



University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Petroleum Geosciences Engineering	Spring semester, 2013 Open
Writer: Bereke Kairanov	<hr/> (Writer's signature)
Faculty supervisor: Rodmar Ravnås External supervisor(s):	
Title of thesis: Reservoir characterization of Sognefjord and Fensfjord formations across Gjøa field, North Sea, Norway.	
Credits (ECTS): 30	
Keywords: Reservoir characterization Gjøa field Sognefjord formation Fensfjord formation	Pages:58 +CD Stavanger, June 2013

ABSTRACT

Gjøa field was discovered in 1989 and first production started in 2010 located about 40 kilometers north of the Fram field. The reservoir contains gas above a relatively thin oil zone in Jurassic sandstones in the Viking, Brent and Dunlin Groups. The main reservoir units of Gjøa field are Fensfjord and Sognefjord formations, Viking group. The stratigraphic evolution from Callovian to Kimmeridgian Fensfjord and Sognefjord formations in the greater Gjøa field hasn't been subject of previous work, but they form perspective reservoir intervals on neighborhood areas like Troll and Brage fields.

The Fensfjord and Sognefjord formations interpreted as tide, wave and fluvial dominated delta environment. The facies association indicates shelfal, pro-delta, delta-front, delta-plain, shoreface and estuarine depositional environments.

The seismic interpretation of the study area revealed changes in structural regimes during deposition of Fensfjord and Sognefjord formations. The N-S extension changed to NW-SE in E. Oxfordian – M. Oxfordian periods, which highly affected the depositional processes of Fensfjord and Sognefjord formations.

The main goal of this study is an integration of data analysis and provided conceptual geological model for tectono-stratigraphic evolution of Gjøa field from Callovian to Kimmeridgian period.

ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisor Rodmar Ravnås. Without his open mind to discuss various interpretations, keen eye and patient to guide me through this challenge, this thesis would not have been possible.

Furthermore I would like to thank A/S Norske Shell for providing with data and facilities throughout the thesis period. Special thank to non operated venture team, Rikkert Moeys and Steve Holyoak for support on the way.

Lastly, thank to my friends and classmates for assistance and moral support, especially to Dodo Pongpandin.

TABLE OF CONTENT

ABSTRACT	ii
ACKNOWLEDGMENTS.....	iii
LIST OF FIGURES.....	vi
LIST OF TABLES	vii
1 INTRODUCTION	1
1.1 Previous works	2
1.2 Objectives	2
2 GEOLOGICAL SETTINGS	3
2.1 Structural settings	3
2.2 Basin infill	4
3 DATASET AND METHODOLOGY.....	6
3.1 Dataset	6
3.1.1 Well data	6
3.1.2 Seismic data.....	6
3.1.3 Internal reports	6
3.2 Methodology.....	6
4 FACIES DESCRIPTION AND INTERPRETATION	8
4.1 Gross depositional environment and depositional elements.....	9
4.1.1 Fensfjord Formation.....	9
4.1.2 Sognefjord Formation	12
5 SEQUENCE STRATIGRAPHY AND CORRELATION	18
5.1 Sequence 1: Lower Fensfjord (Late Bathonian - Early Callovian)	18
5.2 Sequence 2: Upper Fensfjord (Early Callovian - Late Callovian).....	19
5.3 Sequence 3: Sognefjord (Late Callovian - Early Kimmeridgian)	19

5.4	Regional profile	20
6	SEISMIC INTERPRETATION	23
6.1	Seismic well tie.....	23
6.2	Horizon interpretation.....	26
6.3	Fault interpretation	31
6.4	Isochore interpretation	31
6.5	Seismic attribute interpretation.....	35
6.6	Seismic stratigraphy and seismic facies interpretation.....	36
6.6.1	Attribute analysis.....	40
7	CONCEPTUAL GEOLOGICAL MODEL	45
8	CONCLUSION.....	49
9	REFERENCES	50

LIST OF FIGURES

Figure 1-1 Location main with main structural elements	1
Figure 2-1 Stratigraphic column of Northern North Sea (Patruno et al. 2012).....	4
Figure 4-1 Gross depositional environment and depositional elements of Fensfjord Formation	11
Figure 4-2 Gross depositional environment and depositional elements of Sognefjord formation	12
Figure 4-3 Well log panel, displaying Fensfjord and Sognefjord formations subdivision	17
Figure 5-1 Well log panel displaying sequence stratigraphic surfaces and interpretation supported by chronostratigraphic data, well location displayed in Figure 1-1	21
Figure 5-2 Regional sequence stratigraphy surfaces and interpretation, location of this well is displayed in Figure 1-1	22
Figure 6-1 Well to seismic tied process with main well tops.....	24
Figure 6-2 Seismic cross section, displaying seismic well tie results with key well tops	25
Figure 6-3 Seismic Inline 1260, before and after Van Gogh filtering	26
Figure 6-4 Seismic cross section through 3 wells, displaying interpreted horizons	29
Figure 6-5 Location map (up), regional profile with interpreted horizons (middle) and interpreted regional profile (low)	30
Figure 6-6 Top Brent dip map with random cross sections, displaying interpreted fault families	33
Figure 6-7 Middle Fensfjord-Base Fensfjord isochore map (left) and seismic attribute map (max.amplitude) 20 ms below Middle Fensfjord horizon (right).....	34
Figure 6-8 Top Fensfjord-Middle Fensfjord isochore map (left) and seismic attribute map (max.amplitude) 20 ms below Top Fensfjord horizon (right).....	34
Figure 6-9 Top Sognefjord-Top Fensfjord isochore map (left) and seismic attribute map (max.amplitude) 20 ms above Top Fensfjord horizon (right)	35
Figure 6-10 Seismic section, providing with interpreted sequence intervals.....	36
Figure 6-11 Maximum amplitude map 15 ms above Mid Fensfjord horizon. Highlighted area display lateral distribution and arrows showing prograding direction of the clinoforms	38

Figure 6-12 Seismic stratigraphy interpretation, a) seismic inline 1320 b) Interpretation of reservoir intervals, arrows displaying clinoforms outbuilding c) modeled clinoforms (yellow colored). FF=fault family.	39
Figure 6-13 Seismic segment, displaying top of the turbidite units (cyan horizon) calibrated by 35/9-2 GR log.....	40
Figure 6-14 16 Seismic waveform classes with color code defined for the first map	40
Figure 6-15 Seismic segment, displaying top of the tide and wave influenced deltaic units (red horizon) calibrated by 35/9-2 GR log	41
Figure 6-16 16 seismic waveform classes with color code defined for the second map	42
Figure 6-17 First seismic facies map displaying seismic waveform classes variations on Top Fensfjord horizon	43
Figure 6-18 Interpretation based on analyzing seismic waveform pattern recognition.	43
Figure 6-19 Interpretation based on analyzing seismic waveform pattern recognition	44
Figure 6-20 Second seismic facies map displaying seismic waveform classes variations on Top Fensfjord horizon.....	44
Figure 7-1 Schematic sketch of sequence 1 evolution (out of scale).....	45
Figure 7-2 Schematic sketch of sequence 2 evolution: Shifting of shoreline and prograding of Fensfjord deltas basinwards (out of scale)	46
Figure 7-3 Schematic sketch of sequence 3 evolution of early stage (out of scale)	47

LIST OF TABLES

Table 1 Gjøa field facies association.....	13
Table 2 Gjøa field facies description and interpretation	16
Table 3 Interpreted horizons with their characteristics	27

1 INTRODUCTION

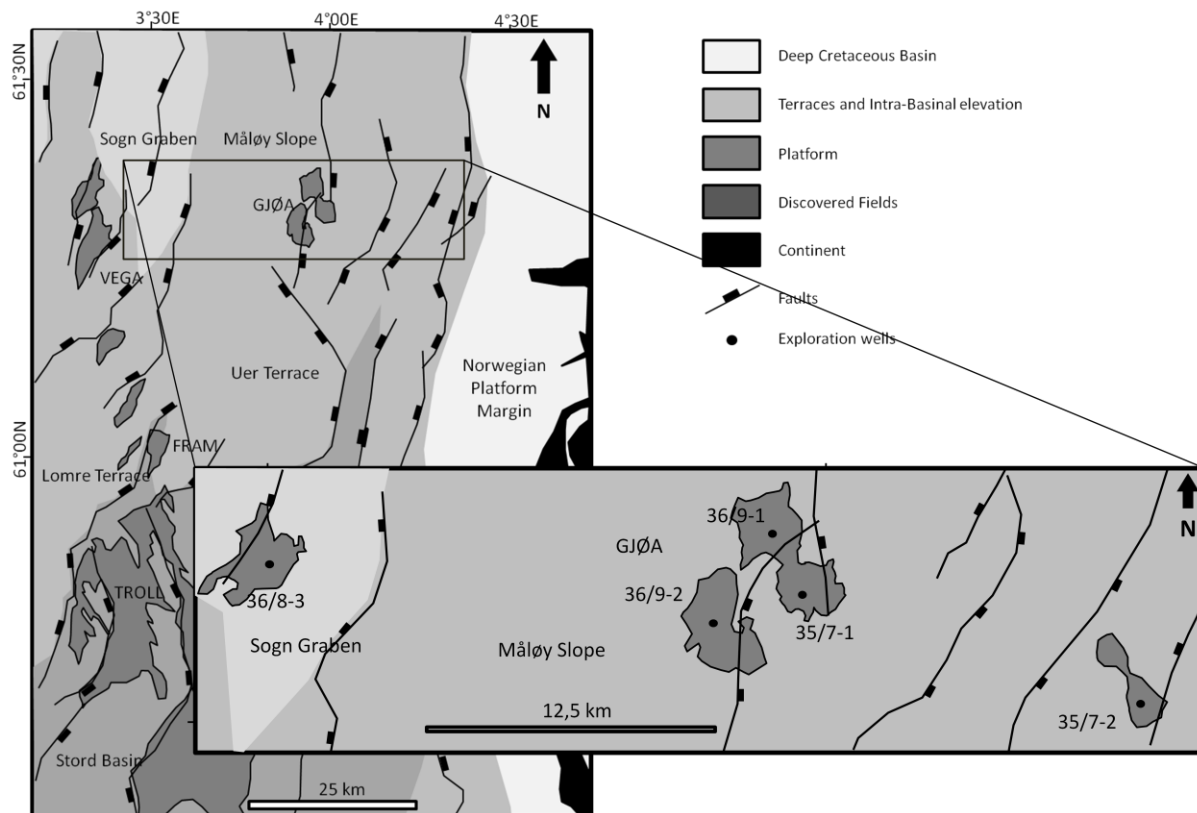


Figure 1-1 Location main with main structural elements

The Gjøa field is located on Northern North Sea, it was discovered in 1989 and first production started in 2010 (Figure 1-1). It is a complex gas field with a thin (10-15m) oil leg. The main reservoir in Gjøa is the Upper Jurassic Sognefjord and Fensfjord Formations, which belong to the Viking group. In Gjøa area these shallow marine sandstones comprises variably developed structureless and highly bioturbated sandstones (Pemberton et al.,1992; Taylor and Gawthorpe, 1993; Martin and Pollard, 1996) which combined with their diachroneity, increase the demands for integrated approach, employing sedimentary analysis with high resolution sequence stratigraphy to understand their spatial distribution (Donovan et al.,1993; Price al.,1993). Moreover, these aspects are further complicated by their tectonic settings, along the margin of the Northern North Sea rift basins through fault block rotation and uplift.

This study is focused on an integrated approach. Core data interpretation with improved sedimentological interpretation combined with detailed sequence stratigraphic analysis and

3D seismic data to have advanced conceptual geological models of these two reservoir units. It provides us with an improved understanding of the tectono-stratigraphic evolution of the Gjøa field. As a result, this project aimed provide solid basis to update the current reservoir model.

1.1 Previous works

There is little published works on the Upper Jurassic of the Gjøa area. Most of available literature mainly focused on the Cretaceous (Jackson, Barber et al. 2008) or on a more regional scale. Fensfjord and Sognefjord formations are in nearby Troll field, which is located at the Southern part of study area, on the Horda platform. According to the recent research the NE part of the Troll field were dominated by Middle Oxfordian delta deposits (Patruno et.al. 2011). The Sognefjord formation on Horda platform characterized as spit to tide dominated delta system (Dreyer, Whitaker et al. 2005). Overall Sognefjord and Fensfjord formations were classified as ‘syn-rift’ as they were deposited during the Middle-to-Late Jurassic rift episode (Ravnås and Bondevik 1997; Ravnås, Nøttvedt et al. 2000).

1.2 Objectives

The main purposes of this study are as follow:

- Document the stratigraphic evolution of the Callovian to Kimmeridgian units in the greater Gjøa field area (on the Måløy fault blocks)
- Identify the gross depositional environments and depositional elements for the Fensfjord and Sognefjord formations based on core information
- Demonstrate lateral facies variability and potential for stratigraphic compartmentalization.
- Identify potential for sand bypass across the Gjøa field and delivery to fronting basins during the Callovian to Kimmeridgian

2 GEOLOGICAL SETTINGS

2.1 Structural settings

Structural changes of the Northern North Sea are results of several multiphase tectonic events. Two important rift phases were occurred in Permian – early Triassic and in mid Jurassic – early Cretaceous time. Each rifting phase was followed by thermal cooling stage, characterized by regional subsidence (Christiansson, Faleide et al. 2000). It is also assumed that the tectonic framework has been influenced by Precambrian and Caledonian structures as well as the extensional collapse of the Caledonides (Odinsen, Christiansson et al. 2000).

The North Sea rift system is limited by the East Shetland Platform to the West and the Øygarden Fault Zone to the East. This area is characterized by large rotated fault blocks with sedimentary basins in asymmetric half-grabens, among them the Viking Graben (Christiansson, Faleide et al. 2000).

The NE-SW trending Viking Graben has been developed in the last important rifting phase. This was initiated in Late Triassic and continued throughout Jurassic times. Permian-early Triassic master faults were partly reactivated, increasing segmentation and subsidence (Odinsen, Christiansson et al. 2000). The structural uplift started with significant erosion during pre-Calloviaian time, which led to form graben relief characterized by platforms, sub-platforms, and platform marginal highs. Subsequently, discontinuous subsidence load and erosion during late Jurassic-early Cretaceous resulted in appreciable thickness variations of the Upper Jurassic units. The extension reached its highest peak in the late Jurassic (Gabrielsen, Foersth et al. 1990).

In early to mid-Cretaceous, the late Jurassic block faulting and extensional structuring ended. A period of rapid subsidence during the Cretaceous and Paleogene followed. Only minor fault movements along some of the master faults occurred (Gabrielsen 1986). The last tectonic event influencing the area was due to the extension in the Norwegian Sea in Paleocene. The graben flanks have been uplifted and eroded. Successively a rapid subsidence of the graben followed.

The study area is located on the Måløy Slope one of several structural terraces located along the eastern side of the Northern North Sea. The Måløy Slope is limited to the east by the large

Øygården fault zone, and to the west by a major normal fault bounding the eastern margin of the Søgne Graben. The syn-rift to postrift transition split a marked change in the structural configuration of the North Sea basin.

The Gjølå reservoir is significantly influenced by NS and/or NE-SW striking normal faults as well, dipping westwards. The activity of the main fault seems to die out towards the south. Faulting generally increases with depth through the Jurassic sequence. Older faults are often re-activated or cut by younger faults.

The faults were active during the Late Jurassic rift phase in the North Sea. The compartmentalization within the study area started in the Callovian (sedimentation of the Fensfjord Formation) and the maximum fault activity was reached in the Volgian (sedimentation of the Draupne Formation).

2.2 Basin infill

Above the heterogeneous pre-Cambrian basement are Jurassic age sediments with varying thicknesses of 300-800 m. The paleo-morphology of the basement and the syn-sedimentary fault activity had a strong impact on the thickness variations. The Gjølå structure has been heavily influenced by a series of erosional events that took place at the end of the Late Jurassic, which in local areas has eroded out more than 60 % of the upper reservoir section. Main sediment source was from hinterland, forming wedge

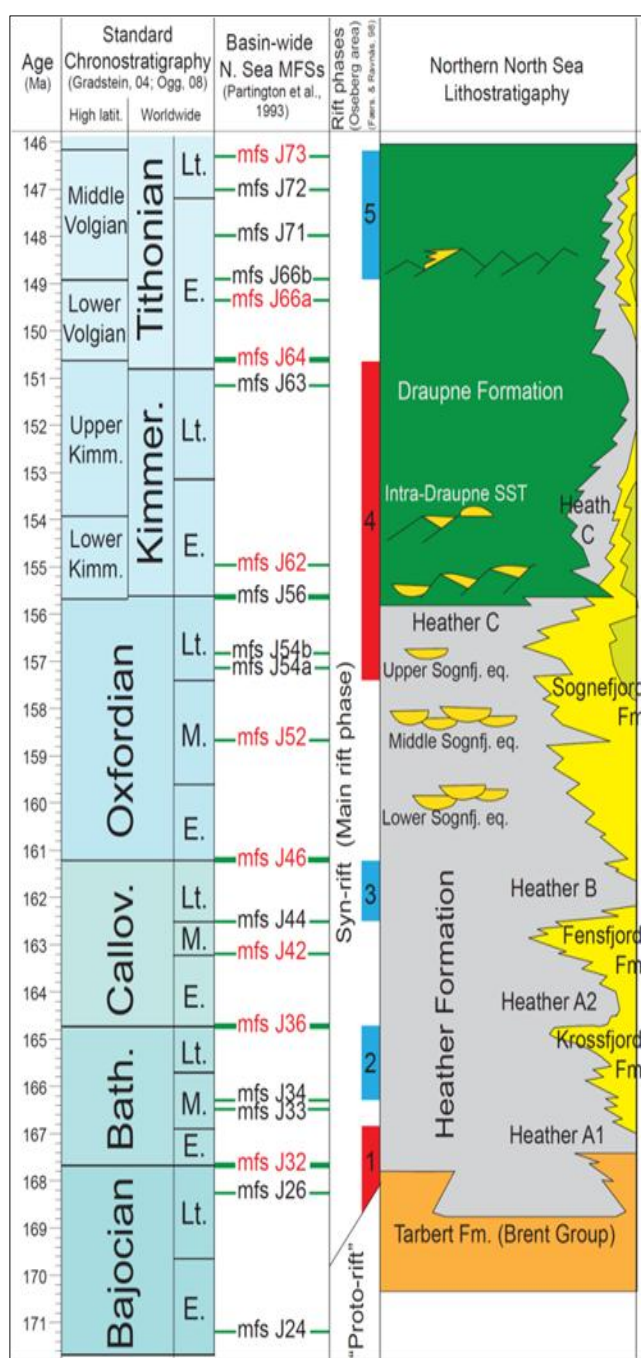


Figure 2-1 Stratigraphic column of Northern North Sea (Patruno et al. 2012)

like depositional structures in grabens.

The reservoir of the Gjøa field consists of sandstones of the Jurassic Dunlip, Brent, and Viking Groups

The Upper Jurassic sediments belong to the Viking Group, which has been subdivided in 5 formations: Heather, Krossfjord, Fensfjord, Sognefjord and Draupne, see Figure 2-1. These formations form the main reservoir in study area. Except for the Draupne Formation, which contains deep marine turbiditic sandstones at the bottom, all formations have been described to be deposited under shallow marine conditions (Dreyer, Whitaker et al. 2005).

3 DATASET AND METHODOLOGY

3.1 Dataset

The dataset was provided by A/S Norske Shell and consists of well data, 3D seismic data and internal reports. Our results comprise the first academic study that integrates core data, wireline logs and seismic data to explain stratigraphic evolution Callovian to Kimmeridgian of the Gjøa area and its implications on hydrocarbon exploration

3.1.1 Well data

Well data comprise of 3 exploration (35/9-1, 35/9-2, and 36/7-1) wells that were used for detailed reservoir study and for regional study 2 more (35/8-3 and 36/7-2) wells were added. All wells contain required wireline logs and checkshot data that was carefully reviewed and adjusted.

The core database comprises 3 wells (35/9-1, 35/9-2, and 36/7-1) with a total of 607,4 m of core material over the Lower to Upper Jurassic interval.

3.1.2 Seismic data

This study is primarily based on the tectono-stratigraphic analysis of 453,96 km² of 3D seismic data (ST07). The main characteristics are: record time 6000 ms, zero phase, SEG normal polarity with 25-30 Hz dominant frequency and interval velocity 2000-2600 m/s will give vertical resolution up to 18 m in particular intervals. Also for regional profile 3D merged seismic data was used (CSO1).The quality of 3D seismic data considered as good.

3.1.3 Internal reports

Biostratigraphy data was provided by Norske Shell as an internal report (document reference 04/771/s).

3.2 Methodology

As the first step core and well data analysis was executed. Core data from interval of interest has been reviewed to identify and characterize reservoir scale depositional elements and facies associations within each well. Non cored intervals were interpreted using the same depositional facies association scheme, using simple wireline log pattern comparison. Results of core interpretation together with biostratigraphy data have provided a good framework for

detailed sequence stratigraphy analysis. Sequence stratigraphy analysis applied the genetic sequence stratigraphic approach (Galloway 1989) as that method appeared more practical in these marginal marine to fluvio-deltaic stratas.

Well-to-seismic tie process required reexamining of well log and checkshot data, which was followed by seismic interpretation. Seismic interpretation focused on the analysis of structural and isochore maps as well as attribute extractions to provide a tectono stratigraphic evolution of the Gjøa area. Seismic data with 25-30Hz frequency allow the interpretation and correlation of 3rd order depositional packages. Seismic facies interpretation was obtained by using seismic waveform classifier tool (Shell in-house software). All these works have been carried out using Petrel (Reservoir modeling software).

4 FACIES DESCRIPTION AND INTERPRETATION

Core data analysis was performed to record the occurrence and characteristics of reservoir scale depositional facies and produce a series of gross depositional environment (with depositional elements) models. A non-cored interval in the wells was interpreted using the same depositional facies association scheme by simple visual comparison of wireline log signature.

Target intervals are Sognefjord and Fensfjord formations, which have been cored in wells 35/9-1 (84m), 35/9-2 (237,4m) and 36/7-1 (286m) with total length of 607, 4 m.

The facies characterization was based on lithology, internal sedimentary structure, sand-mud ratio, degree of bioturbation and specific trace-fossil assemblage presence.

A total of seven distinct lithofacies were recognized from core of 35/9-1; 35/9-2 and 36/7-1 wells. Detailed description of lithofacies is provided in Table 2. The facies has been grouped into six facies associations (FA) characterizing specific depositional environments: (1) Shelfal FA, (2) Pro-delta FA, (3) Delta-front FA, (4) Shoreface FA, (5) Delta-plain FA and (6) Estuarine FA. The component facies and facies associations are described in Table 1.

Sognefjord Formation is characterized by 5 facies associations which mostly comprise elements of delta to shoreline depositional systems displaying: Shelfal FA, Pro-delta FA, Delta-front FA, Shoreface and Estuarine FA. In this unit the Shelfal and Pro-delta FA are dominated by thick packages of turbidite lobes.

Fensfjord Formation is highly complex interval which is characterized by all 6 facies associations some of which are restricted to specific reservoir intervals, whilst others are consistently present throughout the majority of the unit. The interval variably displays deposits characteristic of deposition within delta to shoreline system with tidally-influenced estuarine settings. The interval represented by Shelfal FA, Pro-delta FA and Delta-front FA as well as by Shoreface FA, Delta-plain FA and Estuarine FA in particular intervals.

4.1 Gross depositional environment and depositional elements

4.1.1 Fensfjord Formation

Several Fensfjord Formation deltaic-shoreface FA are recognized and correlated based on biozonation. These are grouped into three higher order strata packages and displayed in Figure 4-3:

- Fensfjord 1 (base)
- Fensfjord 2
- Fensfjord 3 (top)

Fensfjord 1 and Fensfjord 2 represent a series of rapid and short lived delta advance and retreats. In contrast, Fensfjord 3 with its internal stratigraphic complexity, consists of three higher order stacked deltaic and shoreface to estuarine lithosomes, and span a fairly long covering time interval of Late Callovian. The sketch of gross depositional environment and depositional elements is provided in Figure 4-1.

The Fensfjord 1 represented by stack of two sandy, sharp to gradual based, turbidite dominated, wave-influenced deltaic to shoreline lithosomes. Each lithosome would likely form a gross sheet-like architecture, composed of laterally superposed wave-worked delta-lobes. These delta-lobes are likely composed of a series of wave and tide reworked shoreface units, delta-front mouth-bar and channel-fill elements, delta-front and inner pro-delta turbidite lobes. In addition, the Fensfjord 1 fines out westward, with a turbidite receiving pro-delta area present across the 35/9-2 compartment. The latter suggest slightly embayed or curved shoreline, shaling out towards the west-southwest.

The Fensfjord 2 is cored in the 35/9-2 and 36/7-1 wells, and possibly also in well 35/9-1 assuming sandstones belonging to the same biozone. The Fensfjord 2 comprise another wave worked sandy sharp-based, deltaic to shoreline lithosomes, similar to those inferred for Fensfjord 1. The Fensfjord 2 appears thinner and with sharper and more pronounced basal and upper boundaries to embedding shelfal muddy siltstones. There is a transitional interval between the underlying pro-delta siltstones dominated by a 10+ meter thick heterolithic unit of interbedded thin- to medium-bedded turbidites and shelfal to pro-delta units in the 36/7-1 well, whereas the unit is characterized by a stack of heterolithic to sandy pro-delta to delta

front turbidite lobe storeys in well 35/9-2. In consort this suggest that the delta-front was dominated by mass/gravity flow activity, possibly derived from rivers during high discharge events (i.e. major river floods). Higher abundance and thicker packages of turbidite beds potentially suggest progradation into deeper waters compared to the underlying Fensfjord 1 implying relative sea level rise between two.

The Fensfjord 3 comprises three stacked lithosomes; Fensfjord 3/1, Fensfjord 3/2 and Fensfjord 3/3.

Fensfjord 3/1 form yet another Estuarine to Shoreface FA, turbidite dominated deltaic FA that developed from pro-delta to delta front heterolithic turbidite facies tracts overlain by delta-front mouth bars and delta-plain distributary channels. Relatively rapid transitions from pro-delta and delta front facies tracts to shoreface/delta plain facies tracts suggest deposition during slightly falling to relatively stable sea-level conditions.

The overlying Fensfjord 3/2 is developed as a tide-wave influenced gravitationally modified delta with delta-plain distributary channels and estuarine tidal bars/flats overlain by a shoreface beach sands and more estuarine units, this potentially suggesting a change along the depositional profile from a tidal-influenced delta in shallow water areas or platforms (as in well 36/7-1) reaches to a more wave dominated, gravitationally modified delta as the delta reached deeper and more open waters, or the 'shelf-edge' (well 35/9-2).

The overlying Fensfjord 3/3 consists of delta front deposits capped by shelfal to pro-delta FA (in well 36/7-1). The bioturbated sandstone possibly formed by reworking of original delta-front sands (mouth-bars) along a more protected coastline. Gross sheetlike character is inferred, with the potential of more thorough reworking (by wave) to produce a more homogeneous sheet. Thin and sandy nature of the delta front units suggest shallow, rapidly switching channels developed on a sandy 'braid-like' delta-plain area.

Fensfjord 3/1 and Fensfjord 3/2 are both around ~30 meters thick and with gradational, but relatively rapid to normal transitions between facies tracts, suggesting deposition during steady to slightly rising sea-level. Thickness of foresetted delta-front package and shoreface units is 10-15 meters (compacted), which equates to a proxy of the minimum paleowaterdepth.

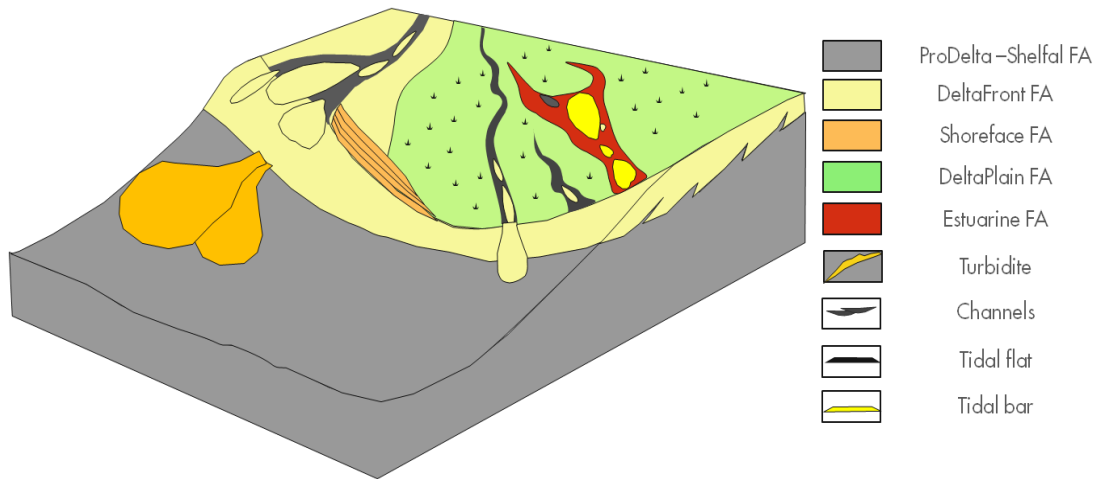


Figure 4-1 Gross depositional environment and depositional elements of Fensfjord Formation

4.1.2 Sognefjord Formation

The Sognefjord Formation represents a turbidite dominated deltaic-shoreface FA. It is developed in pro-delta turbidite bottomsets through delta front turbidite dominated foreset facies, in turn overlain by delta front mouth-bars and distributary channels. The organization of facies tracts suggest that the Sognefjord Formation deltas potentially had a better developed foresetted delta-front, and thereby akin towards a deeper or intermediate water shelfal delta, potentially representing a transitional type between a ‘Gilbert-type’ and steeper face mouth-bar type delta (Figure 4-2). Such a notion implies potential for better developed pro-delta turbidite lobe storey’s and lobe storey sets in fronting lows or depositional sinks.

Transitions from shelfal and pro-delta facies tracts to delta-front/shoreface facies tracts vary from gradual to sharp, potentially suggesting lateral (and to some degree temporal) variations in rate(s) of accommodation creation or relative sea-level variations.

A braided fluvial effluent or delivery system is suggested by the sandy nature and the component facies or depositional elements of the delta-front outer distributary channel-fills motifs.

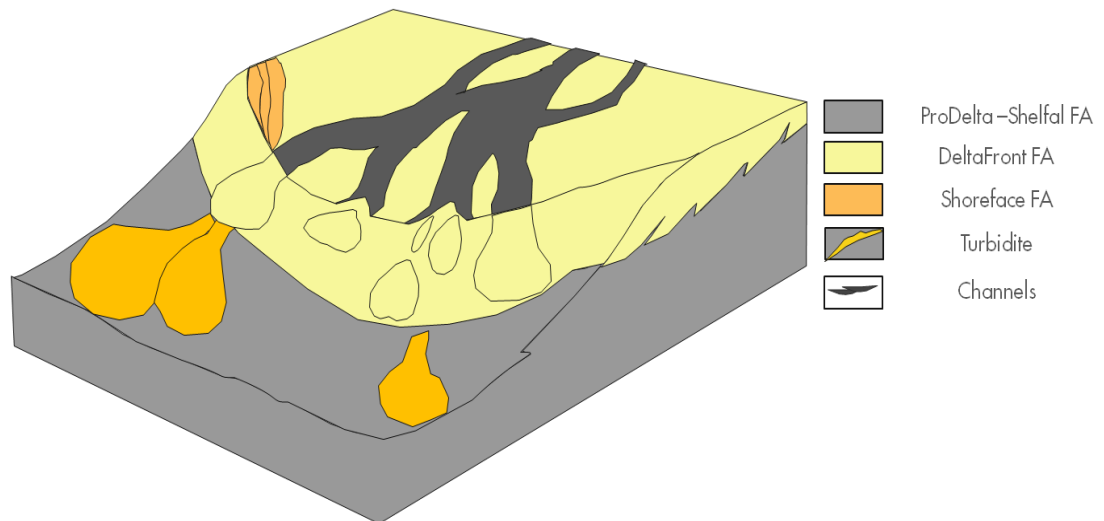
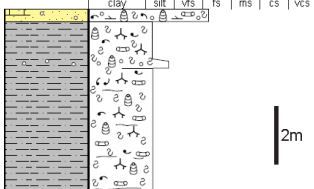
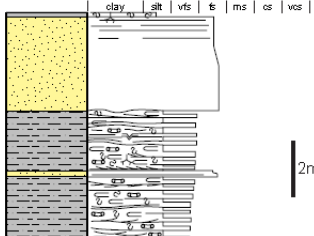
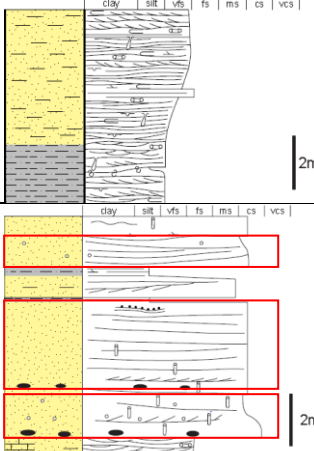
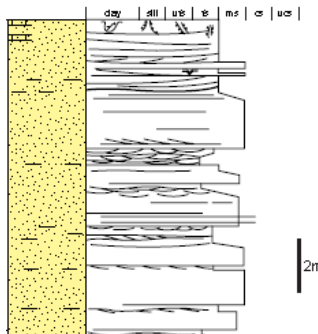
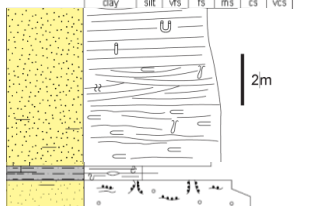
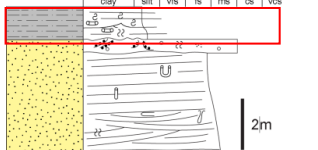
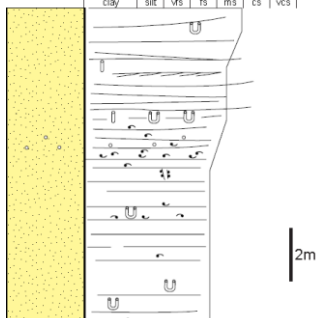


Figure 4-2 Gross depositional environment and depositional elements of Sognefjord formation

Table 1 Gjøa field facies association

Facies association	Description	Log motif	Depositional sub-environment
FA1: Shelfal	Generally comprise of mud and silt (Facies 1) that generally lack of sedimentary structure. Bioturbation intensity is highly variable and represented by <i>Ophiomorpha</i> and large muddy <i>Arenicolites</i> , bivalve burrows and prominent large <i>Dipocraterion</i>		Shelfal deposit
FA2: Pro -delta	<p>Consists of packages of sandy event beds (Facies 4) have embedded within a background of bioturbated siltstones. This packages display sharp bases and sharp tops with often comprise amalgamated or layered units of graded gravitational event beds.. The thickness of sandy event beds varies from cm- to m- scale</p> <p>Comprised of bioturbated siltstones (Facies 2) intercalated with dm scale sandy event beds (Facies 4). Siltstones are generally structureless and bioturbated by <i>Phycosiphon</i> and <i>Planolites</i>.</p>		<p>Pro Delta turbidite lobes</p> <p>Storm or gravity flow dominated Pro-Delta</p>
FA3: Delta-front	<p>Coarsening/"cleaning" upward motif which consists of light grey, very fine to fine grain size, moderate to poorly sorted, planar (Facies 5) to cross stratified (Facies 3) sandstones. Bioturbation is rare or absent.</p> <p>Fining upward (mm- to m- scale) motif characterized by dark grey, very fine to coarse grained, cross stratified (Facies3) sandstones with laminated, bioturbated siltstones (Facies 2) which stacked into 5-7 meter thick packages. Lags of pebble-grade sandstone (Facies 6) and mudstone lithoclasts locally mark the bases of individual channel elements. Large muddy <i>Arenicolites</i> burrows are common within beds whilst <i>Chondrites</i> frequently occurs in muddy drapes.</p>		<p>Delta -front mouth bar</p> <p>Delta-front outer distributary channels</p>

	<p>This facies consist light grey, sharp based, normally graded sandy event beds (Facies 4) (cm- to dm- scale) with very fine to medium grain size, well sorted, and becoming planar (Facies5) to cross (Facies 3) ripple laminated at the top. Bioturbation is rarely observed.</p>		Delta front turbidites
FA4: Delta plain	<p>Fining upward (FU) motif comprise of grey, coarse to very fine grained, cross (Facies 3) to planar (Facies 5) stratified sandstones with rare mm- to cm- scale laminated siltstones (Facies 2). The sandstones at the base are sharply overlain by medium grained “clean” cross stratified sandstones. The basal surface has been colonized and the burrow network has been filled downward the overlying sandstones</p>		Delta plain shallow channels
	<p>This facies contain rare dark grayish, very fine, planar laminated siltstones (Facies 2) interbedded with mudstone (Facies 7). The mudstone display laminated to pinstriped fabrics with low amplitude ripple forms. Bioturbation is very low to moderate and represented by <i>Planolites</i> and <i>Palaeophycus</i>.</p>		Delta plain overbank, shallow ponds or small lagoon deposits.
FA5: Shoreface	<p>The facies comprise of light grey sandstones (in some intervals very “clean”), fine to medium, medium, and medium to coarse grained at the top, coarsening upwards (CU) motif and again with a sharp or gradational base. The sedimentary structure is relatively massive to diffusely planar stratified (Facies 5) and medium-scale cross-stratified (Facies 3). Disarticulated thick-shelled bivalves are common. Bioturbation present in the form of large <i>Arenicolites</i> and <i>Ophiomorpha</i> The same sandstones fining upwards motif are also present, but with higher degree of bioturbation.</p>		<p>Beach deposits, or reworked mouth bar sand. CU motif represent regressive shoreface FU motif transgressive shoreface.</p>

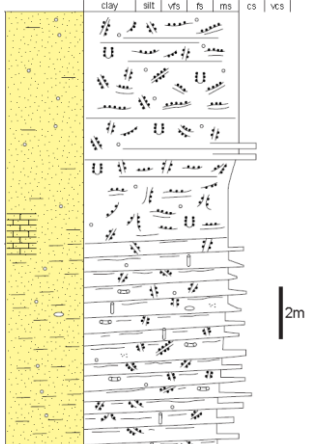
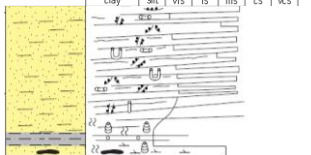
<p>FA6: Estuarine</p>	<p>This facies characterized by light grey sandstones beds (dm- scale), medium to coarse grained, generally coarsening upwards, well sorted, lamination is defined by mm- to cm- scale sandstone layers, low to moderately bioturbated by <i>Ophiomorpha</i>. Plant fragments are also common.</p>		<p>Tidal Bar in inner to outer estuarine settings</p>
	<p>This facies comprise of bedsets (cm- to dm- scale) of fine to medium grained, with angle of ~15° laminated sandstones interbedded with bioturbated muddy siltstones (Facies 1) intervals. Bioturbated layers display clear mm- to cm- scale horizons containing suspension-fallout mud.</p>		<p>Tidal Flat heterolithic, Inclined heterolithic units (IHS) represent tidal point bar within shallow tidal channel or creek</p>

Table 2 Gjøa field facies description and interpretation

Facies type		Description	Bed thickness	Interpretation
1	Highly bioturbated muddy siltstones	Dark grey, structureless mud and silt. Highly bioturbated. Common trace fossils are <i>Ophiomorpha</i> and <i>Arenicolites</i> .	Centimeter to meter	Deposits formed in offshore settings with low sedimentation rate
2	Siltstones	Siltstones mainly structureless, but parallel-laminated intervals are also occur. Bioturbation is low to moderate and represented by <i>Phycosiphon</i> and <i>Planolites</i> .	Millimeter to centimeter	Deposits formed in offshore settings with high sedimentation rate
3	Cross stratified sandstones	Light grey sandstones, fine to coarse grained, low angle to tabular cross stratified, well sorted, sharp or erosively based. Bioturbation is not observed.	Decimeter to meter	Deposits formed by unidirectional currents..
4	Sandy event beds	Light grey sandstones, fine to medium grained, massive to planar, well sorted, and sharp based. Vertical changes of sedimentary structures in the same bed are common. Thinner beds are more amalgamated with Facies 3 and also thicker intervals grain size also varies from fine to medium. Bioturbation is not observed.	Centimeter to meter	Deposits formed due to gravity flows or during major storm events
5	Parallel laminated sandstones	Sandstones, fine to medium grained beds that are usually plane parallel laminated, but also have thin structureless intervals or show low angle laminations, with sharp top and base. Vertical changes of sedimentary structures in the same bed are common, but parallel laminated intervals are thicker. Bioturbation present in form of large <i>Arenicolites</i> and <i>Ophiomorpha</i> . Robust bivalve shell debris and plant fragments are also common.	Decimeter to meter	Deposits formed by gravity underflows with variable flow speed.
6	Very coarse grained sandstones	Occurs very rare in cores but characterized as medium to very coarse grain sandstones, commonly structureless, erosively based with fining upward trend. Bioturbation is low and represented by <i>Chondrites</i>	Centimeter to decimeter	Deposits formed in coastal settings due to erosion or reworking of previous deposits
7	Rippled mudstones	Mudstone, laminated to pinstriped fabrics with low amplitude ripple forms, bioturbation low to moderate and represented by <i>Planolites beverleyensis</i> and <i>Palaeophycus</i> . Some intervals are intercalated with very thin layers of siltstones.	Millimeter to centimeter	Deposit formed and developed in low energy conditions by unidirectional currents, most likely in backshore settings.

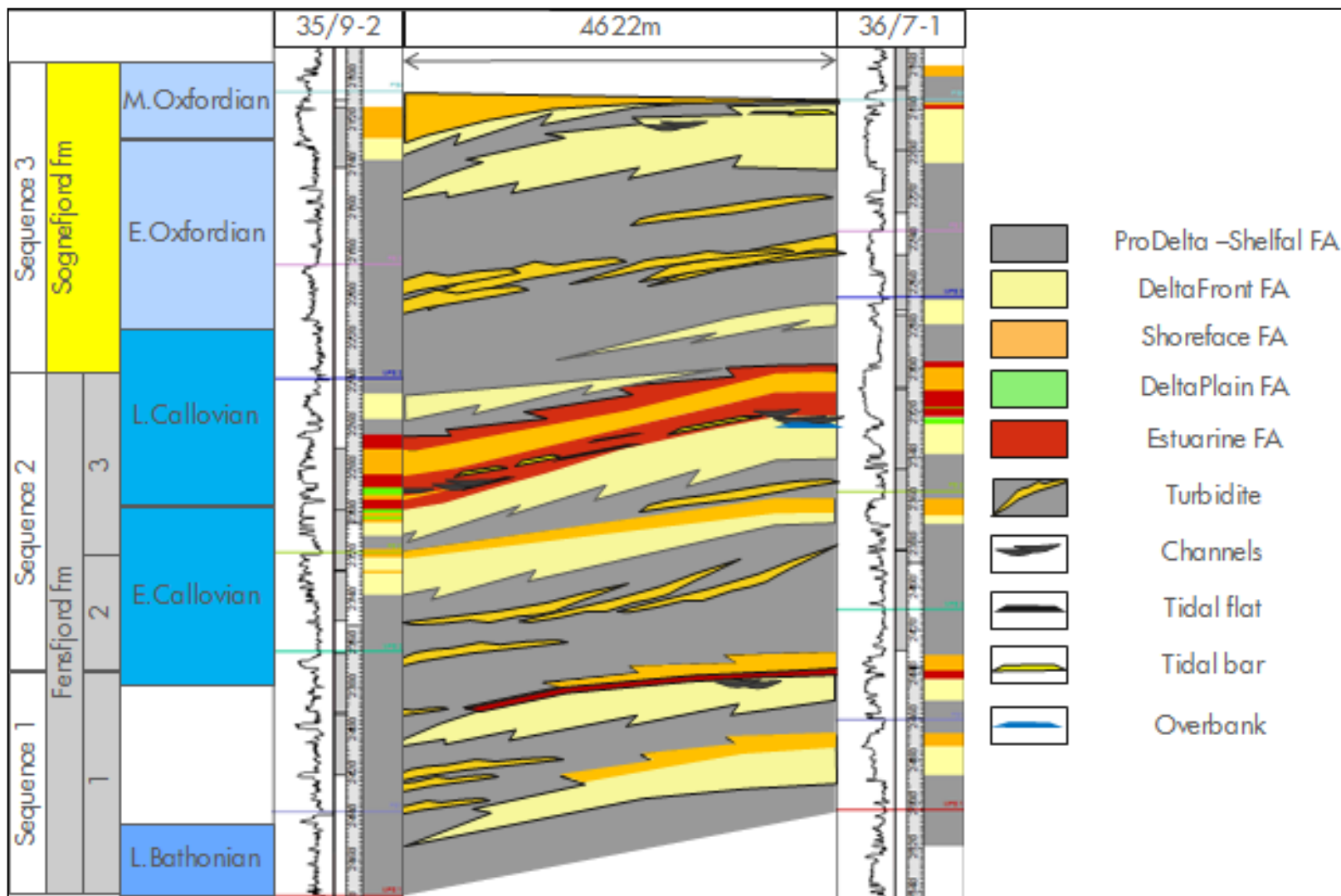


Figure 4-3 Well log panel, displaying Fensfjord and Sognefjord formations subdivision

5 SEQUENCE STRATIGRAPHY AND CORRELATION

Sequence stratigraphy analysis of Sognefjord and Fensfjord formations was performed to ensure robust correlations of depositional packages to develop more detailed framework for reservoir correlation. Interpreted facies association and biostratigraphy data defined a good framework for genetic stratigraphic sequence (Galloway 1989) method, where maximum flooding surfaces (MFS) defined as sequence boundaries (Figure 5-1). Third and fourth order sequences were interpreted and maximum flooding surfaces were picked and correlated between the wells.

Well 35/9-1 was not considered for sequence stratigraphy analysis and well correlation, because of the deep erosion in this well, which has removed significant part of the Upper Jurassic. Non-cored intervals were interpreted using simple well log pattern recognition as discussed in previous chapter.

Marine flooding surfaces (FS) are the easiest recognizable stratigraphic surfaces in the Gjøa area and picked consequently. They are normally underlain by variably developed transgressive shoreline deposits and indicate an abrupt increase in water depth. Maximum flooding surfaces (MFS) were picked in the most marine intervals and they typically represented by muddy intervals with a high degree of bioturbation. In uncored sections, MFS (and higher order FS's) were picked in intervals with maximum separation on Neutron-Density logs. The correlations of these surfaces between wells were quite confident.

Three main 3rd order genetic sequences defined from the vertical succession of 35/9-2 and 36/7-1 wells. They were named according to their appearance in stratigraphic intervals. The results of the sequence stratigraphy interpretation and correlation together with internal sedimentary architecture are presented in Figure 5-1.

5.1 Sequence 1: Lower Fensfjord (Late Bathonian - Early Callovian)

Description: This sequence is bounded by MFS1 and MFS2 and has a thickness of up 90-100m. It corresponds to Fensfjord 1 described in previous chapter (Figure 4-3). The interval consists of two higher order component of fluvio-deltaic lithosomes defines an overall

progradational stacking pattern or regressive structure, which is splited by FS1. Due to fining out towards the West (well 35/9-2) retrogradational pattern is not obvious in well 36/7-1.

In well 36/7-1 this sequence dominated by delta-front and shoreface FA with minor estuarine FA interval on the upper part. However, in well 35/9-2 this sequence represented by shelfal to pro-delta FA with turbidite units.

Interpretation: Thickness variations of sandy packages can be related to the preexisting basin topography, where delta prograding into the basin that formed due to extension.

5.2 Sequence 2: Upper Fensfjord (Early Callovian - Late Callovian)

Description: This sequence is limited by MFS2 and MFS3 with FS2 in between and has thickness up to 130-140m. It corresponds to Fensfjord 2 and Fensfjord 3 described in previous chapter (Figure 4-3). Upper Fensfjord sequence is very complex part of the succession and it has several higher order stacked deltaic parasequences. The general profile is prograding to retrograding.

Prograding segment is dominated by delta-front and shoreface FA with thin delta plain FA intervals. Retrogradational segment is dominated estuarine and shoreface FA, also with thin delta plain FA intervals

Interpretation: Prograding segment indicates normal regression, but the bottom part of sequence represented by normal regression (well 35/9-2) and forced regression (well 36/7-1). Retrograding segments indicating relatively slow transgression period and more pronounced in E side (well 35/9-2), while they shows more aggradational feature in the W (well 36/7-1). Moreover, on the bottom part of this sequence (Fensfjord 2) in well 35/9-2 retrograding parasequence represented in form of the sharp transition to prograding parasequence, while it is more gradual in well 36/7-1. Sandy packages are thicker and more homogeneous on the E (well 36/7-1). These variations interpreted as a consequence of the fault blocks rotation during Late Jurassic extension that allowed delta to prograding further into the deeper areas.

5.3 Sequence 3: Sognefjord (Late Callovian - Early Kimmeridgian)

Description: This sequence bounded by MFS3 and FS4 and has a thickness up to 100-140m. There is a missing stratigraphic intervals in the upper part of this succession that caused by

erosion. The general profile of this succession is prograding with relatively thin layer of retrograding segment on the top.

Prograding segment is dominated by delta-front to shoreface FA, with turbidites that capped by shelfal to pro-delta FA, and retrograding segment is represented by shoreface and thin layer of estuarine FA. The thickness of this sequence changes from 110m in well 36/7-1 to 140m in well 35/9-2.

Interpretation: The prograding segment indicates relatively long and slow sea level fall (normal regression), however on the upper part of the sequence in well 36/7-1 there is an evidence of forced regression. The prograding sequence started from deposition of shelfal to pro-delta units that dominated by thick turbidite lobes, and followed by deposition of deltaic to shoreface units. The retrograding segment represented by shoreface units with thin layer of estuarine units. Sandy packages are thicker on the E around 36/7-1 well. Thickness variation and well developed turbidite lobes suggest steeper slope.

5.4 Regional profile

Interpreted surfaces were extended further basinward and landward to provide regional framework for the local Gjøa sequence development. The results of that are shown in Figure 5-2. In more distal well 35/8-3 located in deeper water (Figure 6-5) relatively thick turbidite units are present within the Heather shelfal deposits. Well 36/7-2 located in most proximal part and represented by thick stacked of mixed tidally and fluvial influenced deltaic lithosomes. Overall Sognefjord and Fensfjord formations represent prograding delta that wedging out towards the deeper basins. The turbidite units in deeper basins (well 35/8-3) most likely related to erosional process.

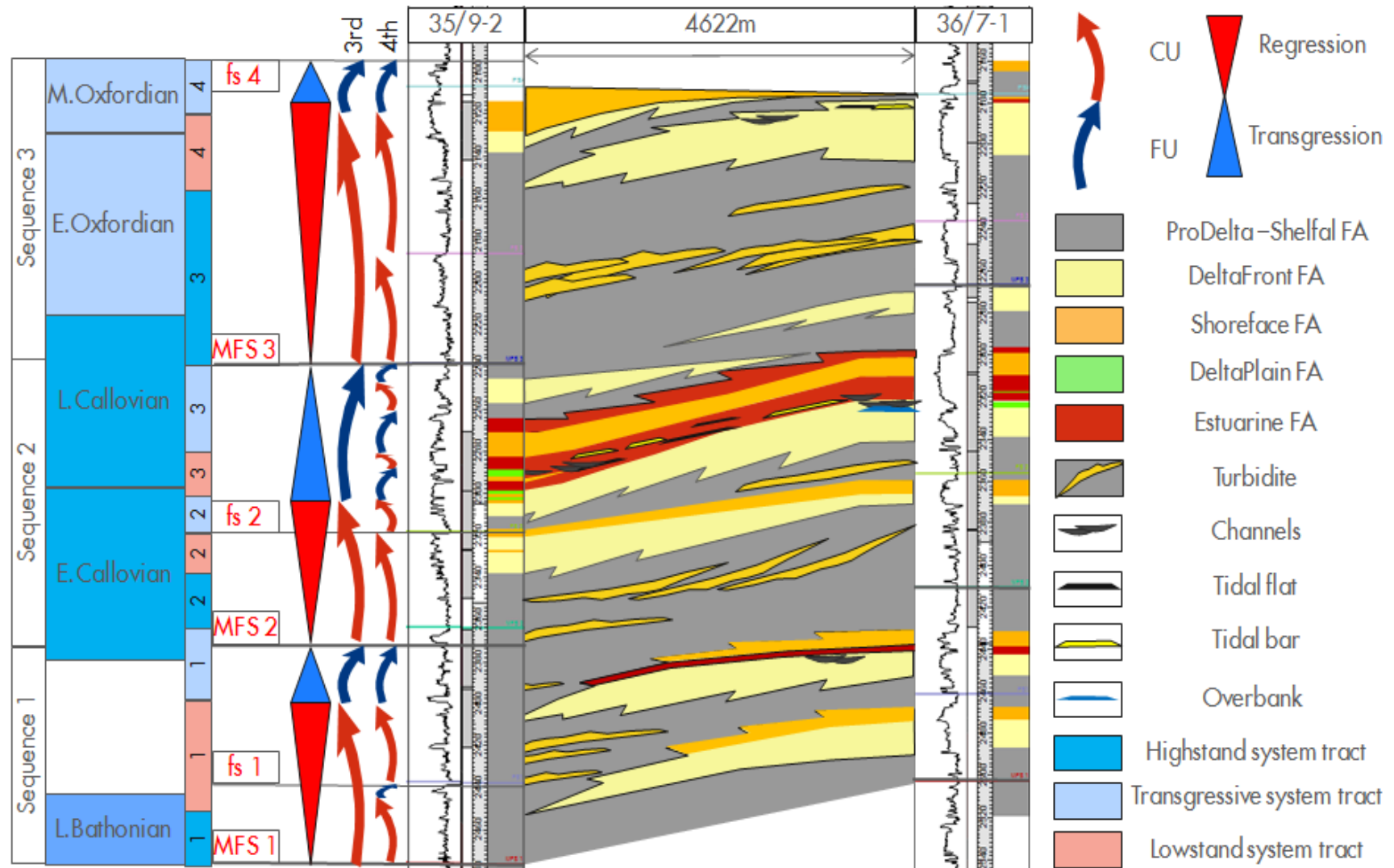


Figure 5-1 Well log panel displaying sequence stratigraphic surfaces and interpretation supported by chronostratigraphic data, well location displayed in Figure 1-1

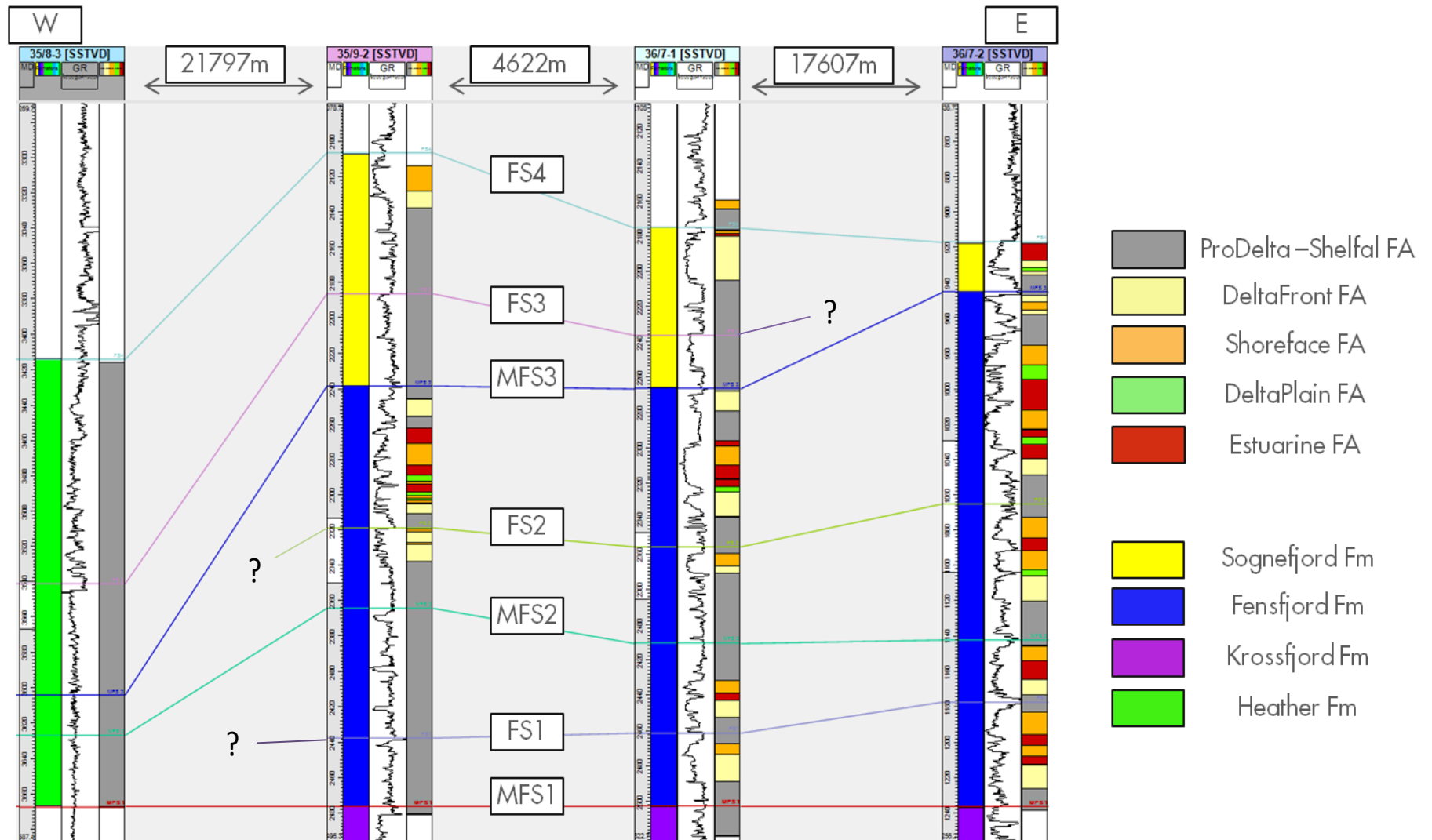


Figure 5-2 Regional sequence stratigraphy surfaces and interpretation, location of this well is displayed in Figure 1-1

6 SEISMIC INTERPRETATION

Seismic interpretation was performed in order to understand lateral distribution of depositional environment and depositional elements along the Gjøa field as well as to provide some further insights into syn depositional structuring of the area. Firstly, seismic well tie process ensured correlation between well and seismic data. It was followed by horizon the interpretation, which was challenging due to partially to completely eroded horizons in Northern side of study area. Structural interpretation was focused on timing activity of major faults and fault trends. Lastly, particular emphasize was made on seismic stratigraphy and facies interpretation.

6.1 Seismic well tie

One of the critical processes to bridge the well data with seismic data is to perform seismic well tie process by creating synthetic seismogram. Synthetic seismograms derived from logs and wavelet was extracted from the seismic data for 35/9-1, 35/9-2 and 36/7-1. Extraction of wavelets based on statistical methods ensured a reliable level of confidence.

Logs (gamma-ray, sonic and density) have been corrected for caving and invasion. The checkshot data was used for initial correction of time-depth relationship. Further corrections to the time-depth relationship were made to improve the correlation between the synthetic and seismic data. Figure 6-1 displaying N well seismic tie process representing correlation between well and seismic data response. The time-depth relationship at reservoir zones can be considered as good enough for further interpretations.

These synthetic seismograms have been carefully tied to the ST07 seismic data both in the reservoir zones and in the overburden. The well ties results with main markers are shown in Figure 6-2.

Time	Well: 35/9-2		Well: 35/9-2		-0.261	RC	0.261	Survey: st0703				Synthetic	Survey: st0703			
SRD	Log set: Log set 1		Log set: Log set 1		: ST0703_full_mig_fin [Real]				: ST0703_full_mig_fin [Real]							
ms																
1.27	DEN (g/cm3)	3.02	GR (gAPI)	150	Inline				Inline							
1777	Calc AI (kPa.s/m)	19384	CALI (in)	20	1252	1252	1252	1252	1252	1252	1252	1252	1252	1252		
165	DT (us/ft)	43			Xline				Xline							
					2410	2413	2416	2419	2420	2420	2423	2426	2429			

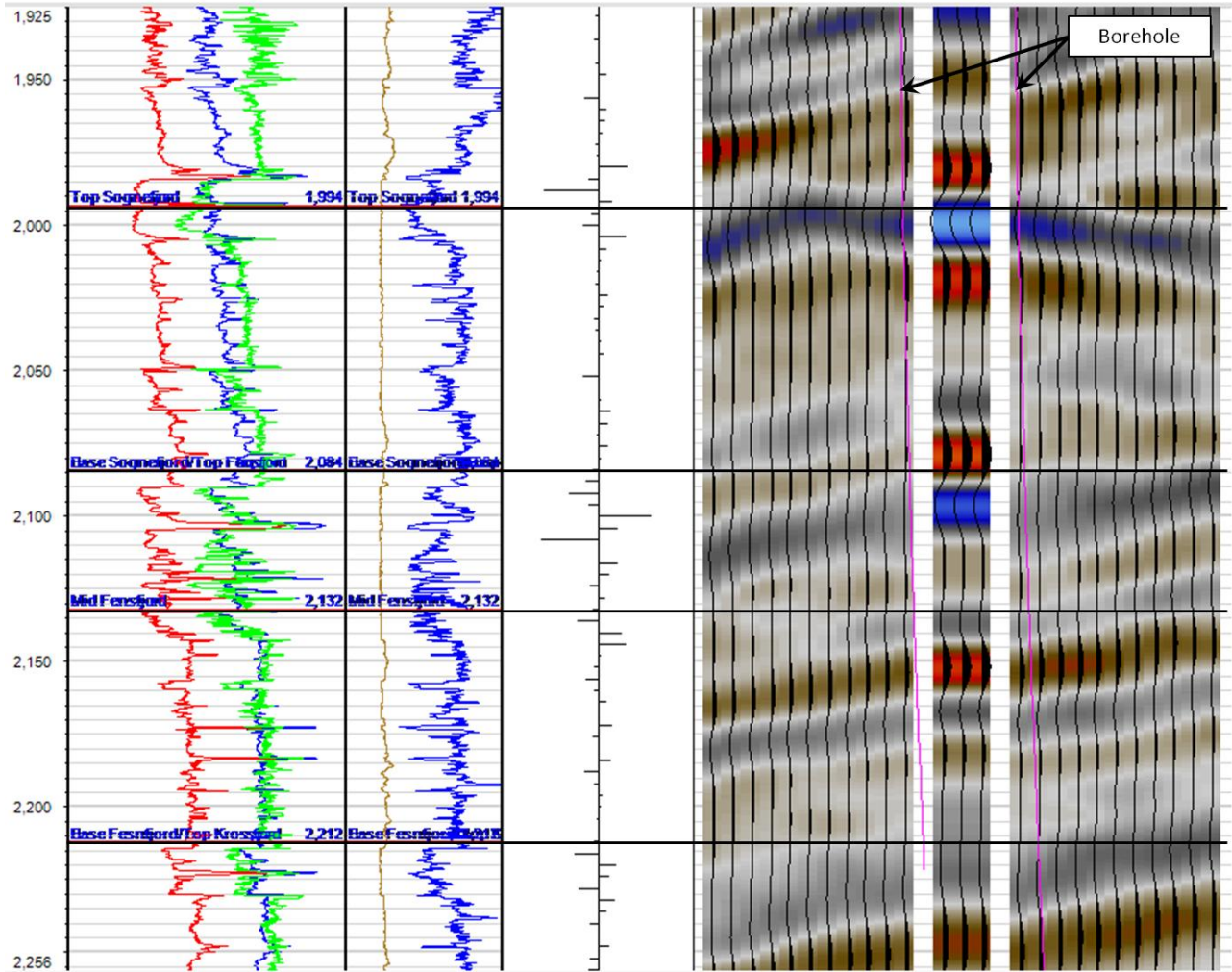


Figure 6-1 Well to seismic tied process with main well tops

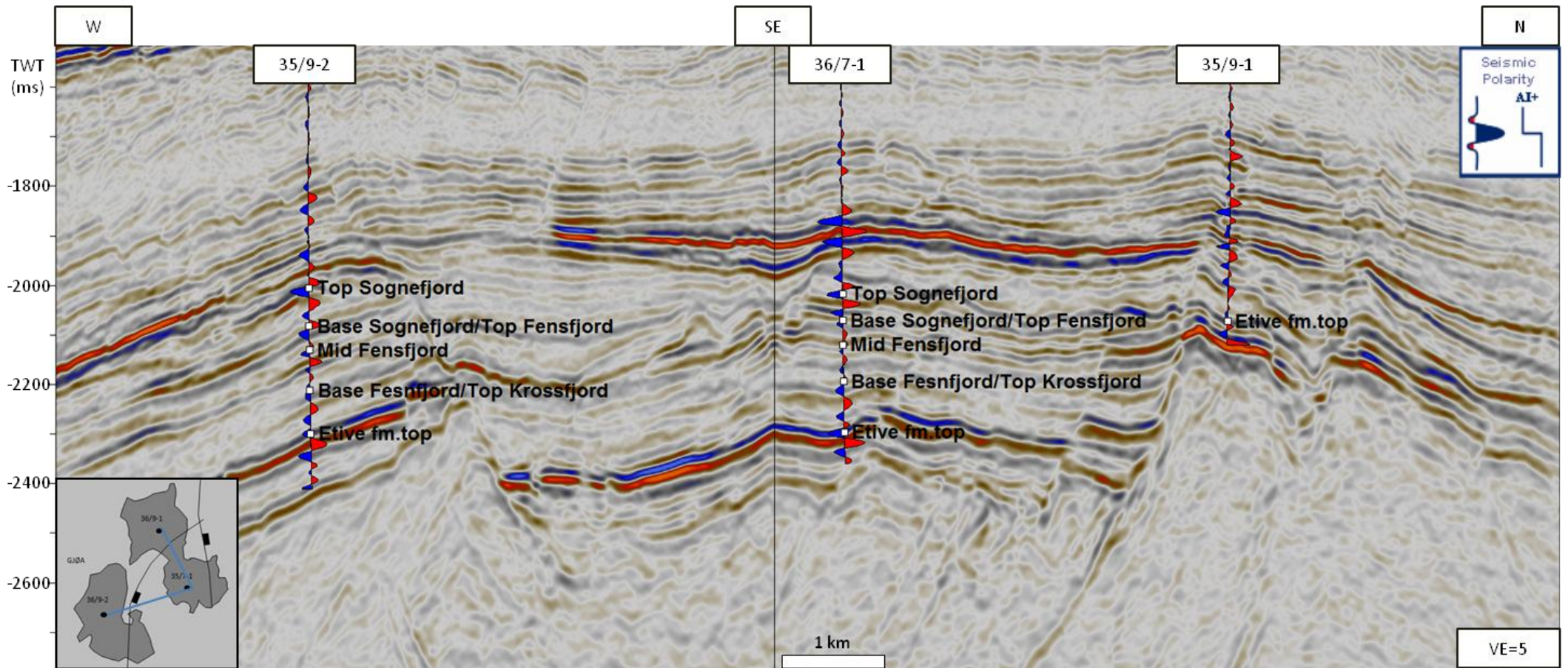


Figure 6-2 Seismic cross section, displaying seismic well tie results with key well tops

6.2 Horizon interpretation

The framework horizons were provided by A/S Norske Shell, however some new horizons were interpreted. The horizons with their characteristics are provided in Table 3 and discussed below. Cross section with interpreted horizons is shown in Figure 6-4. Van Gogh filtering was performed and result presented in Figure 6-3. It slightly improved continuity of horizons and reduced noise.

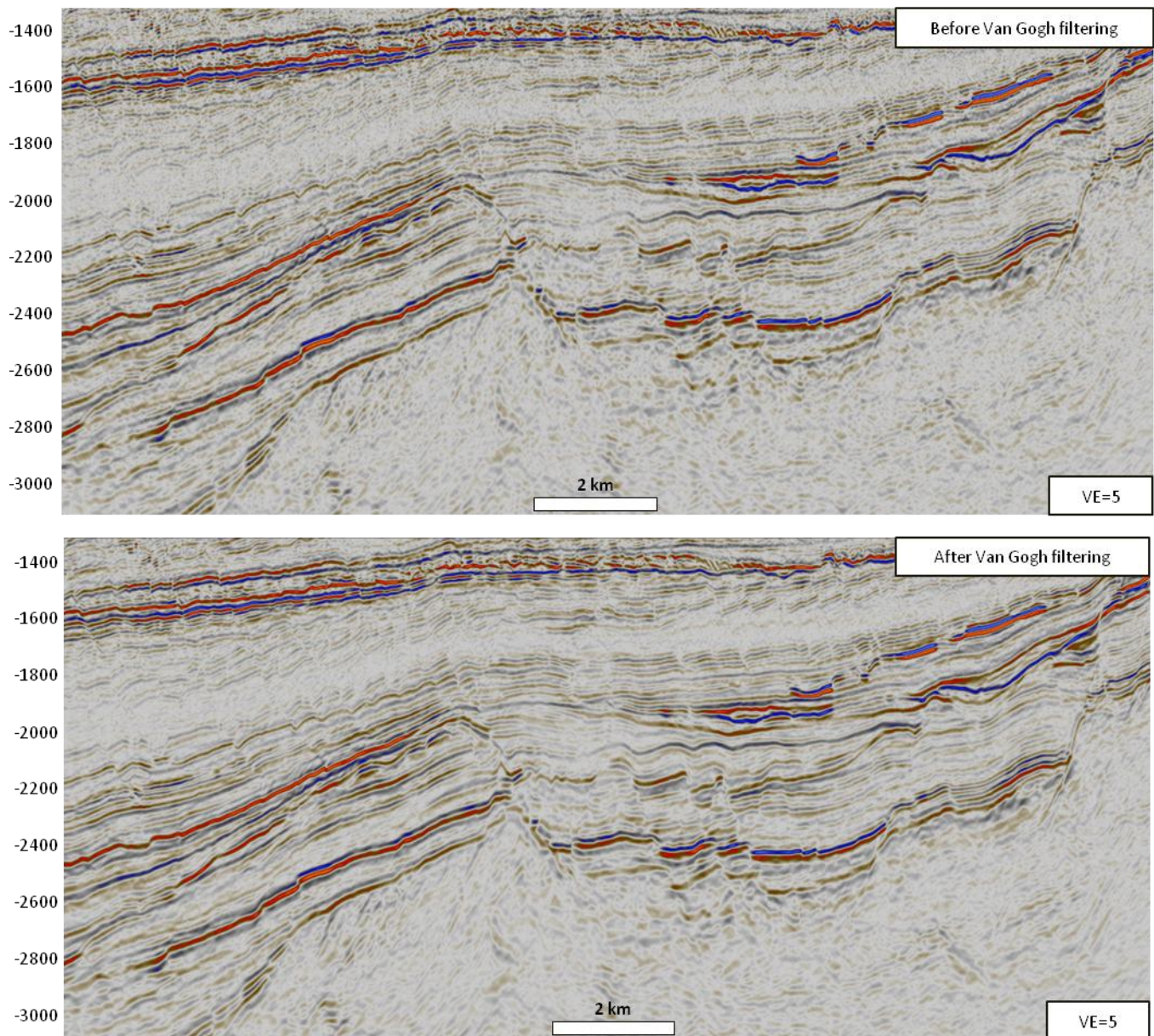


Figure 6-3 Seismic Inline 1260, before and after Van Gogh filtering

Table 3 Interpreted horizons with their characteristics

Horizon	Amplitude	Acoustic impedance	Correlation
Near Top Sognefjord*	Negative	Decrease	Good
Base Sognefjord/Top Fensfjord	Positive	Increase	Good
Mid Fensfjord	Positive	Increase	Poor
Base Fensfjord/Top Krossfjord	Positive	Decrease	Poor
Top Brent*	Negative	Decrease	Good
Top Basement*	Positive	Increase	Good
*horizons provided by A/S Norske Shell			

Top Sognefjord significantly eroded and preserved only in particular areas, so as Top Sognefjord horizon Near Top Sognefjord (erosional surface) was picked. The picking seems reasonable as this is the only continuous reflector that represents Top Sognefjord. It corresponds to a trough at the well locations and was picked confidently.

Base Sognefjord/Top Fensfjord horizon is present in wells 35/9-2 and 36/7-1. It ties in a peak, and was interpreted confidently. It is truncated by an erosional surface in the northern part of the field. This surface is represented as a clear parallel reflector that is partially to completely eroded on the flanks.

Mid Fensfjord ties in a peak for wells 35/9-2 and 36/7-1. It is also truncated by a top erosional surface in the northern part of the field. Interpretation of this horizon was challenging as it was intensively faulted and represented by a low amplitude reflector.

Base Fensfjord was interpreted and it ties in peaks for wells 35/9-1, 35/9-2 and 36/7-1. Interpretation of this horizon was also challenging, because of discontinuities and a low amplitude reflector that disperses in graben areas.

Top Brent is a well-defined and sharp reflector, and ties in a trough for the Gjøa wells. It has been auto-tracked in most areas. This is the best defined horizon.

Top Basement is in most areas a weak and low/transparent reflector. It ties to a peak in all Gjøa wells.

For regional study purpose Top Basement, Base Fensfjord and Top Sognefjord were extended ~20 km to the West and ~7 km to the East of the Gjøa field (Figure 6-5). Although quality of the seismic data was poor all horizons were picked confidently, with small remark that Top Sognefjord outside of the study area was presented in form the erosional surface.

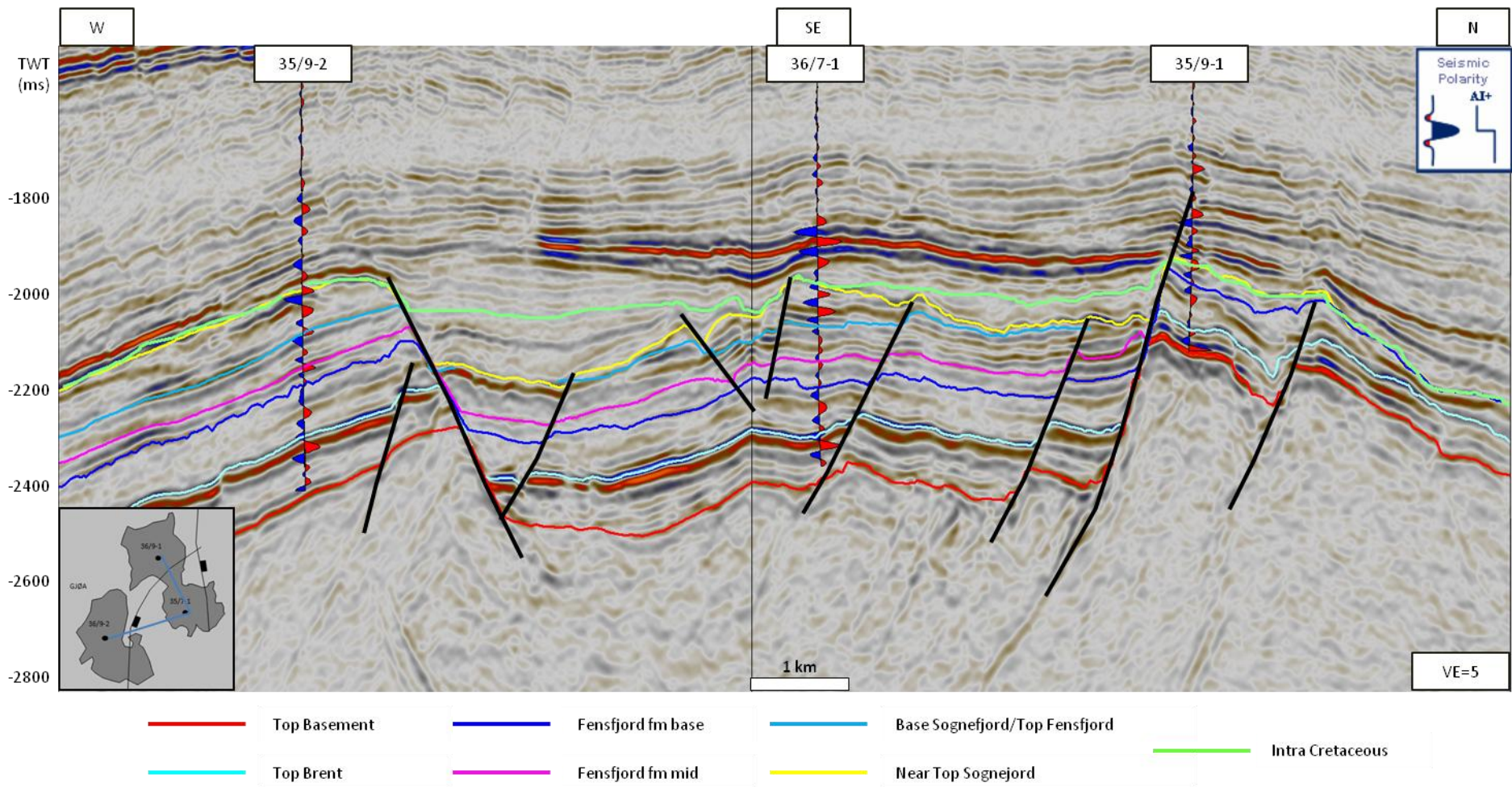


Figure 6-4 Seismic cross section through 3 wells, displaying interpreted horizons

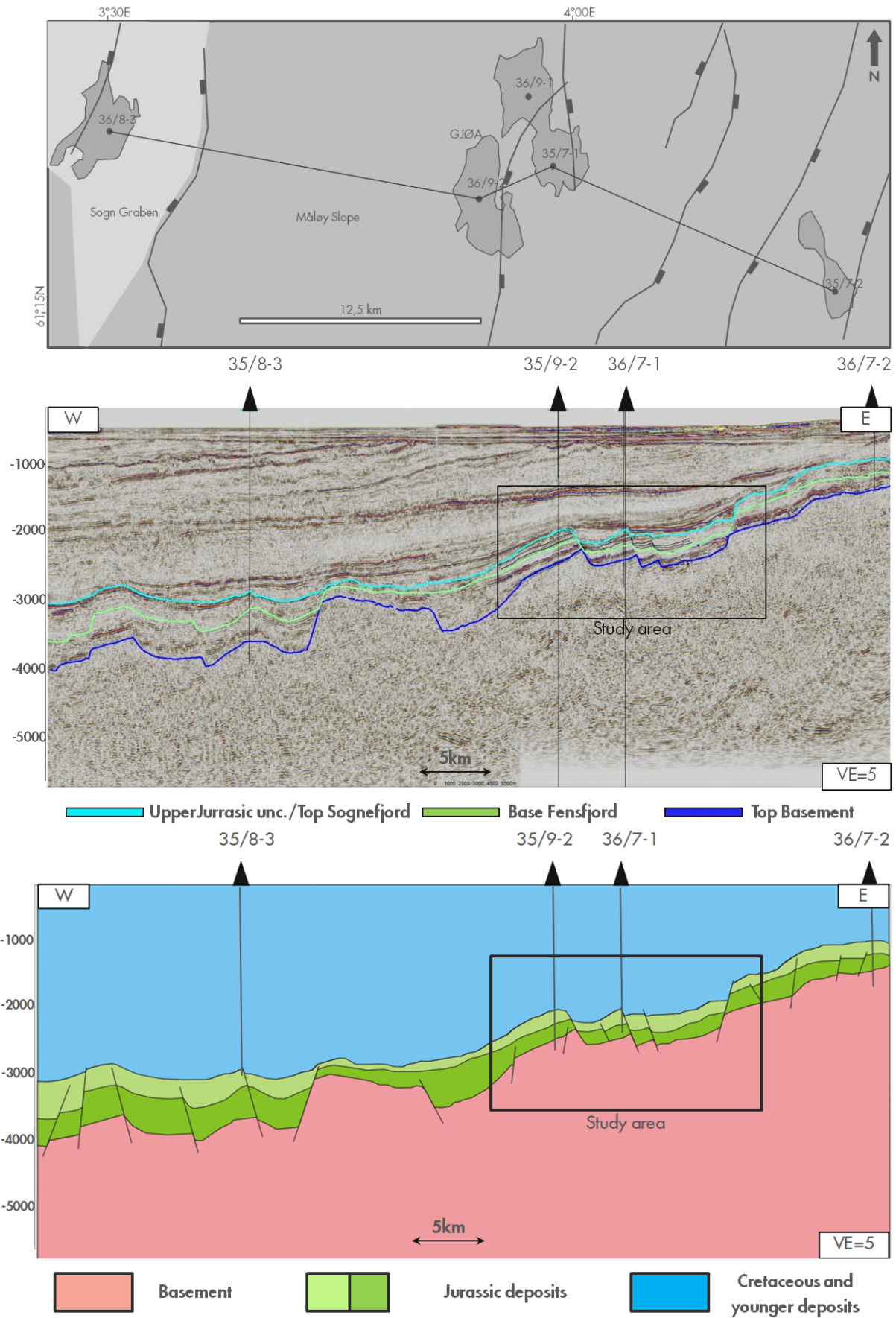


Figure 6-5 Location map (up), regional profile with interpreted horizons (middle) and interpreted regional profile (low)

6.3 Fault interpretation

In order to define impact of faults activity on depositional settings in study area few key faults were studied. Fault interpretation obtained from Top Brent dip map displaying main faults and their trends (Figure 6-6). Faults are grouped into fault families that show the same structural settings.

Fault family 1, defined by normal faults and have main trend N to S with E-W extension and mostly exposed in the Northern part of GjØa, and dies out toward Southern part. Generally, they are 40-60 degree high angle faults and dip towards East and West forming horst structure, the displacement varies from ~100m in the center of the field to ~500 m in Northern sides (forming half graben system).

Fault family 2, defined by normal faults and have main strike direction NE to SW with NW-SE extension and mainly dip towards W forming graben system, they have lower angles about 40-50 degree, most likely it is due to rotation. The displacement varies as well, but relatively smaller ~10-300 m.

Age of the faults are varies, but overall related to Latest Jurassic rifting event. Fault family 1 interpreted as older fault family forming basin morphology during deposition in Early to Late Callovian times. Consequently, fault family 2 interpreted as relatively younger and appears to have controlled deposition during Early Oxfordian to Kimmeridgian.

6.4 Isochore interpretation

Isochore maps were produced to understand how changes in structural regime during Latest Jurassic rifting event controlled the depositional processes of Fensfjord and Sognefjord formations. Isochore maps are generated from Mid Fensfjord-Base Fensfjord, Top Fensfjord-Mid Fensfjord and Top Sognefjord-Top Fensfjord. Because of the extensively eroded of Northern deposits main focus was on describing of Southern parts.

Mid Fensfjord – Base Fensfjord isochore map is displayed in Figure 6-7 (left). Thickness of this interval varies from ~30 ms to ~110 ms. There are at least two depocenters. Major depocenter located in south central edge of study area and minor is in central part around well 36/7-1. Sediment thickness on Western side around well 35/9-2 is homogeneous with average

thickness of ~25 ms, while in Eastern side average thickness is ~75 ms. Distribution of sediment thickness is diverse, but mainly increases towards SE corner of study area.

Changes of sediment thickness from E to W is can be related to existing N-S trending major fault forming structural high in Western area. (In well correlation (Figure 5-1) wells 36/7-1 and 35/9-2 are on structural highs and they are do not reflect true thickness variations in study area)

Top Fensfjord – Middle Fensfjord isochore map displayed in Figure 6-8 (left). Thickness of this interval varies from 25 ms to 85 ms. There are several depocenters are located in the Western and central part of the area nearby well 35/9-2. Average sediment thickness in Western side is ~65 ms and it is gradually decreased towards the Eastern side (average thickness ~25 ms). Distribution of sediment thickness is mainly increasing towards the WNW.

Westward thickness increasing suggest of forming thicker depocenter in W outside of study area. Overall shifting of depocenters basinward can be related to initial stage of fault family 2 activity, which caused uplifting of ESE sides of study area.

Top Sognefjord – Top Fensfjord isochore map displayed in Figure 6-9 (left). Thickness of this interval varies from 0 ms to 140 ms. Due to significant erosion interval partially preserved in Southern areas. It is difficult to define main depocenter, but the thickest area located in Western side nearby 35/9-2 extended to the E. Thickness changes from ~20 ms in the WNW to ~140 ms in ESE.

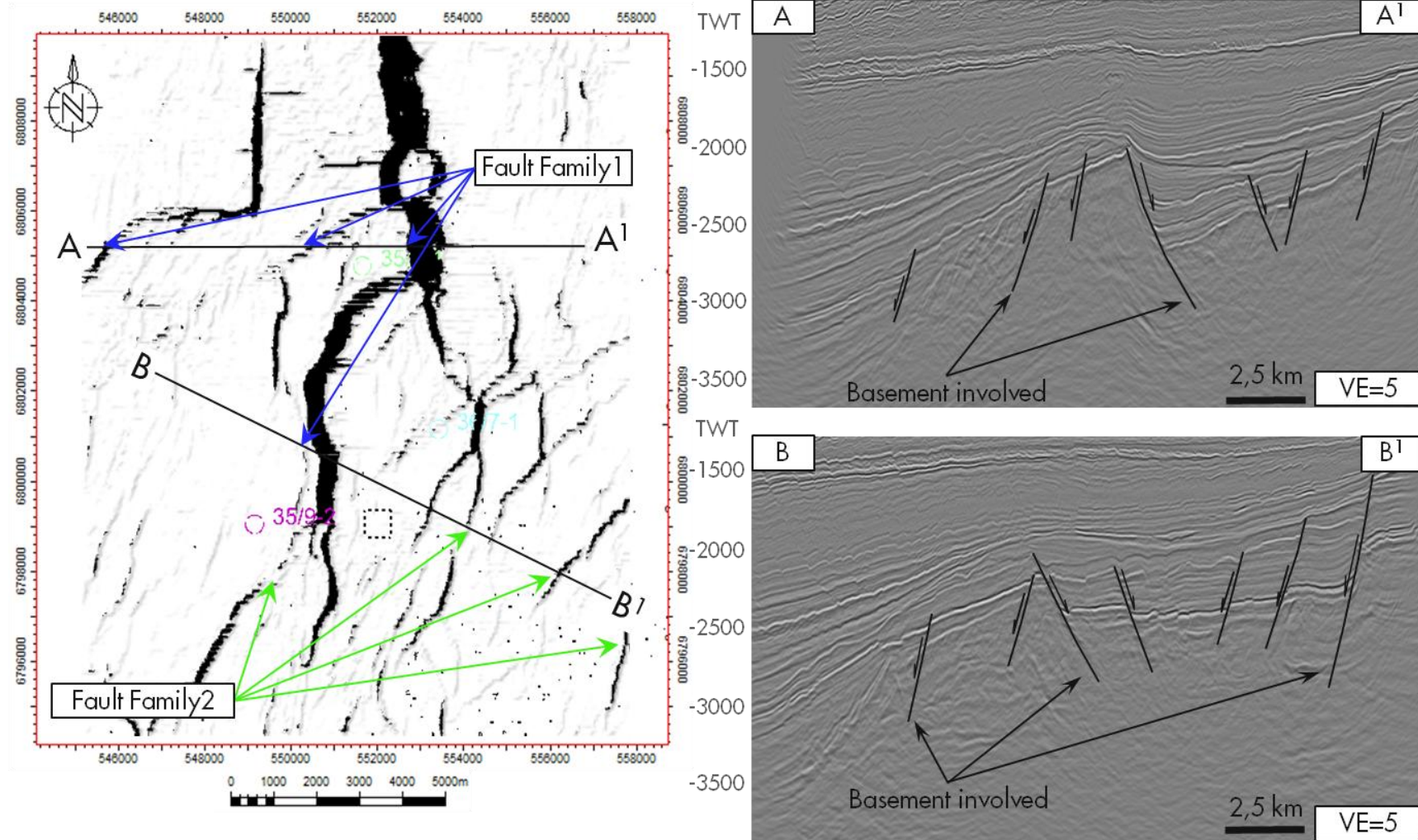


Figure 6-6 Top Brent dip map with random cross sections, displaying interpreted fault families

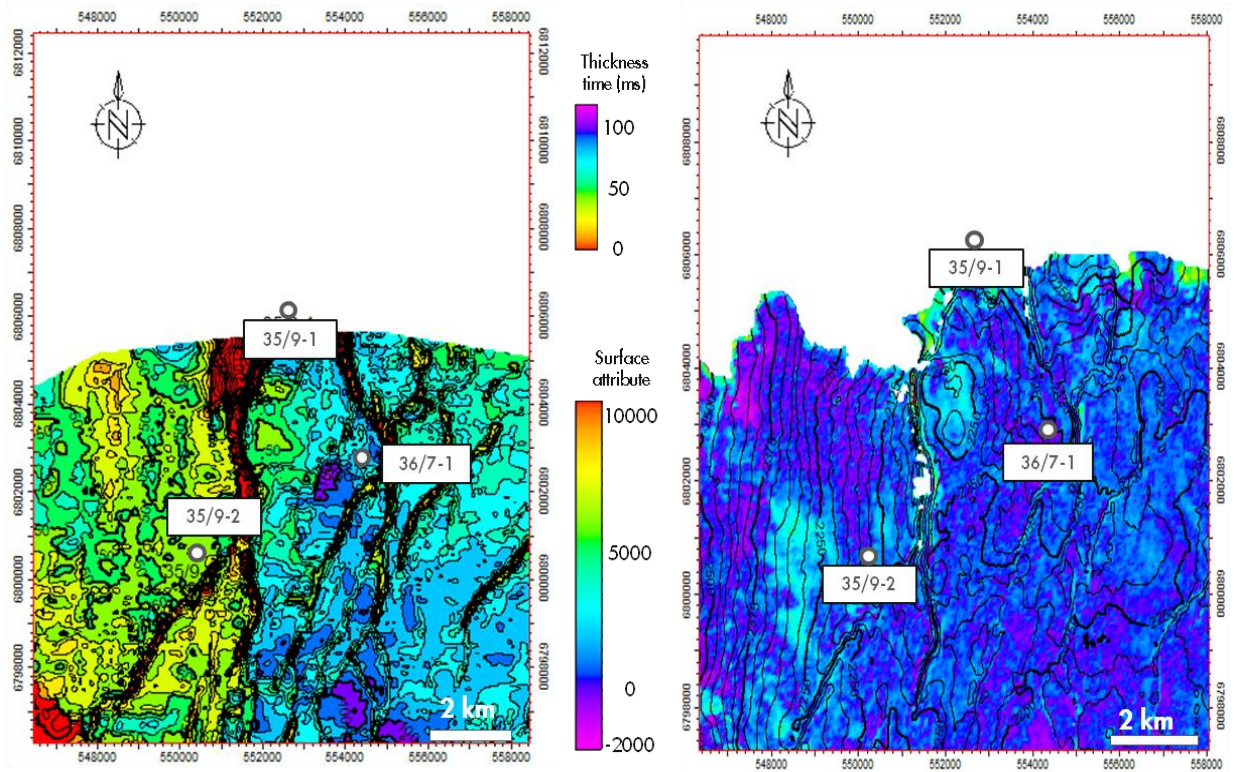


Figure 6-7 Middle Fensfjord-Base Fensfjord isochore map (left) and seismic attribute map (max.amplitude) 20 ms below Middle Fensfjord horizon (right)

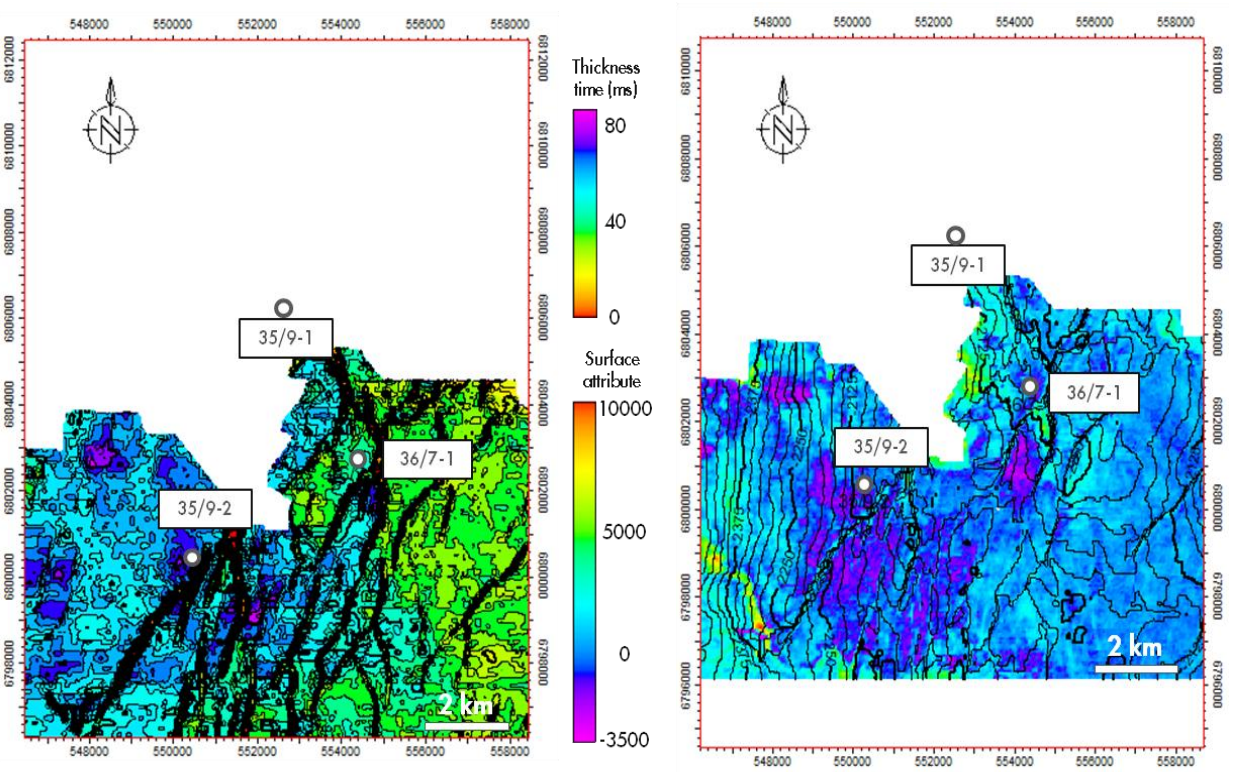


Figure 6-8 Top Fensfjord-Middle Fensfjord isochore map (left) and seismic attribute map (max.amplitude) 20 ms below Top Fensfjord horizon (right)

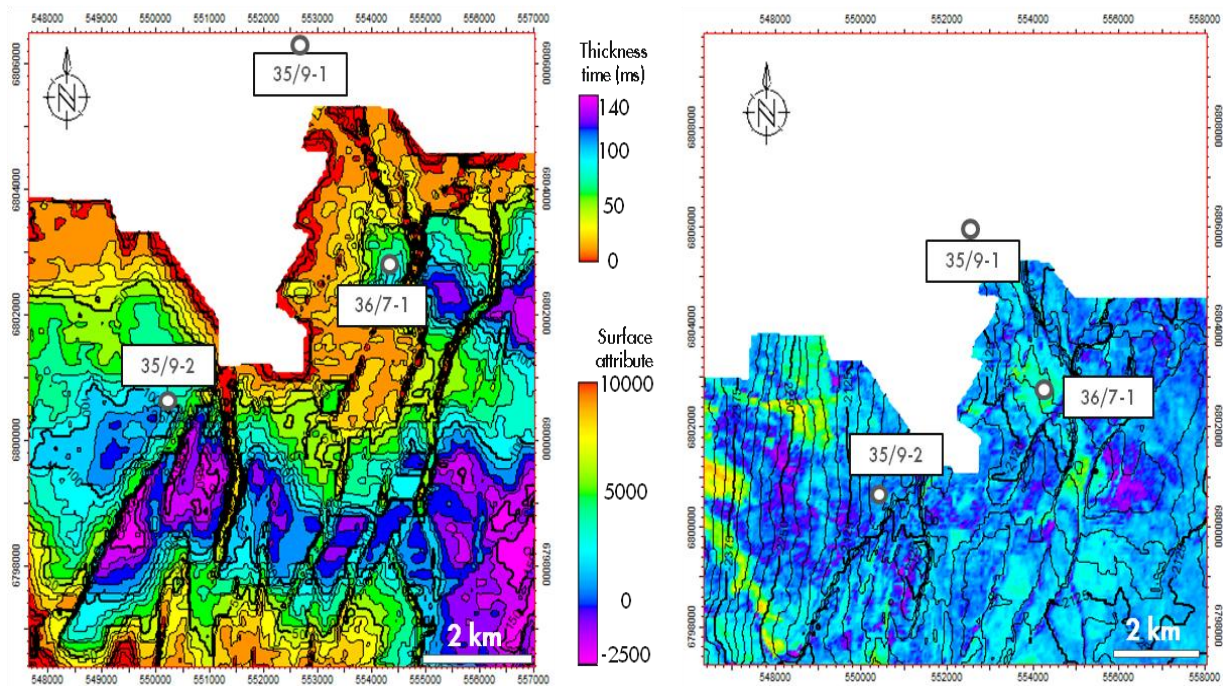


Figure 6-9 Top Sognefjord-Top Fensfjord isochore map (left) and seismic attribute map (max.amplitude) 20 ms above Top Fensfjord horizon (right)

6.5 Seismic attribute interpretation

To gain all possible information from seismic data amplitude extraction process was performed. Maximum amplitudes were extracted, calibrated to well data and used as a main attribute. According to well calibration negative amplitudes can be related to high sand ratio while positive amplitudes are high mud/siltstone ratio. Extraction window was adjusted according to the thickness of particular stratigraphic intervals, which in most case was around 20 ms. The results are provided together with isochore maps in Figure 6-7 – 6-9.

Mid Fensfjord attribute map is dominated by negative amplitudes, however some positive spots are also present. Overall negative amplitudes are concentrated in ESE corner of study area, but some pronounced and disconnected spots located in the W of study area (Figure 6-7 right).

According to the well data pronounced negative amplitude spots around well 35/9-2 can be related to event bed deposits.

Top Fensfjord attribute map is dominated by positive amplitude. However, negative amplitude cloud distributed in central part and extended towards the S of study area. They are more pronounced and have sharper boundaries (Figure 6-8 right).

According to well data, this interval is dominated by deltaic units, so negative amplitudes can represent geomorphology of deltaic sand distribution.

Top Sognefjord is associated with unconformity surface and cannot be related to distribution of depositional features, so instead maximum amplitude was extracted from interval of 20 ms above Top Fensfjord horizon. Overall interval dominated by positive amplitude, however two disconnected negative amplitude spots are observed in W and E areas (Figure 6-9 right).

According to well data, this interval dominated by turbidite lobes, so this negative spots can also be related to geomorphology of the turbidite lobes.

6.6 Seismic stratigraphy and seismic facies interpretation

Brief seismic stratigraphy interpretation was performed in order to identify seismic reflectors character that can be linked to depositional systems. 3D seismic data quality allows resolving

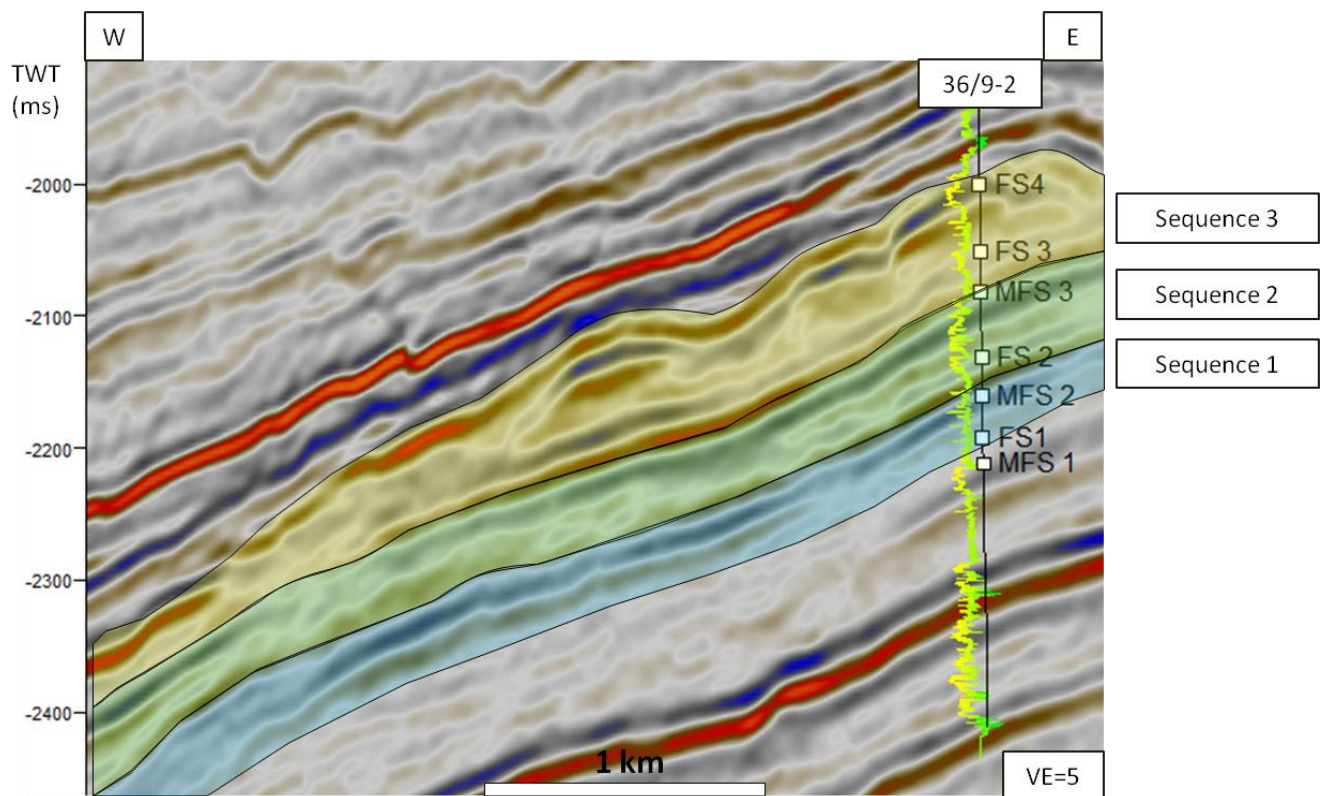


Figure 6-10 Seismic section, providing with interpreted sequence intervals

stratigraphic intervals more than 23 m. With respect to well data analysis, the study interval was divided into 3 sequences and displayed in Figure 5-1. Seismic character of each sequence (Figure 6-10) discussed below:

Sequence 1 internally characterized as discontinuous, parallel to subparallel reflectors with low amplitude values. In graben areas seismic reflectors disperse and become chaotic towards the faults.

Sequence 2 varies internally, but major area characterized as continues parallel to subparallel reflectors with higher amplitude values at the base and top. On the W of the study area around well 35/9-2 this interval has shingled type clinofom (Fensfjord clinofoms) structures, which downlapping on top of sequence 1.

Fensfjord clinofoms defined by low angle continues reflectors that dip towards the West, South-West with angle of 1-2 degree (compacted), top truncated and only developed on uplifted area around 35/9-2 well (Figure 6-12) Interval is relatively thin up to 25 meters and dip gently over 3-5 km.

Interpretation: The clinofoms correlates to the gravity flow/turbidite dominated delta front interval and belongs to Upper Fensfjord formation. This clinofoms are observed only around well 35/9-2 and implies on different structural and depositional settings during Early to Late Callovian times. Dipping westward and south westward allows to state that shoreline trajectory was N-S or NW-SE oriented. Lateral distribution of this clinofoms interpreted from min amplitude extraction from this interval and showed in Figure 6-11

Sequence 3 also varies internally, but major area characterized as continues parallel to subparallel high amplitude reflectors. On the W of study area around well 35/9-2 this interval has clinofoms structure (Sognefjord clinofoms), but missing upper part brings difficulties to identify its type.

Sognefjord clinofoms. The geometry of this clinofoms is provided in Figure 6-12. There is downlapping part of the clinofoms that looks steeper (4-5 degree) than those in Fensfjord fm. However, upper part is completely eroded within whole study area, so that it makes it difficult to quantify them.

Interpretation: steepening and thickening of clinoforms suggest increase in sedimentary supply that can be related to developing of NE-SW trending faults. It is unable to map lateral distribution of this clinoforms due to highly eroded upper part.

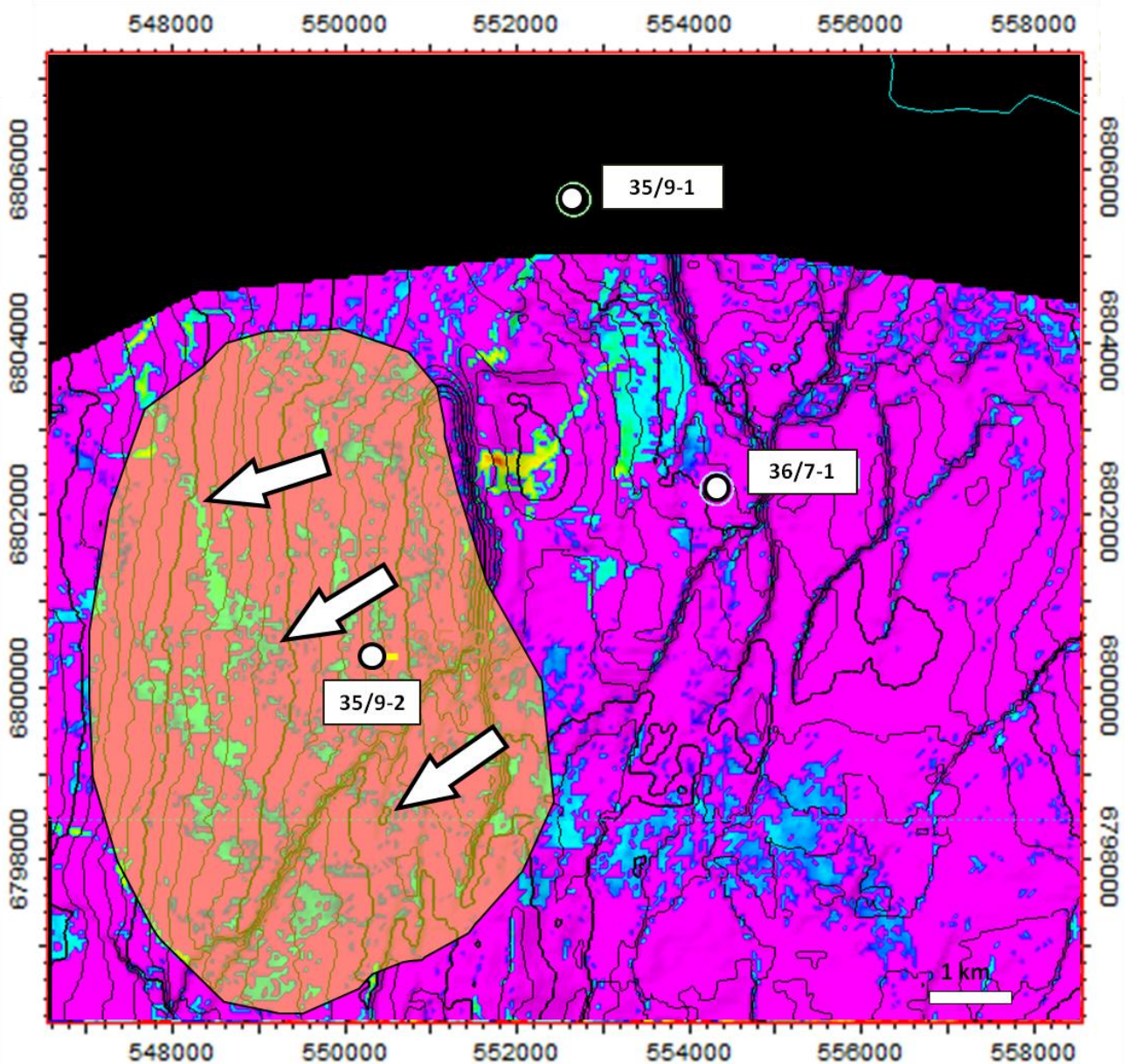


Figure 6-11 Maximum amplitude map 15 ms above Mid Fensfjord horizon. Highlighted area display lateral distribution and arrows showing prograding direction of the clinoforms

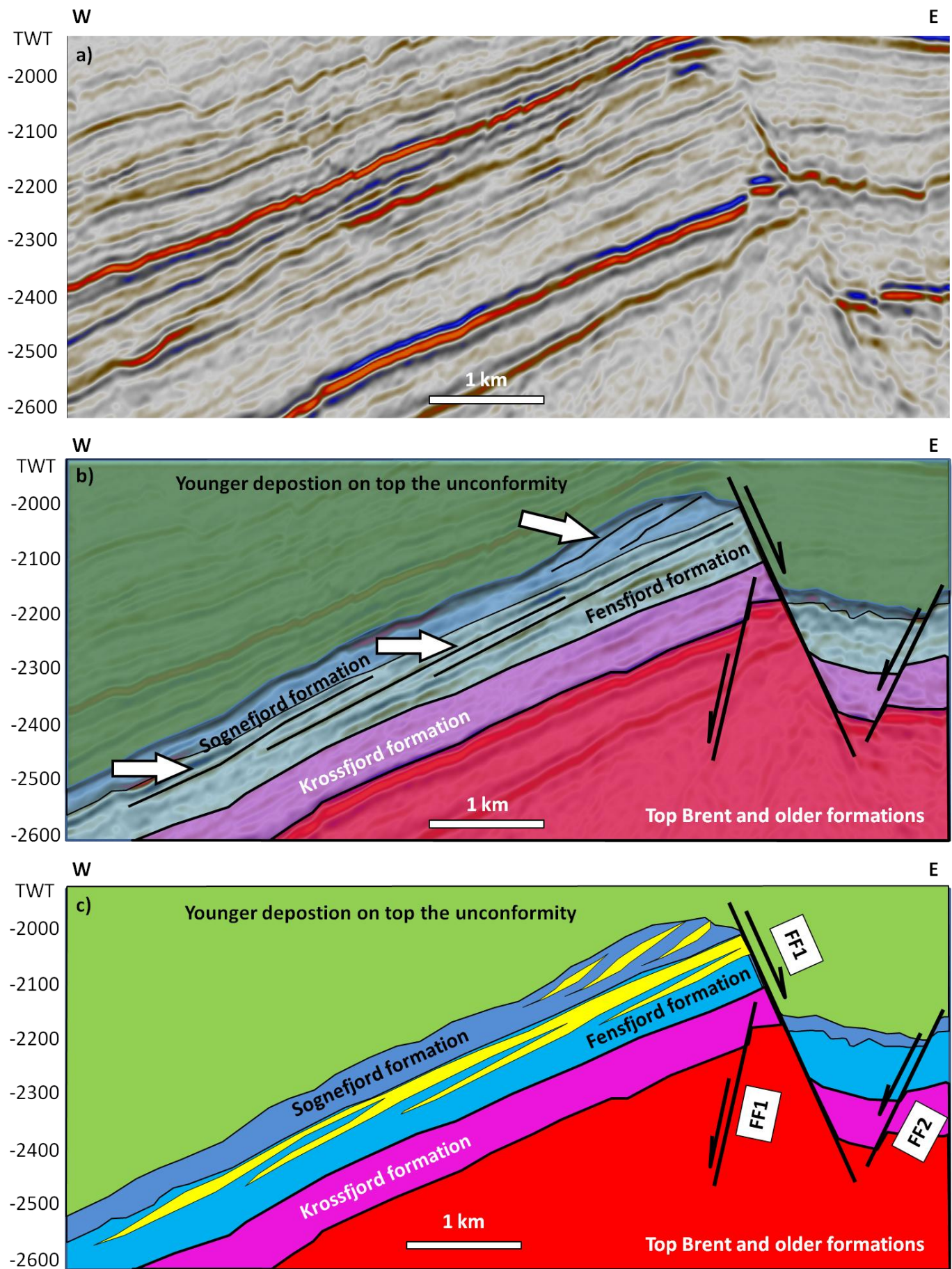


Figure 6-12 Seismic stratigraphy interpretation, a) seismic inline 1320 b) Interpretation of reservoir intervals, arrows displaying clinoforms outbuilding c) modeled clinoforms (yellow colored). FF=fault family.

6.6.1 Attribute analysis

In this study new developing seismic facies analyzing technique was used and carried out by Shell seismic waveform classifier plug-in for Petrel. As an outcome two seismic facies were produced and interpreted. It is based on understanding of changes in shape and character of the seismic waveform to characterize depositional settings. More detailed explanations can be found in paper V. B. Singh et. al.(2004).

For this particular study unsupervised waveform classification was used and as a result two maps were produced.

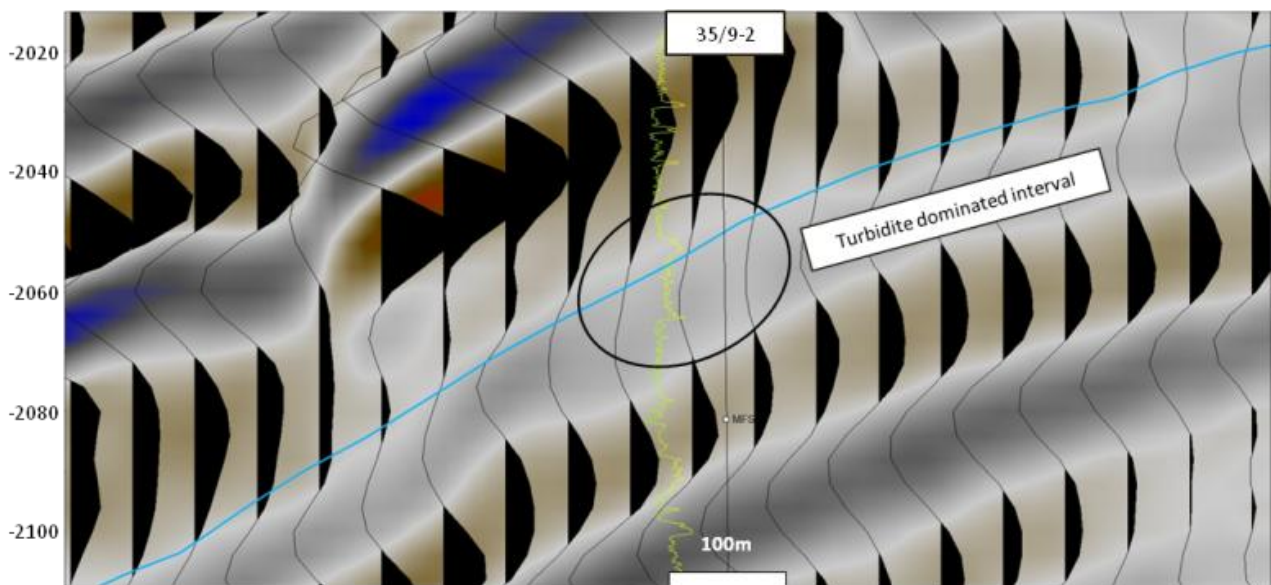


Figure 6-13 Seismic segment, displaying top of the turbidite units (cyan horizon) calibrated by 35/9-2 GR log

First seismic facies map (Figure 6-17) represents lower part of Sognefjord formation. The seismic segment (Figure 6-13) shows top of the interpreted turbidite unit (cyan horizon line) that calibrated by 35/9-2 well log. Within interval of 25 ms 16 different classes with color code are produced (Figure 6-14)

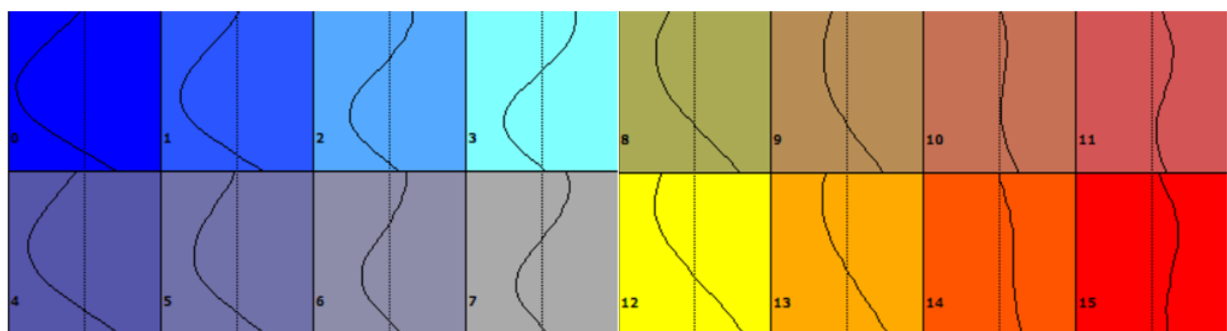


Figure 6-14 16 Seismic waveform classes with color code defined for the first map

Description: Two clear negative amplitude 0 class facies are observed, based on waveform response in seismic segment it represents sand body (Figure 6-18). These NW elongated sand packages interpreted as turbidite units

Interpretation: Turbidite in this interval formed during highstand period in Early Oxfordian (Figure 5-1). This interpretation is in line with structural development of the area when NE-SW fault families are formed. NE-SW trending fault uplifted the SE area and caused steepening of the slope which triggered turbidite and major event deposition. It is also suggested that shoreline trajectory at that time was NE-SW oriented.

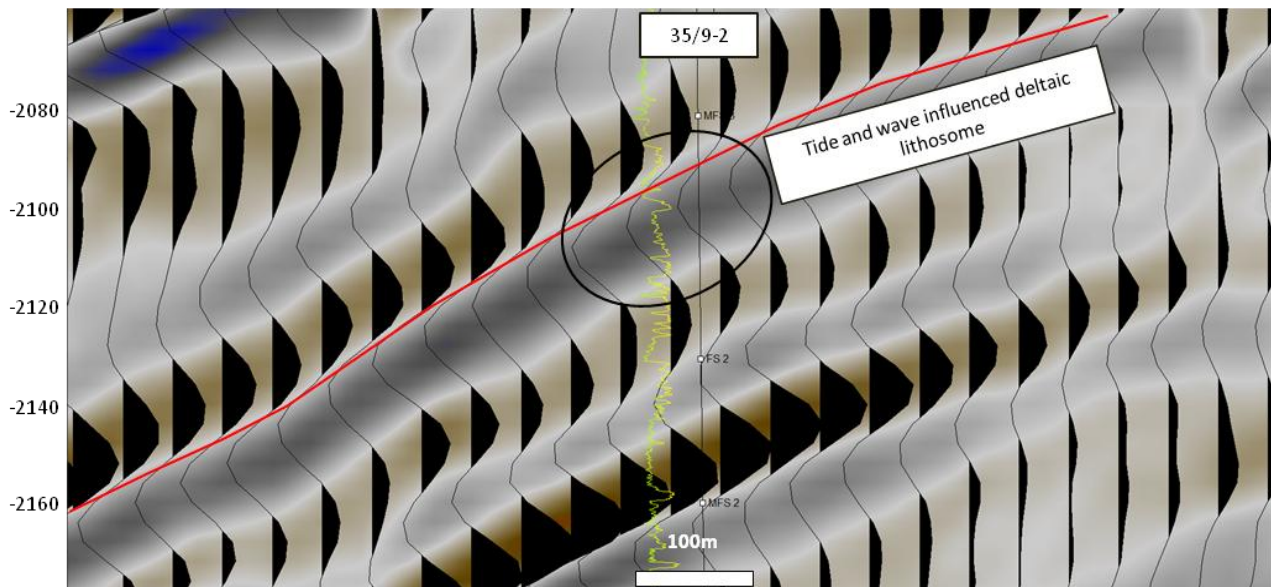


Figure 6-15 Seismic segment, displaying top of the tide and wave influenced deltaic units (red horizon) calibrated by 35/9-2 GR log

Second seismic facies map represents Top Fensfjord interval (Figure 6-20). It was produced in the same manner, interval was calibrated to 35/9-2 well log (Figure 6-15) and within 25 ms interval below horizon (red) 16 different classes (Figure 6-16) with colored code are produced.

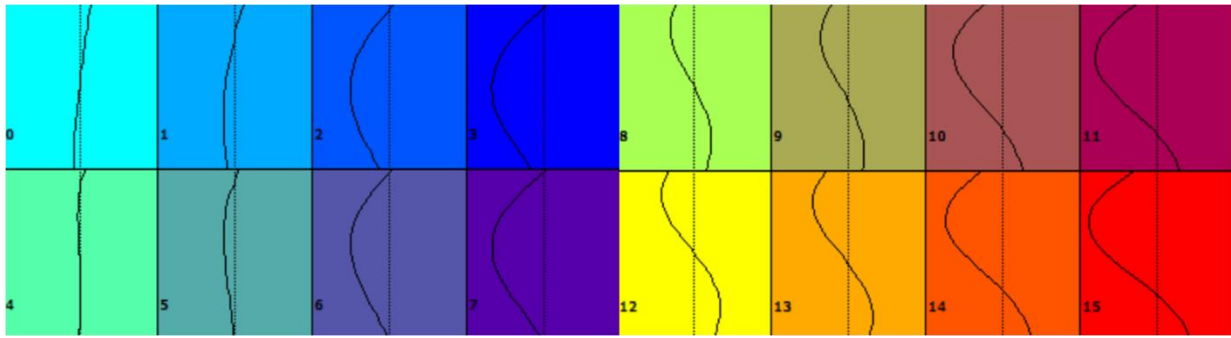


Figure 6-16 16 seismic waveform classes with color code defined for the second map

Description: Central area dominated by 2, 3 and 7 seismic facies classes that interpreted to represent sandier packages (Figure 6-19). This sandy package contoured and interpolated in eroded areas. Form of this contoured package interpreted as delta lobe. This interpretation supported by identified clinoforms just below this delta lobe. On the top this delta lobe structure, 0 class seismic facies that represented by heterolithic units, are observed. Considering sinusoidal form it is interpreted as meandering channel which prograded on top the delta lobe.

Interpretation: This interval represent prograding of Upper Fensfjord delta (Figure 5-1).The shoreline at Early Callovian has mainly N-S trend. Consequently, eastern side of the delta lobe interpreted as delta plain mixed with 15, 12, 0 and 1 class seismic facies.

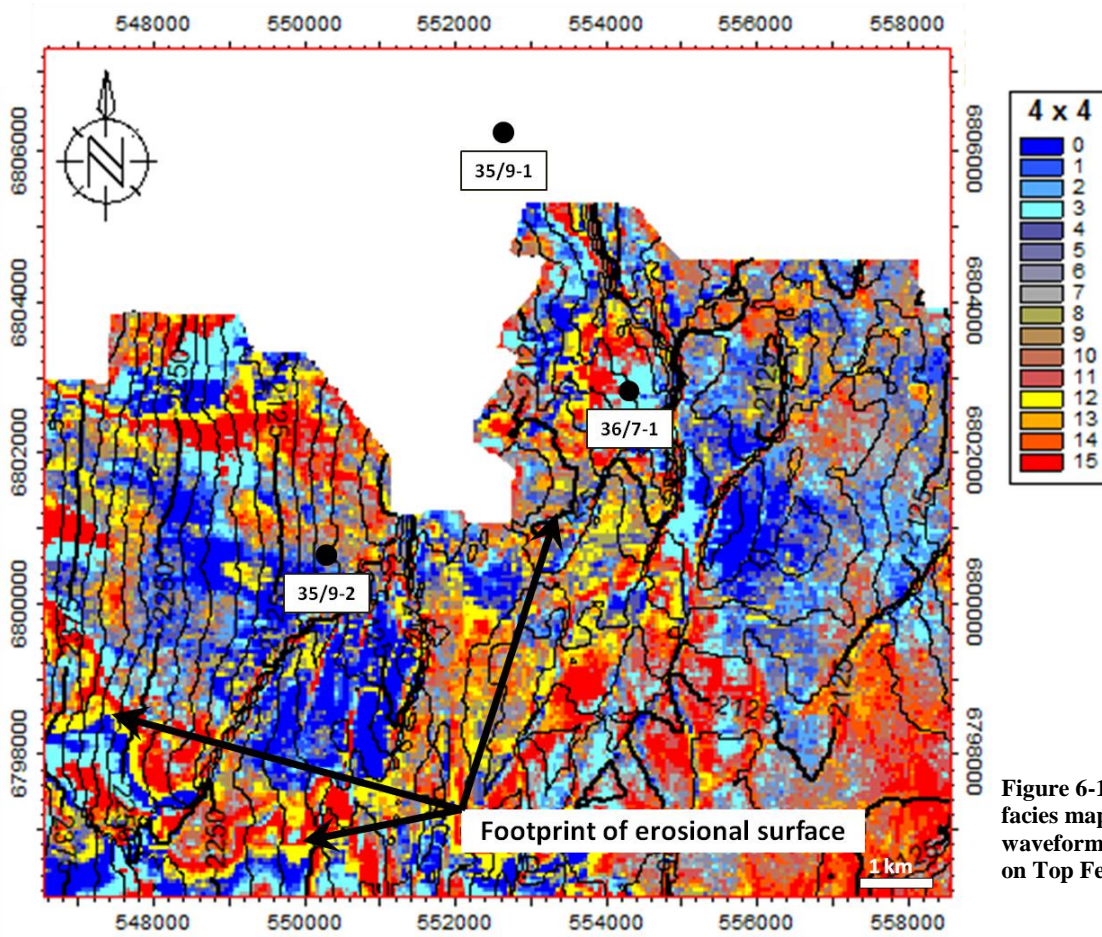


Figure 6-17 First seismic facies map displaying seismic waveform classes variations on Top Fensfjord horizon

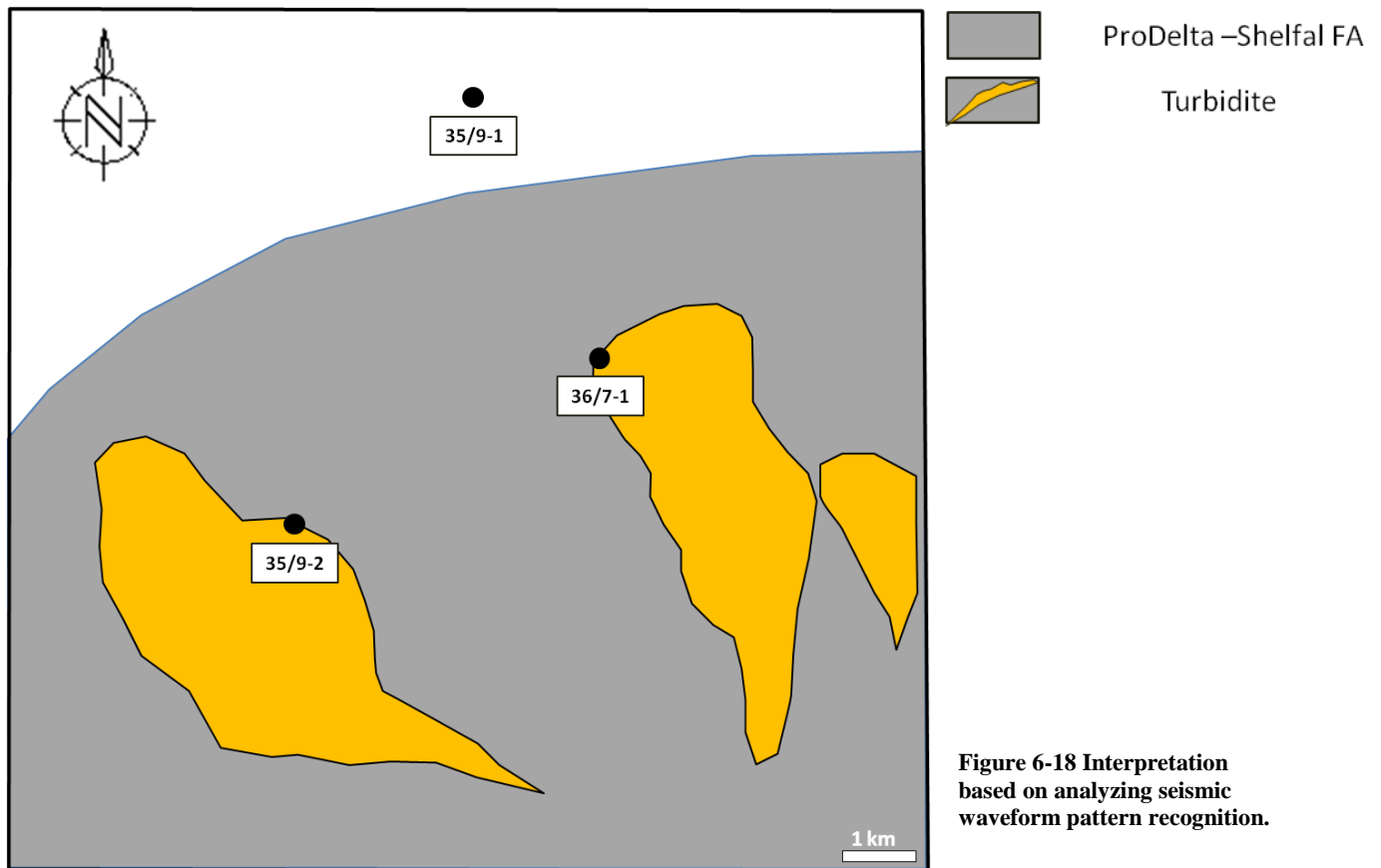


Figure 6-18 Interpretation based on analyzing seismic waveform pattern recognition.

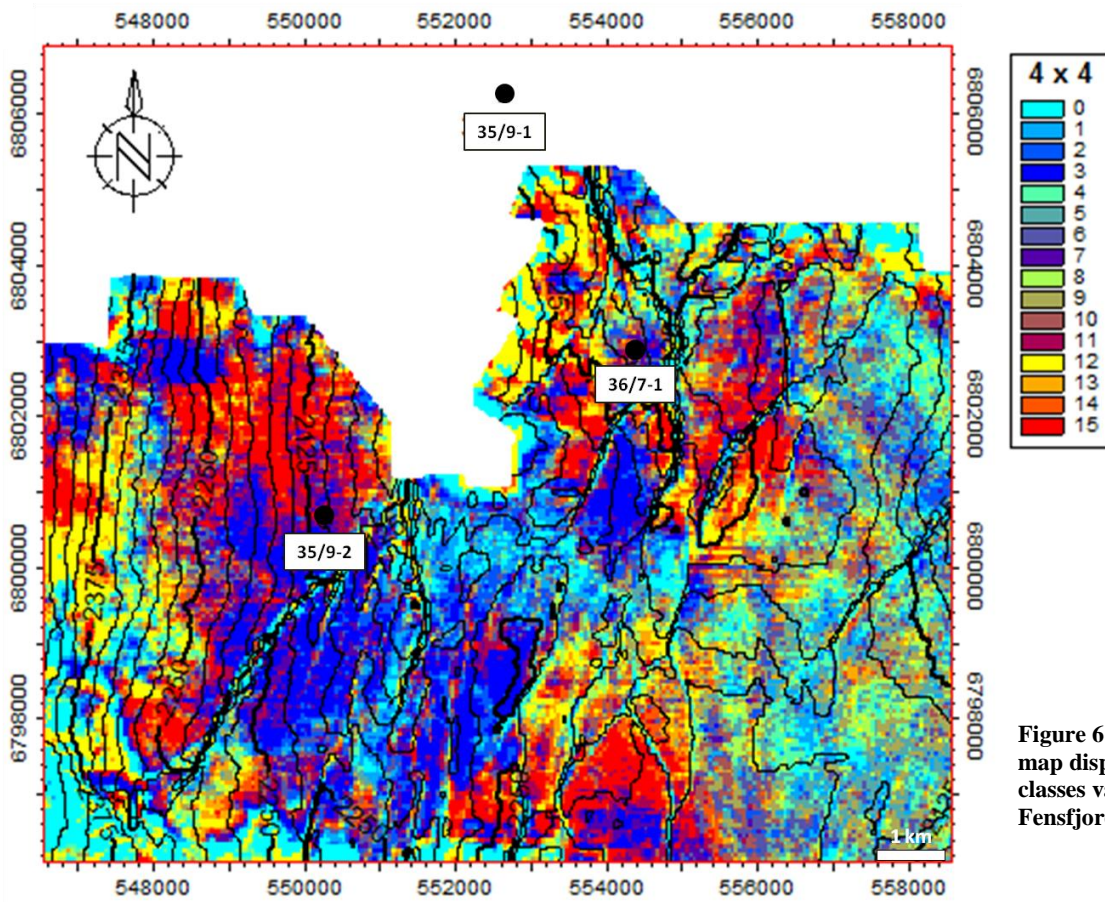


Figure 6-20 Second seismic facies map displaying seismic waveform classes variations on Top Fensfjord horizon

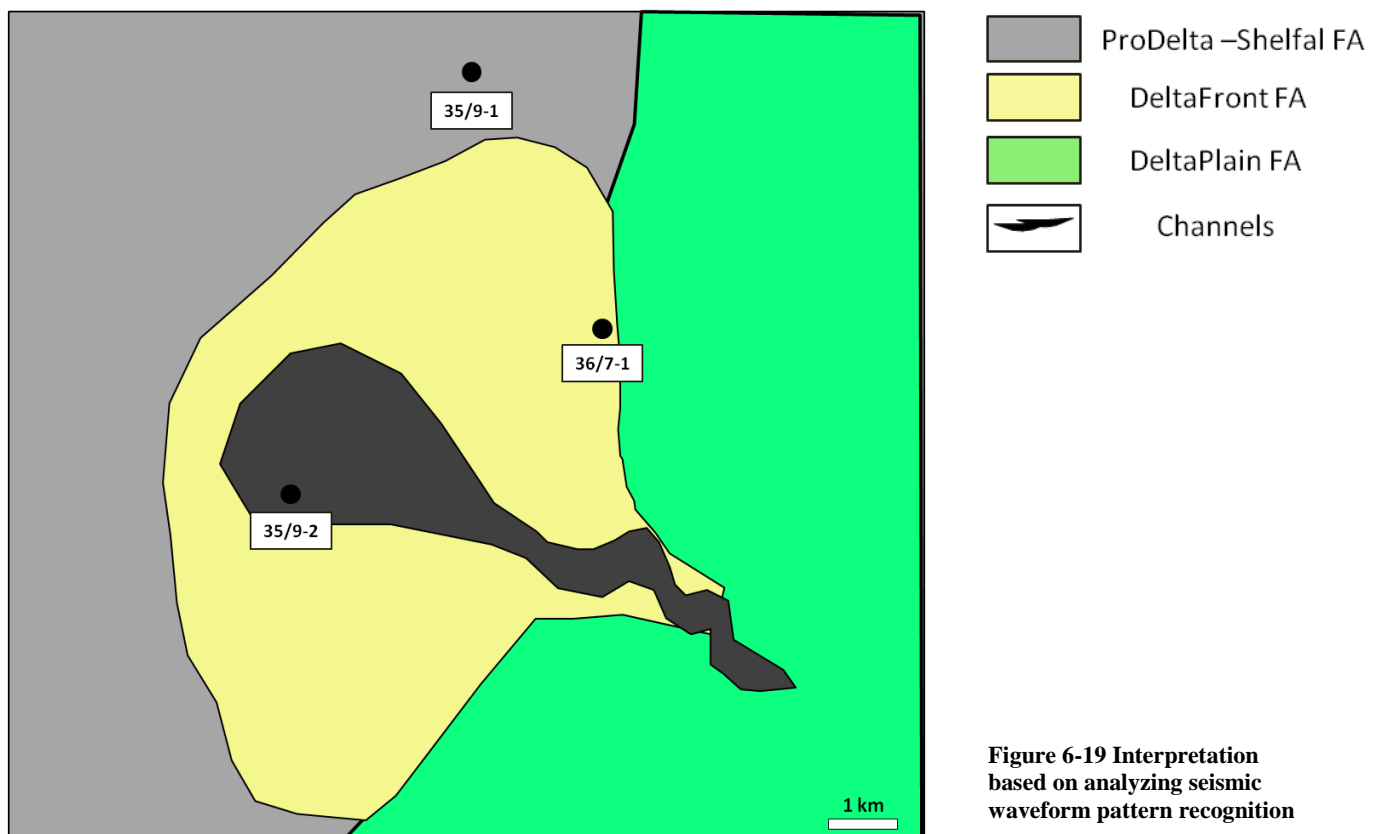


Figure 6-19 Interpretation based on analyzing seismic waveform pattern recognition

7 CONCEPTUAL GEOLOGICAL MODEL

In a present chapter purposed a conceptual geological model for the Callovian to Kimmeridgian tectono-stratigraphy evolution of the Gjøa area. This is based on integration of the sedimentological and sequence stratigraphy analysis which was supported by seismic interpretation presented in previous chapters.

During later period of the M. Jurassic the area was subjected to E-W extension. Extension direction changed to more NW-SE direction during Middle to Late Jurassic transition. As the result there was a change in activity for N-S to NE-SW trending faults.

Sequence1: Lower Fensfjord (**Late Bathonian - Early Callovian**) ~1-2 million years

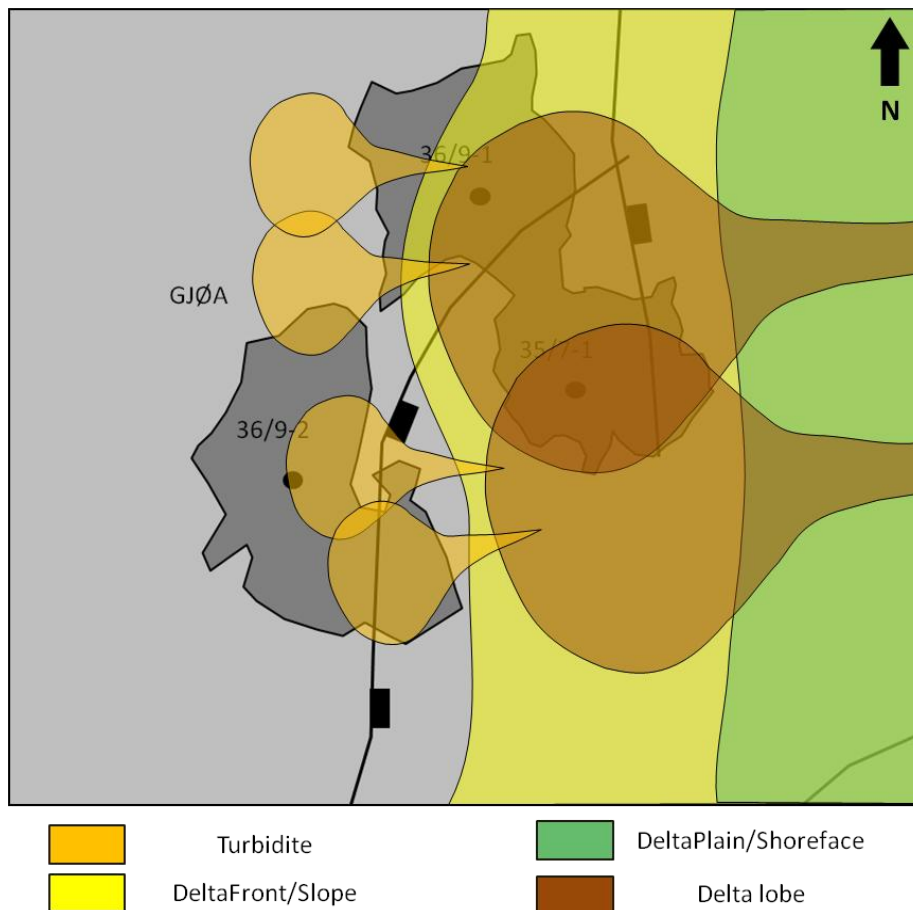


Figure 7-1 Schematic sketch of sequence 1 evolution (out of scale)

During this interval existing structural topography in form of the half graben controlled depocenters and sediment dispersal pattern. This sequence represents an early, normal regression stage. Sediments were supplied by lower Fensfjord deltas which prograded basinward across the eastern part of the Gjøa area in the western part deltas was interfinger with marine siltstones of the Heather formation. Sediments were composed of deltaic to shoreface sandstones (FA3 and FA5) that overlaid by shelfal units (FA1). The shoreline orientation was N-S. The presence pro-delta area with layered and relatively thin event bed suggest (relatively) low angle slope (Figure 7-1).

Sequence 2: Upper Fensfjord (Early Callovian Late Callovian) ~1-2 million years

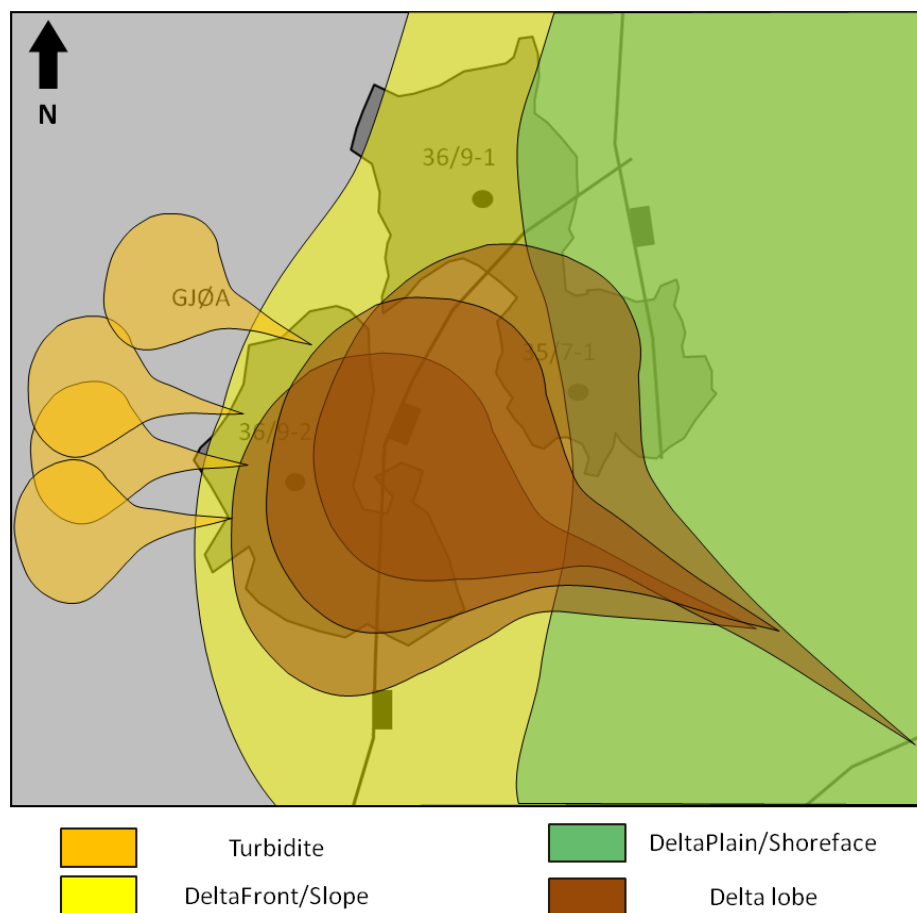


Figure 7-2 Schematic sketch of sequence 2 evolution: Shifting of shoreline and prograding of Fensfjord deltas basinwards (out of scale)

Structural regime in this sequence slightly changed, most likely due to rotation of fault blocks. This is based on identified low angle clinofolds. The shoreline shifted towards the basin and depocenter most likely was formed in structural lows that are located to the west, i.e. outside

the study area (Figure 6-5). This stage is characterized by an initial forced regressive and subsequently transgressive stages. The regressive segment is characterized by a gradual to rapid sea level fall that coincided with the deposition of turbidite units and was followed by rapidly prograding deltaic to shoreline units. Forced regression patterns (Figure 5-1) in form sharp transition between delta-front and pro-delta FA's suggests slightly curved shoreline. Deposition of turbidite units most likely represent resedimentation process or mass flows during major storms or river discharge events. The transgressive segment characterized by a relative sea level rise, however sediment supply was sufficient to keep pace with the sea level rise during the initial stage. This segment highly influenced by tide and wave reworking reshaping the former deltaic into shoreface and estuarine FAs.

Sequence 3: Sognefjord (Late Callovian to Early Kimmeridgian) ~6 million years

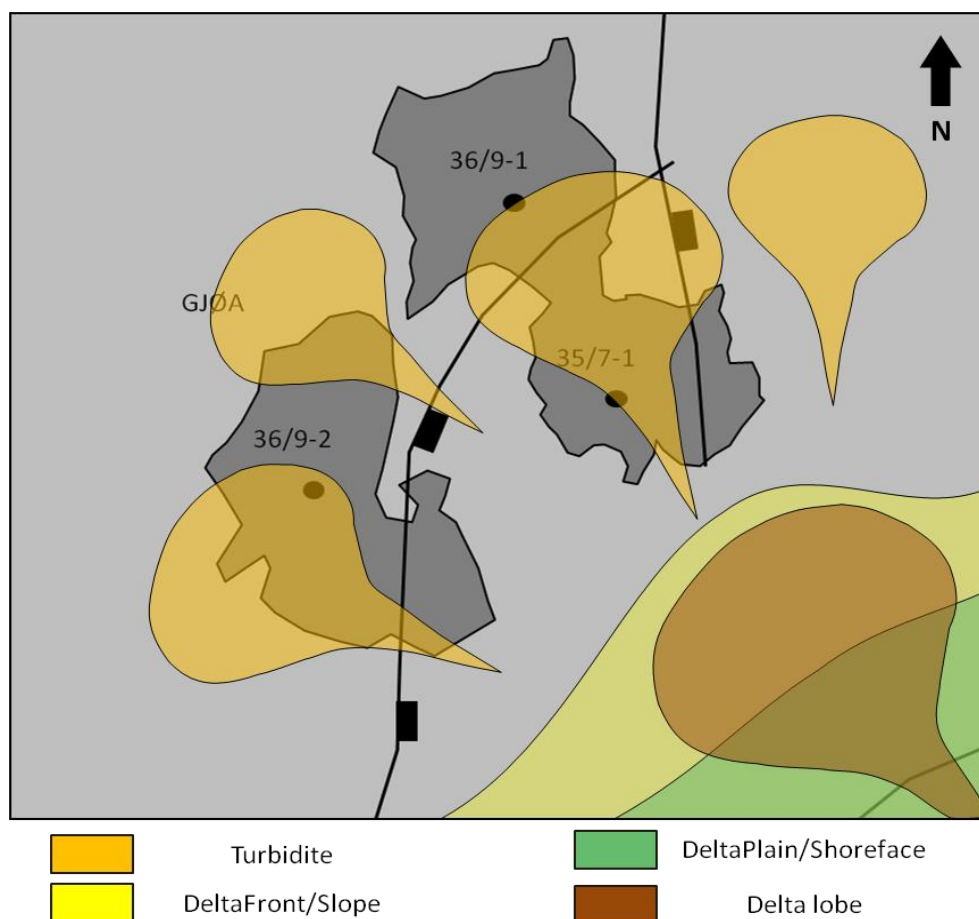


Figure 7-3 Schematic sketch of sequence 3 evolution of early stage (out of scale)

The rapid lateral variations in facies tract transitions most likely reflect syn-depositional structuring with some lateral variations in subsidence/uplift patterns of different fault-blocks, or infilling of existing serrated topography. This sequence significantly varies through the time and as a major part is removed by M.Oxfordian and only the early progradational part is discussed below.

Following flooding of the GjØa area by the E.Oxfordian, the Sognefjord deltas prograded across. This was accompanied with activation both fault families (N-S and NE-SW). The initial stage was dominated by a deeper water delta, with pro-delta area characterized by relatively thick turbidite lobes (Figure 7-3). Subsequently relative sea level fall forced the Sognefjord delta across GjØa area to reach peak regression position basinward of the main field. Consequently, from the M. Oxfordian to E. Kimmeridgian the GjØa area was subaerially exposed and subjected to major erosion potentially related to its margin uplift. The area was transgressed in the early to mid Kimmeridgian, with the establishment of the Draupne shelfal sea across the area slope.

8 CONCLUSION

The main conclusions of this study are:

1) Six facies associations (Table 1) were interpreted from detailed lithofacies analysis (Table 2) of Fensfjord and Sognefjord formations across Gjøa area. Based on facies and sedimentological interpretation gross depositional environment (with depositional elements) models are provided.

2) Three genetic sequences were identified based on sequence stratigraphy analysis. Each of the sequences is differ from each other in terms of depositional settings and facies characteristic.

Sequence 1 (Lower Fensfjord): was interpreted as initial overall regressive stage and dominated by deltaic to shoreline lithosomes (FA 3, FA5 and FA6)

Sequence 2 (Upper Fensfjord): was interpreted as regressive to transgressive stages, where regressive segment is dominated by deltaic to shoreline lithosome (FA3 and FA5) and transgressive segment is dominated by shoreline to estuarine lithosomes (FA 5 and FA6)

Sequence 3 (Sognefjord): was interpreted as overall regressive stage and dominated by deltaic to shoreline lithosomes (FA3 and FA5). Moreover the lower part (or initial stage) of this sequence is dominated by thick turbidite lobes that was capped by shelfal to pro-delta FA's.

3) Two structural regimes were identified from seismic interpretation. N-S extension that in later stage was changed (locally) to NW-SE extension highly influenced depositional processes of the Fensfjord and Sognefjord formations.

4) Proposed conceptual geological model for tectono-stratigraphic evolution of the Gjøa filed was provided by integrated data analysis

9 REFERENCES

- Christiansson, P., J. I. Faleide, et al. (2000). Crustal structure in the northern North Sea: An integrated geophysical study. **167**: 15-40.
- Donovan, A. D., Djakic, A. W., Ioannides, N. S., Garfield, T. R. and Jones, C. R. (1993). "Sequence stratigraphic control on Middle and Upper Jurassic reservoir distribution within the UK Central North Sea. Petroleum Geology of Northwest Europe: Proceeding of the 4th Conference: 251-269. Parker, J. R. (editor). (London: The Geological Society of London)
- Dreyer, T., M. Whitaker, et al. (2005). From spit system to tide-dominated delta: Integrated reservoir model of the upper Jurassic Sognefjord formation on the Troll West Field. **6**: 423-448.
- Gabrielsen, R. H. (1986). "Structural elements in graben systems and their influence on hydrocarbon trap types (Norwegian continental shelf)." Habitat of hydrocarbons on the Norwegian continental shelf. Proc. conference, Stavanger, 1985: 55-60.
- Gabrielsen, R. H., R. B. Foersth, et al. (1990). "Architectural styles of basin fill in the northern Viking Graben." Tectonic evolution of the North Sea rifts: 158-179.
- Galloway, W. E. (1989). "Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units." American Association of Petroleum Geologists Bulletin **73**(2): 125-142.
- Jackson, C. A. L., G. P. Barber, et al. (2008). "Submarine slope morphology as a control on the development of sand-rich turbidite depositional systems: 3D seismic analysis of the Kyrre Fm (Upper Cretaceous), Måløy Slope, offshore Norway." Marine and Petroleum Geology **25**(8): 663-680.
- Martin, M. A. and Pollard, J. E. (1996), "The role of trace fossil (ichnofabric) analysis in the development of depositional models from the Upper Jurassic Fulamr Formation of the Kittiwake Field (Quadrant 21, UKCS). in Geology of Humber Group: Central Graben and Moray Firth, UKCS. Hurst, A., Johnson, H. D., Burley, S. D., Canham, A. C. and Mackertich, D. S. (editors). Special Publication of the Geological Society of London, No. 114: 163-183.
- Odinsen, T., P. Christiansson, et al. (2000). The geometries and deep structure of the northern North Sea rift system. **167**: 41-57.
- Partruno, S., Hampson, G. J. and Jackson C. A-L. (2011). "Sand-prone subaqueous deltas: a subsurface example from the lower Sognefjord Formation, Northern North Sea, offshore Norway". (Oral). BSRG AGM 2011, Imperial College London, London, UK.
- Pemberton, S.G., Maceachern, J.A., and Frey, R.W. (1992). "Trace fossil facies models: their environmental and allostratigraphic significance". In: Walker, R.G., and James, N.P. (eds.),

Facies Models: A Response to Sea-Level Changes. Geological Association of Canada, P.47-72.

Price, J. and five others (1993). "Effective stratigraphical subdivision of the Hamber Group and the Late Jurassic evolution of the UK Central Graben". Petroleum Geology of Northwest Europe: Proceeding of the 4th Conference: 443-458. Parker, J. R. (editor). (London: The Geological Society of London).

Ravnås, R. and K. Bondevik (1997). "Architecture and controls on Bathonian-Kimmeridgian shallow-marine synrift wedges of the Oseberg-Brage area, northern North Sea." Basin Research **9**(3): 197-226.

Ravnås, R., A. Nøttvedt, et al. (2000). Syn-rift sedimentary architectures in the Northern North Sea. **167**: 133-177.

Taylor, A. M. and Gawthorpe, R. L. (1993). "Application of sequence stratigraphy and trace fossil analysis to reservoir description: example from the Jurassic of the North Sea". Petroleum Geology of Northern west Europe: Proceeding of the 4th Conference. Parker, J. R. (editor). (London: The Geological Society of London): 317-335.