude set 1, upper part of system 3, amplitude map without interpretation

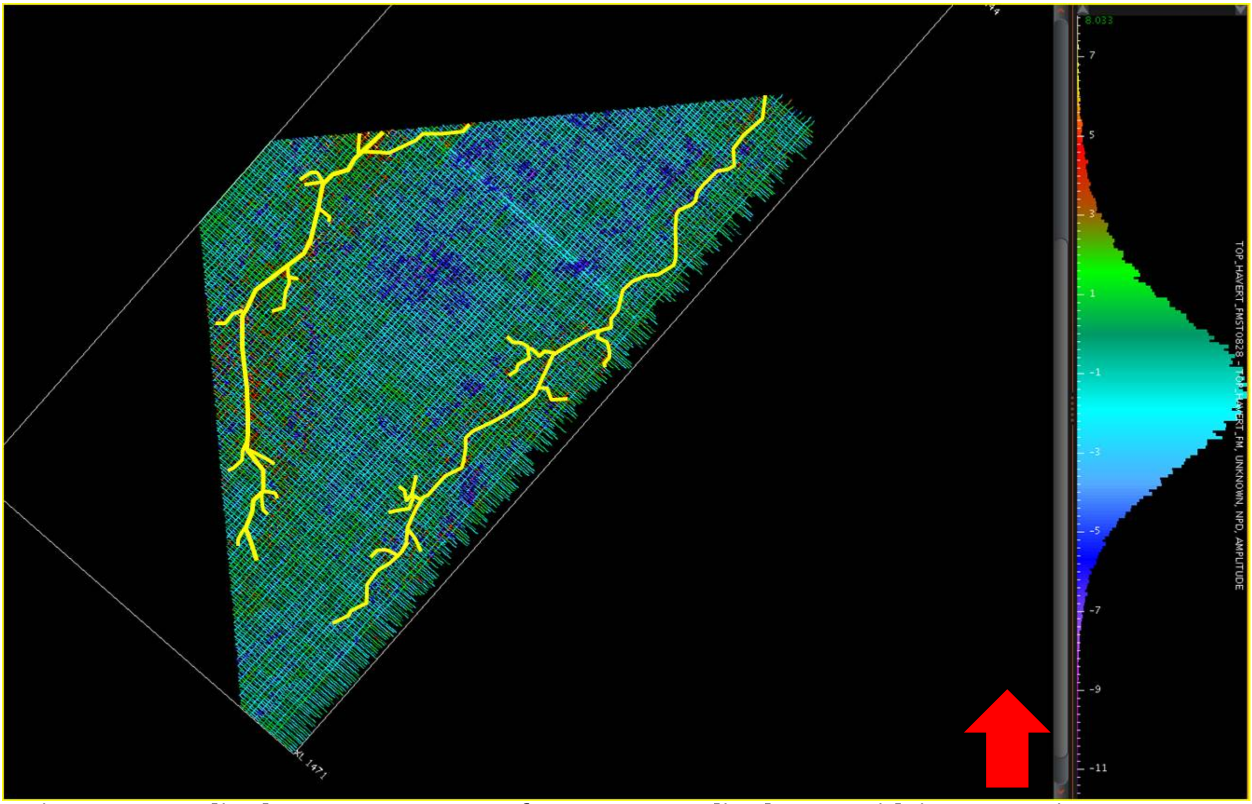


Figure 33 Amplitude set 1, upper part of system 3, amplitude map with interpretation

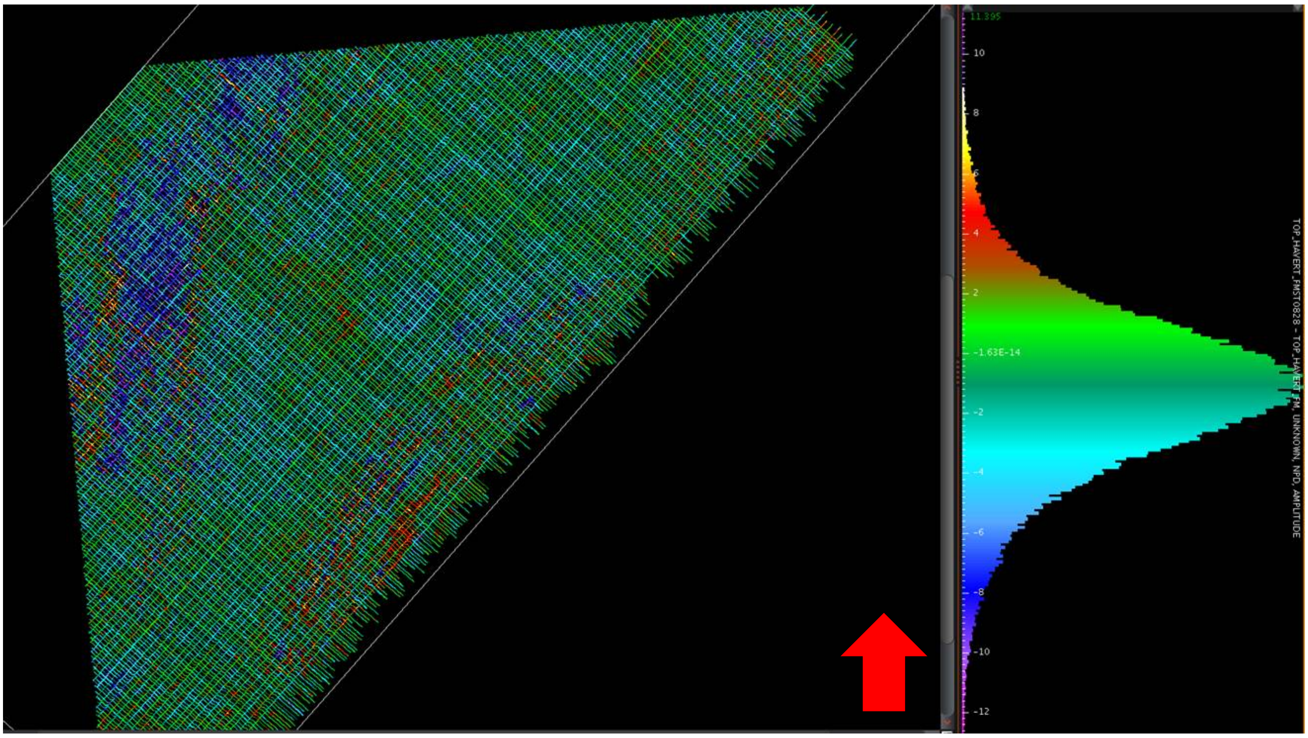


Figure 34 Amplitude set 2, lower part of system 3, amplitude map without interpretation

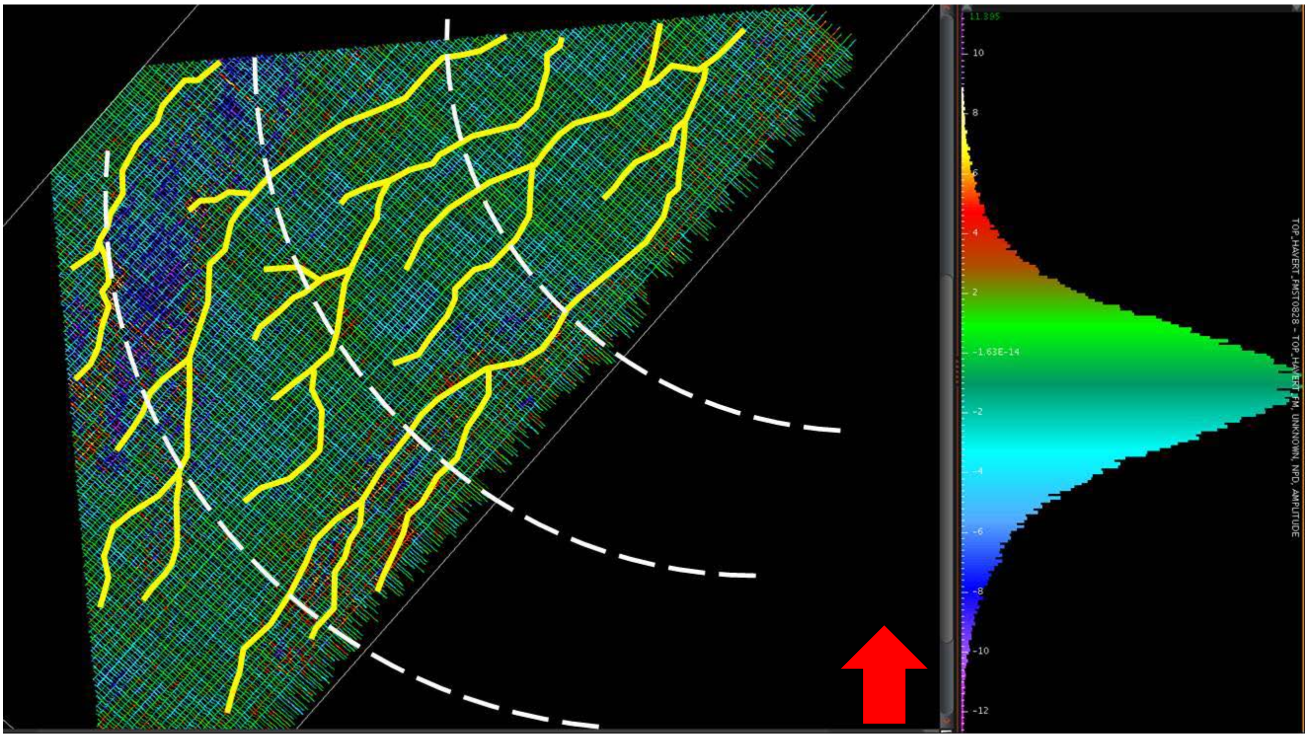


Figure 35 Amplitude set 2, lower part of system 3, amplitude map with interpretation

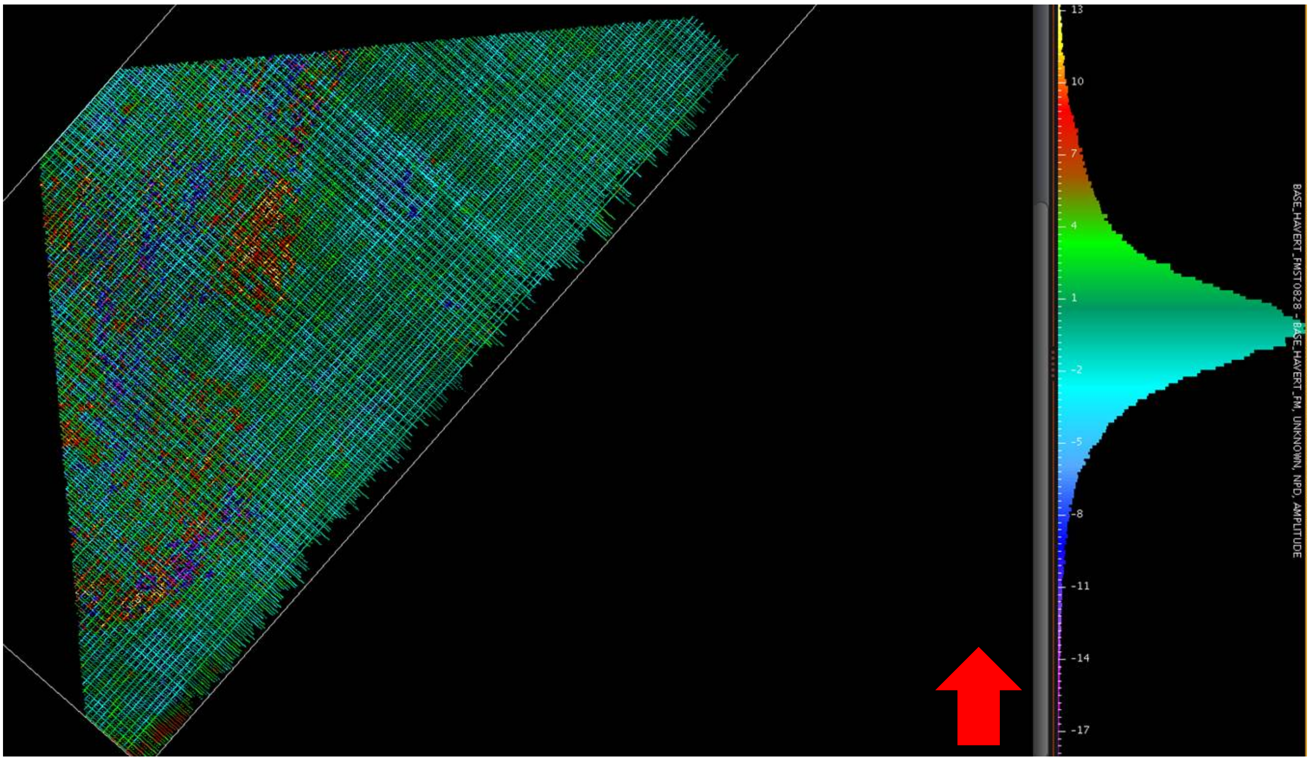


Figure 36 Amplitude set 3, system 2, amplitude map without interpretation

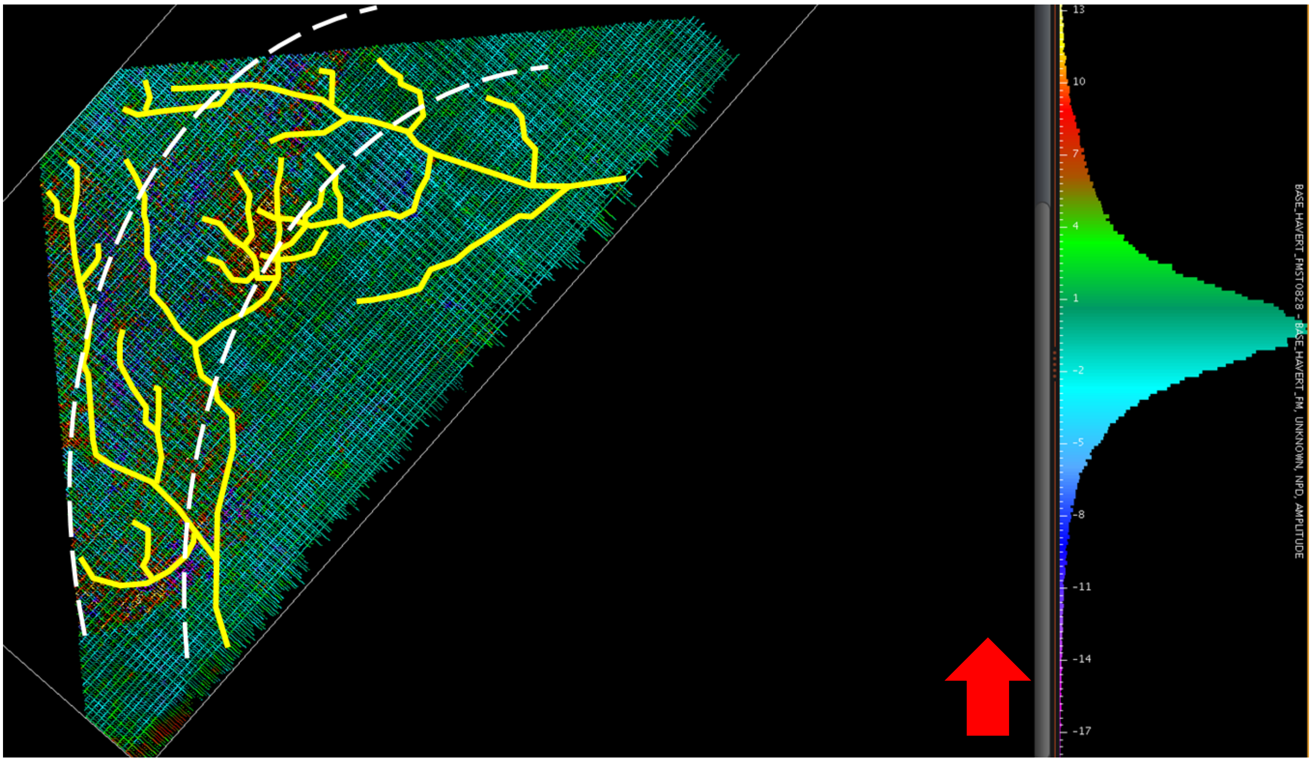


Figure 37 Amplitude set 3, system 2, amplitude map with interpretation

6. Havert FM on Norsel – Integrated well and seismic

6.1 Introduction

Integration of the different datasets, core, well and 3D seismic interpretation, which is supported by regional 2D data and well correlation, creating integrated conceptual geological models and placing Norsel in an predicted large scale depositional environment. Havert FM is interpreted to be a mixed influenced deltaic system, comprises mainly of the two delta systems deep water delta and platform delta. Main facies association within the formations are wave and tide influenced delta plain, distributary channel systems or fluvial systems, delta front and pro delta. According to NPD the Havert Formation located on Norsel is only defined by thin sandstone stringer without good indication of hydrocarbon.

6.2 Havert Stratigraphy & GDE's

The Induan – Early Norian succession shows a total thickness of 2500 m across the Norwegian sector, with the four lithostratigraphic formations, Havert, Klappmyss, Kobbe and Snadd, which can each be related to regional regressive – transgressive cycles, with the formation boundaries picked at inferred maximum flooding events (Henriksen, Ryseth et al. 2011). As such the Norsel well can be divided in three seismic scale mega-sequences, where the Havert Formation represents one. Above the Havert Formation a mega-sequence combined with the formations Kobbe and Klappmyss and on top the Snadd Formation. The Havert Formation is the main target for the stratigraphy analysis. The Formation consists of five sequences defined by the genetic sequence interpretation and divided between the maximum flooding surfaces. The entire Havert Formation consists of a large-scale coarsening upwards section with a relative rough flooding on top. Figure 38 displays the well with the prograding clinoforms systems, divided in the four mega-sequences and numbered by which part of the well represents which gross depositional environment, which will be further discussed in the following subchapter 6.3 Havert FM – conceptual geological model.

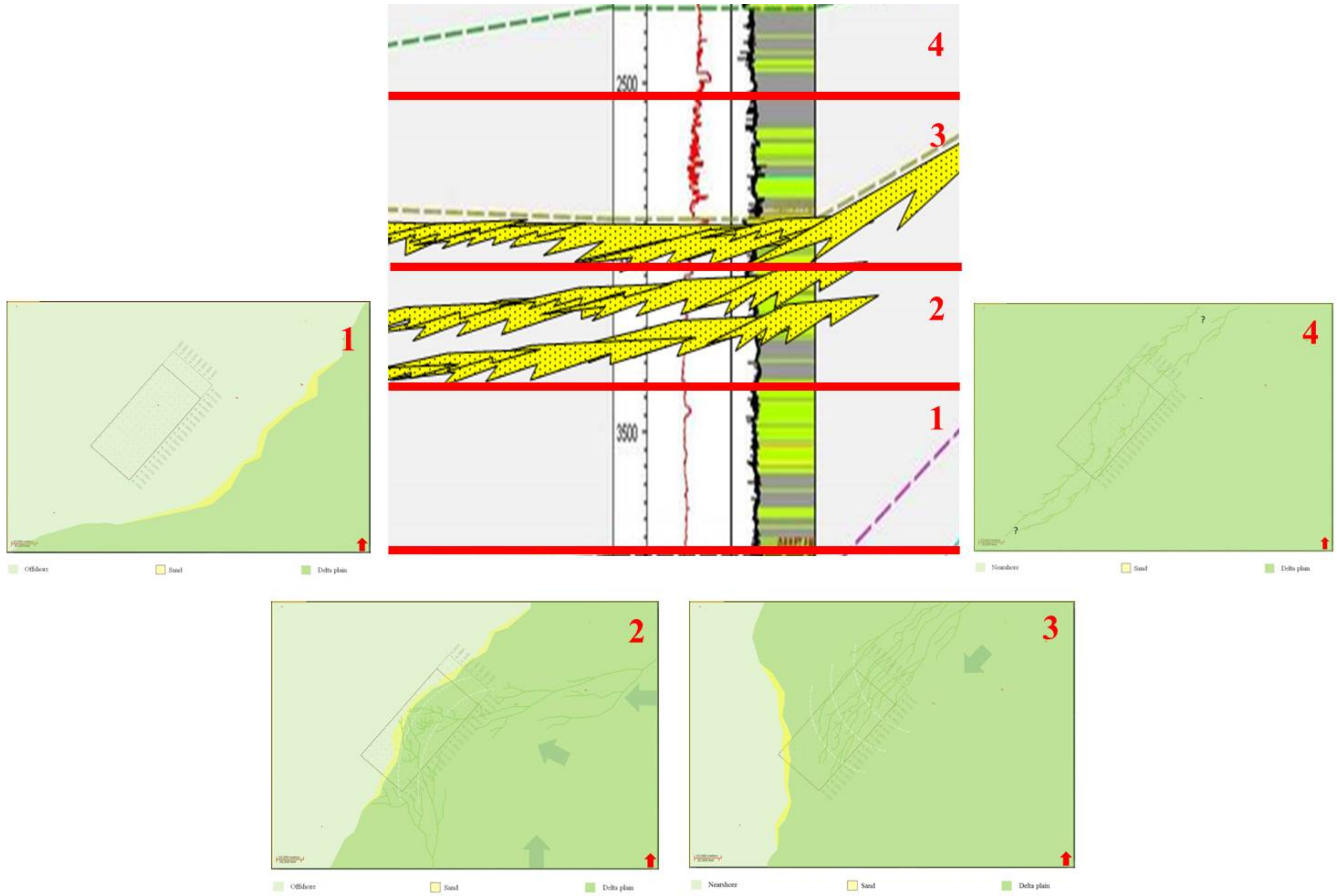


Figure 38 Well data connected to the gross depositional environment – conceptual models

6.3 Havert FM – conceptual geological model

The depositional geometries – conceptual geological models are based on the 3D amplitude maps in chapter 5.3 3D seismic interpretation. The conceptual models are large – scale regional frames. The following conceptual geological models are based on integration of the facies association analysis, sequence stratigraphic analysis which has its support from the seismic interpretation of the Havert Formation. The first figure is the location map, showing where the 3D survey is located relative to onshore Norway, see Figure 39

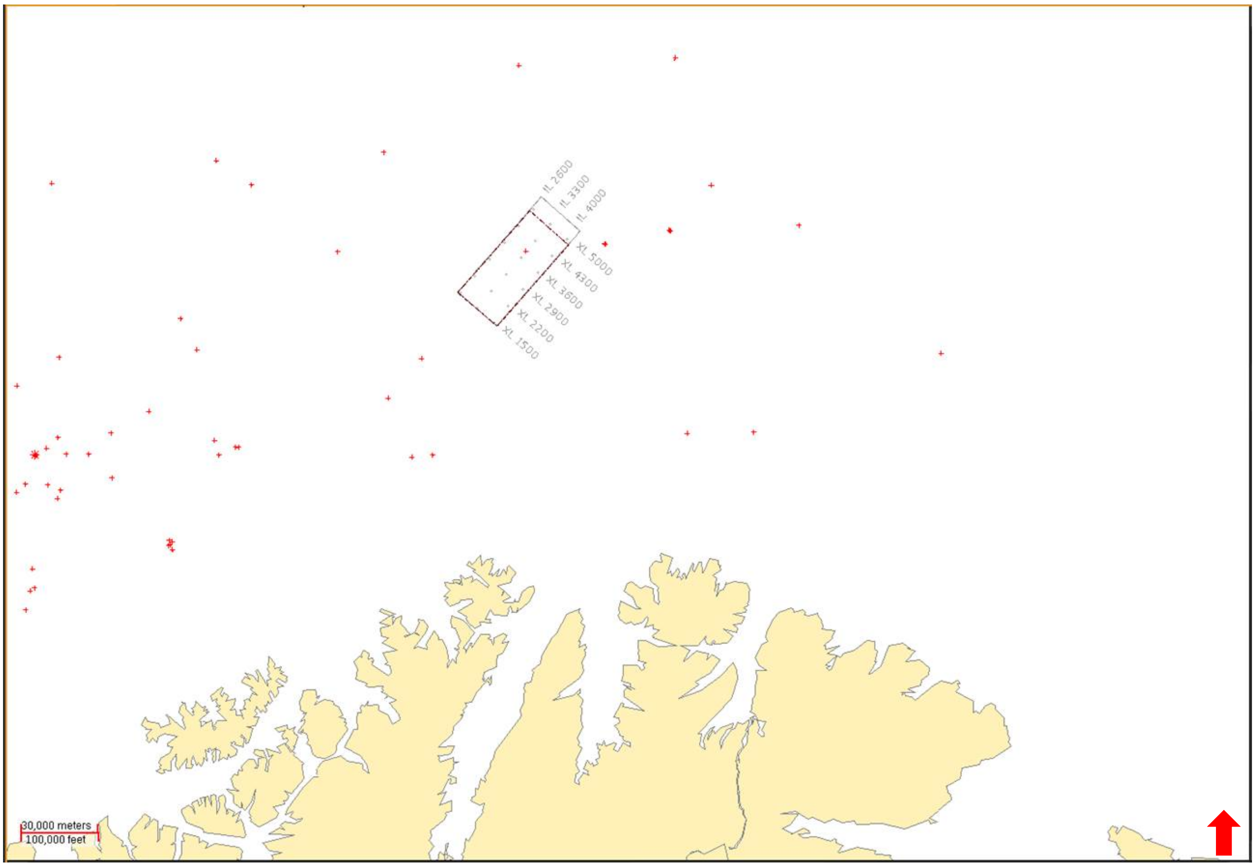


Figure 39 Location map for the 3D survey

The first model is the bottom set of the Havert Formation, representing system 1, see Figure 40, where the delta plain has not yet reached the 3D survey. The delta has not yet reached the 3D survey. The dark green with the yellow boarder indicated the coastline. Figure 40 represents a shelf-prodelta

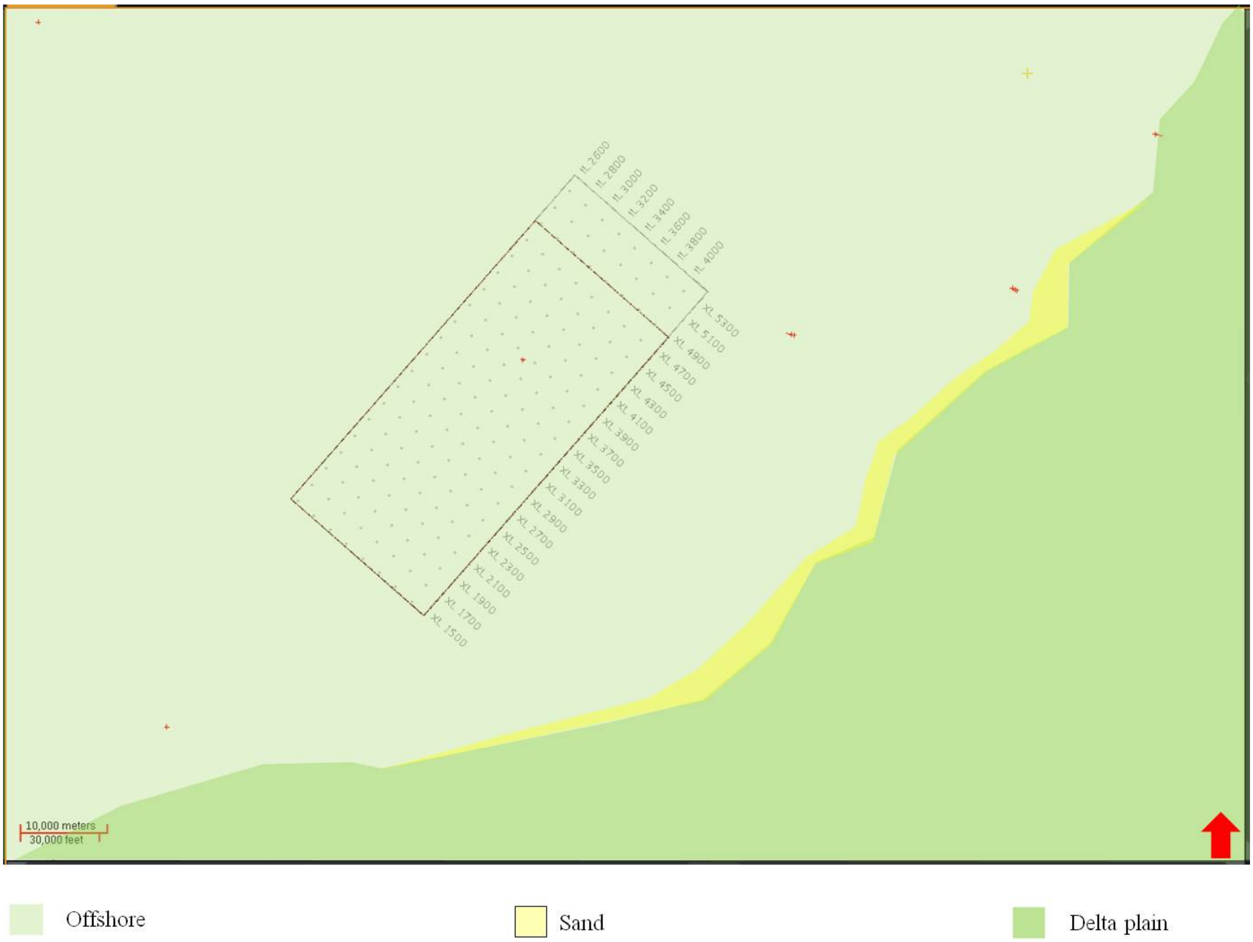


Figure 40 Conceptual geological model representing the bottom of the Havert Formation, system 1

The second model represents the middle section of the Havert Formation, system 2, see Figure 41. The delta has reached the 3D survey. According to the amplitude mad, see Figure 37, the direction of the sediments have its source from both south and east, combined a southeast prograding clinoform system building out in the northwest direction. The white dashed lines indicate the knickpoint of the prograding clinoform systems. The coastline has moved in the northwest direction. The knickpoints represent also previously location of the coastline. Figure 41 represents a deep water deltaic system, with the delta-front.

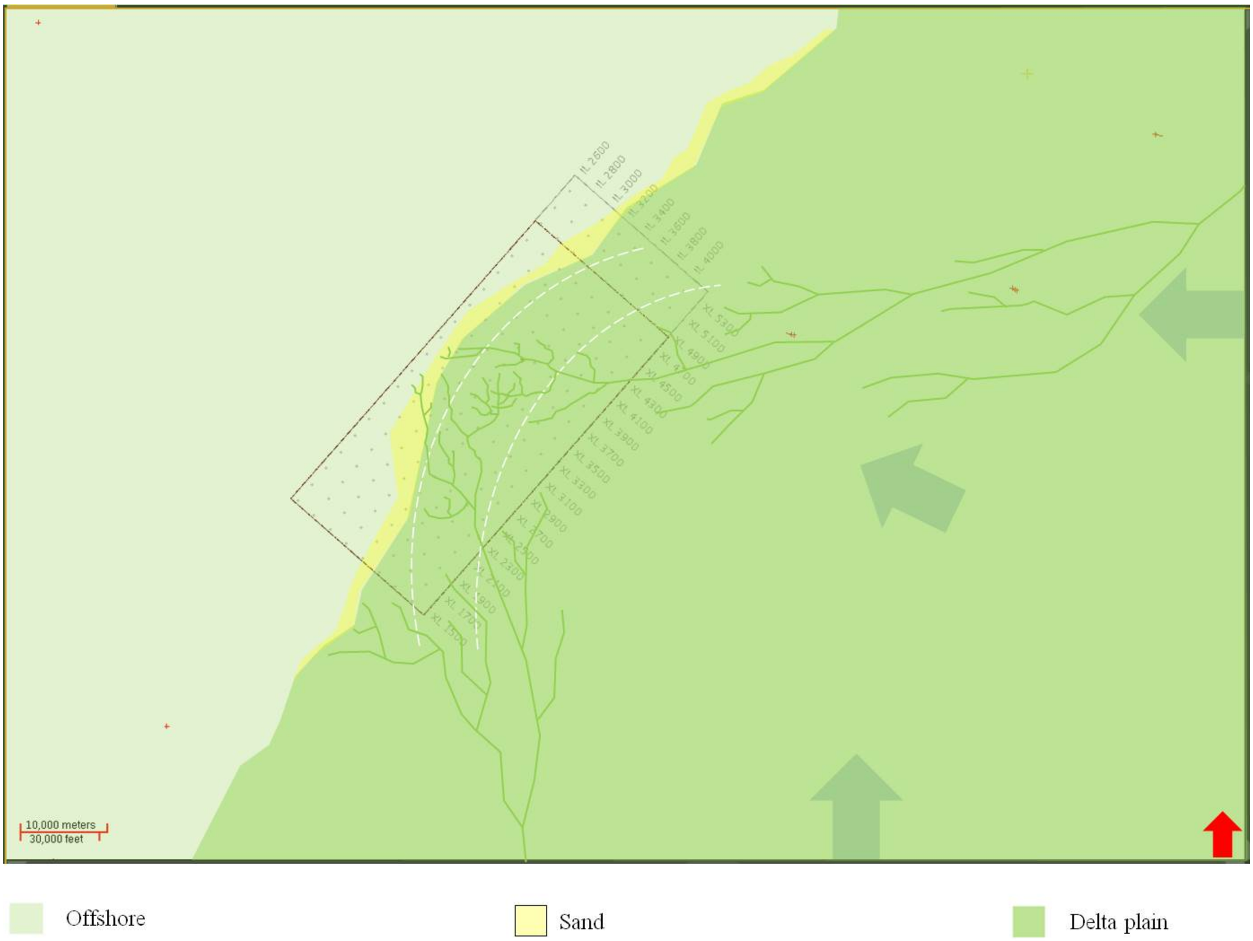


Figure 41 Conceptual geological model representing the middle section of the Havert Formation, system 2

The third model represents the top section of the Havert Formation, the lower part of system 3, Figure 42. System 3 displays the shifting of source area and the coastline has also shifted according to the amplitude map displayed in Figure 35. The source area is now orientated from the northeast. There are three dashed curved lines, representing the knickpoints for this prograding clinoform system that also displays the previously location of the coastline and how it moved in the southeast direction. Figure 42 represents a shallow deltaic system with bays and distributary channels.

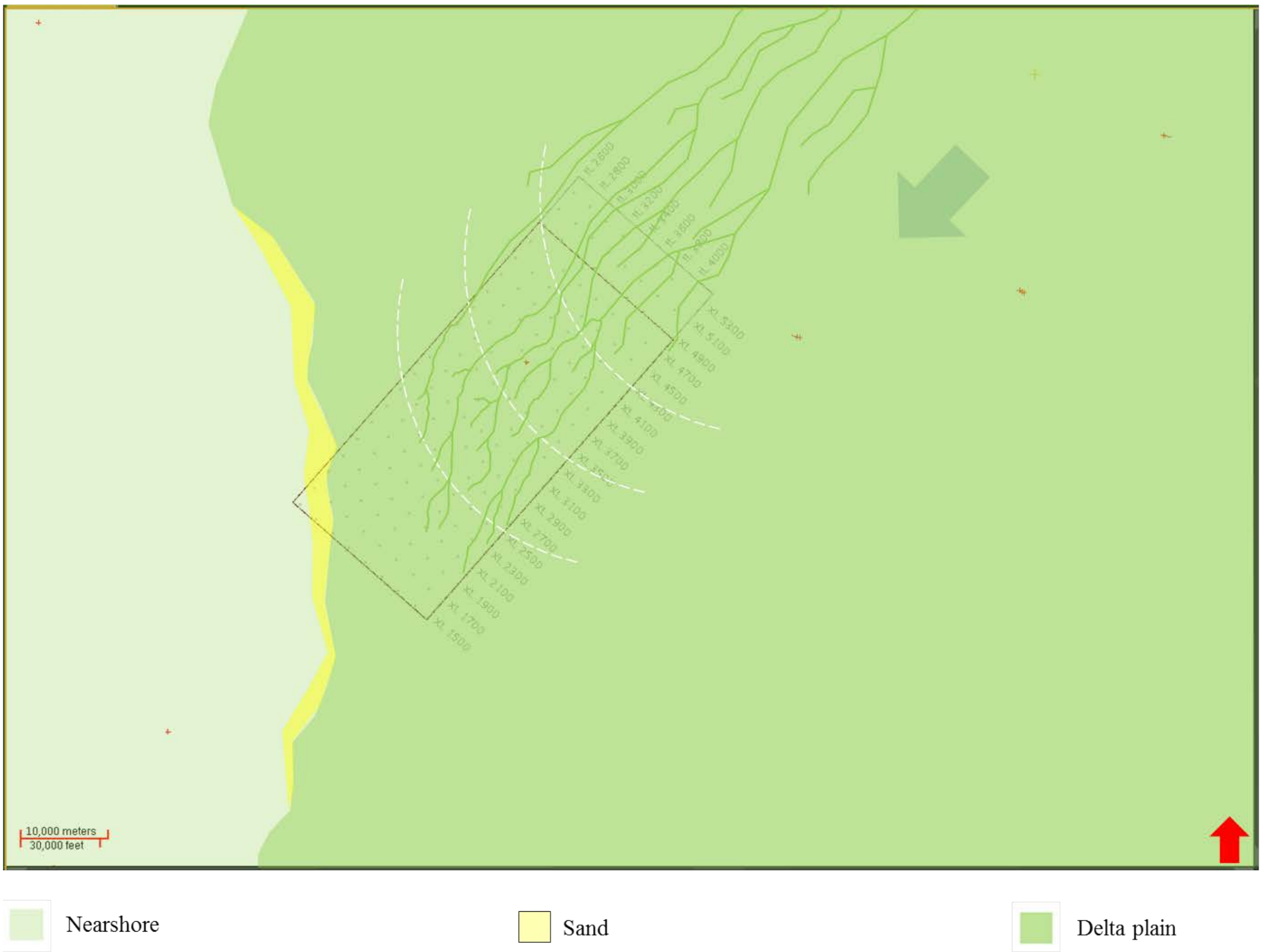


Figure 42 Conceptual geological model representing the lower section of the upper part of the Havert Formation, system 3

The fourth model, Figure 43, represents the top section of the Havert Formation, the upper part of system 3. This model displays the flooding event on the uppermost part of the Havert Formation. According to the amplitude map, some channels are displayed, most likely reflection from the lower part of system 3, therefore the uncertainty of the direction of the channel direction in the northeast and southwest related to the 3D survey, represented by the question marks.

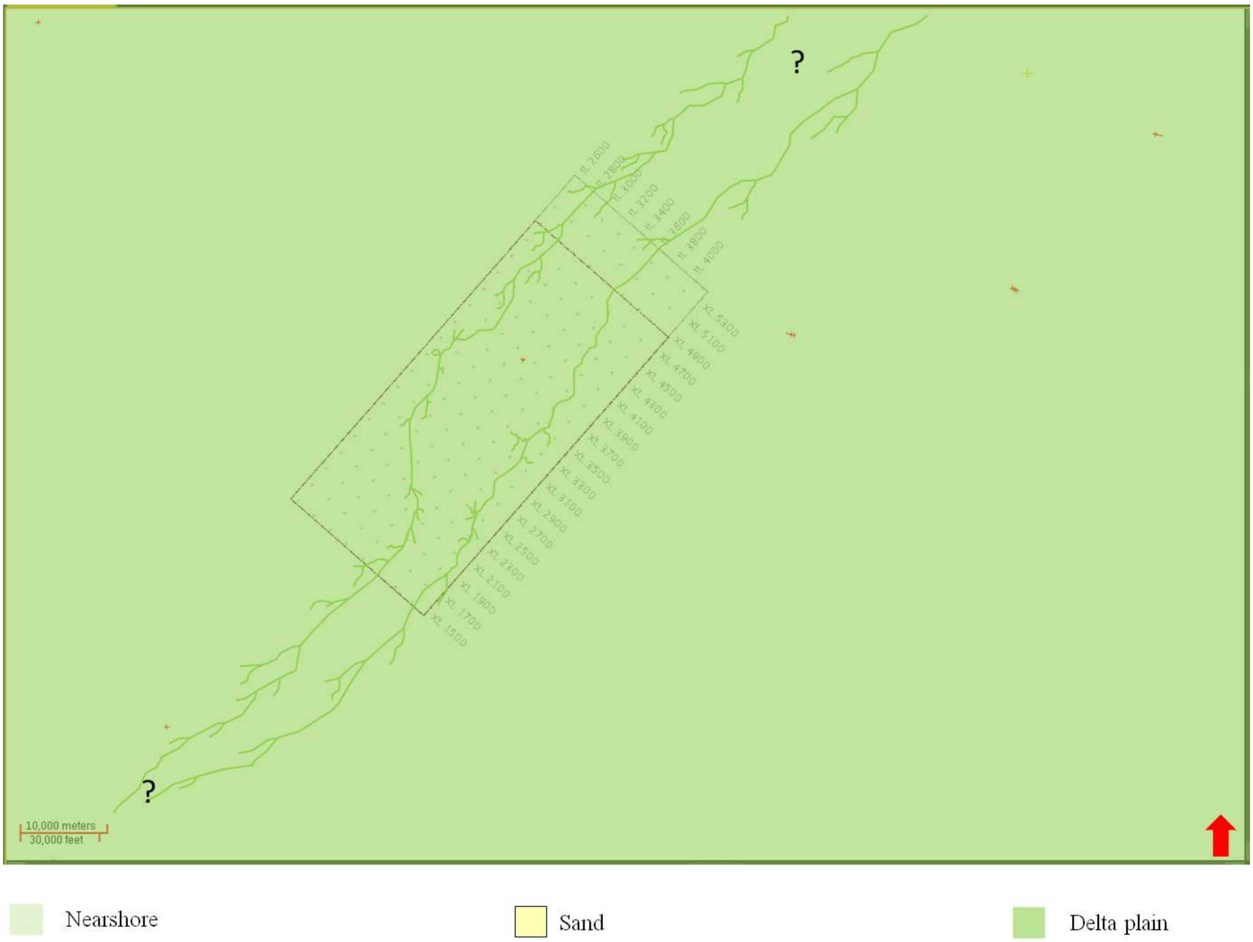


Figure 43 Conceptual geological model representing the top section of the upper part of the Havert Formation, system 3

The second and third model can be tied up to the seismic interpretation and is interpreted to represent clinoform packages. These clinoform packages depend on the position within the basin, either small-scaled clinoforms which are building out over a previous delta-platform or a bit more large-scale clinoform system, at the front of the delta. Tied up to the seismic, there are two main deltaic depositional systems. These two deltaic systems are represented in the conceptual geological models Figure 41 and Figure 42 and also displayed in two gross depositional models, Figure 44 and Figure 45. These two models represent a delta which is building out in deep waters, deep water delta, and a delta which are located more on top of a platform, a shallower delta, platform delta. Within these two there can be expected variation in facies associations. Model 2, located on top of a delta platform, the water the delta is building out in is shallower, therefore it is expected that waves will be damped, which will lead a less wave-influenced delta, and may be the reason why it represent more tide-influences delta. Moving beyond the prograding clinoform system, a delta is located in deeper waters, a deep water delta. The deep water delta is dominated by other aspects like gravitational processes and is more wave-influences.

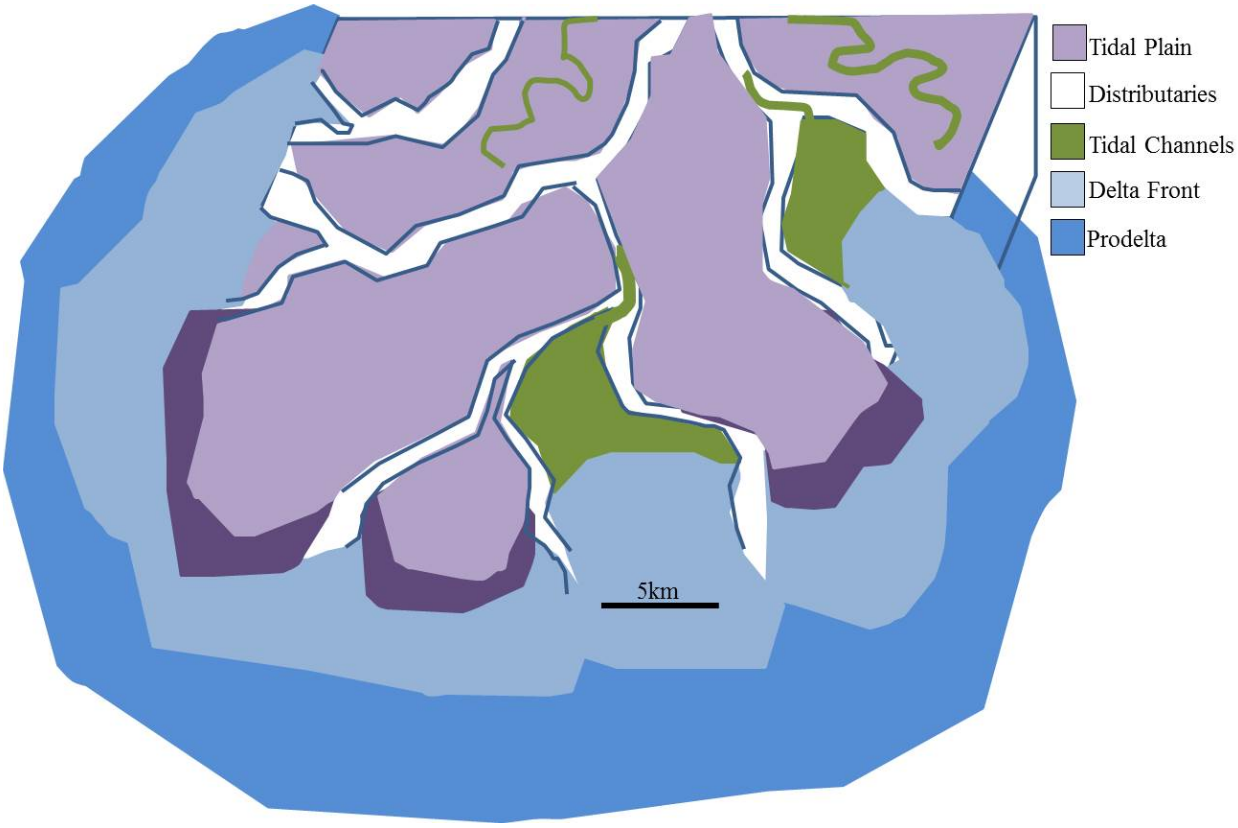


Figure 44 Delta model 1: Deep water delta

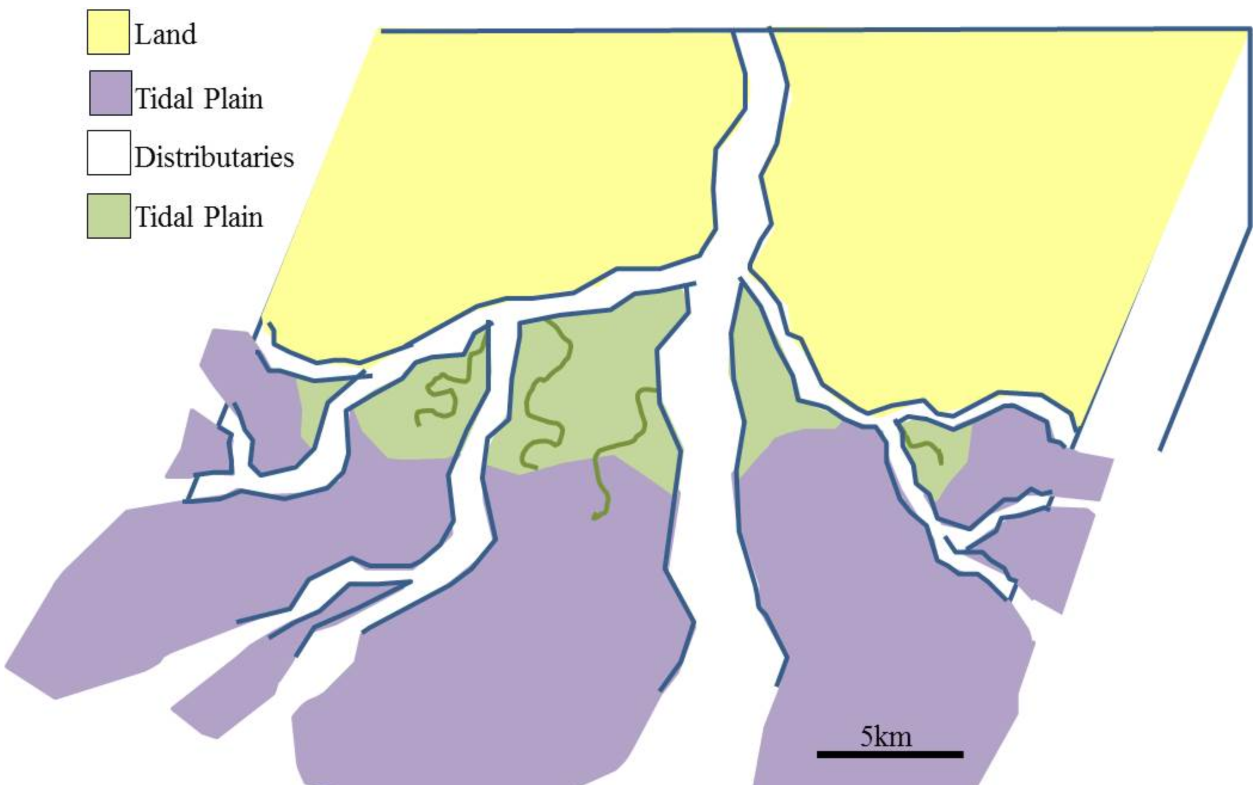


Figure 45 Delta model 2: platform delta

6.4 Havert Formation, Barents Sea

According to the NPD's webpages only thin sandstone strings were encountered between 2280 m to 2310 m without good indications of hydrocarbons. It was drilled to 2913 m where a sudden increase in drilling velocity was experienced. Fluid flowing into the hole and high gas readings indicated top reservoir (Havert Formation, Dienerian age) at 2913 m.

According to the core interpretation there are several indications of more than just thin sandstone strings. Throughout the Havert Formation, within the well there have been interpreted depositional environments like fluvial systems mixed-influenced delta plain, delta front and prodelta sections. With the correlation of Finnmark platform, Norsel and Norvarg, there is a connection of the prograding clinoform systems. In Figure 46 it is shown by a cartoon, the different prograding delta systems within the depositional environments and where these environments are located. The fluvial system on top, transgressive system beneath, then there is a delta plain, with a thick delta front beneath and a prodelta at the bottom. Combining this with the two deltaic models, Figure 44 and Figure 45, the deep water delta would be located around location 1, delta which is dominated by gravitational processes and is more wave-influenced. The platform delta, the second deltaic model, would be located around location 4, where the delta is building out in shallower waters and therefore it is expected that waves will be damped, which will lead to less wave-influenced delta, and may be the reason why it represent more tide-influenced delta.

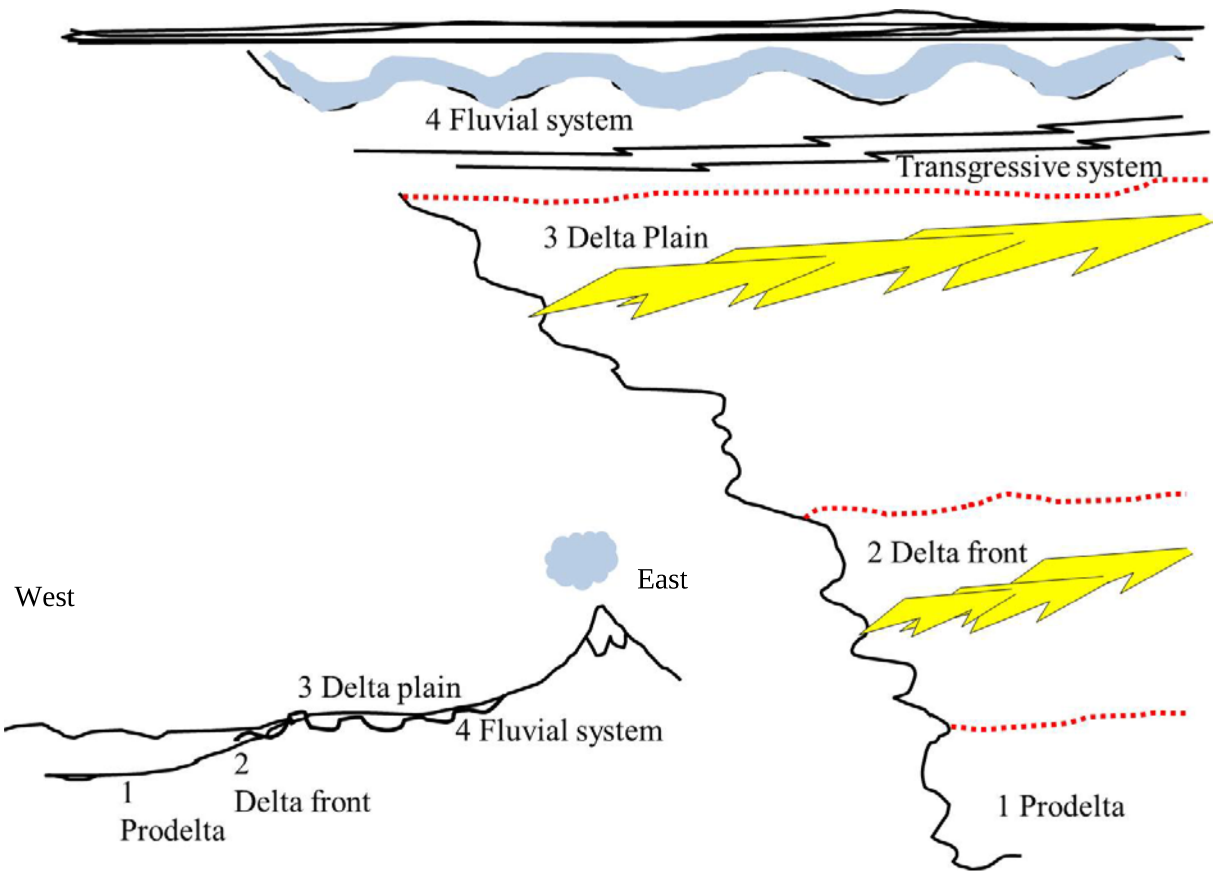


Figure 46 Cartoon displaying speculations on controls on regional variability

7. Sequence architecture

7.1 Introduction

The sequence stratigraphic analysis of the Havert Formation was conducted to ensure a more solid correlation of depositional package to develop a more detailed framework for the depositional environment within the formation.

7.2 Sequence stratigraphy

“The sub-division of sedimentary basin fills into genetic packages bounded by unconformities and their correlative conformities” (Emery and Myers 2009) is perhaps the simplest and the most preferred by the authors of the many definitions of sequence stratigraphy over the years. Sequence stratigraphy is used to provide a chronostratigraphic framework for the mapping and correlation of sedimentary facies and for stratigraphic prediction (Emery and Myers 2009). The Induan – Early Norian succession shows a total thickness in excess of 2500 m across the Norwegian sector, with the four lithostratigraphic formations, which is, in ascending order: Havert, Klappmyss, Kobbe and Snadd. Each of these can be related to a regional regressive – transgressive cycles, with the formation boundaries picked at inferred maximum flooding events (Henriksen, Ryseth et al. 2011). As such we can divide the Norsel well in three seismic scale mega-sequences, and those mega-sequences comprises of the Havert Formation at the first mega-sequence, the second comprises of the Klappmyss Formation and Kobbe Formation and the third mega-sequence is the Snadd Formation on the top of the well. The first seismic scale mega-sequence, the Havert Formation is the main target for the sequence stratigraphic interpretation, focusing on the upper part of the Formation because that is where the cores are located. The maximum flooding surfaces interpreted on the Havert Formation is based on the definition giving of Galloway, Figure 47, and a defined maximum flooding surface based on log response. The log response is the maximum separation of the neutron and density log.

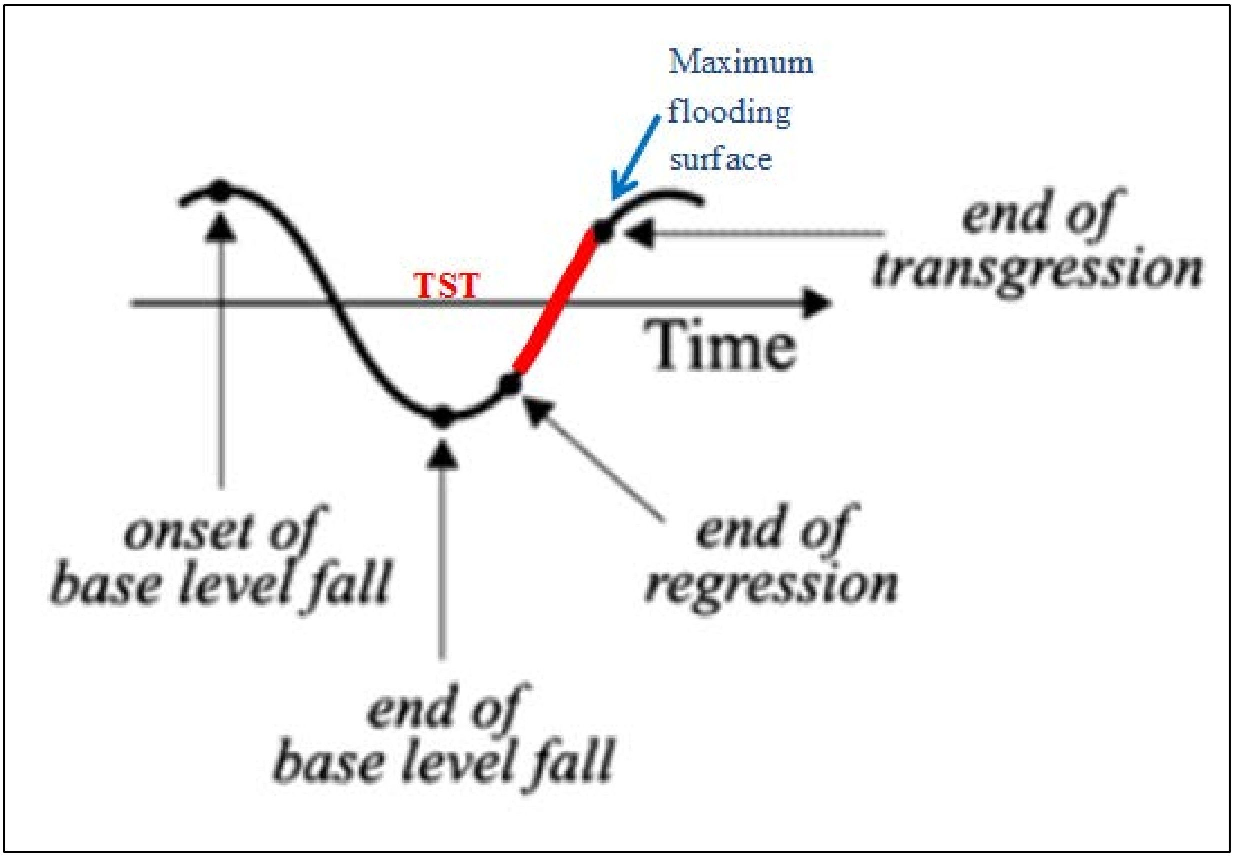


Figure 47 Genetic sequence was defined by Galloway (1989) as "A type of sequence bounded by maximum flooding surface (MFS)"

7.3 Havert Formation

The first figure of the well, Figure 48, represents the entire Norsel well, with a red box indicating where the area of interest is locate, the Havert Formation. The second figure of the well consists of the entire Havert Formation, which has been interpreted in tectonic - , genetic – and para – sequences, see Figure 49. The Formation consists of four sequences defined by the genetic sequence interpretation and divided between the maximum flooding surfaces. The entire Havert Formation consists of a large-scale coarsening upwards section with a relative rough flooding on top. The third figure of the well is a zoomed in section of the upper Havert Formation, which is the main target because of the cores which are located in this upper part of Havert, see Figure 50. The interpretation of the zoomed inn area of the well is also interpreted based on tectonic - , genetic – and para – sequences and is divided in four sequences, again defined by the genetic sequence interpretation and divided between the maximum flooding surfaces. The main sequence stratigraphic interpretation is based in the genetic sequences. The tectonic-sequence may be a bit too large-scale sequence for the Havert interval, with the one change from progradation to retrogradation on the top of the Havert Formation, with a very clear flooding surface. The Para – sequences are represented with more variation of prograding, retrograding and aggradating arrows, which follows the pattern of the gamma ray, but that can be discussed if that really follows the sea – level rise and fall sequences or not, the para – sequences interpretation is a bit more uncertain, and therefore the main sequence stratigraphic interpretation is based in the genetic sequences. Each sequence from the bottom to the top of the Havert Formation is getting thinner, the reason for that is unclear, but could be because of the rate of the sedimentation combined with the sea – level change. There are clearly defined flooding surfaces which separated each sequence within the genetic sequence interpretation. Where the #5 core is located there is a fining upwards sequence representing a delta plain with a river system, such as fluvially or distributary channels, on top, indicating a near coast environment. This is a combination of progradation with erosional surfaces and base of regressive surface. Where the #6 core is located there is also a fining upwards section, implying the locating of a tide and wave influenced delta plain. Also here, this is a progradation sequence with possible erosive surface. Where the #7 core is located, a somewhat fining upwards section, implying a delta front, but more aggradating, indication of mouth bar or tidal bar, with the sequences stratigraphic progradation and regression or transgression framework.

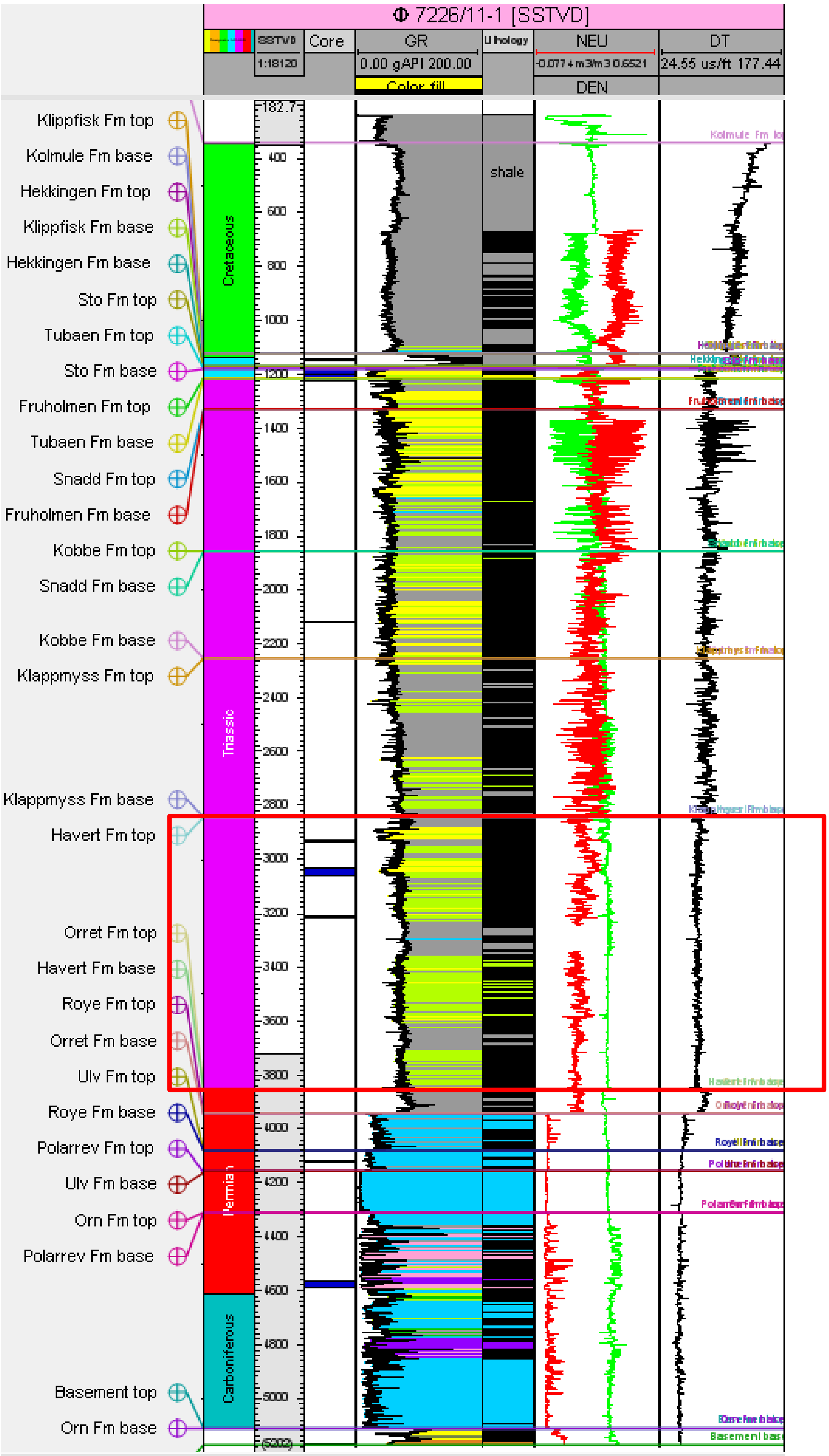


Figure 48 Gamma – ray of the entire Norsel well, displaying lithology together with density and neutron logs. The red box represents the Havert Formation.

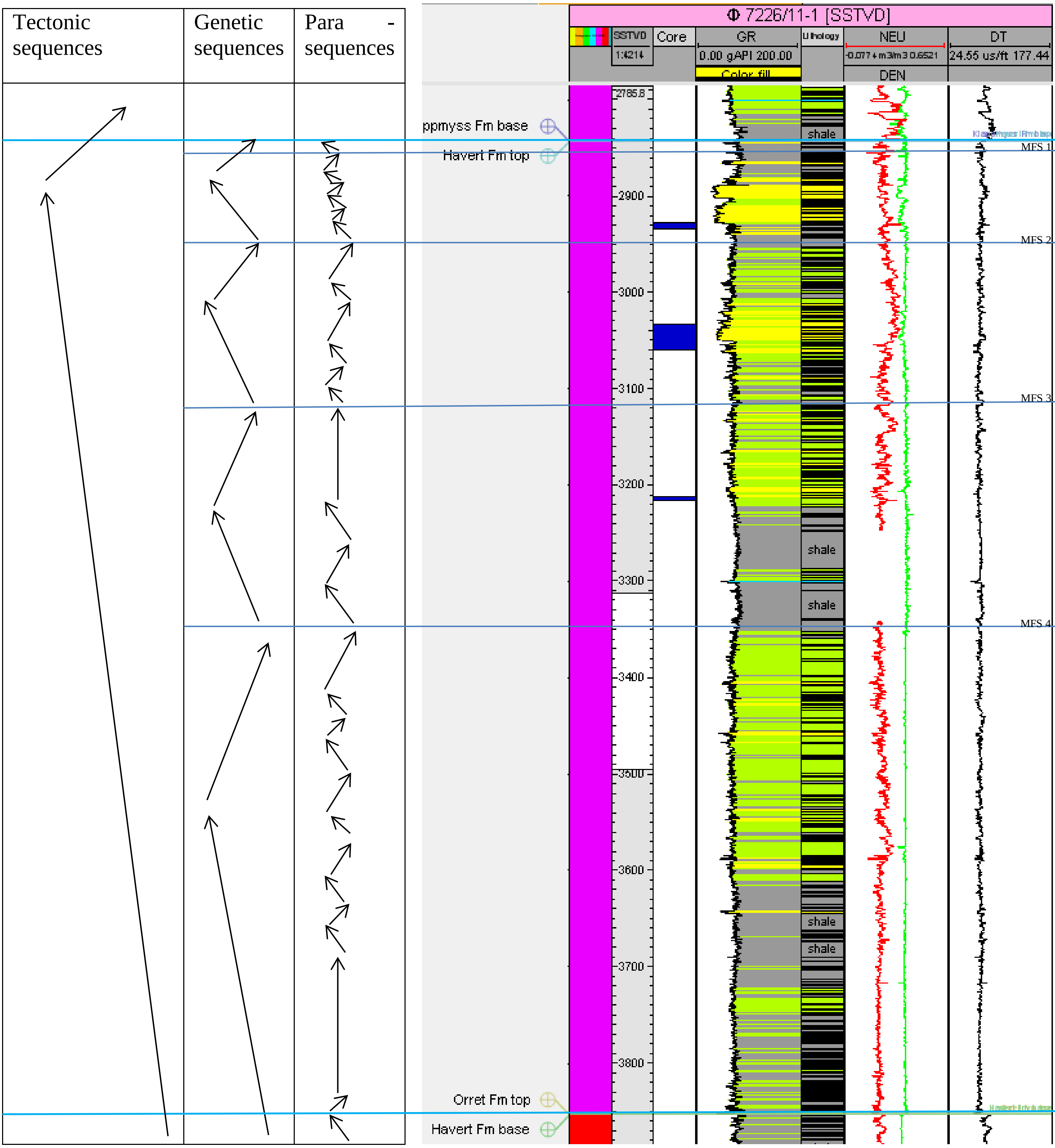
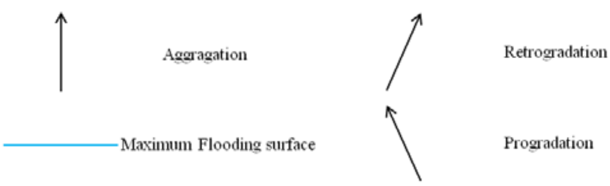


Figure 49 Sequence stratigraphic analysis of the Havert Formation



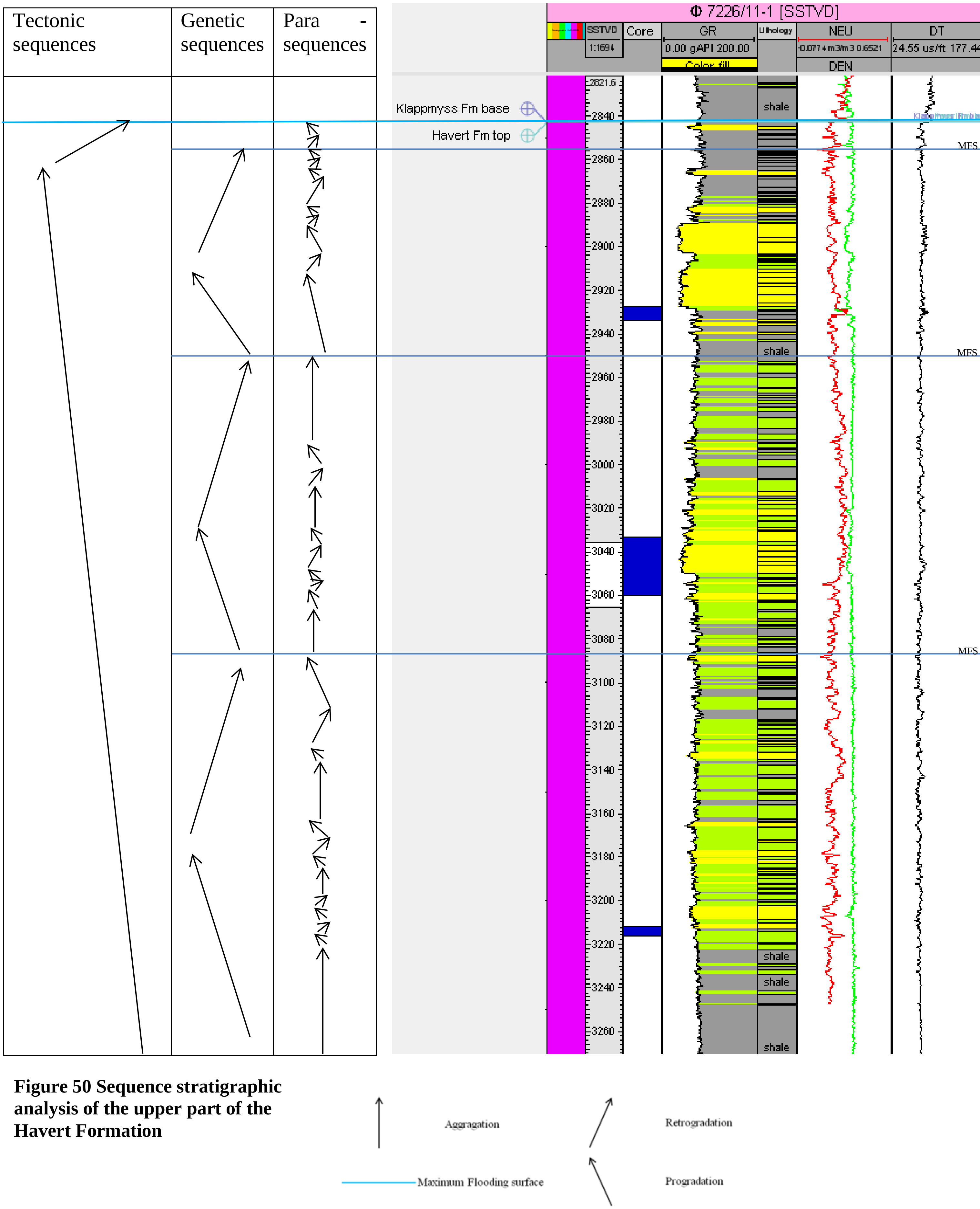


Figure 50 Sequence stratigraphic analysis of the upper part of the Havert Formation

8. Discussion

8.1 Havert FM vs. NPD

The Havert Formation has been has been interpreted to be dominated by mixed –influenced delta systems with impacts from fluvial inputs, tidal action and drift currents. The only information about the Havert Formation according to the NPD’s webpages is that Havert Formation is of only thin sandstone strings were en encountered between 2280 m to 2310 m without good indications of hydrocarbons. It was drilled to 2913 m where a sudden increase in drilling velocity was experienced. Fluid flowing into the hole and high gas readings indicated top reservoir (Havert Formation, Dienerian age) at 2913 m.

8.2 Havert FM

According to the different interpretation methods of the Havert Formation, the Formation has similar aspects as the Mahakam delta, and therefore the Mahakam delta is used as an analog for the Havert Formation interpretation of a mixed – influenced delta system. Sand is relatively minor in this type of system, and is mainly confined to the distributaries and tidally modified mouth bars (Walker and James 1992). Interdistributary tidal channels may actually incise deeper than the distributary channels, but usually mud filled and beach ridges are developed, but are composed of retransported lignite than quartz sand (Walker and James 1992).

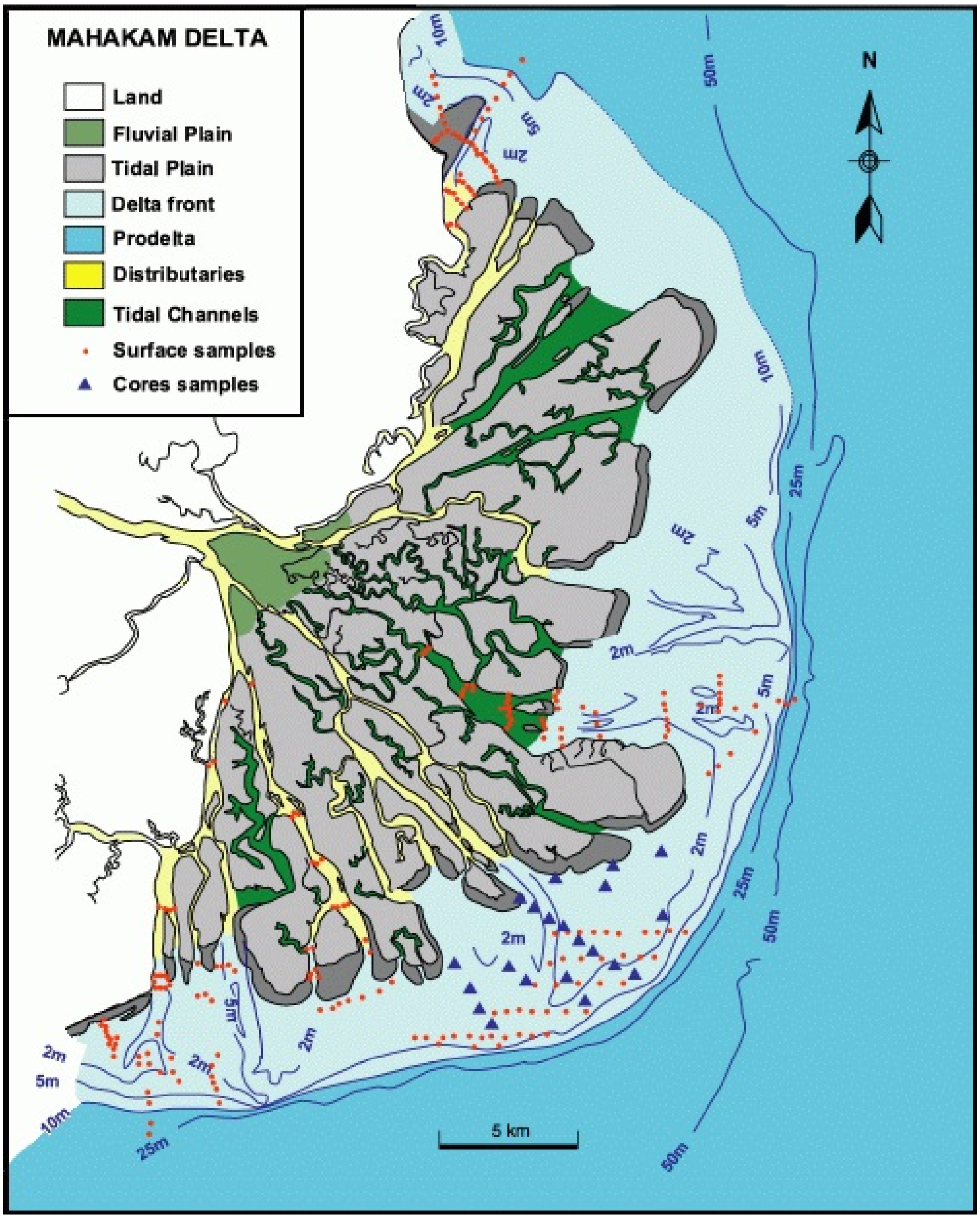


Figure 51 Mahakam delta sedimentological features (Lambert 2003)

Mahakam delta is a classic example of a mixed – influenced delta which shows a combination of the effects of river, wave and tidal processes (Walker and James 1992), see Figure 41. The Mahakam delta is located in Indonesia on the east coast of Kalimantan Island (Lambert 2003). Like all modern deltas, this delta is a recent feature, meaning that this delta has been developed in the last phase of the Holocene transgression. The development has continued over a 5000 to 7000 year period, during which delta progradation gave rise to a system comprising approximately 1300 km^2 of subaerial delta plain, 1000 km^2 of delta front and 2700 km^2 of prodelta accumulations (Lambert 2003). The delta plain, delta front and prodelta is the three general morphology radially concentric systems the Mahakam delta can be divided into.

The delta plain forms the subaerial part of the delta (Lambert 2003). The delta plain can be subdivided into a tidal delta plain and a fluvial delta plain. The fluvial delta plain is characterized by highly compacted and well drained ground, with its width between 10 and 20 km. The tidal delta plain is characterized by its low elevation that consequently is subject to daily inundations (Lambert 2003). The tidal deltaic plain is incised by both distributaries and tidal channels, with width ranges between 20 and 30 km (Lambert 2003). The delta front is an intertidal to shallow subtidal platform with width ranges between 8 and 10 km. The inner part is made up of extensive tidal flats (Lambert 2003). Perpendicular to the coast forming bars and shoals the topography consists of linear undulations. Similar to the delta plain, the delta front too is incised by distributary channels. These distributary channels extend seaward to its limit, terminating in a mouth bar (Lambert 2003). The prodelta is a smooth seaward slope, the inner part set off by an abrupt break in the slope at the 5 m isobath and the outer limit is between the 60 and 70 m isobaths. The width of the prodelta shows a sharp asymmetry, which is an effect of the drift current (Lambert 2003). The Mahakam delta is a deltaic system which is controlled by three factors: fluvial input, tidal action and drift currents which may act in parallel or in opposition (Lambert 2003). The cores of the Havert Formation suggest the same facies associations as within the Mahakam delta. Facies associations like fluvially and tidally influenced delta (FA2), wave – influenced delta (FA5), delta – front (FA4), pro – delta (FA3A and FA3B) and distributary channel (FA1), see Table 1: Havert Formation Facies association. The seismic implies the same architecture as the Mahakam delta according to the conceptual geological models based on the amplitude maps extracted from the 3D seismic interpretation, see chapter 7. Depositional geometries – conceptual geological model. And according to the sequence stratigraphic well interpretation the Havert Formation, consisting of the delta systems, represent a large – scale coarsening upwards section with a relative rough flooding on top, similar to the Mahakam delta development in the last phase of the Holocene transgression, see chapter 5.1 Sequence stratigraphy.

8.3 Predictions

The Havert Formation is a complex system. The sediment sources are from south-east and north, north-east. Mainly, the Havert Formation is composed of heterolithic, sand and silt, protected tide-wave influenced deltaic systems which characterize Havert. Looking at a large-scale perspective, within the Barents Sea, Norsel is located within a bay, protected from high energy processes. Moving further out from the bay in a location which is more wave dominated delta systems, the reservoir have a possibility to be of better quality.

8.4 Further work

Scale to predict better Havert systems, where there are more clinoforms systems located, likewise the well located on Norsel High, perhaps in an earlier phase Havert, where the basin is more open, and there are possibility for better quality reservoirs.

9. Conclusion

9.1 Havert on Norsel High

Based on this study, the Havert Information has been interpreted as a mixed – influenced deltaic system, where this interpretation is based on core description, well interpretation, 2D seismic and 3D seismic interpretation. Depositional systems influenced by fluvial input, tidal action and drift action in the form of wave activity. By using core description of the Havert Formation from the three core samples of the Norsel well 7226/11-1 on Norsel High, the well has been divided into facies association. Based on the facies associations the Havert Formation has been provided with the basis of being linked to the depositional environments. Further interpretation, well interpretation, has backed up the facies associations, by interpreting the well based on sequence stratigraphy. Both the entire Havert Formation and the upper part of the formation, where the cores are located, have been interpreted in tectonic sequences, genetic sequences and para – sequences. The well has been divided in sequences with the boundary between the sequences defined by the maximum flooding surfaces. For the seismic interpretation, the 2D seismic were interpreted for the purpose of a semi – regional framework, and a step – by – step process were performed on the seismic line where the well is located. This step – by – step process provided structural interpretation of the clinoform systems of the Havert Formation, which were confirmed by the 3D seismic interpretation. The 3D seismic interpretation also provided amplitude maps extracted from both top and base Havert Formation, displaying the interpreted clinoform systems, giving a seismic facies classification of the Havert Formation clinoform system and resulting in depositional geometries creating conceptual geological models of the different systems dividing the Havert Formation representing the three stages of the deposition. By combining the different dataset the Havert Formation can be compared to the Mahakam delta system as an analog system. The Havert Formation and the Mahakam delta are sharing the same main facies association, geometries and sequence of deposition.

9.2 Regional implications

Within the Barents Sea, Norsel High is located within a bay, protected from high energy processes. Based on core interpretation, seismic and well interpretation, Figure 46 Cartoon displaying speculation on control on regional variability, indicated the different environment, fluvial system, delta plain, delta front and prodelta. Based on the interpreted datasets and the facies associations the regional implications show a fluvial system to the east and a prograding delta system to the west, where this delta system in the west, northwest, most likely would be wave-dominated, with good-quality reservoirs and in the east moving up in a more fluvial system where also here there most likely would be of good quality.

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