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Seismic interpretation at the Horda Platform, North Sea. Detailed characterization of Sognefjord Formation.

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ABSTRACT

Due to the intense hydrocarbon exploration the North Sea has become one of the most studied area in the world with respect to seismic surveys, exploration drilling to learn about sedimentary architecture of rift zones. Following the discovery of Troll Field in 1979, a large amount of exploration wells were drilled on Horda Platform. Interpretation of 2D surveys and the deepest exploration well in the area (31/6-1) allowed to make the reconstruction of the main tectonic events in the area together with allocation of the main sequences in sedimentation history. The main feature of Horda Platform are sandstone tongue-shaped Sognefjord, Fensfjord and Krossfjord Formations. These formations consist of sandstone sourced from Norwegian mainland from the east that pinch out into Heather Formation represented by offshore deep marine shales. The detailed interpretation of these formations is challenging because of a large amount of noise and multiples appearing on the seismic data. The geological model of Sognefjord Formation together with wells correlation study presents the detailed characterization of the formation.

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"There are no problems, only challenges" ***Professor Ståle Emil Johansen***

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1. INTRODUCTION

Since the discovery of Ekofisk Field in 1969, the North Sea now has been one of the most explored continental shelves in the world. The exploration activity has been concentrated on Jurassic rotated fault blocks along the Viking Graben margins. After the discovery of Troll Field in 1979, a large amount of exploration activities was made on eastern flank of the Viking Graben in the Horda Platform area. Several exploration wells have penetrated the pre-Jurassic strata and one (31/6-1) reached the basement. Three 2D lines of 'MN9103' seismic survey were interpreted in the study for better understanding of tectonic and depositional events in the Horda Platform area.

The Troll field is located on Horda Platform. It is divided into the Troll West and Troll East fields. Both accumulations are defined by rotated fault blocks. The main reservoir is shallow-marine sandstones of Sognefjord Formation. The underlying Fensfjord Formation forms a part of the reservoir in the Troll East field. Sognefjord and Fensfjord Formations together with Krossfjord Formation form an east to west propagating sand bodies. The sandstones of the formations were sourced from East, Norwegian mainland and pinch out into the Heather Formation. Interpretation of the formations was made using the 'SG9202' 3D seismic survey. The quality of the data brought a lot of challenges during the interpretation. The main reservoir Sognefjord Formation was studied in details using the seismic and well data. The detailed characterization of the reservoir formation was presented together with all the noise affecting the data.

The main objectives of this study are:

- Interpretation of 2D data for better understanding of tectonic and depositional events in the Horda Platform area.
- Interpretation of 3D data and mapping of the main reservoir units of the Troll East Field.
- Detailed integrated seismic and well data study of the main reservoir units to determine the reservoir characterization and depositional environments.

2. GEOLOGICAL SETTING AND PREVOIUS STUDY

2.1 Horda Platform

The study area is located on Horda Platform which is located in the northern North Sea between Viking Graben on the west and the western coast of Norway on the east (Figure 2.1). The most import structural elements of the northern North Sea are deep faulted Viking Graben to the west and more stable Horda platform to the east (Stewart et al., 1995).

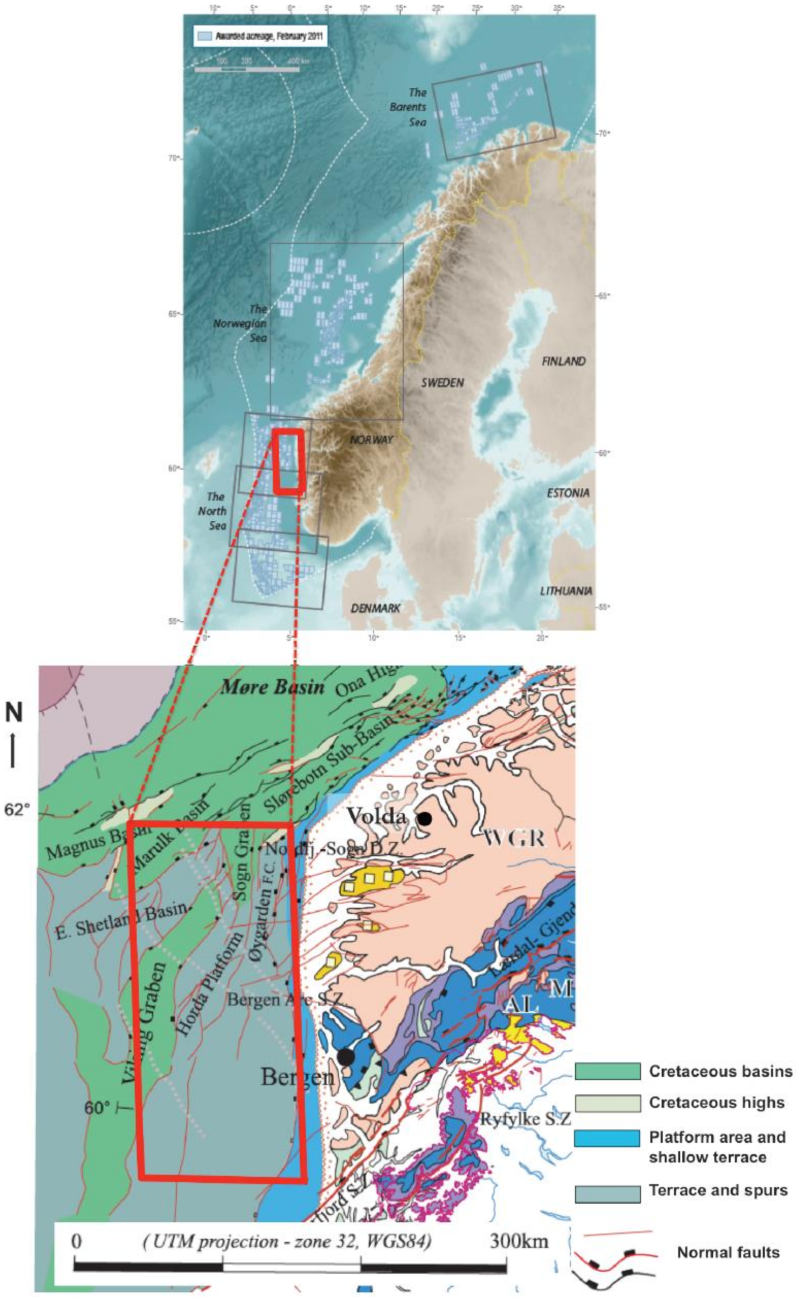


Figure 2.1: Location of Horda Platform shown in the red square (modified from www.npd.no)

The Viking Graben rift system originated during the Permo-Triassic. The evidence for that can be a large amount of half grabens seen below the Horda platform (Figure 2.2) with early Triassic sedimentary infill. At the same time, the late Triassic to lower Jurassic succession shows higher variation in thickness distributions and covers the syn-rift sediments. It can be related to the late post-rift sedimentary infill which resulted from thermal subsidence following rifting. This subsidence continued through the lower part of the Middle Jurassic with just some evidence of sedimentary faulting. During the Early Bathonian the extension and rotation of fault blocks continued and became more important in Oxfordian and later in the Kimmeridgian to Ryazanian when the major phase of rifting and tilting of fault blocks took place. Hereby, the differentiation between the major graben and Horda Platform which can be observed today took place at that time (Stewart et al., 1995).

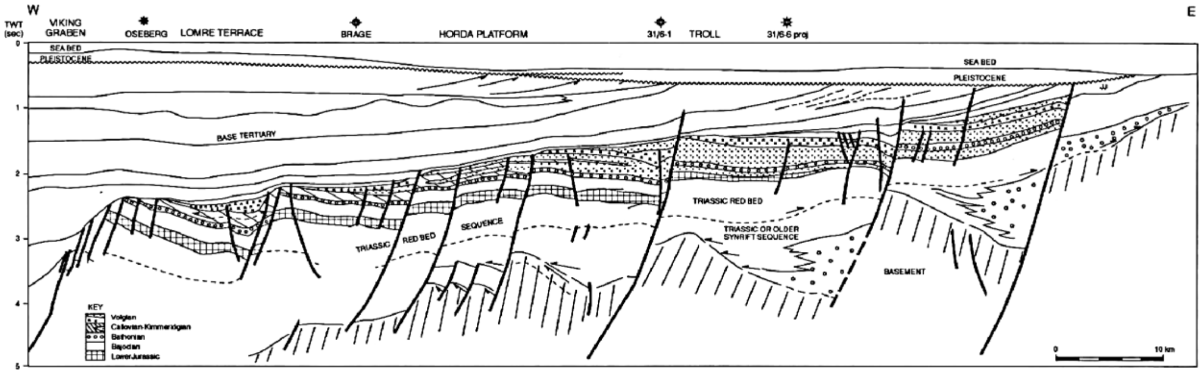


Figure 2.2: Structural cross-section showing the stable Horda Platform and deep faulted Viking Grabenhe cross-section shows the earlier Permo-Triassic rifting phase. (Stewart et al., 1995).

2.2 Troll Field

The Troll field is a huge gas accumulation underlained by an oil rim with variable thickness located on the Horda Platform on the eastern margin of Viking Graben in the northern North Sea. The field is located offshore Norway about 80 km north-west of Bergen (Figure 2.3) and the water depths are up to 355m. The Troll field is located in four Norwegian exploration blocks: 31/2, 31/3, 31/5, 31/6 and covers the area of 710 km^2 (Bolle, 1992).

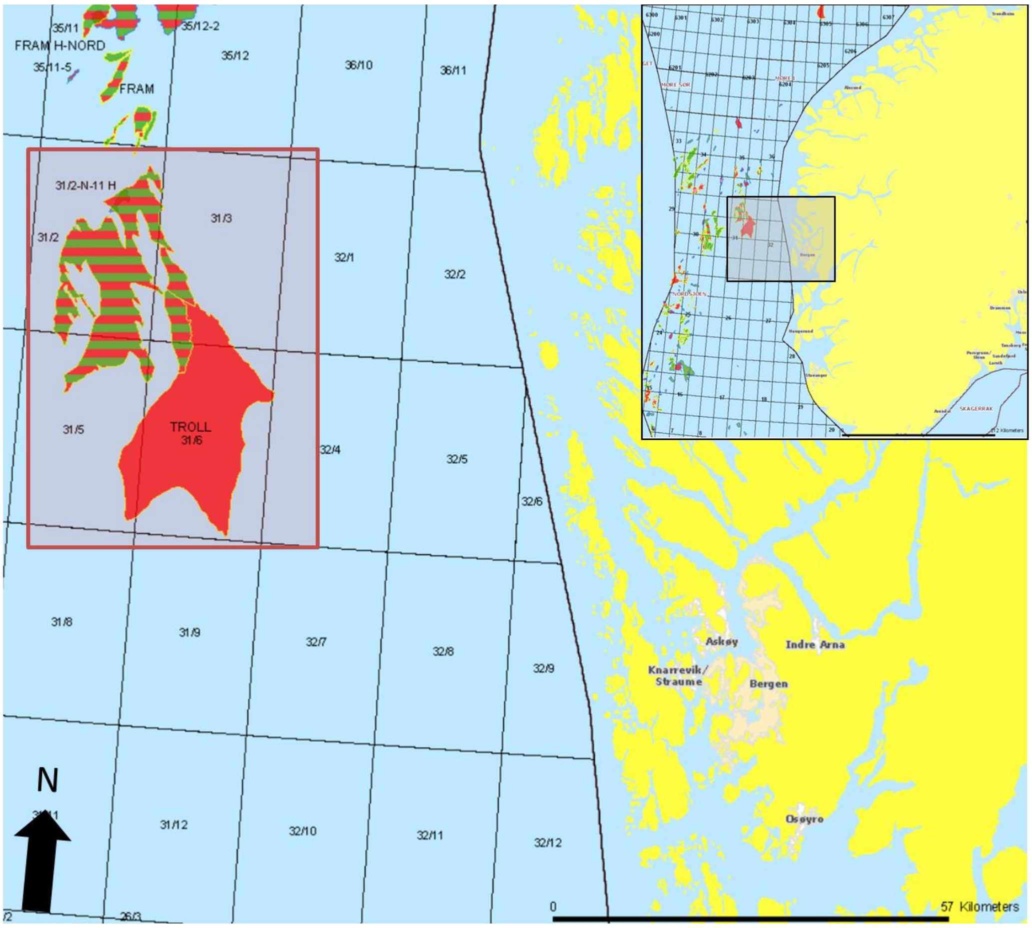


Figure 2.3: Location of the Troll field shown in the red square (fact maps at www.npd.no)

The Troll field contains 1670 billion m^3 (59 tcf) of gas and 615 million m^3 (3.9 billion bbl) of oil initially in place. It was classified as a super-giant field (www.npd.no).

The Troll field is divided into two main accumulations which are Troll West and Troll East (Figure 2.4). However it is divided the pressure communications have been proven between those two accumulations (NPD 2011). The traps for both accumulations are specified by rotated fault blocks. The main reservoir is characterized by shallow-marine sandstones. The production is going from Sognefjord Formation. The subjacent Fensfjord formation is a part of reservoir too. It has a proven oil column from 0 to 4 meters in the Troll East part of the field. The underlying Krossfjord formation together with the Fensfjod and Sognefjord formations organize the Viking Group which is overlaying the productive Brent Group (Holgate et al., 2013).

2.3 Tectonic-stratigraphical evolution of Horda Platform and Troll Field.

The whole tectostratigraphical evolution of the Horda Platform and the northern North Sea rift system was developing in three main structural provinces:

- In the East – comparatively stable Horda Platform;

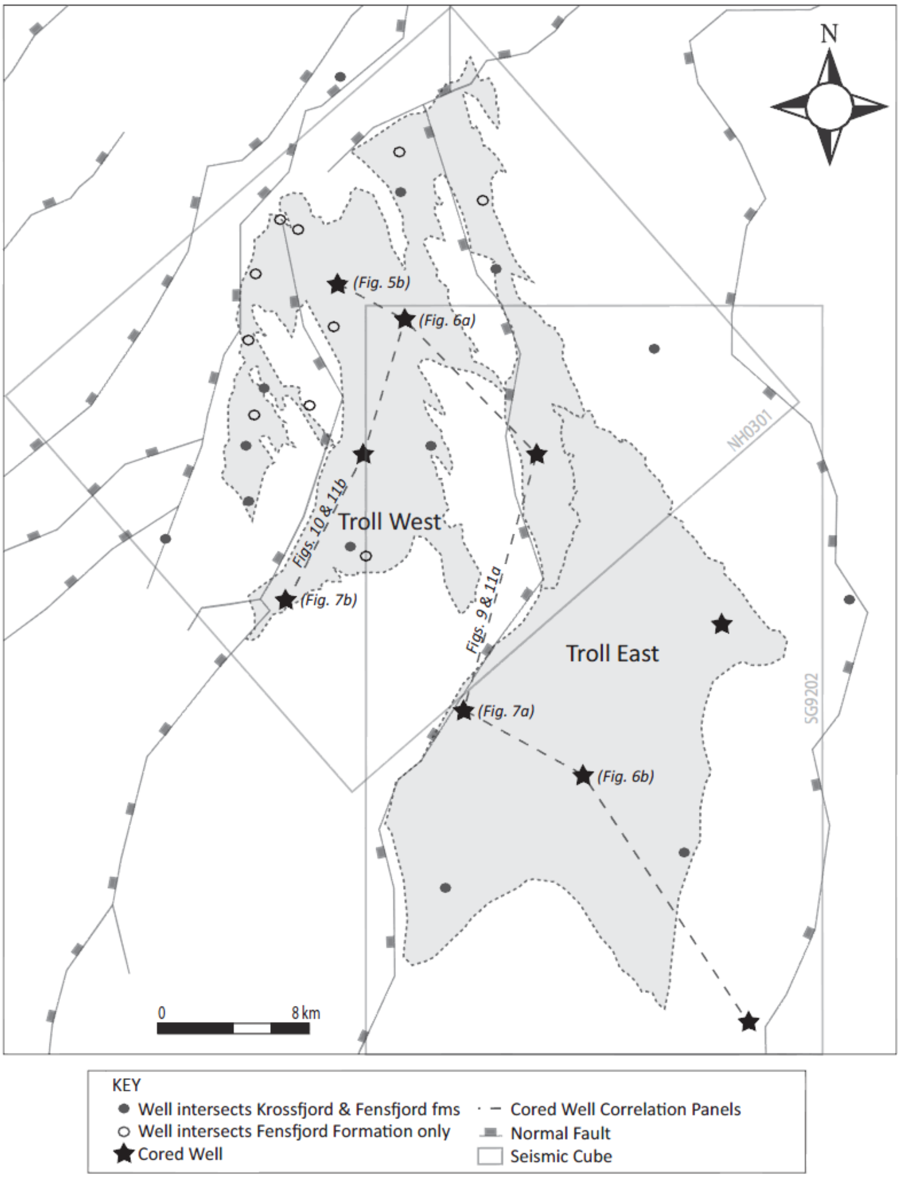


Figure 2.4: Simplified map of the Troll field (Holgate et al., 2013)

- In the middle - such fields as Troll, Oseberg, Fram and Brage located in a tilted half grabens;
- In the West – the deep faulted North Viking Graben (Stewart et al., 1995).

2.3.1 Early Jurassic

During the Sinemurian to Pliensbachian the downfaulting of Oseberg structure took place. The downfaulting of the Bergen High during Hettangian to Early Pliensbachian resulted in minor shifting of the Brage Horst. Later in Toarcian the main movement of the Brage Horst continued mainly due to subsidence of the blocks on both sides and shifting of these blocks respectively to the west in the direction of the Bergen High and more significantly to the east. This movement resulted in the formation of accommodation basin to the west in latest Toarcian (Johnsen et al., 1995).

2.3.2 Middle Jurassic.

The normal faulting took place in Bajocian affecting significantly the major faults. (Jonsen et al., 1995) Later, the Bathonian–latest Callovian period of rifting was a significant phase when a number of faulted terraces occurred between the Horda Platform and the Viking Gaben (Figure 2.5) (Johnsen et al., 1995). The normal fault blocks rotation resulted in reworking of upper Ness and Tarbert formations on the Horda Platform. This faulting provided the accommodation space for Fensfjod and Krossfjord formations. In the area of Troll Field the Krossfjord Formation can be described as a progradation system of a sand-rich delta (Holgate et al., 2013). The Fensfjord Formation has a transgressive evolution. The possible explanation can be the migration of maximum of deposition in the south – southward direction (Fraser et al., 2002). Fensfjord Formation forms a delta (Holgate et al., 2013) which covered the entire Horda Platform at the point of maximum regression in the Late Callovian.

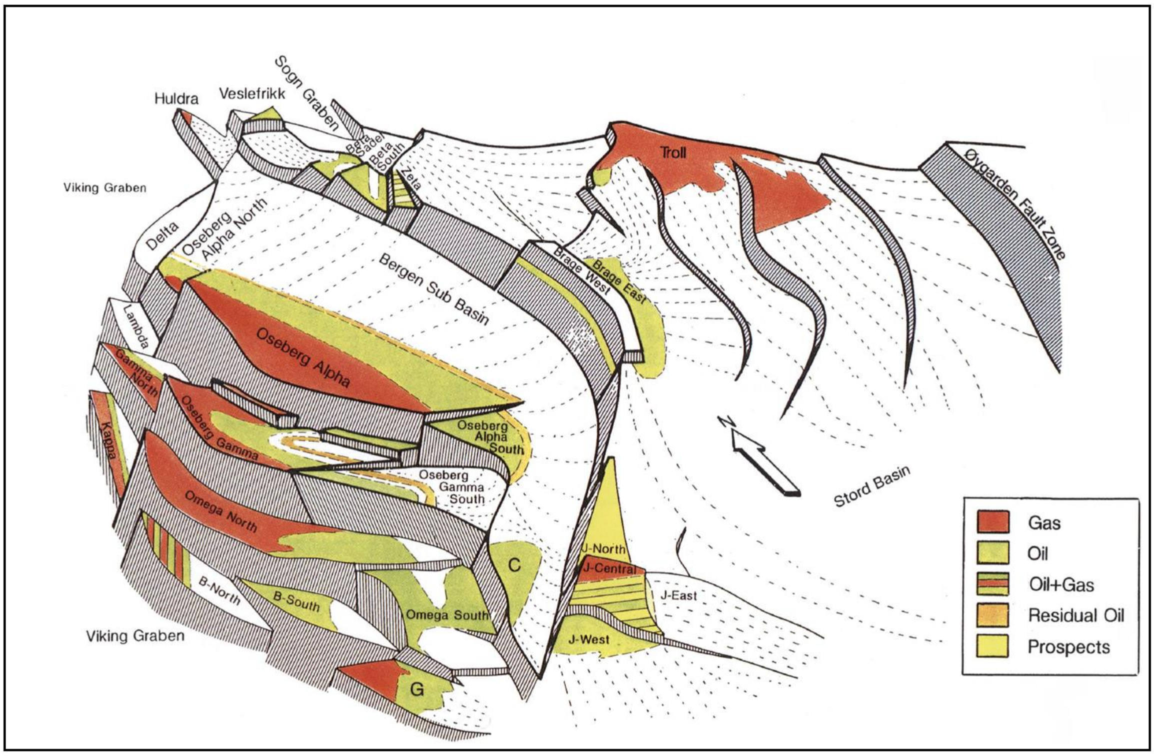


Figure 2.5: Schematic illustration of the main structural elements of the Horda Platform (Johnsen et al., 1995)

2.3.3 Late Jurassic.

The rotation of Bergen High continued during the Oxfordian and earliest Kimmeridgian. During that period rifting reached its end and Sognefjord Formation was deposited. Also the significant structural differentiation between the Horda Platform and the Viking Graben finished at that time (Stewart et al., 1995). The increasing of extension process led to the uplifting and tilting of fault blocks. It resulted in the rising of the fault block footwalls of the Horda Platform above the sea level. As a result, erosion took place on these footwalls so older sediments were reworked and deposited (Fraser et al., 2002). It is worth mentioning that both Callovian and Oxfordian sandstones are presented on the east part of the Horda Platform. However, the Oxfordian sediments are presented in a minor amount while the Collovian sediments are presented by mudstones. It shows the variation of sand deposition east and westwords around the Platform (Johnsen et al., 1995).

The final stage of faulting during the Early and Middle Volgian resulted in extensive faulting on the Horda Platform and in the west of the Viking Graben. The erosion process of tilted fault blocks resulted in truncation of Lower and Middle Jurassik strata against Upper Jurassik strata in several places on the Horda Platform (Holgate et al., 2013). The start of marine flooding finished the deposition of shale-marine Sognefjord formation and started deposition of deep-marine mudstones of the Draupne Formation (Johnsen et al., 1995).

2.4 Reservoir Stratigraphy of the Troll structure

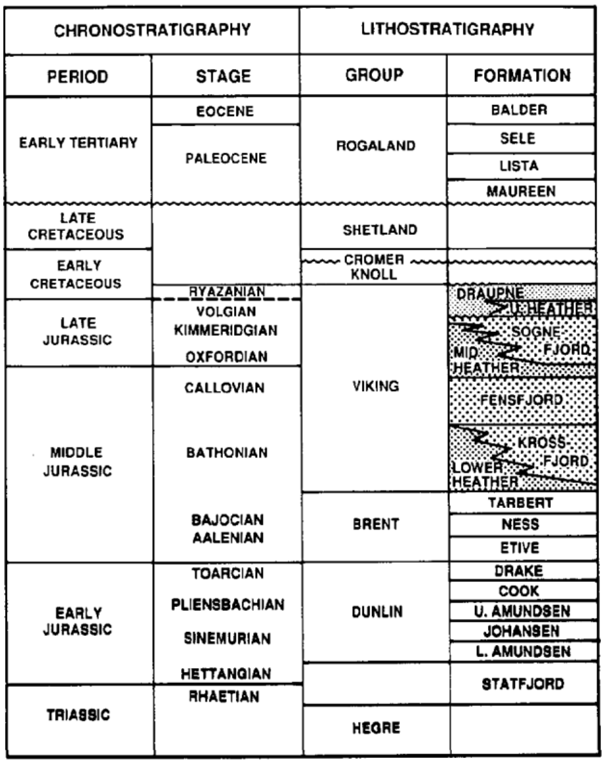
The reservoir rock containing oil and gas accumulations of the Troll field are presented by medium to coarse grained, hardly consolidated sands, siltstones and fine micaceous sandstones of the Middle to Upper Jurassic Viking Group. The Viking Group is characterized by shales and claystones with some thin intercalations of sandstones in the northern North Sea. The Troll field is special because it contains less shale. All the shales are stacked shallow marine sand sequences of Heather, Sognefjord, Fensfjord and Krosfjord Formations (Figure 2.6).

Deposition was taking place on a shelf. It was a number of cyclic sequences with alteration of transgressive sands on the one hand and progradation of shoreface facies on the other. The minor regional sea level changes resulted in sequence architecture which took part in late Callovian – early Volgian regional transgression. The propagation of “double drape“ stratification indicates the tidal influence in the area. The deposits underlying shallow marine sands are coarse and poorly sorted as well as bioturbated (Bolle, 1992).

The Fensfjord Formation includes a large amount of series of small, coarsening upward units. It has fine micaceous sand at the base which is coarsering upwards. This sequence can be interpreted as a progradational shoreface facies. The maximum thickness of the seqejnce is 300 m and porosities between 25 and 30 %.The Fensfjord Formation contains just a small amount of hydrocarbons (Bolle, 1992).

The Heather B and Sognefjord Formations consist of six depositional cycles. Each of the cycles is marked by a rapid rise in the sea level. Each cycle starts with a fine micaceous sand and coarse upwards to a clean sand which represents the shoreface progradation at the top. In the eastern part upward cleaning is less effective due to the lower energy level. The reservoir rocks of Sognefjord Formation show perfect porosities up to 35% and permeabilities up to several Darcys. This formation has a major part of hydrocarbon accumulations (Bolle, 1992).

The Heather C Formation shows very poor reservoir characteristics than Sognefjord Formation. It is mostly open marine, low energy siltstones. The Heather C siltstones are well cemented with porosities less than 20% and permeability below 10 mD. The unit forms a wedge pinching out in a west direction with maximum thicknesses about 44 m (Bolle, 1992).



CHRONOSTRATIGRAPHY		LITHOSTRATIGRAPHY	
PERIOD	STAGE	GROUP	FORMATION
EARLY TERTIARY	EOCENE	ROGALAND	BALDER
	PALEOCENE		SELE
			LISTA
			MAUREEN
LATE CRETACEOUS		SHETLAND	
EARLY CRETACEOUS		CROMER KNOLL	
	RYAZANIAN	VIKING	DRAUPNE U. HEATHER
LATE JURASSIC	VOLGIAN KIMMERIDGIAN OXFORDIAN		SOGNE FJORD MID HEATHER
MIDDLE JURASSIC	CALLOVIAN		FENSFJORD
	BATHONIAN		KROSS FJORD LOWER HEATHER
	BAJOCIAN AALENIAN	BRENT	TARBERT NESS ETIVE
EARLY JURASSIC	TOARCIAN	DUNLIN	DRAKE
	PLIENSBACHIAN		COOK
			U. AMUNDSEN
	SINEMURIAN		JOHANSEN
			L. AMUNDSEN
	HETTANGIAN		STATFJORD
TRIASSIC	RHAETIAN		
		HEGRE	

Figure 2.6: Stratigraphic table for the Troll East area (Bolle, 1992).

2.5 Structure and trap development

In the Troll field hydrocarbons are trapped in three eastward tilted fault blocks. The trend also shows the decrease of crestal depth from east to west (Figure 2.7). According to those three major fault blocks and those based on their properties the Troll Field is divided into three hydrocarbon provinces (Johnsen, 1995):

- The Troll West Oil province
- The Troll West Gas province
- The Troll East (gas) province

The hydrocarbons traps developed in two main stages. The ongoing rifting activity during late Kimmerian caused block faulting and tilting which resulted in formation of early traps in the western part of the field. Later, the same process of block rotation and faulting continued in the eastern direction and gave a rise to the central and eastern fault blocks (Bolle, 1992).

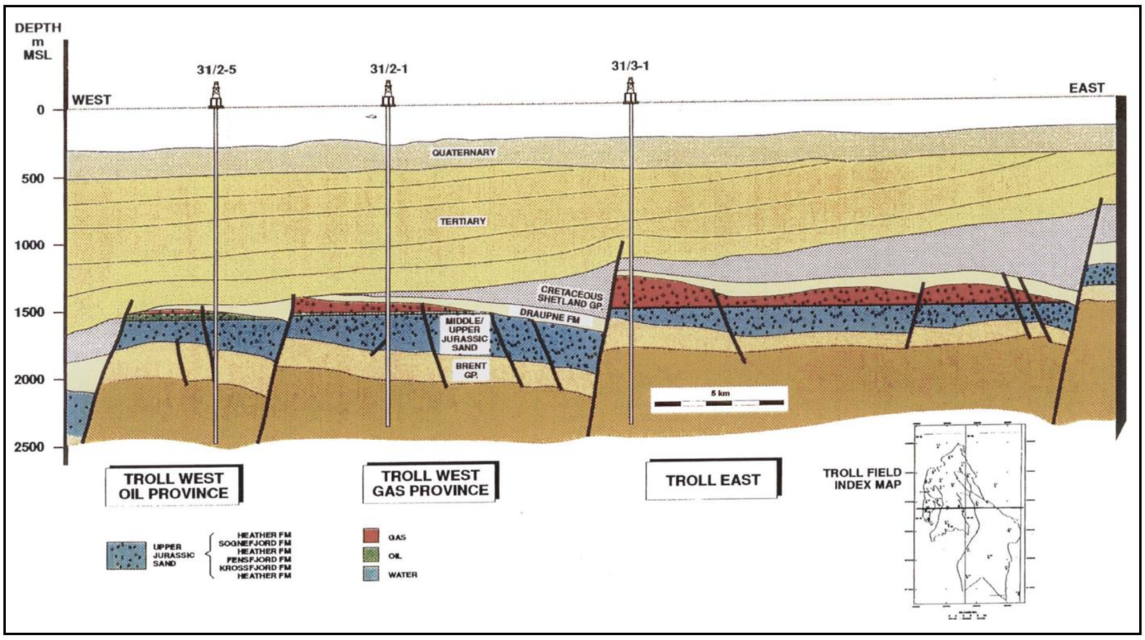


Figure 2.7: Structural cross section and hydrocarbon distribution of the Troll Field (Johnsen, 1995)

Intrafield faulting shows small displacement. Most of the intrareservoir faults are nonsealing. Clay smearing has a small chance to be observed in the Troll field as there is no clay development in the reservoir rock. Some other tectonic and diagenetic effects are possible but have not been observed in the Troll Field area yet (Holgate et al., 2013).

The thicknesses of gas column are structurally controlled. The thickest accumulations are observed at the western parts of the fault blocks. Nevertheless, the distribution of oil is controlled by a combination of stratigraphy and structure. The juxtaposition of high and low permeable sands may cause the oil-water and gas-oil contacts variations (Figure 2.8) (Bolle, 1992).

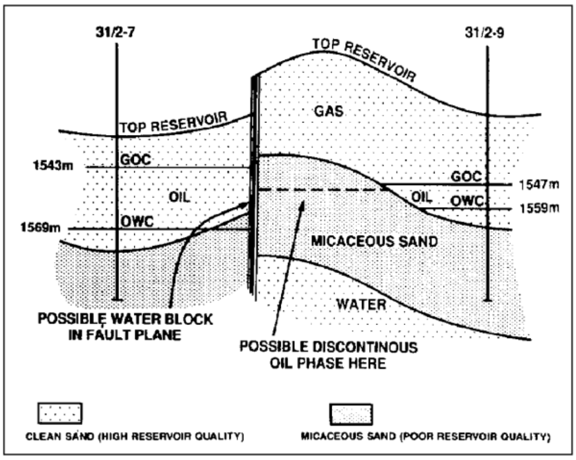


Figure 2.8: Explanation of permeability barriers for oil (Bolle, 1992)

2.6 Hydrocarbon emplacement and distribution

The main source of hydrocarbons in the Horda Platform was Upper Jurassic ‘hot’ shales. These Draupne Formation shales constitute the main source rock for Troll and Oseberg reservoirs (Figure 2.9). The main areas for oil and gas generation are found in Viking Graben and Sgn Graben for Oseberg and Troll reservoirs respectively. The possible spillage from Oseberg to Toll via Brage is possible but not proved (Dahl et al., 1987). During the late Maastrichtian to Paleocene the earliest oil generation took place. The additional heat input in the region during the Eocene resulted in the second period of gas generation. The migration is possibly still ongoing but to a less extent than during the peak generation (Dahl et al., 1987). Source rock maturation modelling for the Troll accumulation shows that the peak of oil generation and migration began during the Paleocene-Eocene times while the gradual maturation of the source rock during Oligocene-Miocene resulted in gas generation. Some additional gas was generated and migrated from the Brent Group and Statfjord Formation coals. The Draupne Formation shales overlaying the reservoir in the Troll area are immature (Bolle, 1992).

The alignment of major fault played the main role in the migration pathways. The comparative analysis shows that Troll area was mainly filled from west and northwest of the Horda Platform while the presence of Frigg type of oil Osuberg south J-structure propose a chance that Troll was also partly sourced from southwest of the Horda Platform (Johnsen, 1995). The residual oil zone that can be observed in the Troll West possibly indicates an earlier entrapment of oil preceding tectonic alignment which shifted the closure from Troll West to Troll East (Dahl et al., 1987).

In the Troll East province the maximum gas cap reaches 250 meters and overlies a very thin oil leg from 0 to 4 meters. The maximum gas column thickness in Troll West Gas province reaches 210 meters while the average thickness of oil rim is about 12 meters. The Troll West Oil province has a gas column reaching its maximum in the northern part being 43 meters thick while oil column varies from 22 to 28 meters. The volumes and distributions of hydrocarbon accumulations are presented in Table 1 (Bolle, 1992).

			Volumes	
Compartment	Oil-water contact (m, TVD)	Gas-oil contact (m, TVD)	Gas (billion m3)	Oil (million m3)
Troll East (gas) province	1549	1547	1072	83
Troll West Gas Province	1559	1547	576	411
Troll West Oil province				
North	1569	1543	13	81
South	1569	1547	9	40
Total			1670	615

Table 1: Volumes and distributions of hydrocarbons initially in place in the Troll Field (internal Norsk Hydro report)

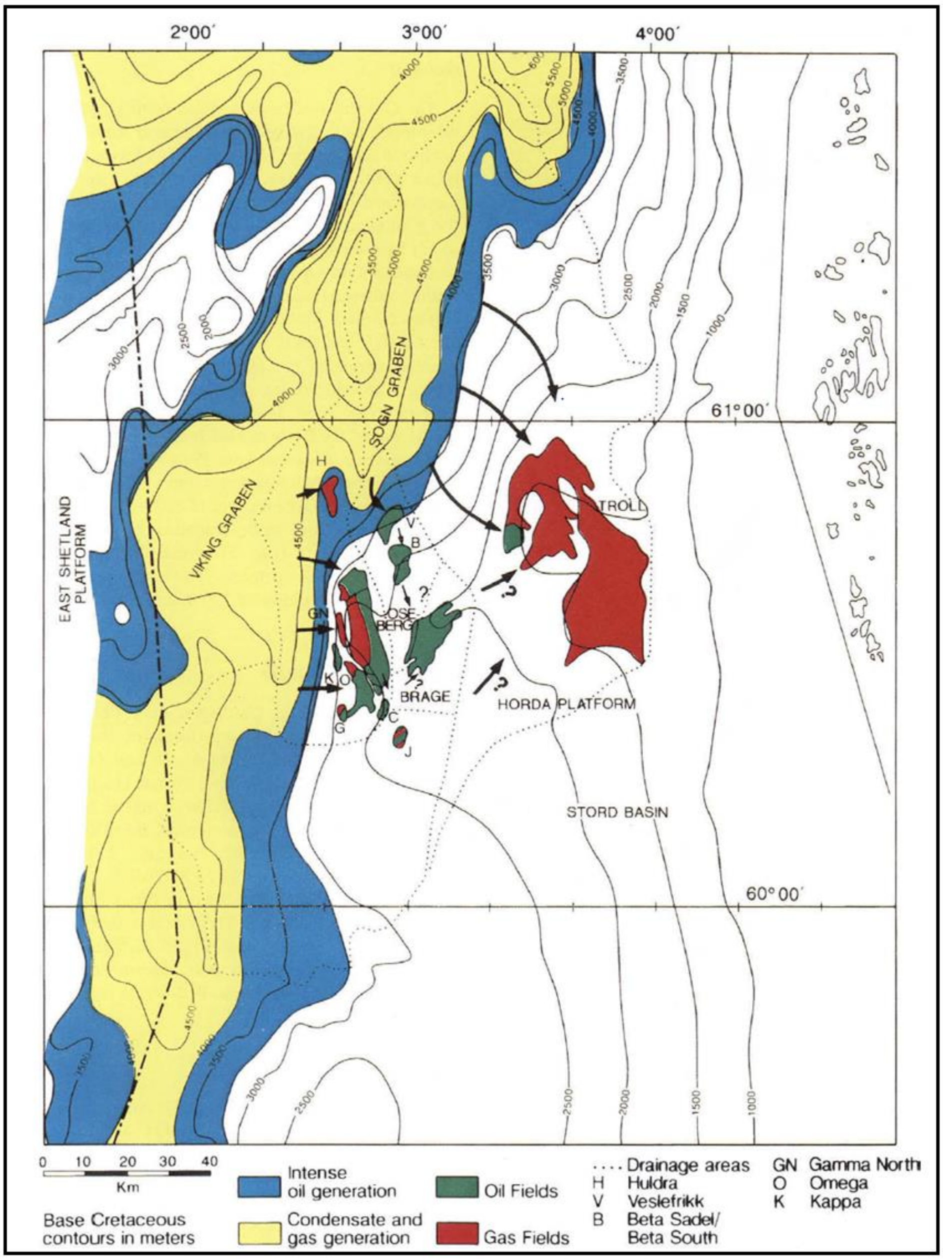


Figure 2.9: Source areas and possible migration paths of the Troll field shown with black arrows (Johnsen, 1995)

Over 90% of hydrocarbons in the Troll area lie in the Sognefjord Formation. This formation shows relatively good reservoir quality which will allow recovering between 75 or 80 % of gas. The Heather C Formation siltstones show poorer recovery factors. The oil recovery factors vary and depend on the height of oil column.

3. DATA AND QUALITY

3.1 Seismic data

The data used for this study contains a number of seismic surveys both 2D and 3D and well data from northern North Sea. Most of the work was done in Troll East area which contains a seismic survey ‘SG9202’. This survey covers about 900 km^2 with line spacing of 25 meters in both crosslines (north – south) and in-lines (east-west) directions. It is located in the North Sea exploration blocks 31/3, 31/5, 31/6 (Figure 3.1 a). This survey images a depth of approximately 2400ms in a TWT. The ‘SG9202’ survey was completed in December, 1992 by Saga Petroleum ASA.

In addition, several 2D seismic lines were used in this project from a survey ‘MN9103’. This survey was completed in December, 1991 by Mobil Exploration Norway INC. Three lines were used in this study: ‘MN9103-302’, ‘MN9103-305’, ‘MN9103-308’. The lines are oriented from northwest to southeast and propagate for 78, 78 and 195 km respectively (Figure 3.1, b). All the data was uploaded and interpreted using the Petrel 2013 software. Several well logs have been interpreted using the Interactive Petrophysics v4.1 software.

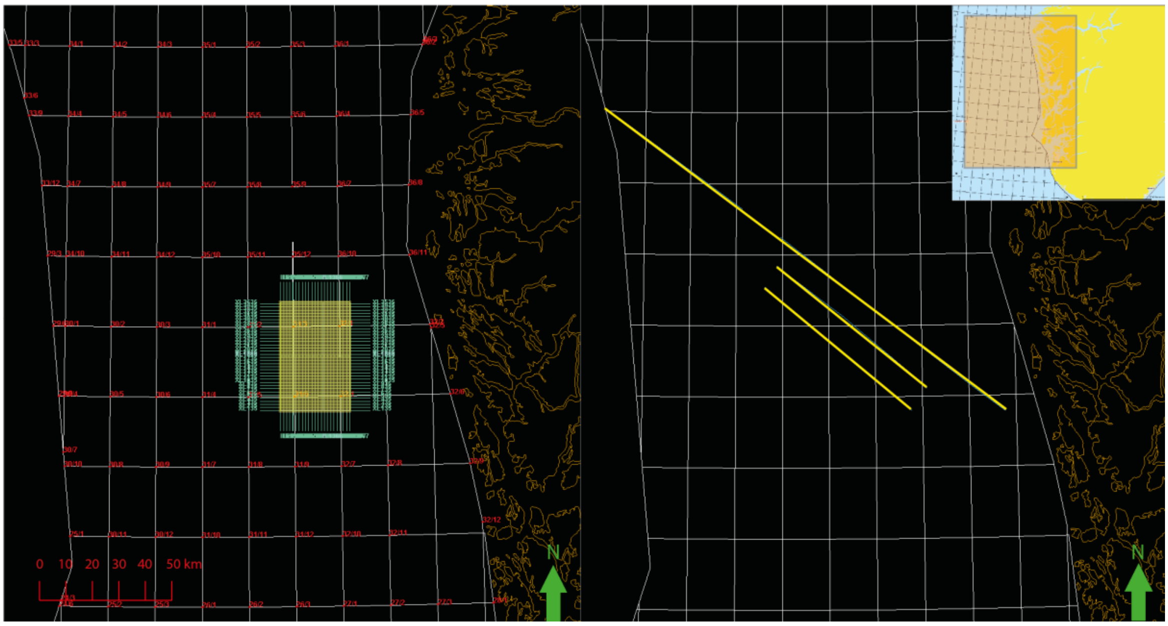


Figure 3.1: a) location of 3D survey on the left, yellow square; b) location of 2D lines on the right, yellow lines

3.2 Polarity

It is very important to take the polarity of seismic into account. There are two international standards for polarity interpretation. The American standard uses positive amplitude to interpret the peak and negative amplitude to interpret the trough, while

European standard uses positive amplitude to show a trough and negative amplitude to show a peak. It means that the increase in acoustic impedance, which happens because of going from media with lower density and velocity to media with higher density and velocity, has different impression on seismic section. The sea bed is always a good example of observing the polarities. Going from sea water to hard media leads to the increase of acoustic impedance. So assuming the zero phase being used in the surveys, the sea bottom is positive (red) in American standard and negative (blue) in European standard. According to Figure 3.2 which shows the sea bottom of 3D and 2D surveys from left to right, the 3D survey is done with the European standard while 2D survey is done with the American standard for polarity interpretation.

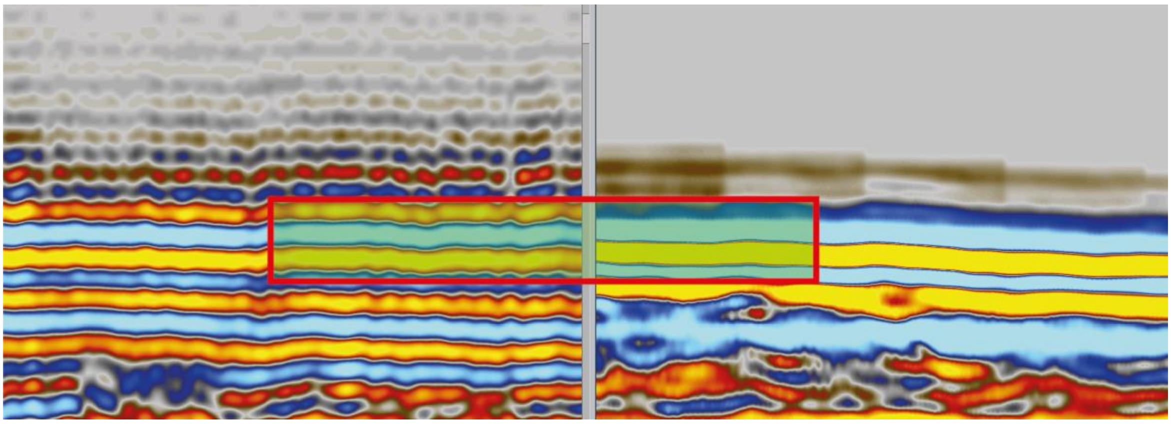


Figure 3.2: Examples of sea bed: European standard used in 3D survey on the left; American standard used in 2D survey on the right

3.3 Quality of the data

During the interpretation of seismic data a lot of challenges were detected regarding the seismic data. Both 3D and 2D surveys were done at the beginning of 1990s and can be evaluated as respectively old data. The 3D seismic cube used in the study contains a lot of noise, discontinuities in layers, changing of resolutions and one very strong multiple which hardly affects the interpretation within the zone of interest. In addition, the area of study is affected by a huge and strong flat event regarding the Troll East gas field. The zone bellow the flat event (possible aquifer zone) shows a very poor quality of data and is hardly affected by multiple. It is very important to pay attention at the interpretation in that zone to avoid misinterpretation of real geological features (Figure 3.3, a). The data below 2500 ms is very chaotic in the 3D survey what makes interpretation of basement extremely challenging. Three 2D lines were used for that purpose as they show better reflections in a deeper part of the area.

The multiple event can be caused by the strongest reflector in the survey which probably corresponds to the high increase in acoustic impedance between the softer Tertiary sediments and underlying Cretaceous sediments. The distance between the strongest reflector and multiple is the same around the area and is about 411 to 412 ms in TWT. There are two main types of multiples (Figure 3.4) and ghost reflections. The distance in

TWT between sea level and sea bottom varies from 410 to 413 ms. This fact and the fact that the multiple perfectly follows the trend of the strongest reflector can be summed up in the supposition that there is a Near-Surface multiple in the aquifer zone (Figure 3.3, b). This multiple is very important to be taken into account because it crosses the horizons of interest.

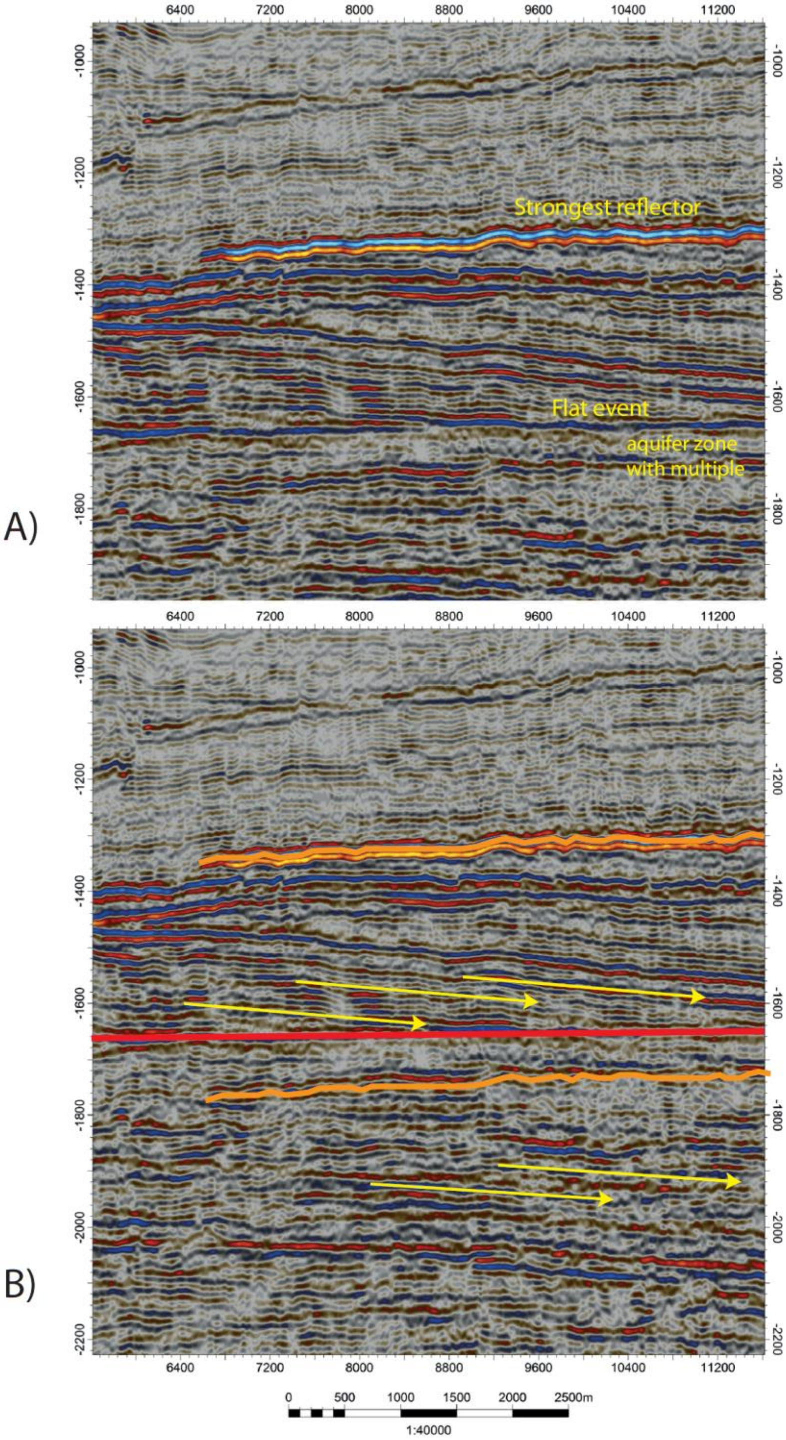


Figure 3.3: A) Example of clear seismic section showing the strongest reflector, flat event, propagation pattern and multiple within the aquifer. B) The same section interpreted. Good example showing that multiple follows the pattern of strongest reflector.

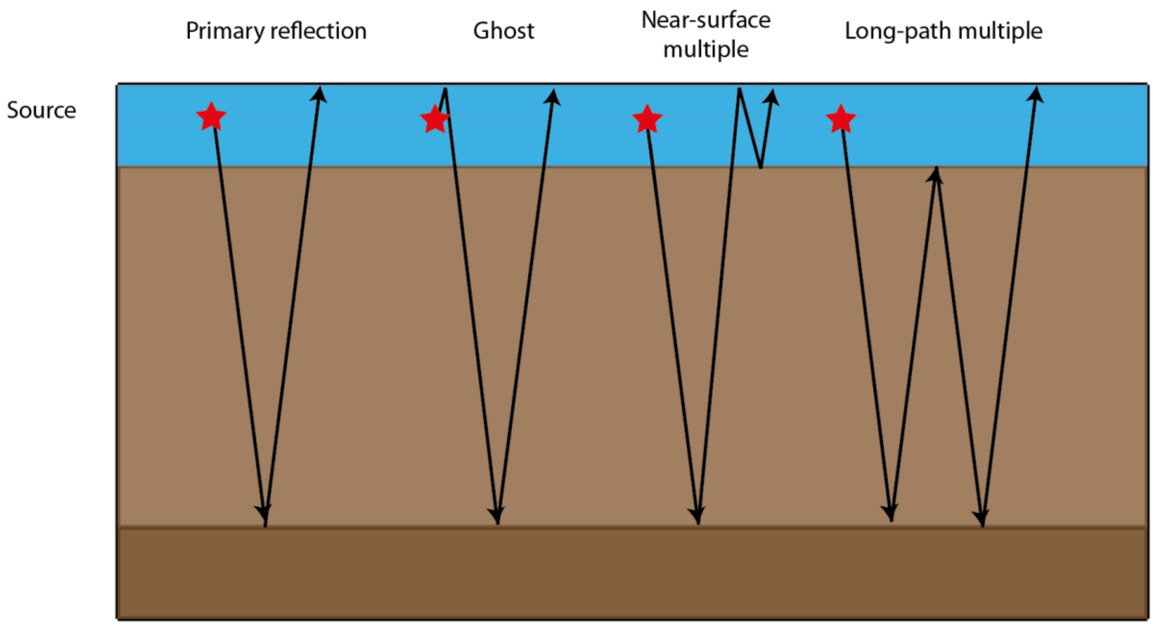


Figure 3.4: Sketch of possible pathways for seismic wave between the source and receiver.

As a result, the 3D data used in the project can be considered as a data with respectively moderate quality to poor quality in some parts of the survey. Several horizons of interest lie below the flat event in the aquifer zone and are affected by multiple which makes the interpretation of those horizons very challenging.

3.4 Well data

Well data used in the project was taken from PTS database. The wells include log data, deviation data, checkshots and depth converted well tops. The data from NPD has also been used. Wells are a very important part of interpretation because of a challenging data quality. Six exploration wells were used in this study (Figure3.5). The selection of wells was based on the amount of information they contain and on their location in relation to the study area.

Exploration wells

31/6-1

The exploration well 31/6-1 was drilled in 1983 with a primary objective to test Late and Middle Jurassic on the main top of the Troll East structure. This well is also the deepest well in the study area. The planned TVD was 3800 meters but the well penetrates pre-Devonian basement rock at 4070m and stops 4070.8m (www.npd.no)

31/3-1
The exploration well 31/3-1 was drilled in 1983 at the same time as the 31/6-1. These two wells were drilled together to prove the existence of Troll East field. The objective of 31/3-1 was to test possible gas and oil accumulations in the Late to Middle Jurassic sandstones. The final vertical depth of the well is 2374 m and the oldest penetrated age is Triassic. (www.npd.no)

31/6-2
The appraisal well 31/6-2 was drilled in 1983 to test the gas and oil accumulations in the Late to Middle Jurassic age sandstones. It is also the reference well to the Hardrade Formation and to the undifferentiated Shetland Group in the Troll East structure. The final vertical depth of the well is 2020 m and the oldest penetrated age is Early Jurassic. (www.npd.no)

31/6-5
Well 31/6-5 was drilled in 1984 to appraise the possible oil and gas accumulations in sandstones of the Late Jurassic age. It was also used to get the information about lateral facies changes within the reservoir. The final vertical depth is 2082 m and the oldest penetrated age is Early Jurassic. (www.npd.no)

31/6-6
This exploration well was drilled in 1984 to test the possible gas accumulations in the Late to Middle Jurassic sandstones. The second purpose to drill the well was to test the reservoir quality of siltstones in Heather C Formation. The final vertical depth is 2291 m and the oldest penetrated age is Late Triassic. (www.npd.no)

31/6-8
The exploration well 31/6-8 was drilled in 1985 in the southwest corner of the Troll East structure to determine the lateral distribution of the reservoir and to determine fluid water contact of Sognefjord Formation. The final vertical depth is 2138 m and the oldest penetrated age is Early Jurassic. (www.npd.no)

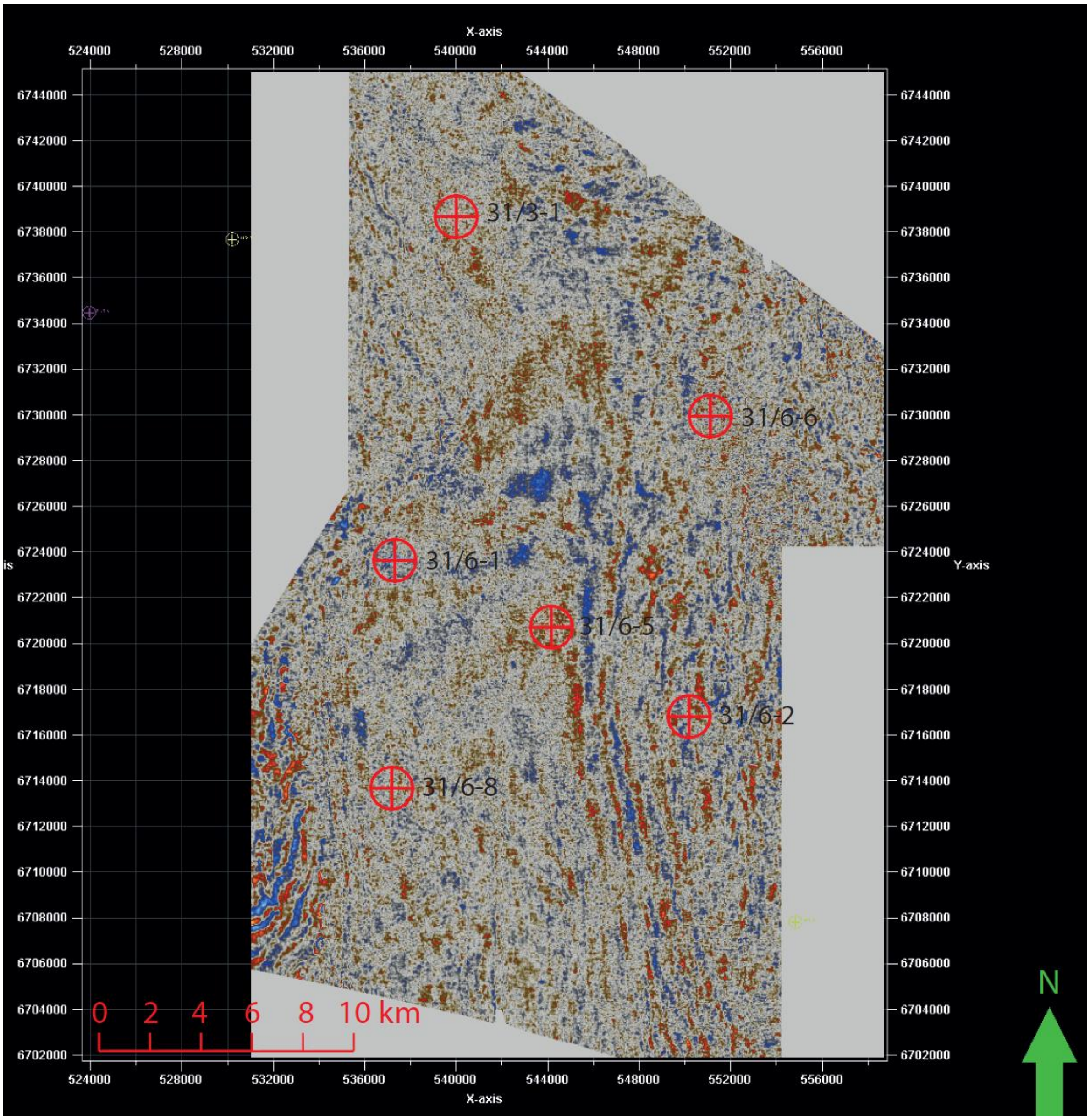


Figure 3.5: Map showing the location of exploration wells used in the project.

4. METHODOLOGY

The technical part of the work was done using the Petrel 2013 software developed by Schlumberger. A big effort was made to understand the lateral distribution of reservoir formations within the Troll East gas field. The general workflow is shown in Figure 4.1. It was used for better understanding of both large and small scale geology in the area of study. The 2D data helped with understanding of the regional settings of the area while 3D data with a precise interpretation of well data were used to get better understanding of depositional environment, lithology and lateral distribution of the reservoir and other important formations.

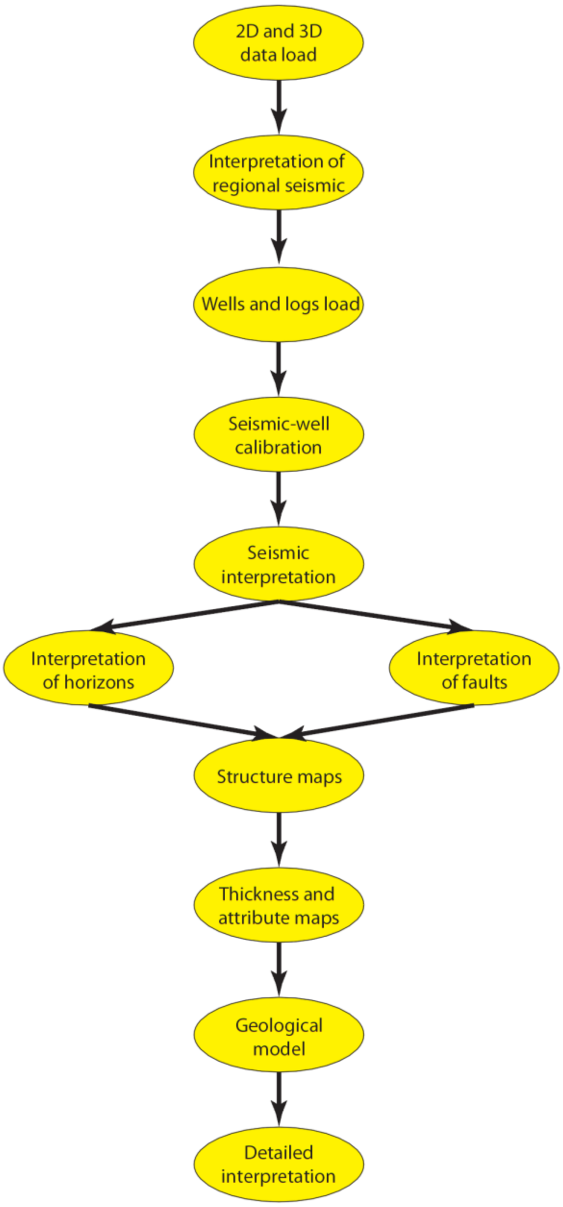


Figure 4.1: The general workflow used in the technical part of the study.

4.1 Interpretation of 2D seismic

As it is already mentioned in the previous chapter, the problem of 3D survey is that it doesn’t have proper quality of the data in a deeper part. That’s why three 2D seismic lines were used for better understanding of deeper geology.

These three lines are part of the same study, hence the quality of the data is more or less the same. The quality of seismic is respectively poor below the 2500 – 2600 ms. But one feature can be observed through all three lines. The strong dipping reflector could be observed at the sections from 3250 to 4000 ms. The depth is varying slightly and the trend stays the same. An example from line ‘MN9103-302’ is shown in Figure 4.2.

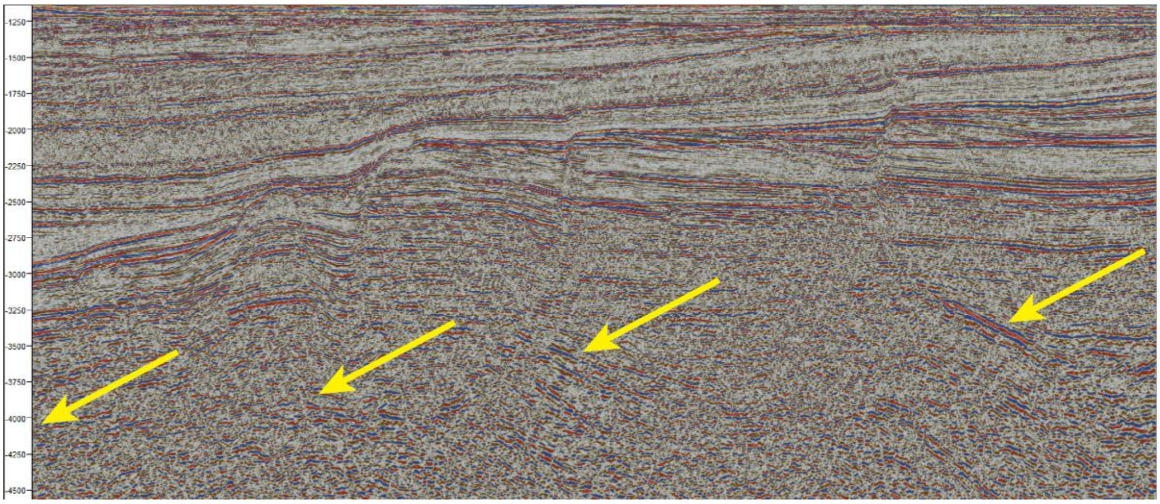


Figure 4.2: The part of seismic in-line 1665, yellow arrows show the possible sequence boundaries.

High increase in acoustic impedance is an evidence for an increase of velocities and densities in that area. These reflectors could also be interpreted as a sequence boundary as there are a lot of weaker reflectors truncating against the ones listed above (Figure 4.3).

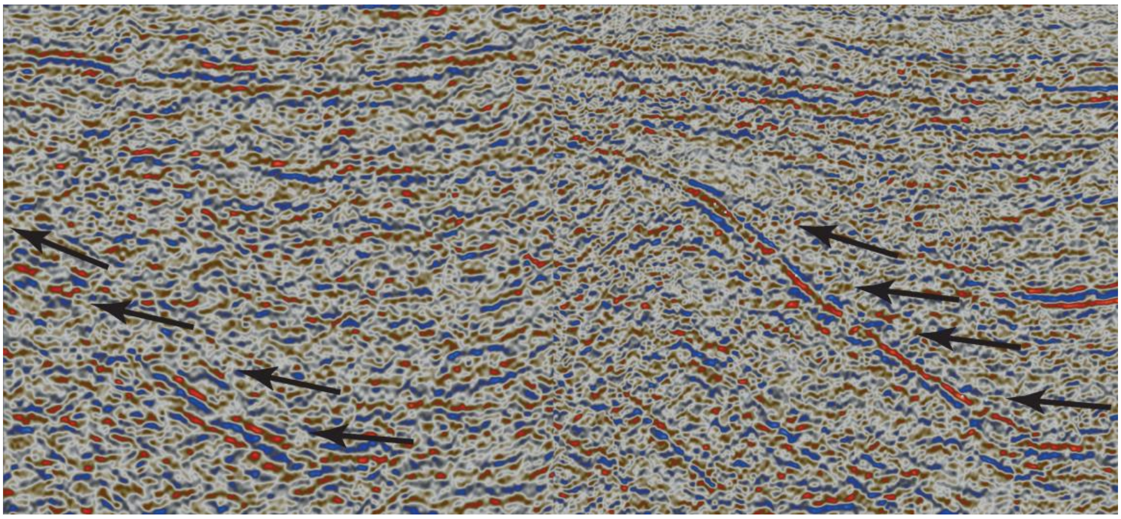


Figure 4.3: The zoomed in part of seismic section (in-line 1665) showing the on-laps against the sequence boundaries

The listed evidences in addition to the knowledge of geological settings of the area could be summarized in a proposal that these reflectors represent the boundary between the basement and overburden. During the interpretation of 2D lines the strongest horizons were highlighted. The discontinuities and unreal geometries together with geological knowledge were used to set the faults during interpretation. The example of interpreted line is shown in Figure 4.5. The same procedure was done for two other lines. Interpreted lines together with produced geological model are presented in the next chapter.

4.2 Well-to-seismic tie

The well-to-seismic tie is a very important step before going to seismic interpretation. This procedure helps to find out the connections between the geological information given from well data in depth and the geophysical information which is in Two Way Travel time in this particular study. At least three logs from a well should be available to proceed the well-to-seismic tie and they are: Density log, Gamma Ray log (GR), and Sonic log. Bad logs quality can cause mistakes in calculations which will affect reflectivity strength. Problems with the sonic log are the most dangerous as the log is integrated to create a time-depth relationship for the well. Any errors in the log are propagated throughout the time-depth relationship. The procedure of despiking is very useful to prepare the sonic log for further usage (Figure 4.4). It helps to identify thinner layers and calibrate it with seismic sections.

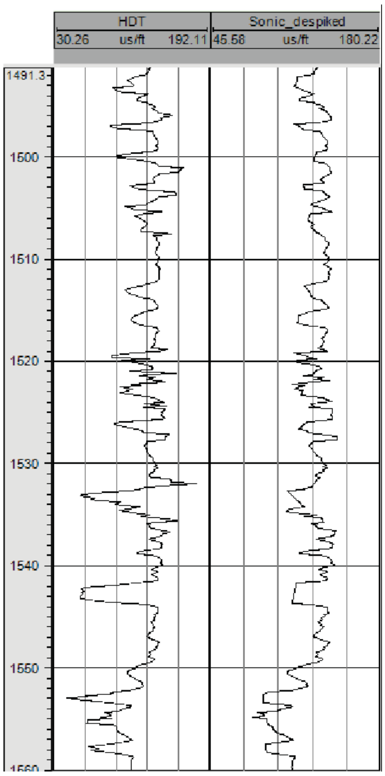


Figure 4.4: The example of original sonic log on the left and despiked on the right

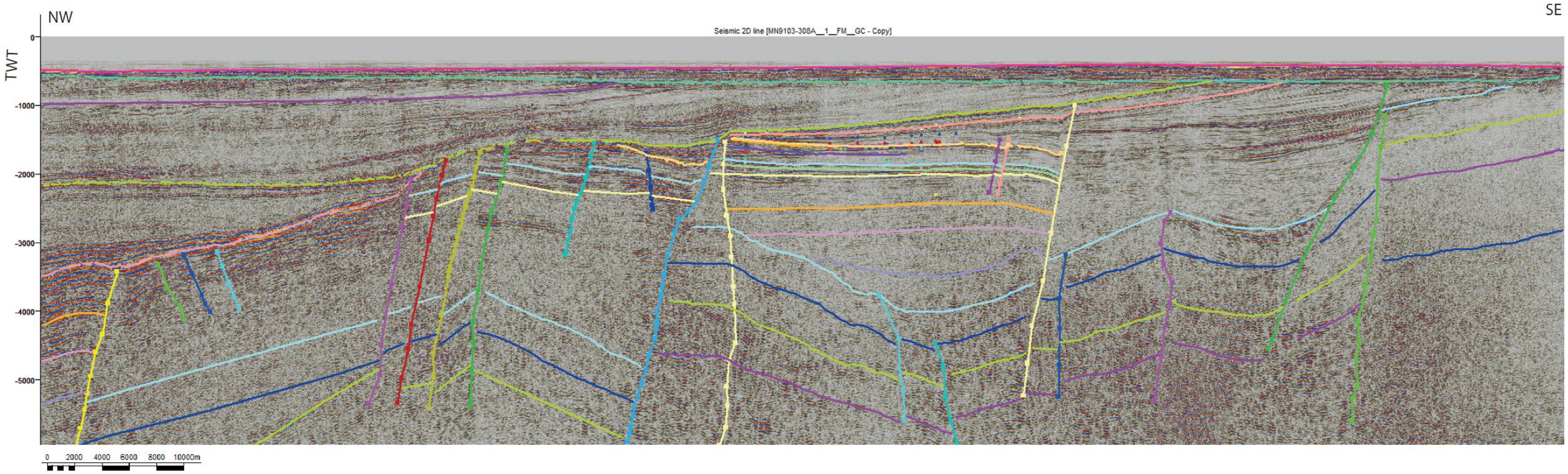


Figure 4.5: The example of interpreted eastern part of 2D line ‘MN9103-308A

When all the logs are ready and checkshots data for the wells are uploaded, the Seismic Well Tie process can be started. It consists of three main workflows (Figure 4.6):

- Sonic Calibration
- Synthetic Generation
- Integrated Seismic Well Tie

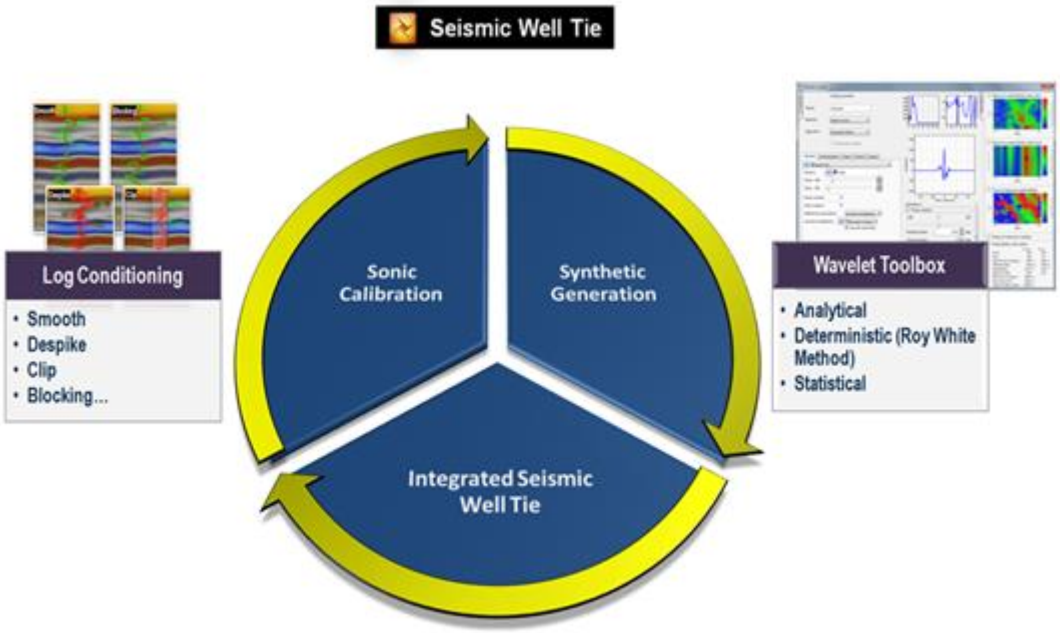


Figure 4.6: Three main steps of Seismic-to-well tie

4.2.1 Sonic Calibration

The aim of sonic calibration is matching of seismic times from checkshots and integrated sonic times for any given depth in a well. The results of sonic calibration used in the Seismic-to- well tie process include the ability to interactively perform a sonic calibration and view the results of calibrated sonic log while editing (Figure 4.7).

4.2.2 Synthetic Generation

Generated synthetic seismograms create the bridges between geological and geophysical information. Synthetic seismograms give opportunity to:

- Tie geologic markers to seismic horizons
- Generate accurate time-depth relationships
- Understand the seismic response of lithologies and fluids at well location
- Understand the phase characteristics of the seismic data.

The Synthetic Generation process used in the Seismic-to-well tie process ties a synthetic seismic trace with a seismic survey. A new time-depth is built during this process. The synthetic generation involves essentially the following steps:

- Time conversion of the well and logs information by means of checkshot data or sonic log. A time-depth relationship is established.
- Calculation of acoustic impedance and reflection coefficients from different logs
- Generation or extraction of wavelet from the seismic
- Generation of synthetic seismograms from density logs, sonic logs, and a seismic wavelet by calculating acoustic impedance and reflection coefficients (Figure 4.8)

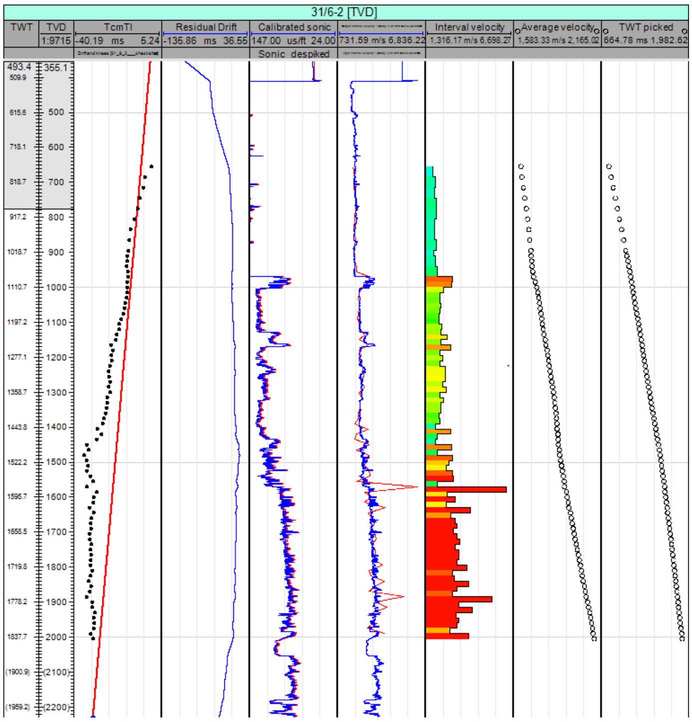


Figure 4.7: Sonic Calibration workflow for the well 31/6-2

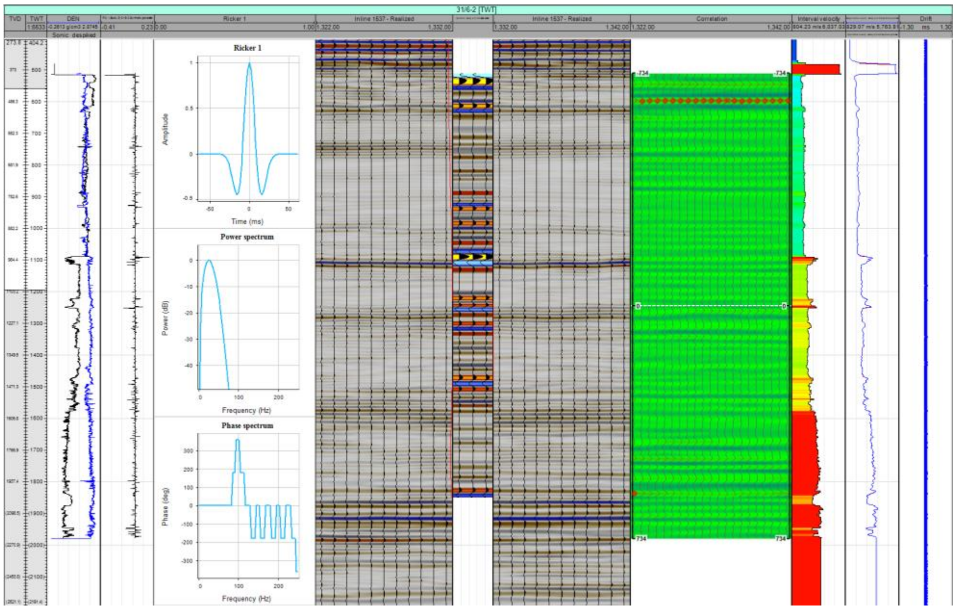


Figure 4.8: Synthetic Generation workflow for the well 31/6-2

4.2.3 Integrated Seismic Well Tie

This last step is the process where Sonic Calibration and Synthetic Generation can be executed using the same WSW canvas. This step is necessary just to finish the Seismic-to-well tie workflow. After that wells are converted in time and could be shown on a seismic section. Uploaded welltops can be shown on seismic as well (Figure 4.9).

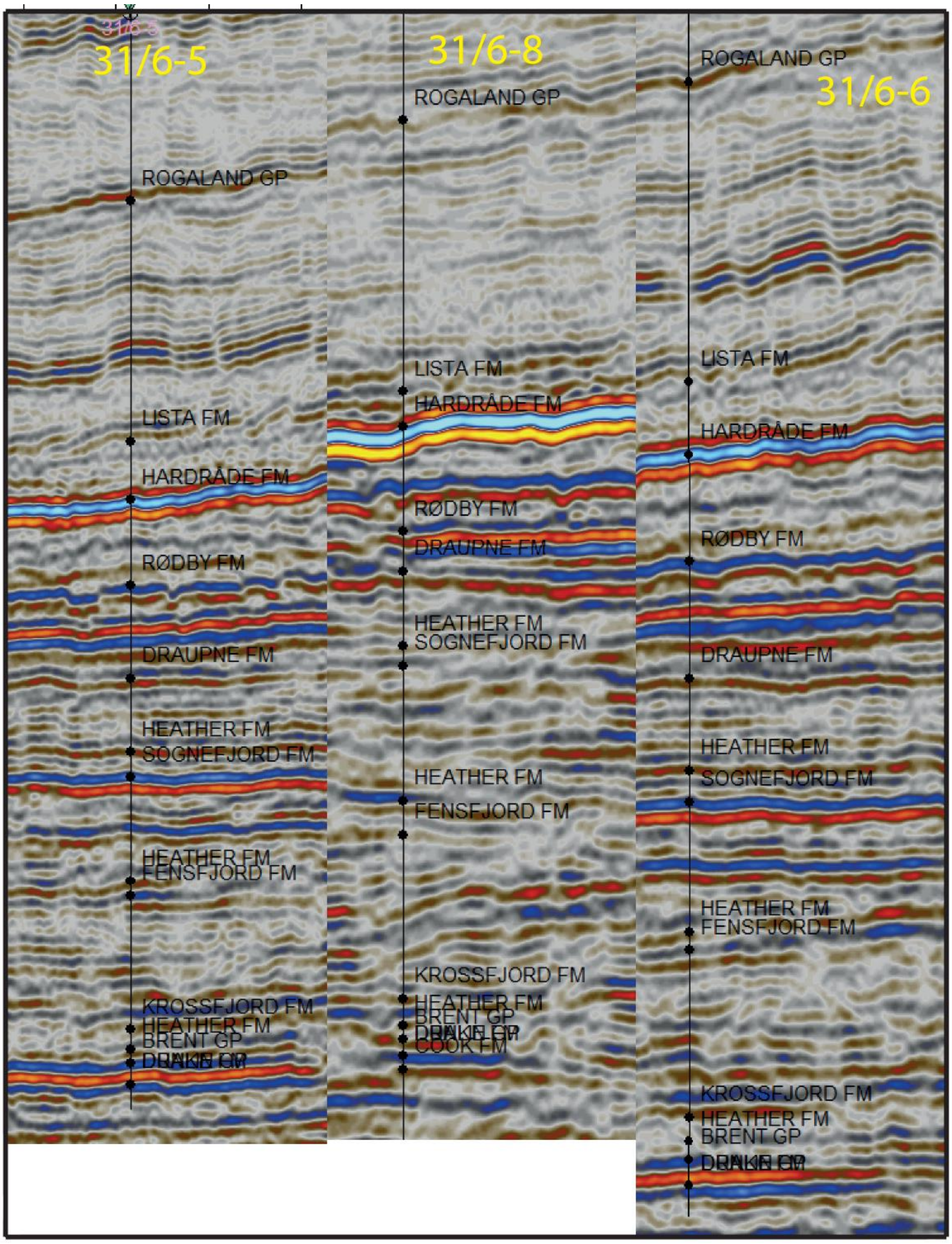


Figure 4.9: Examples of well tops shown on seismic after seismic-to-well tie

4.3 Seismic interpretation of 3D seismic cube

When well tops are shown on seismic it is much easier to start the process of seismic interpretation. This process is necessary to verify the geological history, so several stages of seismic interpretation were conducted to be resulted in surface maps, fault surfaces, thickness maps, and geological models. The interpretation process was done by mapping horizons in the 3D seismic cube and tying the interpreted horizons with wells data.

Interpretation of strong reflectors

Due to restrictions of seismic data not all the horizons were observable through the area of study. The first part of interpretation the seismic cube was to interpret the main sequence and stratigraphic borders. Using the NPD well tops and data provided in 3D seismic cube 10 horizons were interpreted and mapped (Figure 4.10). The horizons represent:

Seabed

HORDALAND GROUP

Hordaland Group represents the border between overlaying horizontally bedded Quaternary sediments and underlying Tertiary sediments. The top of Hordaland can represent the erosional surface because massive Tertiary sediments are truncating against this surface throughout the whole area of study. Hordaland Group is mostly presented by clay grading to claystone with occasional sand and siltstone stringers. The depositional environment is recognized to be marine, with reduced bottom water circulation to normal marine.

SHETLAND GROUP

The start of Shetland Group and Hardråde Formation is presented by the strongest reflector in the study. This surface also represents the unconformity as all the main faults observed in the area are truncating against it and are not crossing this border between Cretaceous and Tertiary sediments. The formation is presented by interbedded claystone, limestone and marl. The depositional environment was outer-marginal marine shelf.

CROMER KNOLL GROUP

The Cromer Knoll group Rødby Formation package represents the Lower Cretaceous sediments. The top of the formation is a hardl discontinuous layer. This can be a consequence of outer-marginal marine shelf depositional environment as the listed above Shetland group is an erosional surface it shows stronger reflectance. The Rødby formation is presented by claystone and marl with minor amounts of limestone.

VIKING GROUP

Draupne Formation

Top of Viking Group is an import horizon to interpret as it also represents the base of Cretaceous sediments. The reflector is quite weak and was interpreted with the help of well data. The Draupne Formation consists of carbonaceous claystones and the depositional environment is low energy, marine, anoxic seafloor.

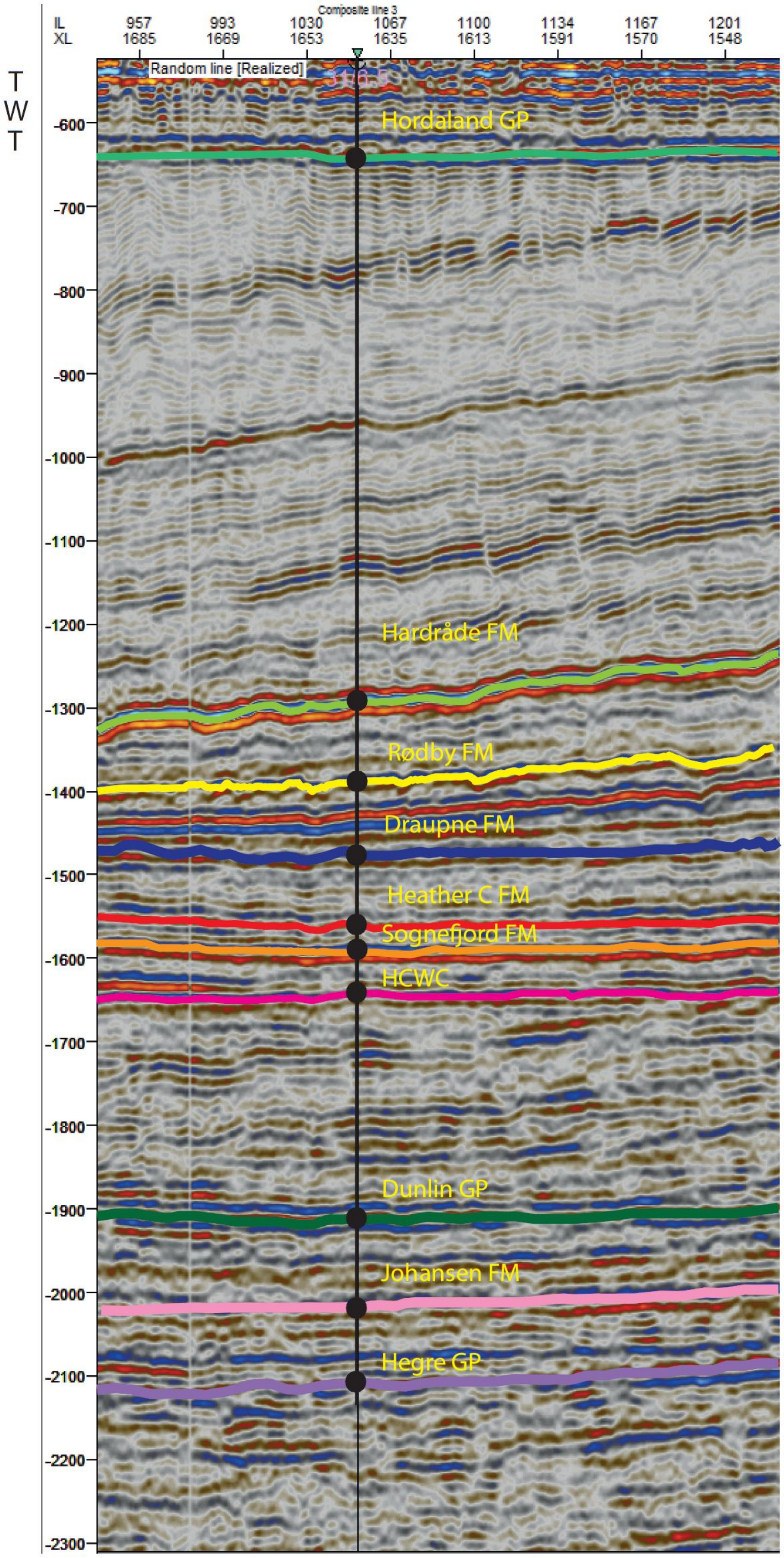


Figure 4.10: Part of cross section showing the interpreted horizons.

Heather C Formation

As it was mentioned in Geological Settings chapter, the Heather Formation in the study area is divided in three parts by coming from west sand bodies. That is why it was important to interpret the tops of Heather bodies to understand the geology of that event.

Heather formation is represented by carbonaceous mixture of siltstone and sandstone and the depositional environment in contrast to Draupne Formation which is marginal marine.

Sognefjord Formation

The reflector of the Sognefjord Formation was important to interpret as it represents both, the top of the reservoir for the Troll East field and the top of the area which was studied in details in this work.

The formation consists of micaceous and glauconitic sandstone with traces of coal and the depositional informant is shallow marine.

Hydrocarbon – water contact

The Troll East field is famous for its huge and wide propagating flatspot which represents the border between hydrocarbon and aquifer. Going from hydrocarbon to aquifer always causes an increase in acoustic impedance as water is much dense than gas and oil. Hereby, using the European standard of seismic it should be shown as a peak (blue) reflector. This flat event was recognized and interpreted in the area of study.

DUNLIN GROUP

It is the first observable and continuous reflector below the flatspot. The Dunlin Group is presented by Drake and Johansen Formations. Drake Formations lithology is primarily characterized by claystone with rarely thin beds of sandstone and limestone, while the dominating lithology of Johansen Formation is light gray sandstones which finning downwards to olive gray siltstone. The depositional environment is inner-marginal marine

HEGRE GROUP

The Triassic Hegre group is penetrated by only one well in the area. The reflector is weak but can still be observed and interpreted in the area. The messy reflections within the Hegre group show the same trend of laying as overlaying Jurassic sediments. It is a very thick package consisting of interbedded claystones, siltstones and sandstones.

BASEMENT

The interpretation of 2D dataset gave a proposal of basement interpretation. In addition, in the deeper part of the 3D survey one reflector should be observed. There is also the well 31/6-1 which penetrates the basement (Figure 4.11).

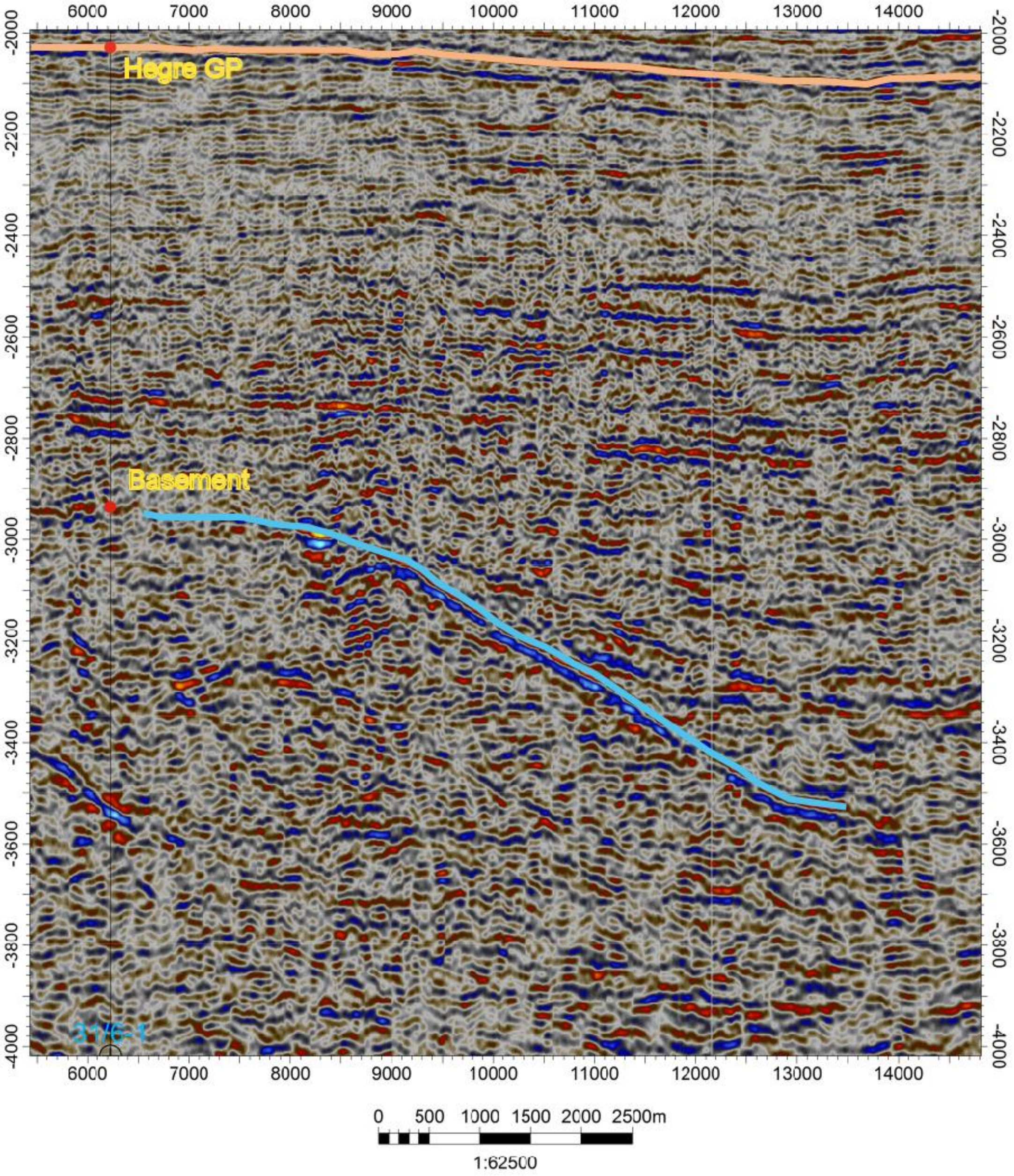


Figure 4.11: The well top corresponding to the basement (red dot) and possible reflector of the basement marked with blue, crossline 1880

4.4 Interpretation of faults

Interpretation of faults is a very important task as it is necessary to understand the geometries, geology and tectonics of the area. The understanding of fault propagation also prevents from misinterpreting of important horizons. During the interpretation of 3D survey 12 major and minor faults were observed and interpreted (Figure 4.12). All the faults are normal faults dipping in different directions. The map of faults is presented in the next chapter.

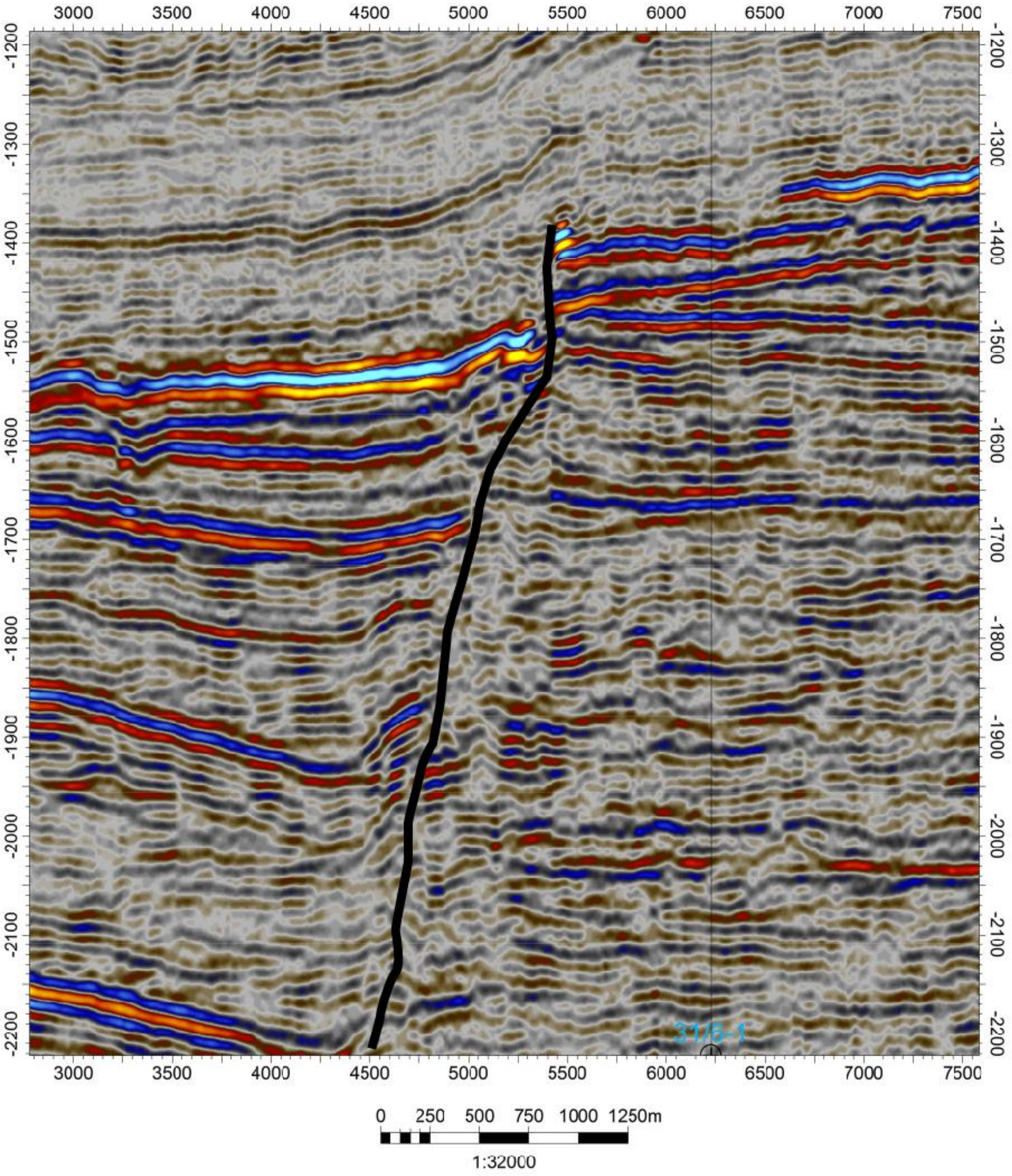


Figure 4.12: Example of fault interpretation, crossline 1880

4.5 Interpretation of discontinuous horizons

As mentioned in subchapter 4.3, 10 horizons were mapped during the interpretation process. Unfortunately, due to a low quality of data below the flat spot, the interpretation of Fensfjord, Heather B, Krossfjord and Heather A formations appeared to be challenging. The interpretation of Fensfjord and Heather B was possible only above the flat spot in a small western part of the area, while the interpretation of Heather A and Krossfjord was very difficult because these horizons were truncating against the Multiple in the aquifer (Figure 4.13).

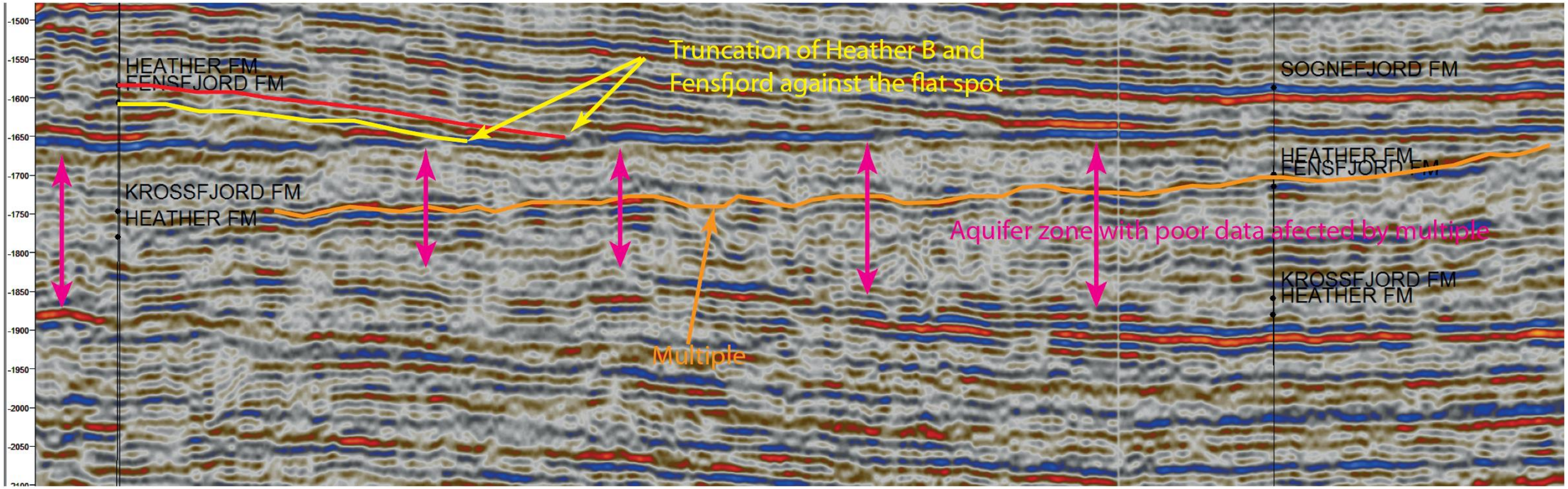


Figure 4.13: Example of poor, discontinuous data affected by multiple below the flatspot.

To interpret these horizons several advantages in Petrel software were used. Tied wells were connected with each other by composite lines. These composite lines and 2D lines (as they are not affected by flatspot and multiple) were used to interpret the listed horizons (Figure 4.14). After that these four horizons were interpreted in in- and crosslines using the tie points and going in loops. The horizons are well interpreted in the middle of the survey (area below the HC water contact) and have some in interpreted parts in the east and west margins of the survey.

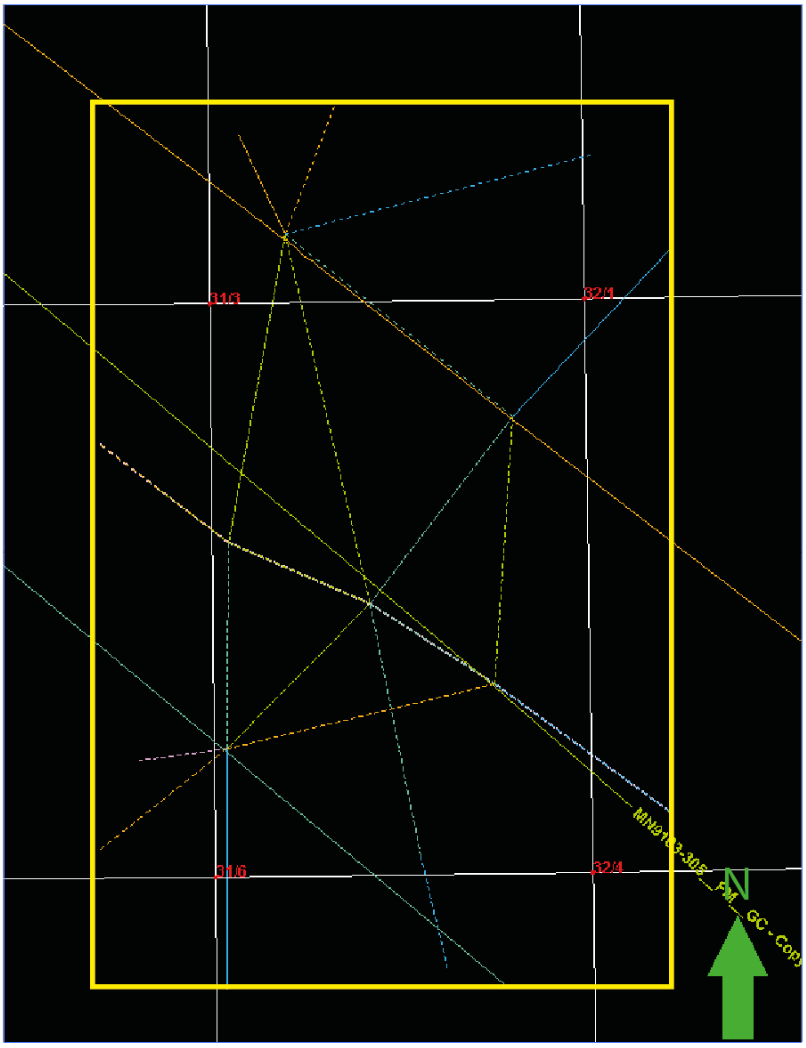


Figure 4.14: Map of composite and 2D lines being used to interpret challenging horizons

4.6 Detailed interpretation of Sognefjord formation

When all the maps were produced it became possible to reinterpret the top and bottom of Sognefjord Formation with a very fine gridding. The interpretation of Sognefjord and Heather B was done with a gridding step 20 to see more details and notice smaller changes. This also allowed to produce thickness map and geological model to study the lateral distribution of Sognefjord Formation.

5. RESULTS

During the work on this thesis, knowledge of the geological history, rifting processes and lateral distribution of sandstone bodies has been gained and used for better understanding of regional geology in the northern North Sea and later on Horda Platform. This chapter represents the results of 2D and 3D interpretation together with a log interpretation. The first part represents the results of 2D interpretation and the final reconstruction of geological history of the area while the second part is concentrated on summarizing the information gained while studying the characterization of Sognefjord Formation and its correlations between seismic data and real geology.

5.1 Interpretation of 2D survey

The first part of the study is the interpretation of 2D survey around the northern part of North Sea. It was done for better understanding of geological history of the area. The information gained from the previous studies and seismic-to-well tie (well 31/6-1) together with the interpretation was summarized in geological cross section and litho-stratigraphic column. The purpose of 2D interpretation was to distinguish the geological events in the area.

During the interpretation the aim was to highlight the stragraphic sequences. Examples of two interpreted 2D lines are presented in Figures 5.1, 5.2, 5.3. Figures 5.2 and 5.3 are parts of one seismic section (MN9103-308) separated because of a gap between them in the middle of Viking Graben, while Figure 5.1 represents the seismic section ‘MN9103-305’ and covers only the area of Horda Platform. Nevertheless, these two lines give the fullest picture of the subsurface of northern North Sea. All three lines were interpreted to show the base of Quaternary (orange), base of Tertiary (green), base of Cretaceous (brown), base of Jurassic (purple) and Basement (blue) and fault systems. The lines stretch NW-SE and cross Horda Platform at about 61^{o}N. On the very east margin of ‘MN9103-308’ a shallow basement is identified. The faults are characterized as normal syn- and antithetic faults, locally with minor sediment-filled halfgraben basins.

The ‘MN9103-308’ line was used to produce a geological cross section of northern North Sea (Figure 5.4 in the text and Attachment 1). In this cross section the SE part is recognized as Øygarden Fault Zone. It is an extensional fault zone with westerly vergence separating the shallow basement area from Horda Platform. Mesozoic and Paleozoic megaunits can be followed westwards across the faulted Horda Platform where the sharp change in structural dip appears at one of the major faults.

The Horda Platform area has a border to the west with an eastern graben margin fault system. It is represented as a series of normal faults at the Mesozoic levels. This border system is represented by easterly-tilted fault blocks on the east, whereas faults closer to the graben are westerly-tilted. The number of antithetic faults also increase westwards. The Cretaceous sequence in the Horda Platform area truncates into the basin margins.

It is hard to interpret the Viking Graben part in the area because of the gap in seismic survey. Nevertheless, one trend can easily be observed. The missing part of Viking Graben can be defined as a point where the tilt of fault blocks changes from easterly to westerly. The Tampen Spur situated in the NW margin of the area consists of several large, rotated fault blocks.

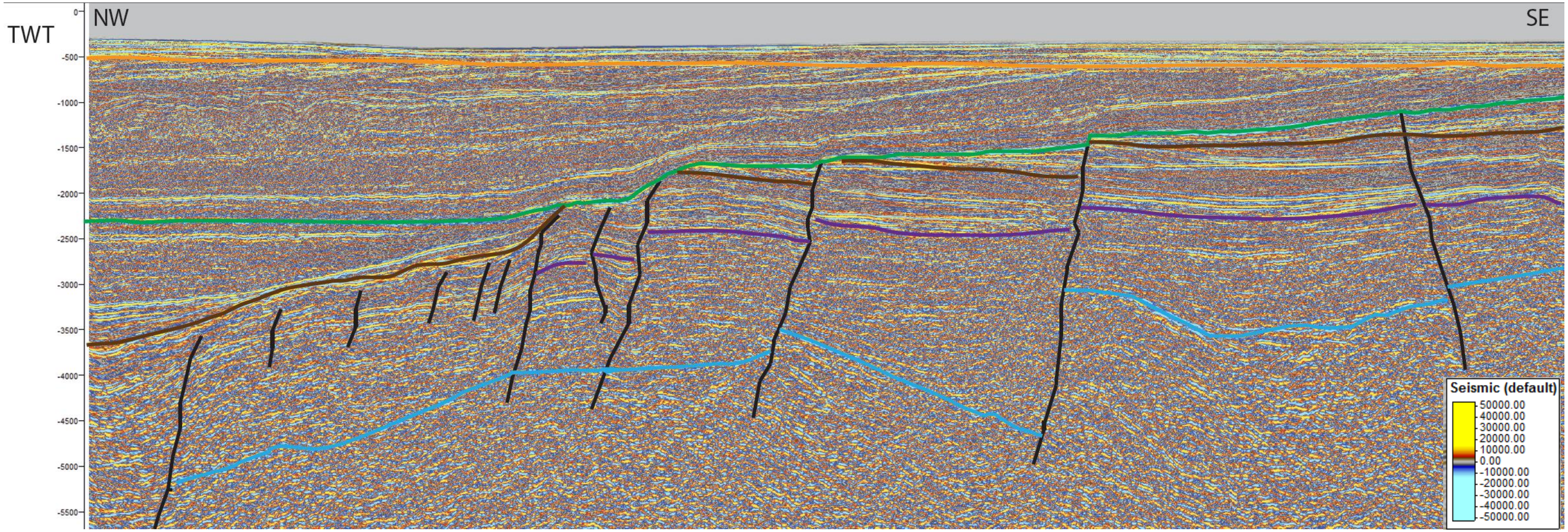


Figure 5.1: Seismic section 'MN9103-305', Quaternary - orange, base of Tertiary - green, base of Cretaceous - brown, base of Jurassic – purple, Basement – blue, faults - black

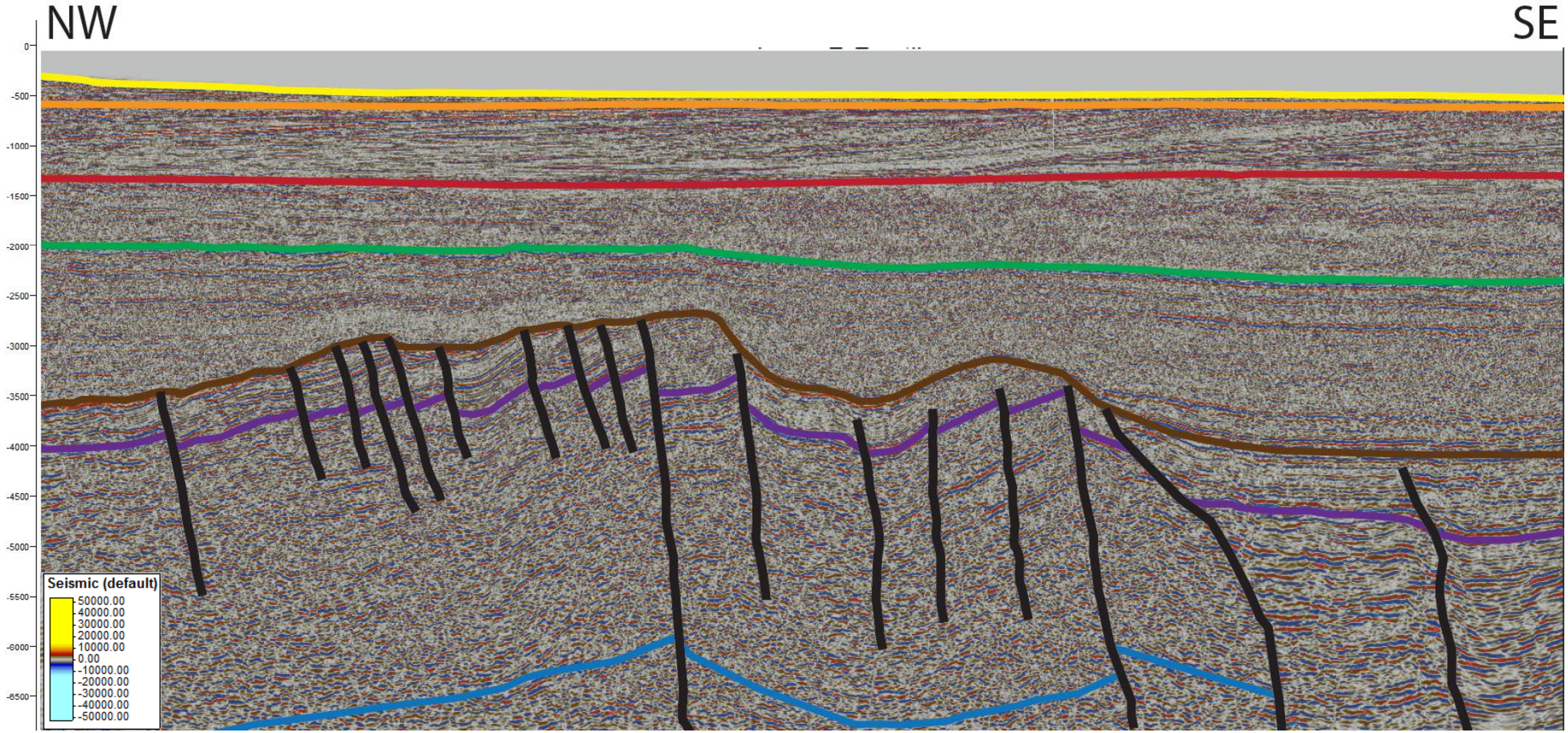


Figure 5.2: Western part of seismic section 'MN9103-308', Quaternary - orange, base of Tertiary - green, base of Cretaceous - brown, base of Jurassic – purple, Basement – blue, faults - black

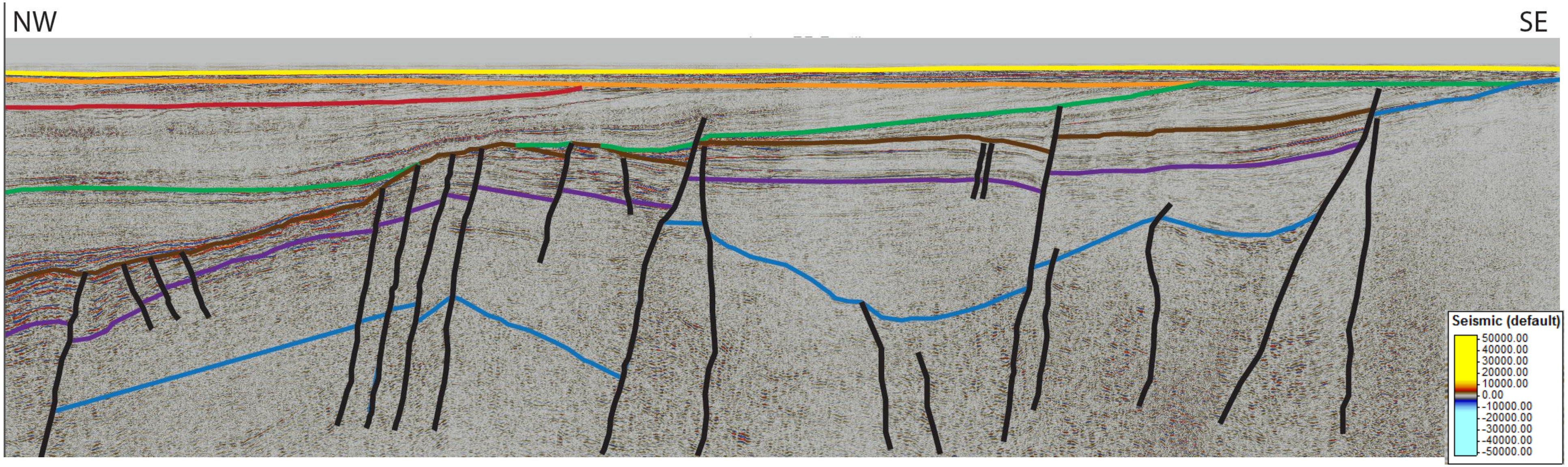


Figure 5.3: Eastern part of seismic section 'MN9103-308', Quaternary - orange, base of Tertiary - green, base of Cretaceous - brown, base of Jurassic – purple, Basement – blue, faults - black

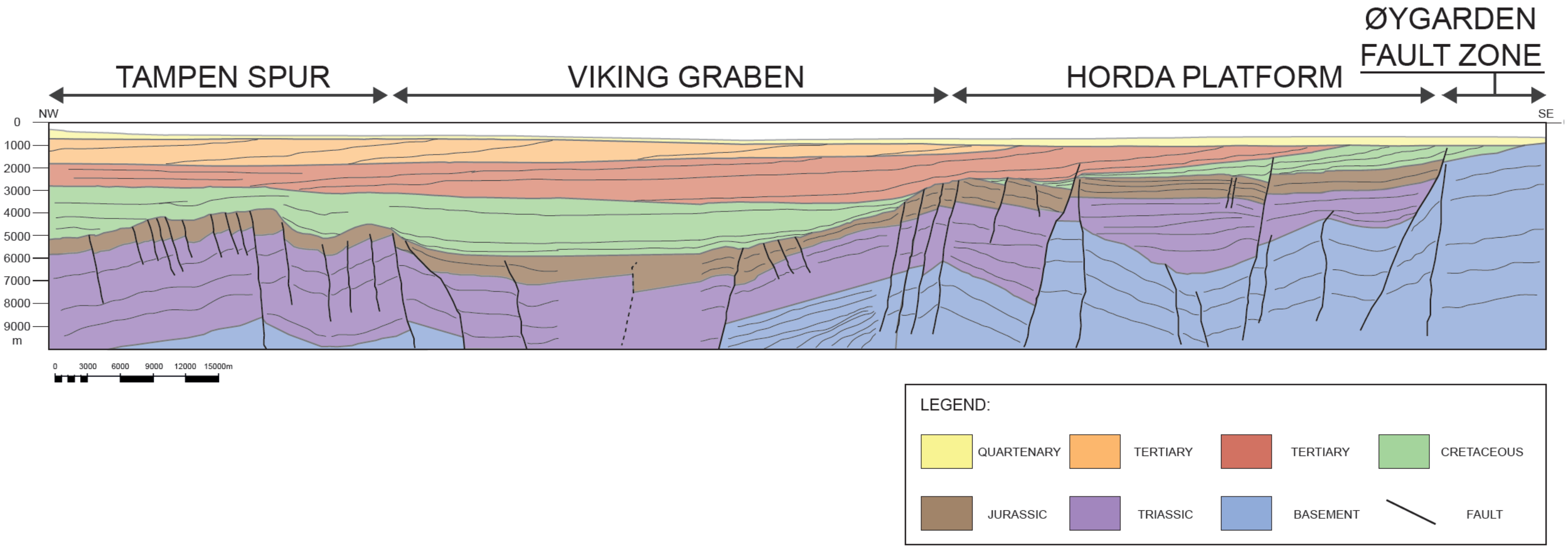


Figure 5.4: Geological cross-section based on line 'MN9103-308'

The eastern and western margins of the Viking Graben have highly variable geometries changing from east to west, even though the Horda Platform is dominated by westerly-dipping north-south propagating normal faults.

Seismo-stratigraphic subdivision.

The observation of seismic sections listed above tighter with the interpretation of log data in IP software showing the shale to sand variations in well 31/6-1 resulted in Table 5.1 showing the separation of Horda Platform area into the sequences according to both seismic impressions and lithology.

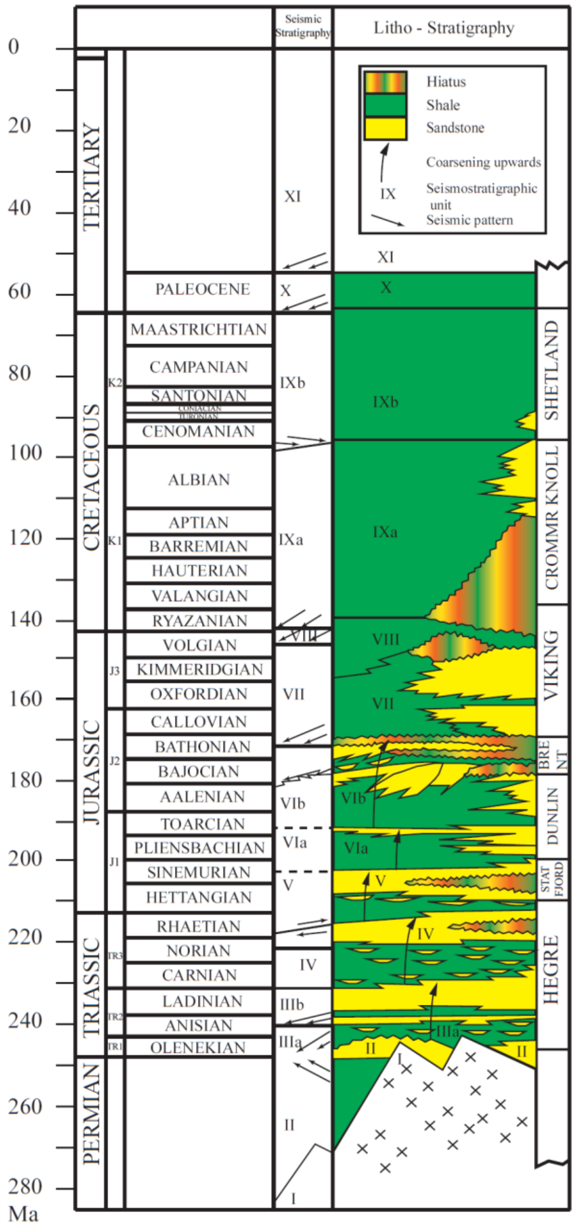


Table 5.1 Tectono-sedimintalogical events of Horda Platform (summarized and modified from Gabrielsen et al. and www.npd.no)

Sequence I

The reflector is very hard to follow but it can be correlated to well 31/6-1 as the top of the basement. The basement reflection has a stratified unit on top of it. It is hard to separate this reflector from the reflector of Sequence II, but the onlap observed in the part of Horda platform shows this angular unconformity.

Sequence II (Late Paleozoic – early Triassic)

This sequence is also very hard to identify on seismic. It fills the low area between strongly tiled fault blocks. It onlaps the basement and shows a bit stronger reflectivity than overburden.

Sequence III (Scythian – Ladinian)

In the area of Horda Platform sequence III appears in places to lap on to the early Triassic erosional surface. The faults are not observed in this area, only on the margins. The sequence is thickening towards eastern margin.

Sequence IV (Carnian – Rhaetian)

This sequence follows the same depositional pattern, it thins eastwards. According to the well data this sequence is 550 m thick in the area of 31/6-1 well. It consists of shale interbedded with sands in the lower part and sand rich in the upper part.

Sequence V (Rhaetian – Sinemurian)

Sequence V is between 300 and 600 m thick. It includes shaly/silty unit below Statfjord Formation and the Statfjord Formation itself. In the area of Horda Platform Sequence V shows a coarsening upwards character. It is also possible to observe local fault movement which probably affects lateral thickness and lithology changes.

Sequence VI (Sinemurian – Bathonian)

Sequence VI can be divided in two parts. Both of them follow the same pattern as sequence V. Sequence VI a includes Amundsen, Johansen and Cook formations and is about 200 – 300 m thick. It consists of shaly and sandy units. Shale dominated Amundsen and Johansen represented an offshore deep marine environment while Cook Formation sandstones show a shelf environment. Sequence VIb consists of Drake Formation shales and overlying Brent Group which is sand rich. The thickness is around 300 meters.

Sequence VII (Bathonian – Oxfordian) and Sequence VIII (Oxfordian – Ryazanian)

The Late Jurassic rift sequence contains the shaly Heather formation which is separated in the Horda Platform area by three west propagating sand bodies: Krossfjord, Fensfjord and Sognefjord. These three formations consist of sandstones accumulated during the lagoon lacustrine environment which makes a big contrast with overlaying Sequence VIII presented by deep marine sandstones of Draupne Formation. These sequences are locally separated by an unconformity at the top of the Viking Group.

Sequence IX (Cretaceous)

The closing of Jurassic period was the most dramatic shift in basin development of the study area. The latest Jurassic – earliest Cretaceous period can be characterized by the development of several regional unconformities. Sequence IX is about 3000 meters thick in the center of the Viking Graben, however in the platform areas the thickness varies from 100 to several hundred meters. This type of geometry could be controlled by the balance between sediment supply and the high relative sea level in Cretaceous time.

Sequences X and XI (Tertiary and younger)

The Tertiary sediments are characterized by westwards propagating clinoforms.

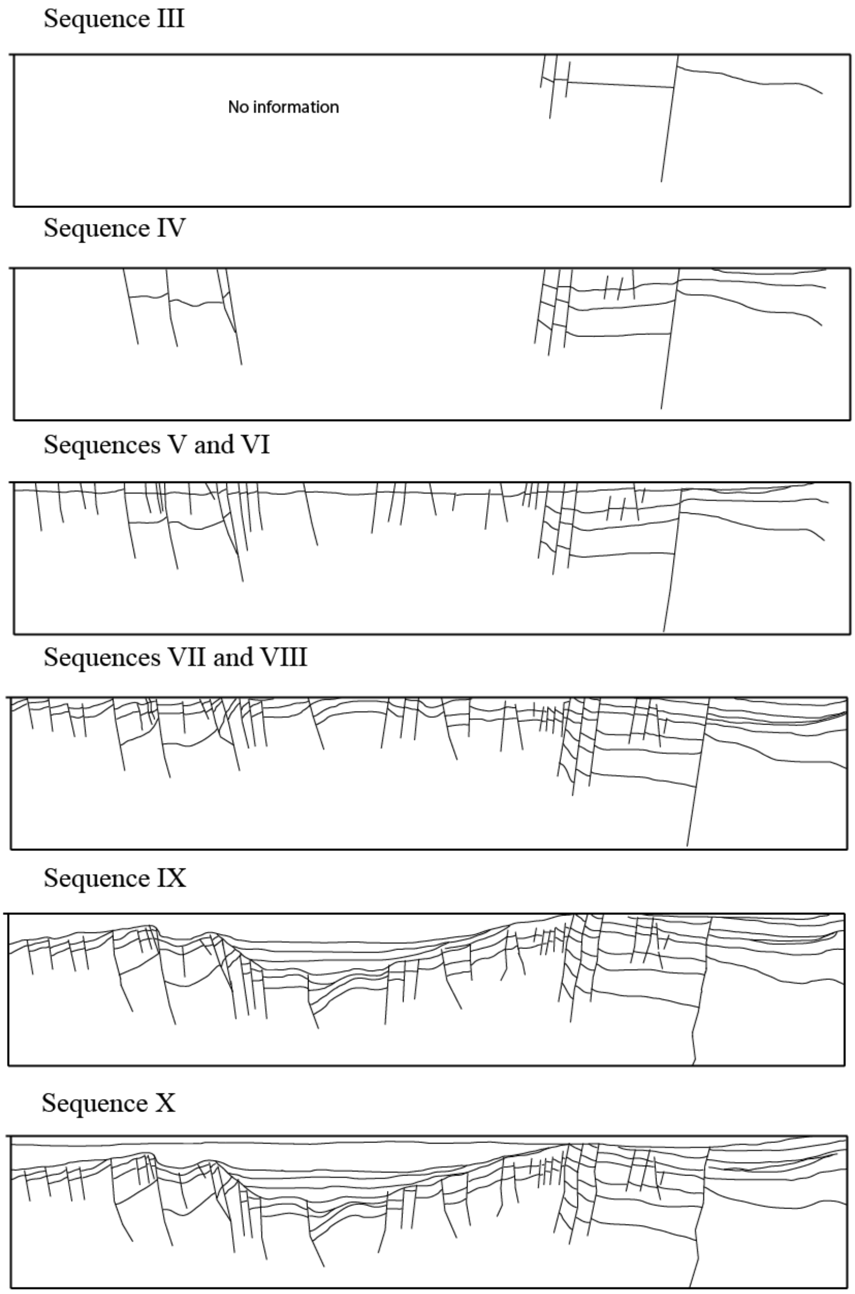


Figure 5.5: Schematic basin development

From all listed above it could be summarized that sand distribution and development in the area was controlled by tectonics (Figure 5.5). During the stages of rifting and half-graben development, sand accumulations were usually locally distributed because of topographic trapping and sedimentary tilt-trapping. The distribution of sand depended on sand availability and drainage patterns. The sand was mostly laterally derived from erosion areas. Fine-grained deposits mostly accumulated in actively subsiding areas and reach great thicknesses.

5.2 3D Survey

Interpreted reflectors

Base of Tertiary and multiple

The Base of Tertiary was interpreted as it shows the highest increase in acoustic impedance in the survey. This horizon was important to map as it creates a multiple in the zone of interest. The horizon is continuous, showing strong amplitudes in most parts of the Troll East field. Nevertheless, interpretation of multiple showed that there are several conditions to be represented for multiple to appear on seismic:

- Respectively high amplitude of Base of Tertiary
- Hydrocarbon water contact as multiple appear only in aquifer

The attribute map in Figure 5.6 shows the change in reflectivity strength of Base of tertiary, contour of interpreted multiple in pink and contour of HCWC in red. As it could be seen both conditions should be fulfilled for multiple to appear.

The horizon is constantly dipping westward and is affected only by a main fault propagating in north-south direction (Figure 5.7).

BCU

The interpretation of BCU appeared to be a challenging task in this study. The reflector doesn’t show a high contrast in impedance and is not continuous (Figure5.8). It was interpreted with the help of tying of the well data with composite lines. Although the reflector is not strong, BCU is still a termination point of majority of faults as it symbolizes a change in tectonic styles. In addition, it is a sequence boundary where cretaceous sediments are onlappnig underlying Jurassic sediments. Heavily faulted Jurassic sediments are overlaid with mostly unfaulted Cretaceous (Figure5.9). It is the boundary between post-rift and syn-rift sequences. It displays a wedge shaped geometry and overlays the pre-rift Jurassic sediments.

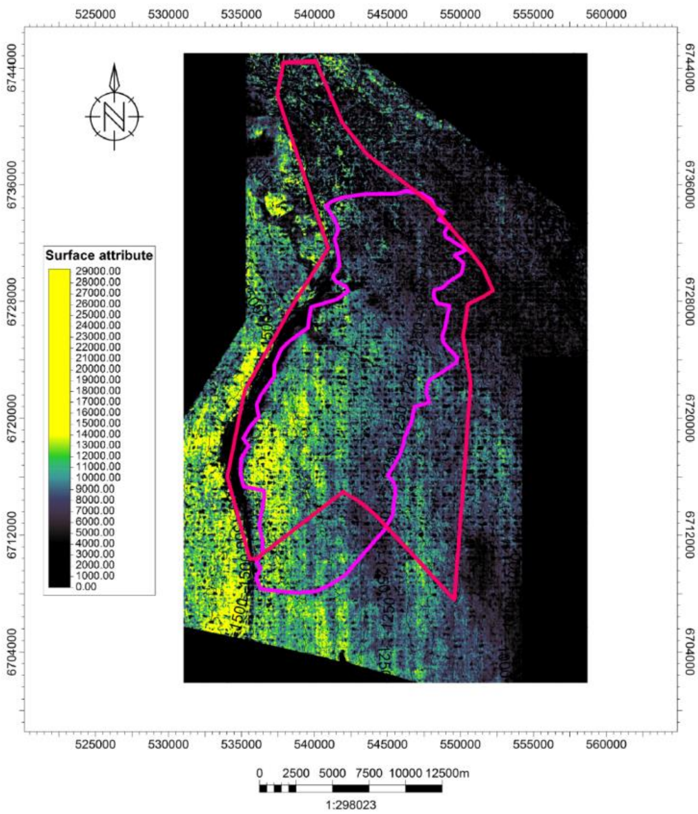


Figure 5.6: Attribute map for Base of Tertiary. GWC contour – red, multiple contour - pink

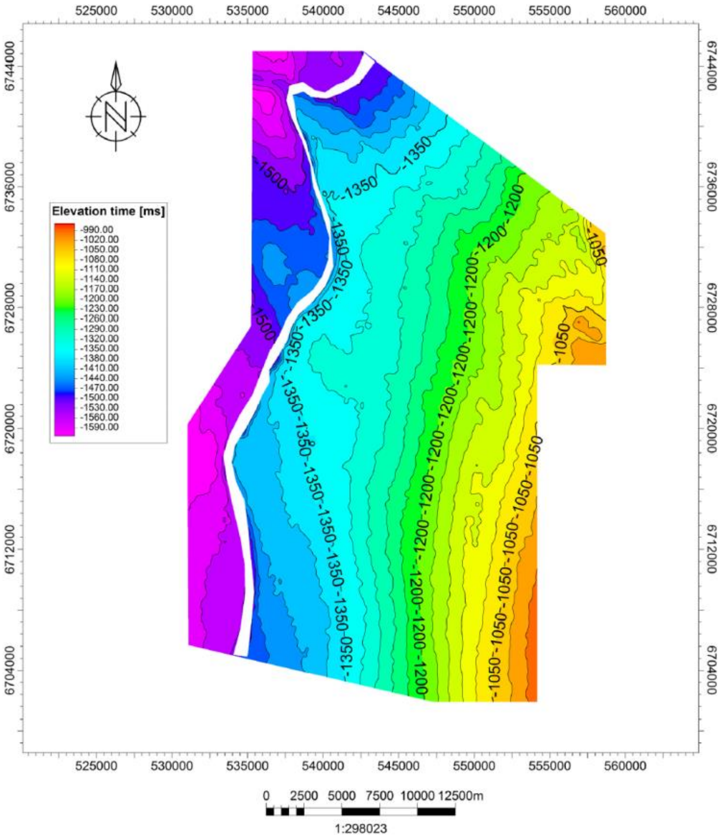


Figure 5.7: Surface map of Base of Tertiary

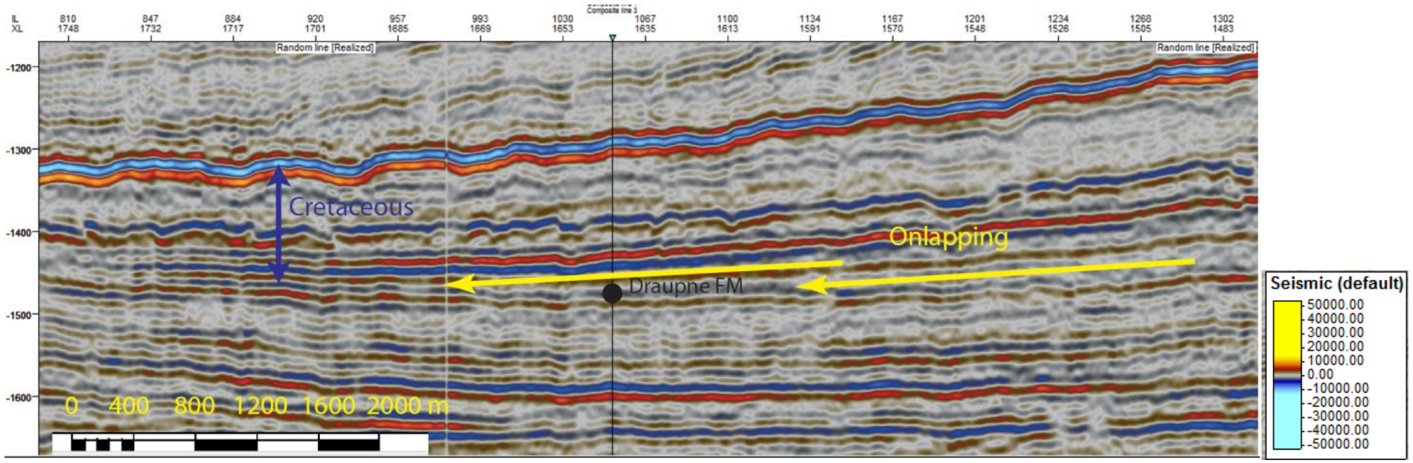


Figure 5.8: Absence of strong amplitude change at BCU, also showing down – and onlapping against the BCU

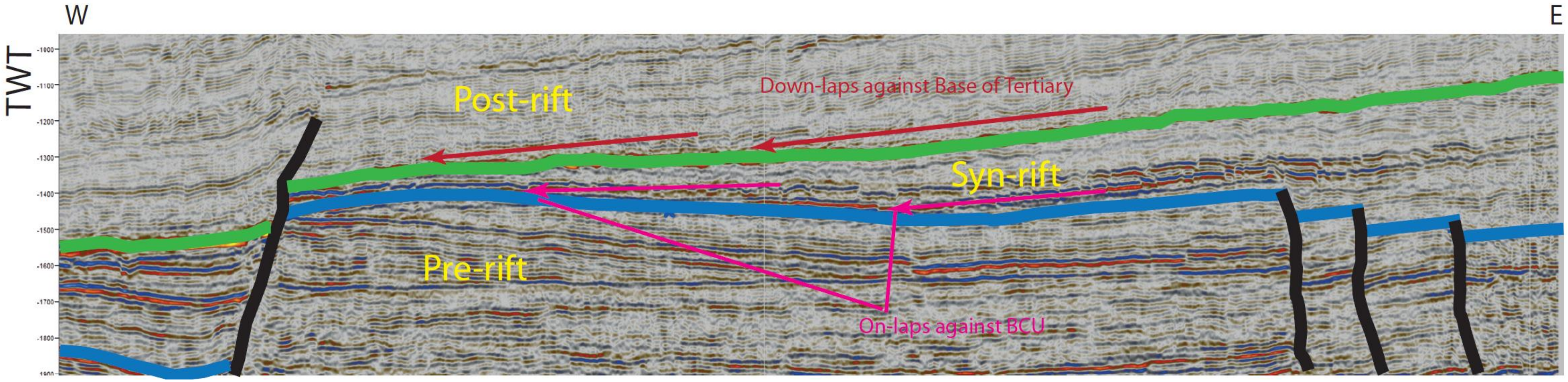


Figure 5.9: Shows the difference in seismic impressions of pre-, syn- and post-rift sediments, base of Tertiary is marked with green, BCU is marked with blue

Sognefjord Formation

The main objective of this study is a detailed interpretation of the reservoir formation in the Troll East field. Sognefjord presents the top of the reservoir which is overlaid with Heather C Formation. The reflector is strong and continuous across the area. It was interpreted with a fine gridding for better understanding of the reservoir distribution. The produced map shows that the main trend of Sognefjord is dipping into the center of the study area from east and west flanges. This horizon together with BCU shows the main trend of Jurassic sediments distribution. Figure 5.10 shows the map of Sognefjord top.

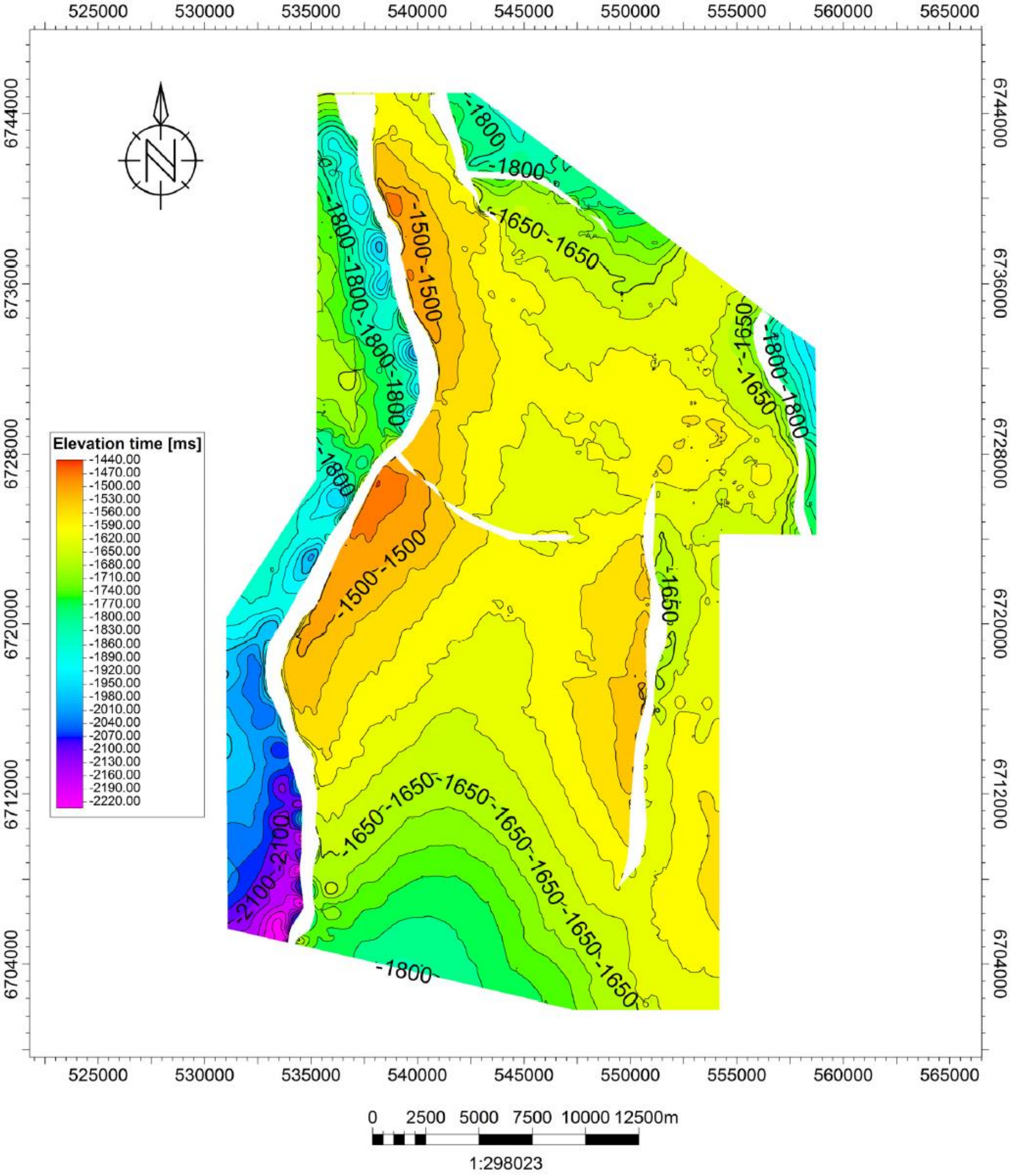


Figure 5.10: Surface map of Sognefjord Formation

The main trend is that Jurassic formations are affected by two main faults dipping in opposite directions. The main fault on the west is dipping eastwards, while the fault on the east is dipping westwards. These two faults create a horst where the gas field is located.

Fensfjord and Krossfjord Formations

These two formations are part of Viking Group and together with Sognefjord they form a tongue sand bodies propagating westwards into the Heather Formation. The interpretation of both horizons was very difficult because of poor data quality in the aquifer and multiple in the gas field area. As it was mentioned in the previous chapter, a number of composite lines between the wells were used for the interpretation of these horizons. The interpretation covers only the central and eastern part of the area and truncates into main fault on the west as there is now well data to prove the horizons on the western side of main fault Figure 5.11.

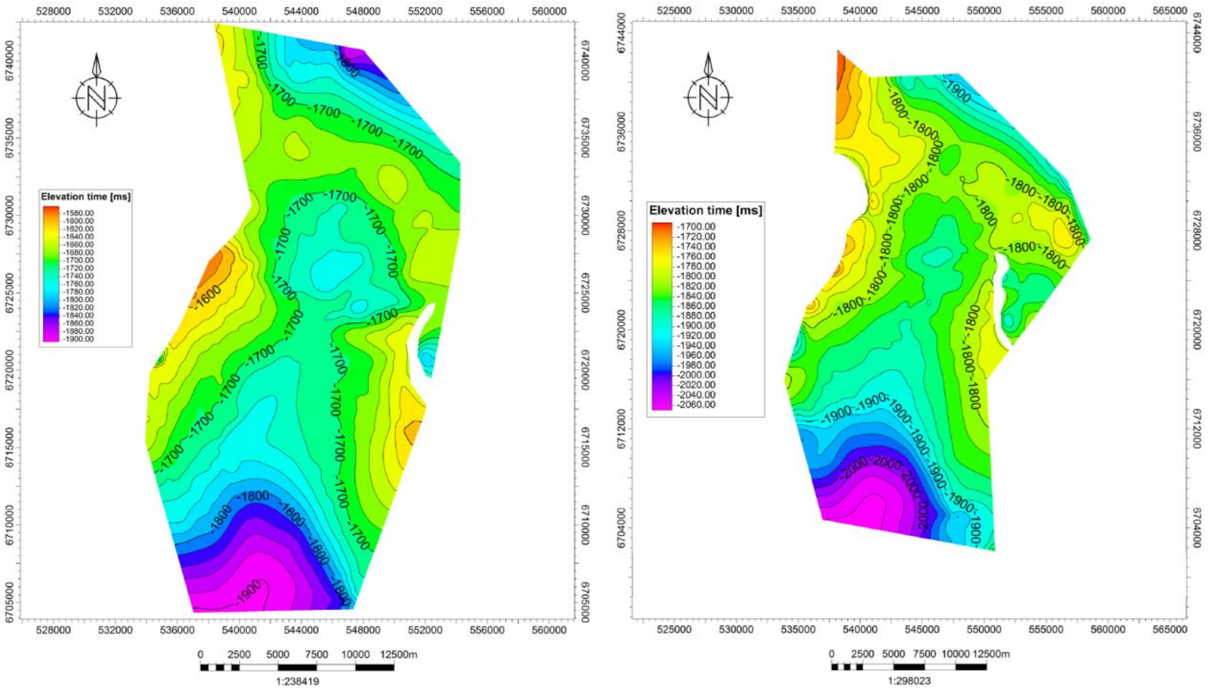


Figure 5.11: Surface maps of Krossfjord Formation on the left and Fensfjord Formation on the right

As it could be observed from the Figure 5.11, Fensfjord and Krossfjord Formations show the same depositional trend as Sognefjord Formation. They are dipping in the central part of the area. It is also obvious that the central part is lifted up and dips in north and south directions.

Geological cross-sections

The Interpretation of 15 horizons around the area shown in Figure 5.12 was summed in two geological cross-sections. Note the dashed red horizon representing the GWC. It is dipping in the northwest direction. This feature will be discussed in the next chapter. The cross sections are NW-SE and NE-SW directions and are based on 5 wells presented in the area of study (Figures 5.13 and 5.14). These lines are also printed and attached to this paper in a larger size. The location of these lines is shown in Figure 5.15.

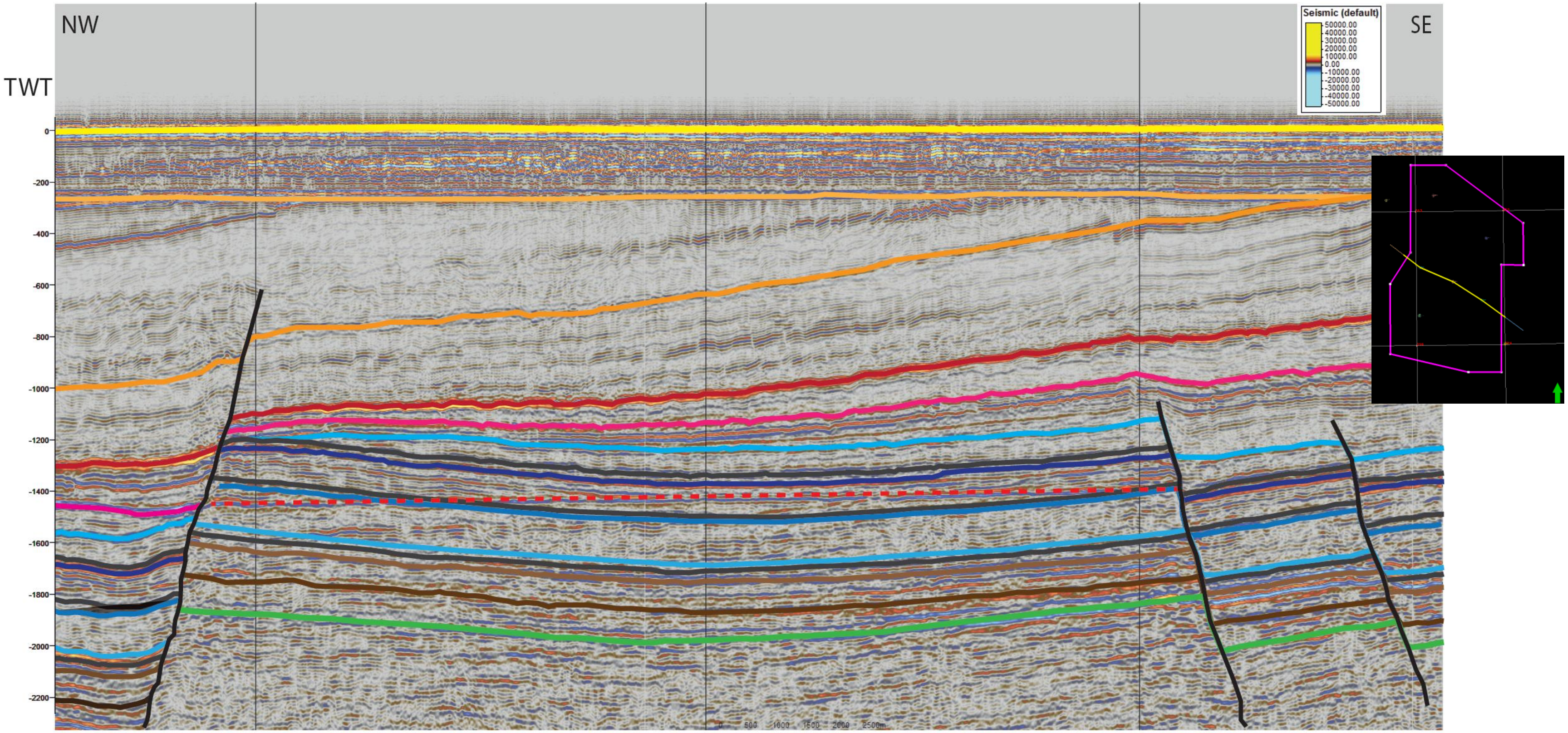


Figure 5.12: Seismic cross section showing the horizons interpreted in the study

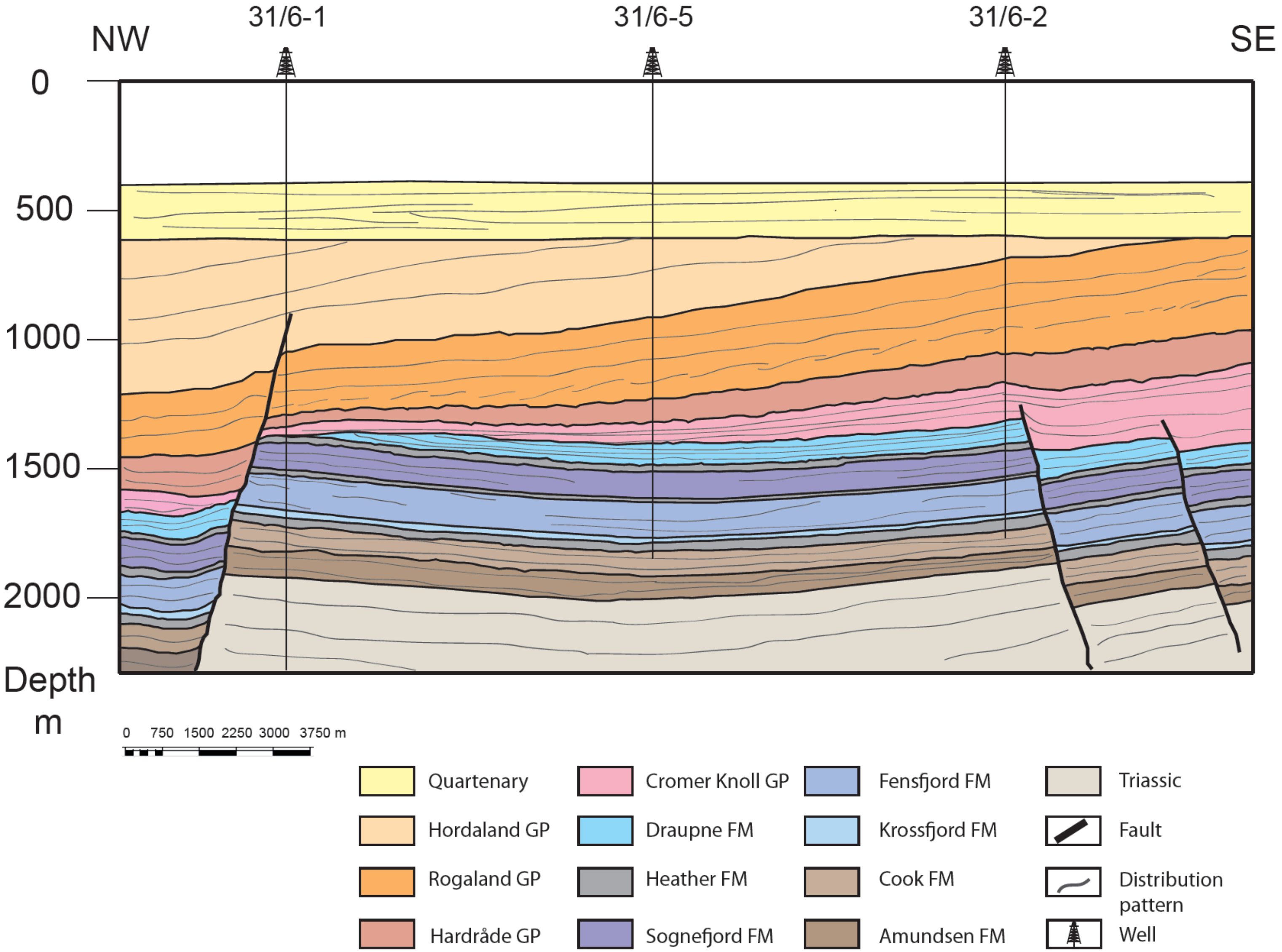


Figure 5.13: Northwest-southeast geological cross section

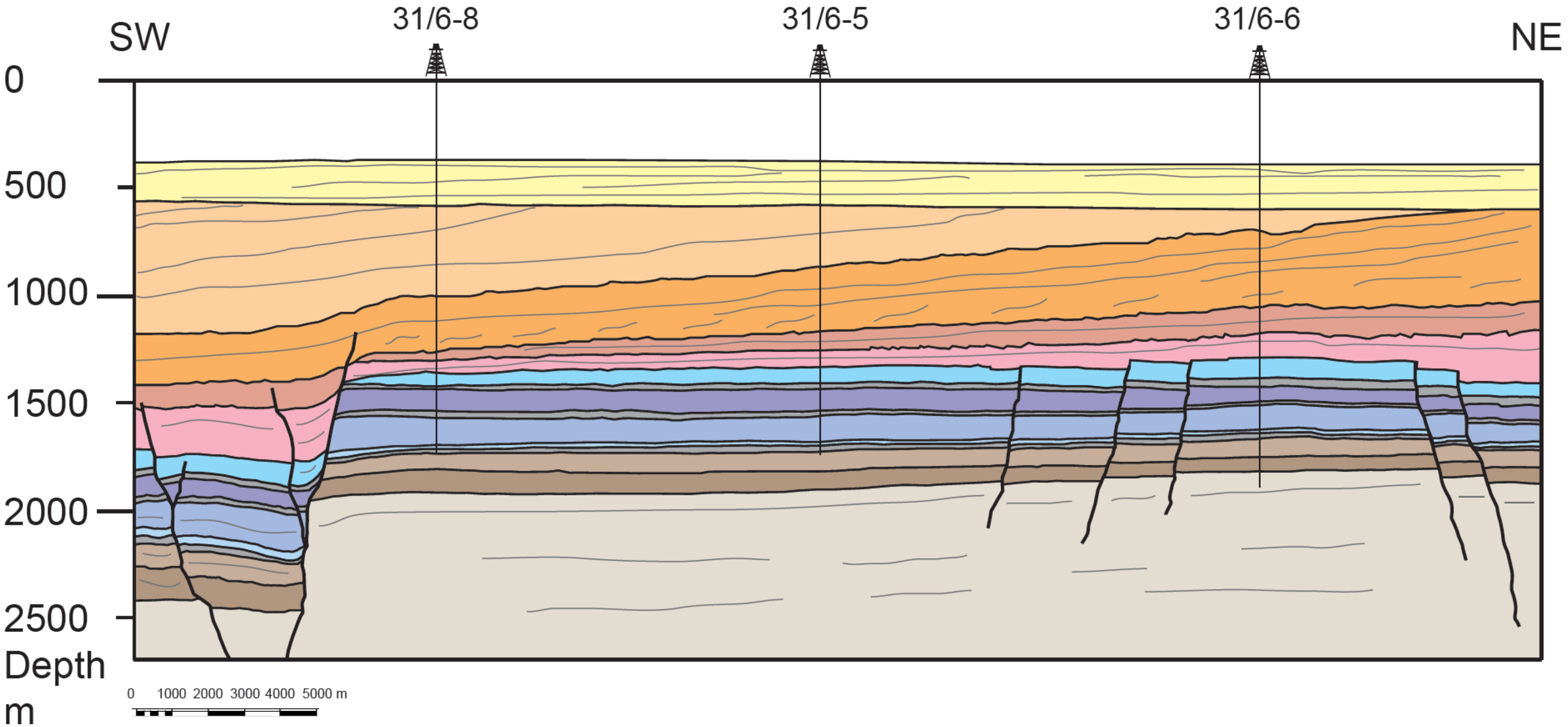


Figure 5.14: Southwest-northeast geological cross section

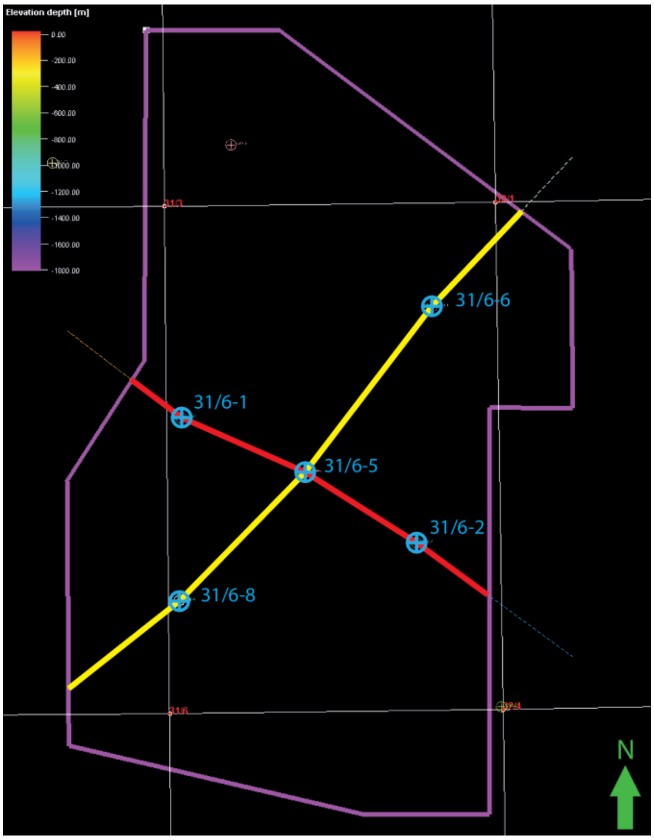


Figure 5.15: Map showing the location of geological cross sections built on composite lines

6. DISCUSSION

The Observation of results obtained in the study gave a lot of opportunities for discussion. Further in this chapter all the main challenges and uncertainties will be described.

6.1 Geological cross sections

From figures 5.13 and 5.14 showed in the previous chapter it could be observed that the Sognefjord Formation is dipping in the center of the area from the northwest and southeast directions, while it stays respectively flat in the northeast – southwest direction. This pattern could be interpreted as horst structure created during the rifting phase as the result of extension regime (Figure 6.1).

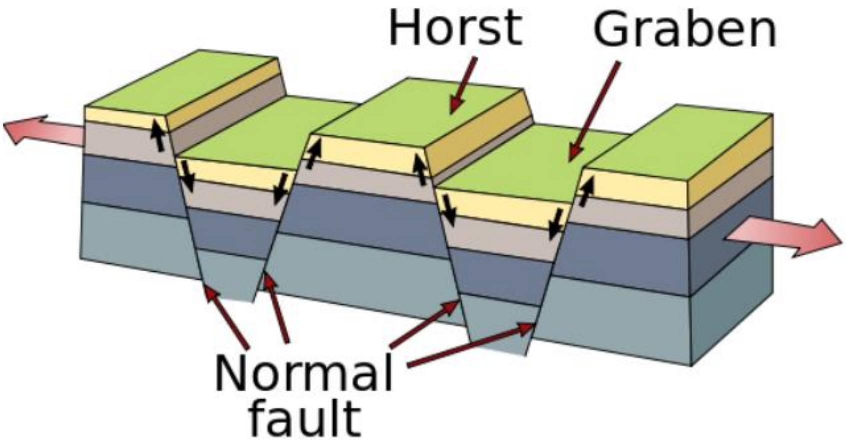


Figure 6.1: Example of horst and graben appearance during the extension regime (USGS)

The extension was propagating in southeast-northwest direction. This phase may also explain the symmetrical dipping of the Jurassic and earlier Formations into the central part of the area. Nevertheless, these geological cross sections didn’t show any major changes in Sognefjord Formation. For this purpose a well correlation study and geological model study were done.

6.2 Wells correlation

Well correlation was done using the Interactive Petrophysics v4.1 software. The study was done in the Sognefjord Formation and the output was the lithology definition. The procedure was done for exploration wells 31/6-1, 31/6-3, 31/6-5, 31/6-6, and 31/6-8. Neutron, Density, Gamma Ray and Resistivity logs were used for the definition. Gamma Ray log was used for basic log analysis to define the lithology variation between shale and sandstone, while Neutron and Density logs were used to generate neutron/density crossplot for porosities.

The workflow was done to obtain the lithology variation. Example of workflow for well 31/6-5 is shown in Figure 6.2.

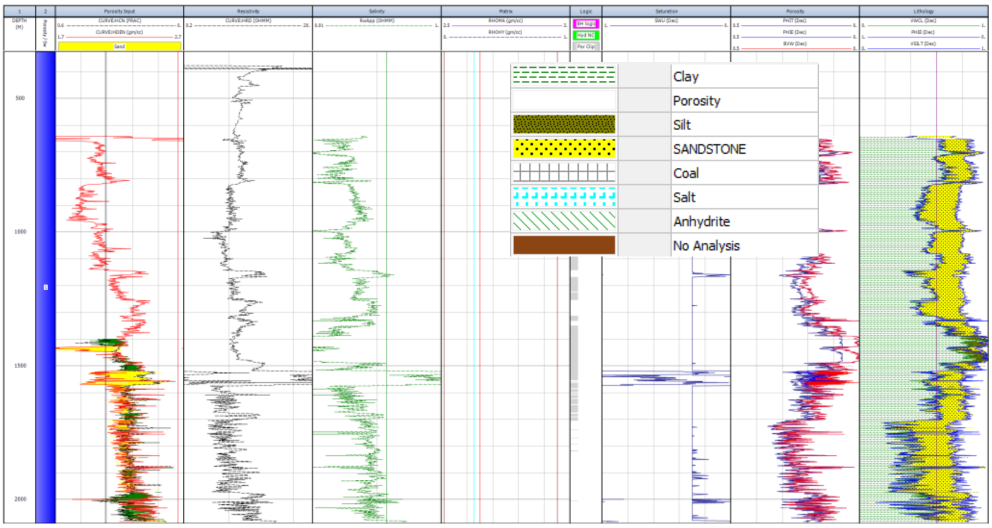


Figure 6.2: Example of workflow in Interactive Petrophysics v4.1 to identify lithology variation for well 31/6-5

The analysis of the results showed that Sognefjord Formation is dominated by shaly sandstones with good porosities. The lithological columns for Sognefjord Formation together with logs from Petrel were used to create a well correlation images (Figure 6.4 and 6.5). These wells correlations follow the same directions as composite lines used for geological models in the previous chapter. The observations from figures are:

- Sognefjord is mostly dominated with sandstones and interbedded with shales
- The frequency of interbedded shales increase westwards, while the quality of sand is less shaly westwards
- The Sognefjord Formation is slightly thinning in the northwest direction. From northeast to southwest Formation is thickening in the central part of the field and then thinning afterwards.

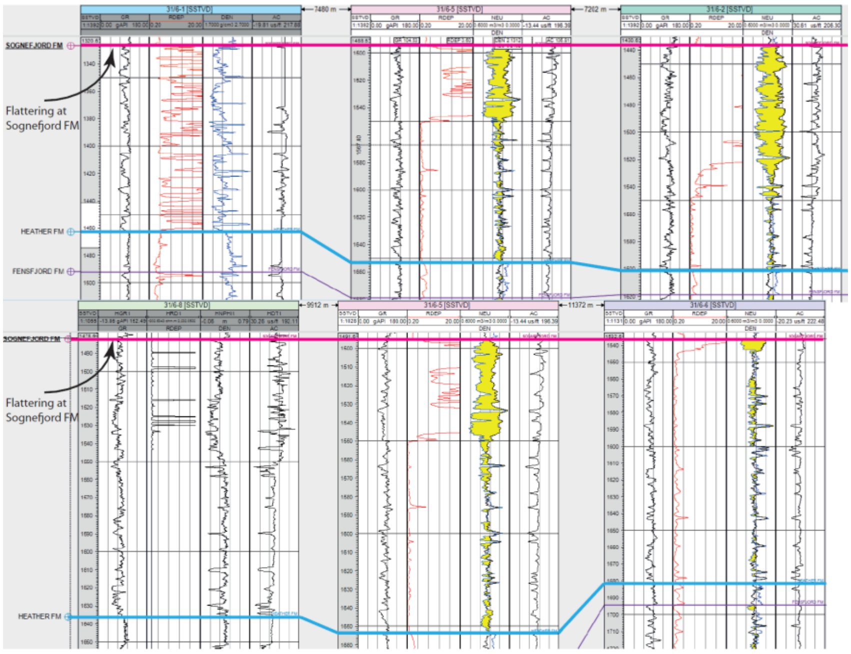


Figure 6.3: Shows flattering of Sognefjord Formation against the top in wells correlation study

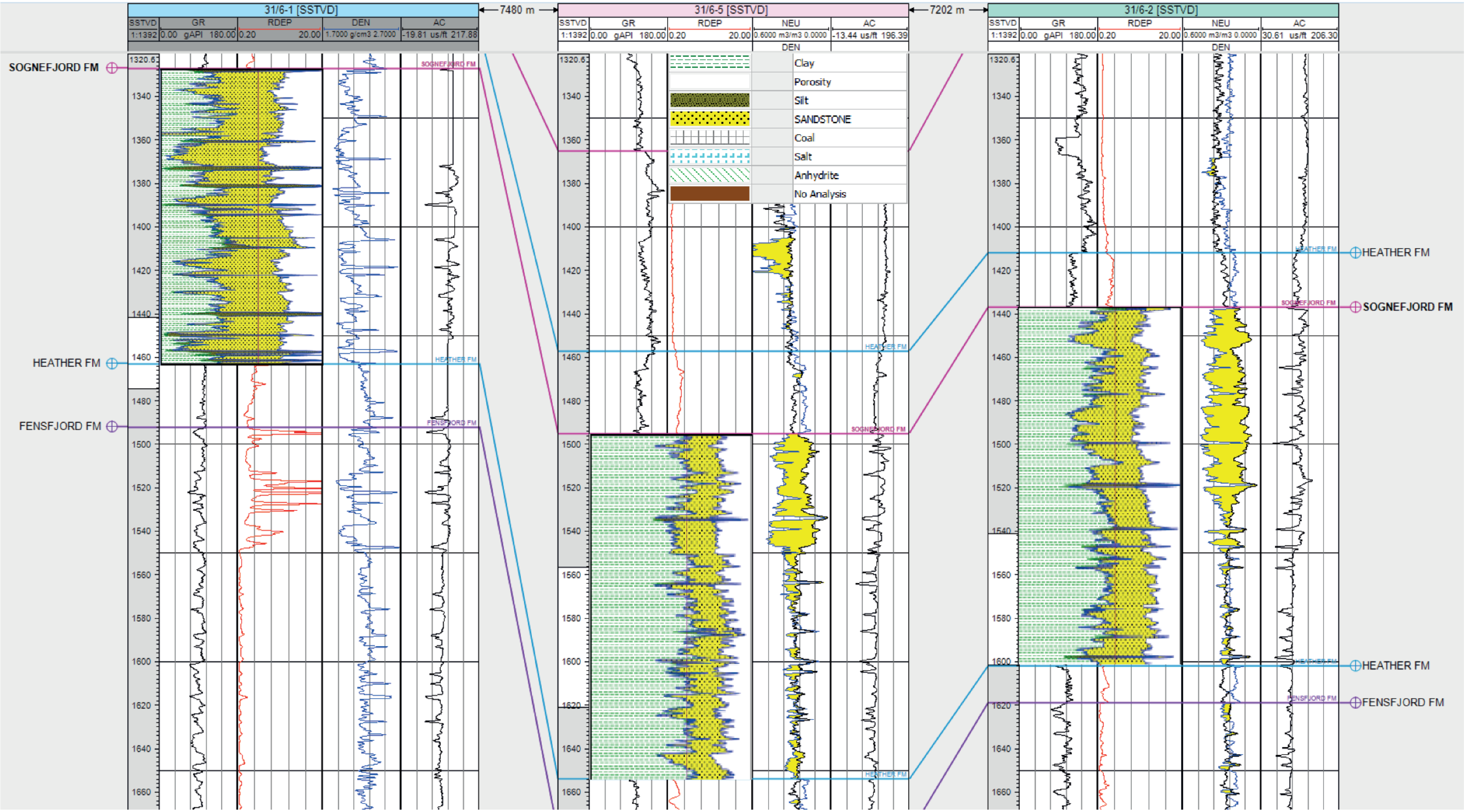


Figure 6.4: Wells correlation of 31/6-1, 31/6-5 and 31/6-2 wells in NW – SE direction

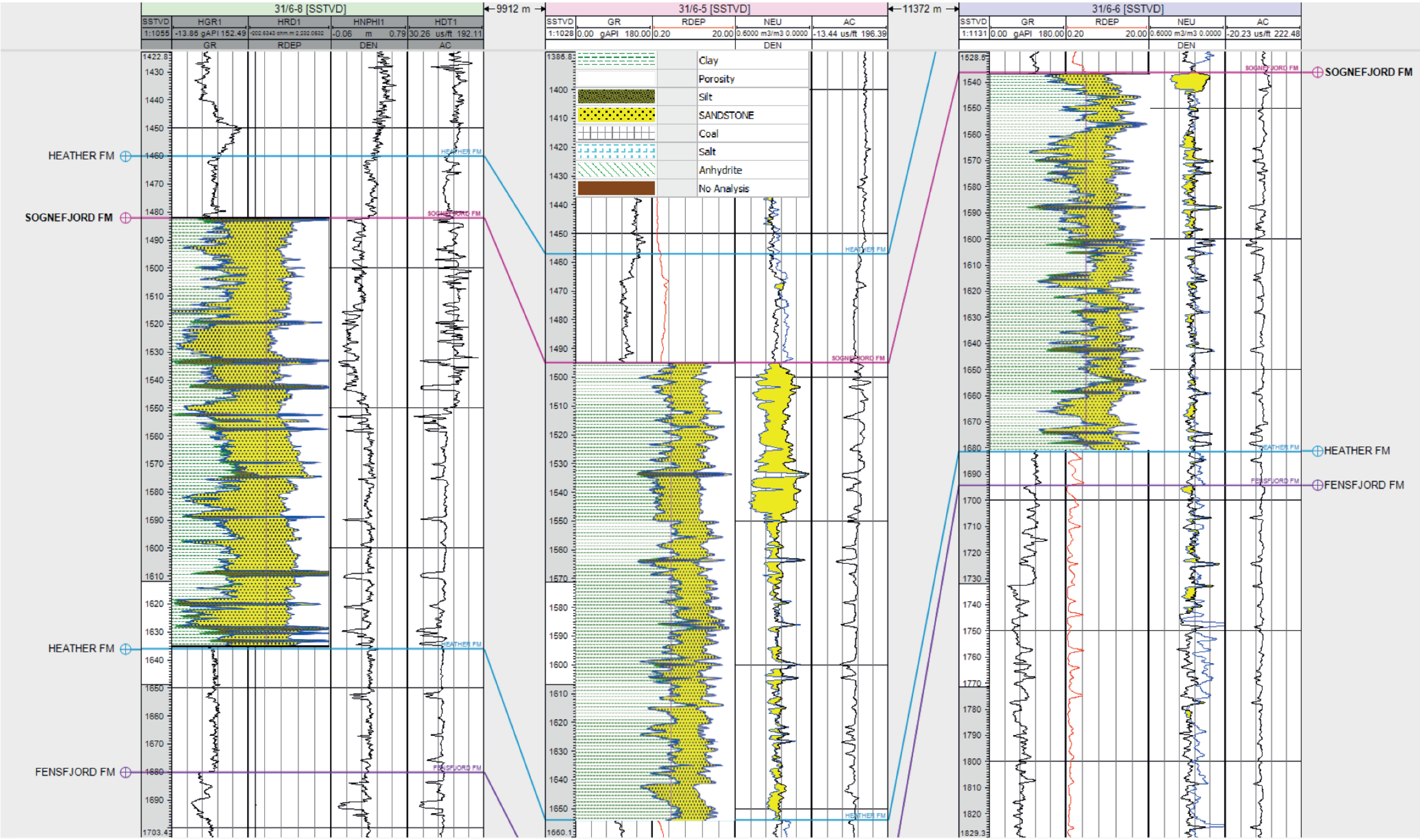


Figure 6.5: Wells correlation of 31/6-8, 31/6-5 and 31/6-6 in SW – NE direction

6.3 Geological model

A part of Sognefjord Formation was converted into the geological model. Due to limitations of seismic it was very challenging to interpret the base of Sognefjord in the margin areas of the field. The geological model was created for the central part of the area filled with exploration wells.

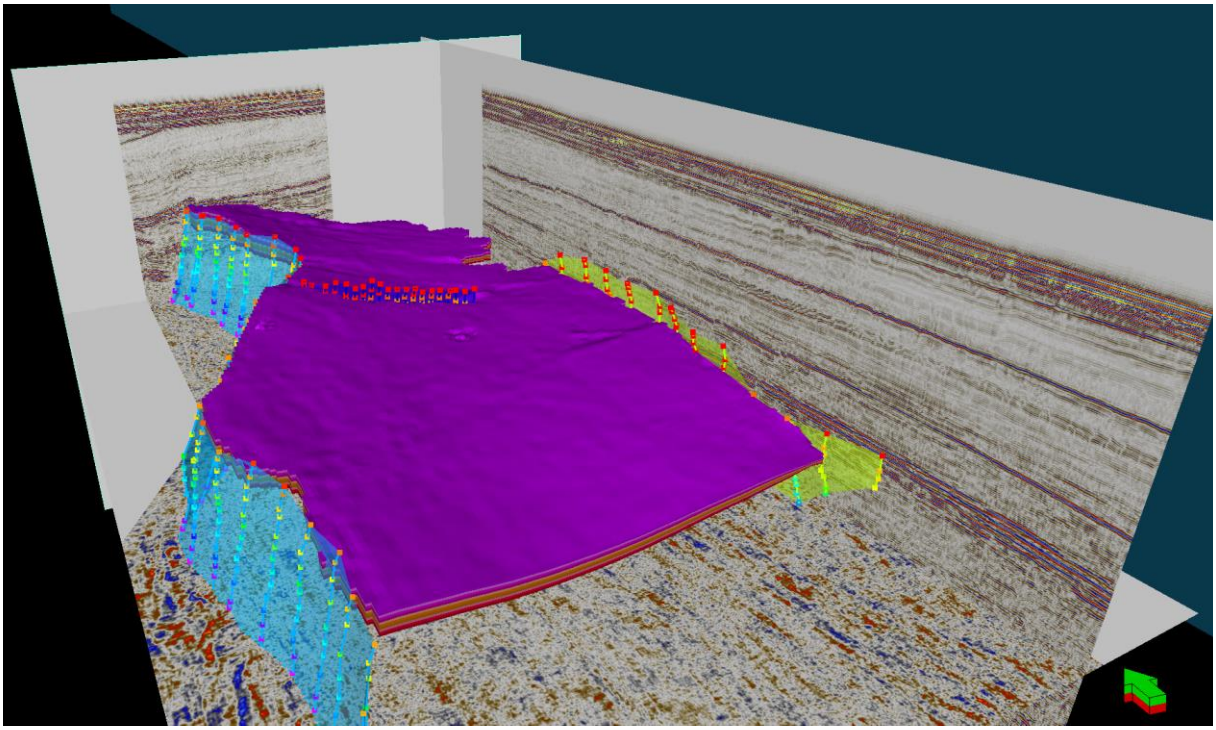


Figure 6.6: 3D view of geo-body of Sognefjord Formation

The obtained model together with a more descriptive thickness map of Sognefjord formation show the thickness variation of the formation (Figure 6.7). It is important to notice that Sognefjord Formation is thickening westwards which is contrary to the information obtained from well correlation study. It follows the same pattern in the northeast – southwest direction as wells correlation study, but the southeast-northwest direction pattern shows thinning in wells correlation and thickening on the thickness map and geological model. This discrepancy of results arouses several questions. Both the top and the bottom of the reservoir were checked whether they have any mistakes in interpretation, but those were not observed. At that time dipping of GWC was noticed. These two events led to the Velocity study of the area.

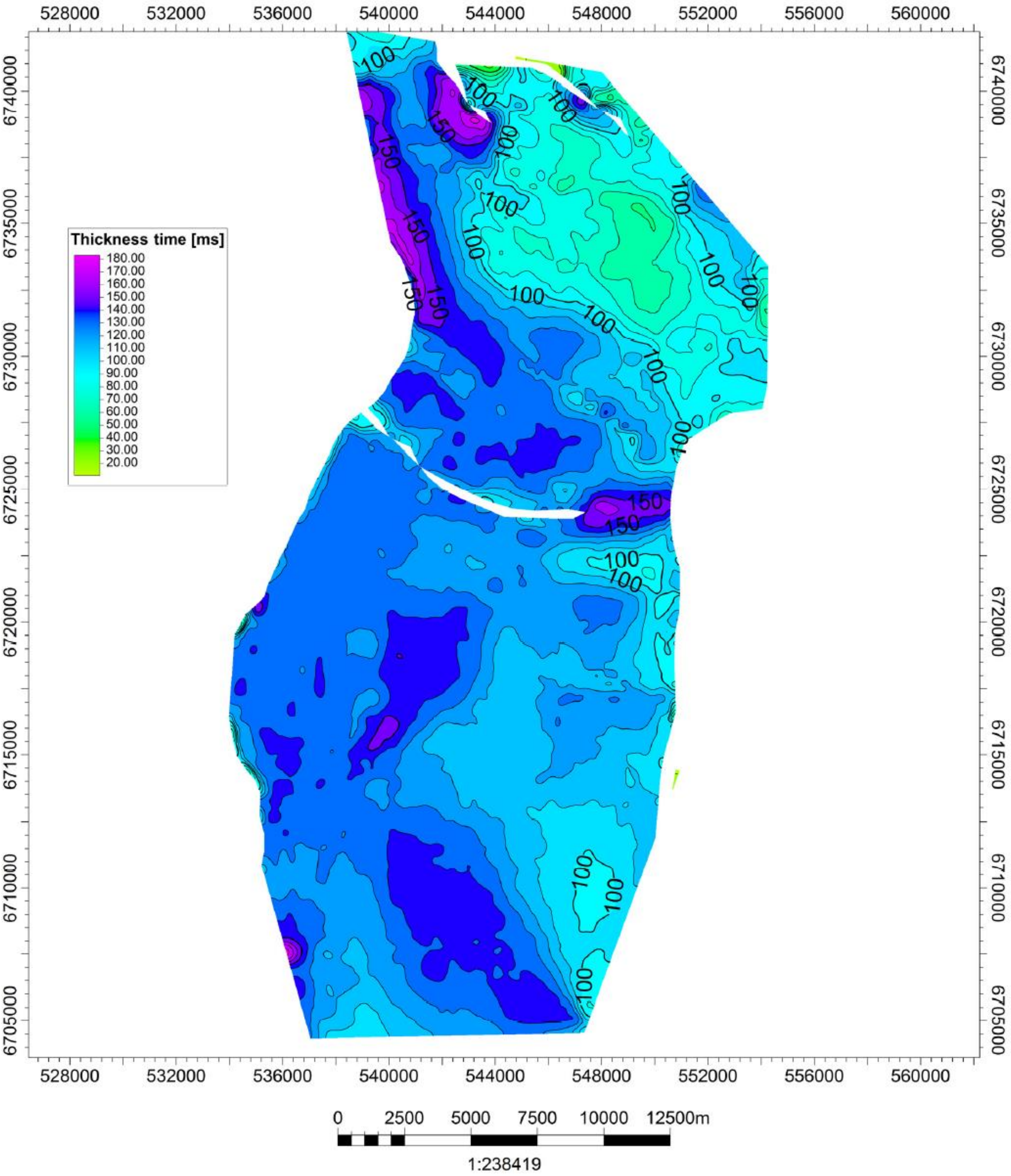


Figure 6.7: Thickness map of Sognefjord Formation

6.4 Velocity study

The difference in the results of well correlations and thickness map of Sognefjord Formation has been noticed. The dipping of GWC might be caused by the variation of seismic waves velocities in the subsurface of the area. Figure 6.8 shows the surface map of GWC.

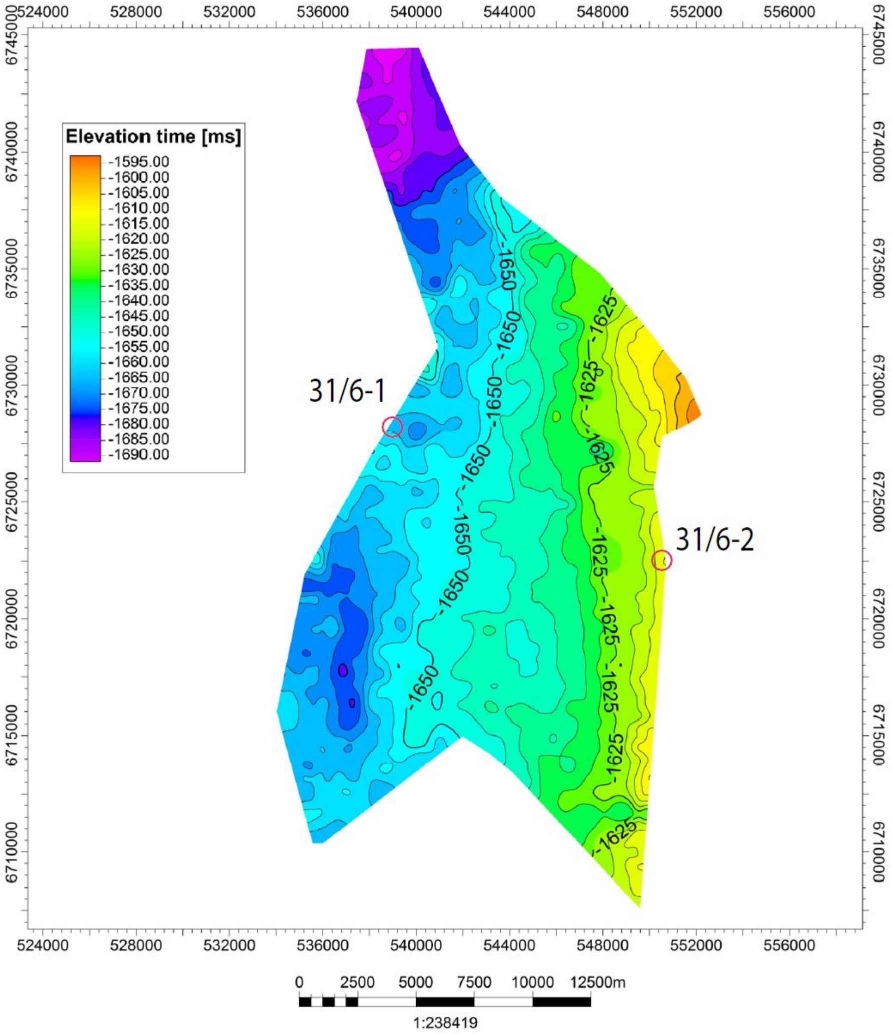


Figure 6.8: Surface map of GWC

As it could be seen from the figure, the fluid contact is dipping westwards. The total difference between the eastern and western margins varies from 80 to 100 ms. It is quite unusual as fluid contacts are generally flat due to density differences and gravitation effect. There is a hydraulic trap type where water contacts are not flat but they are always much smaller. It is quite difficult to imagine what amount of water could affect the accumulation to dip the contact so dramatically.

For better understanding of this event a velocity study was done to identify velocities in the study area. Figure 6.8 also shows two wells 31/6-1 and 31/6-2. These wells together with other wells in the area provided all the information required such as the depth of formations in meters and two-way-traveltime in milliseconds. As it is seen in the picture, the difference between wells 31/6-1 and 31/6-2 in TWT depth is approximately 45 ms. As it is shown in Figure 6.9 Sognefjord Formation is the closest non affected reflection nearby GWC. It was used to calculate the approximate velocity in overburden. Petrel 2013 software together with www.npd.no provided all the necessary data such as TWT and TVD of formation well tops. The calculation was done and summed in a Table 6.1.

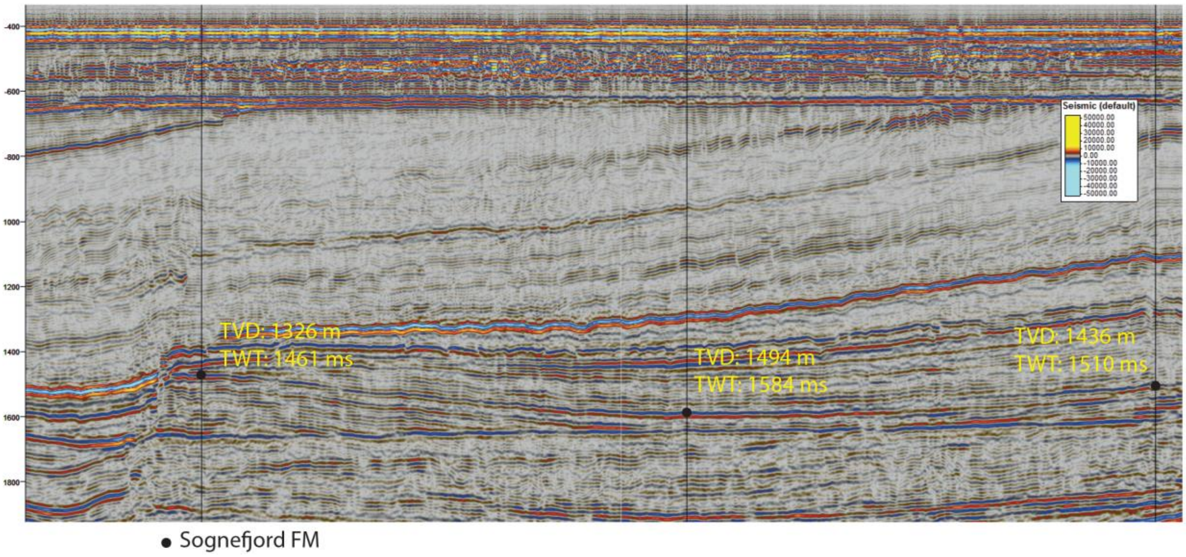


Figure 6.9: Figure shows TVD and TWT depths of Sognefjord well tops in wells 31/6-1, 31/6-5, 31/6-2 in NW – SE direction

Well name	31-6-1	31-6-5	31-6-2
TVD, m	1326	1494	1436
TWT, ms	1461	1584	1510
Average Velocities, m/s	907,5975	943,1818	950,9934

Table 6.1: Average velocities in overburden of Sognefjord Formation

The difference of overburden velocities between wells 31/6-1 and 31/6-2 is 43ms. It coincides with the difference of TWT depth of GWC. This fact might be explained as a slight pull down of the area in location of 31/6-1. Slower velocity takes more time to reach the horizon and return to be caught by the receiver. There is a possibility that this minor effect was not noticed during the processing of the data. It can also be a possible explanation of different thickness variations of Sognefjord Formation presented in wells correlation and thickness mapping studies.

6.5 Internal Configuration of Sognefjord Formation

For better understanding the characterization of Sognefjord Formation, a seismic facies analysis was done. Seismic facies analysis concentrates on the reflector configuration. How it is affected by depositional environment and lithological content. As seen in Figure 6.10 subdividing of seismic section into packages was done to follow the depositional sequences.

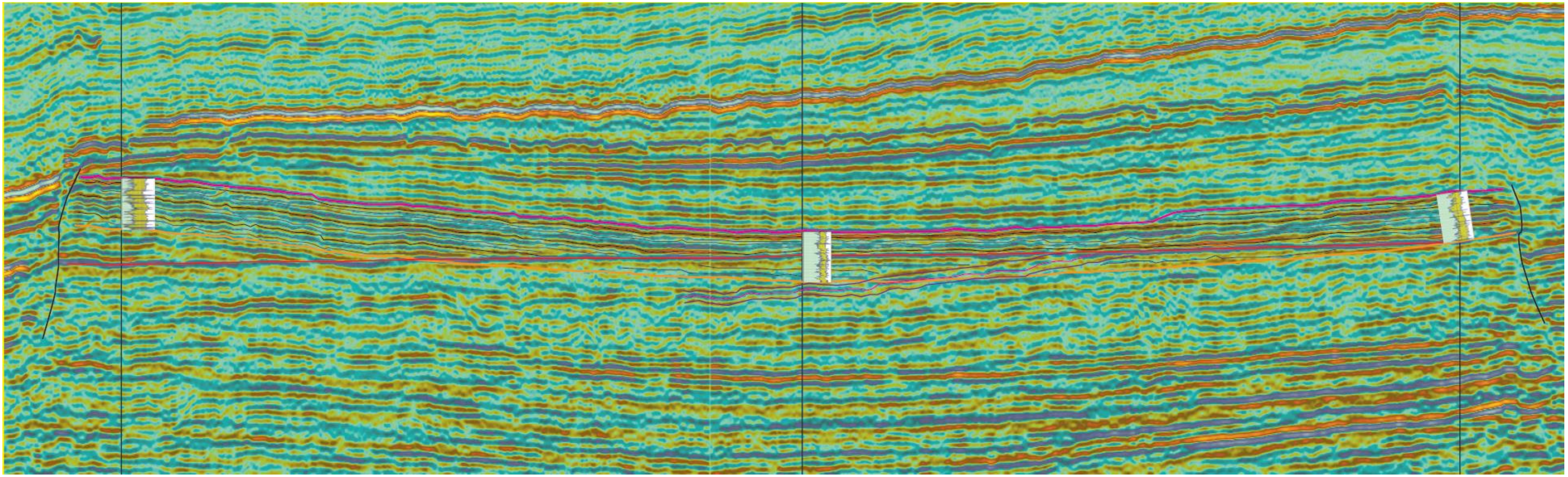


Figure 6.10: Detailed interpretation within Sognefjord Formation

Looking closer at this seismic section with attached lithological description it can be noticed that between the top and the bottom of the formation there are three strong reflectors. There are also several weaker and less continuous reflectors between them. According to Mitchum Jr, 1973, these reflectors could be identified as a subparelel pattern (Figure 6.11).

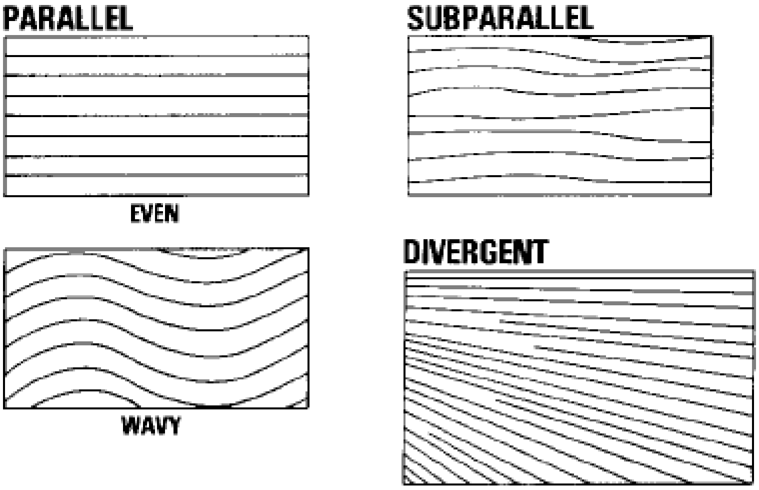


Figure 6.11: Parallel, subparallel, and divergent seismic reflection configurations (Mitchum Jr, 1973)

The correlation between seismic and lithological description shows that stronger reflectors marked with black could be correlated with interbedded shales (Figure 6.12).

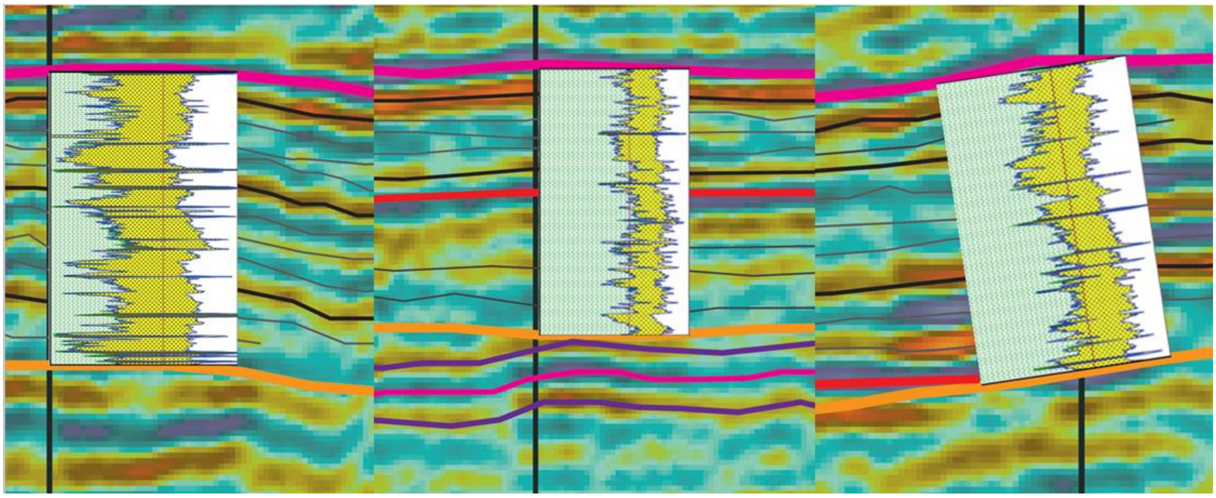


Figure 6.12: Wells 31/6-1, 31/6-5 and 31/6-2 showing the correlation between strong reflectors and interbedded shales

It is also important to mention the seismic impression of the zone below the GWC. The reflections are respectively weak and truncate against the multiple. The correlation between reflectors and lithology is hard to be seen (Figure 6.13).

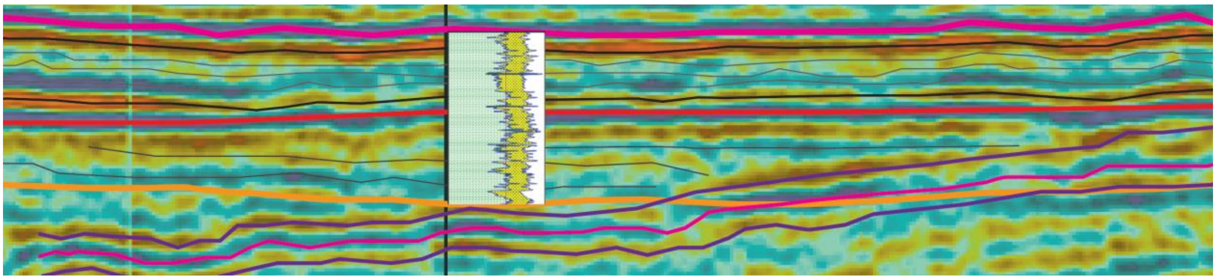


Figure 6.13: Seismic impression of zone below the GWC

Another interesting feature was detected in the Sognefjord Formation. It appears in the formation mostly in the upper part (Figure 6.14).

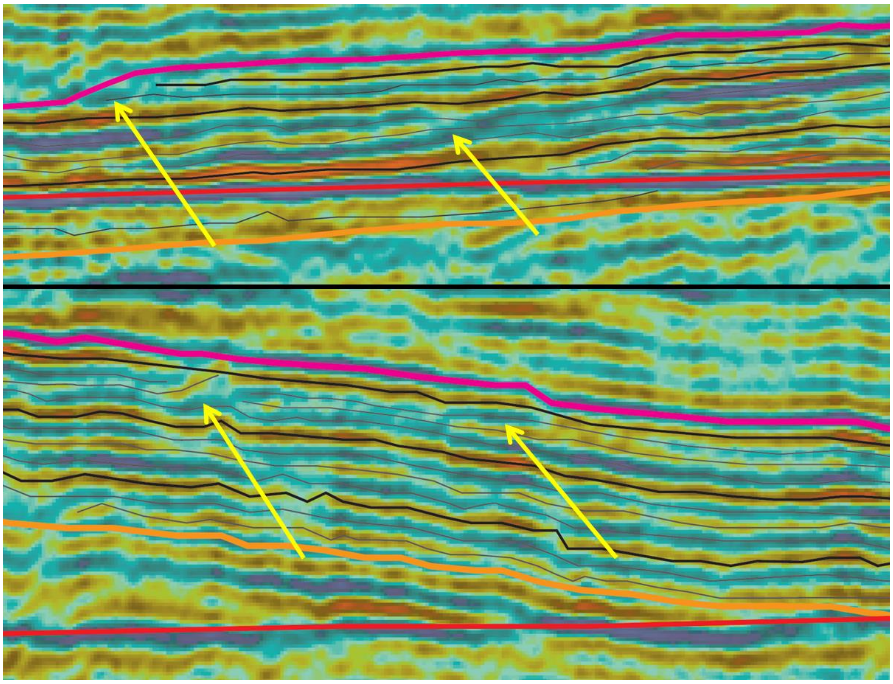


Figure 6.14: Sigmoidal shapes observed in Sognefjord Formation

These features were recognized as a possible sigmoidal pattern (Figure 6.15), (Mitchum Jr, 1973). A sigmoid progradation configuration is the pattern formed by S-shaped reflections.

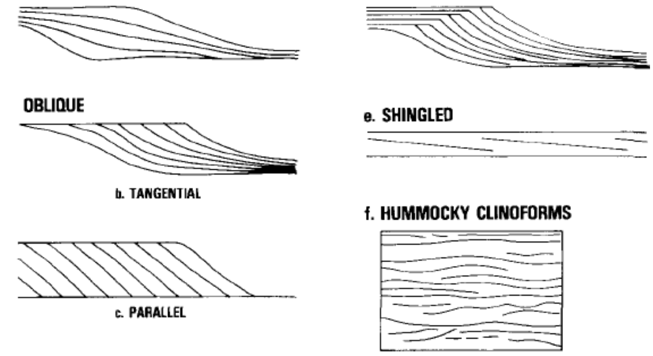


Figure 6.15: Seismic reflection patterns interpreted as prograding clinoforms (Mitchum Jr, 1973).

All these observation can be summed to show the relatively rapid subsidence of the basin with transgression and regression of the sea level. A relatively fast sedimentation regime in the shore face area can be interpreted. To find any evidence of the shore line the attribute slicing of Sognefjord Formation was done.

6.6 Attribute slicing

The Petrel 2013 software allows to do arithmetical operations with surfaces. The top of Sognefjord was used to create 15 additional surfaces with a vertical gridding of 10 ms. These surfaces were used as an input to create RMS attribute slices within the Sognefjord Formation.

There are several interesting features observed from the slicing. The first one is that all the higher attributes are located in the zone of GWC which means that seismic is dramatically affected by fluid contact (Figure 6.16). The second one is that the highest amplitudes could be found in the zones of intersection between GWC and the top of Sognefjord formation. The main evidence for that is matching of bright patterns with counter lines (Figure 6.17). Finally, the most interesting feature is a flat event appearing in the first half of the formation. It is a flat event propagating from NE to SW. This event is also prograding in the northwest direction with a deeper slicing (Figure 6.18). This event might be an evidence of prograding shore line during the sedimentation of the formation.

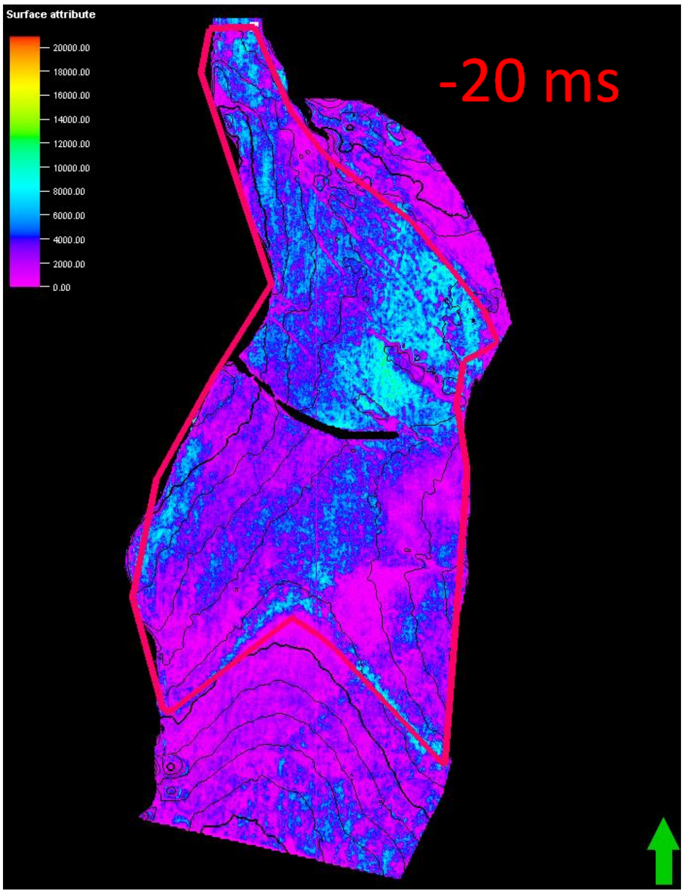


Figure 6.16: Amplitude slice at 20ms showing the match between high amplitudes and GWC contour

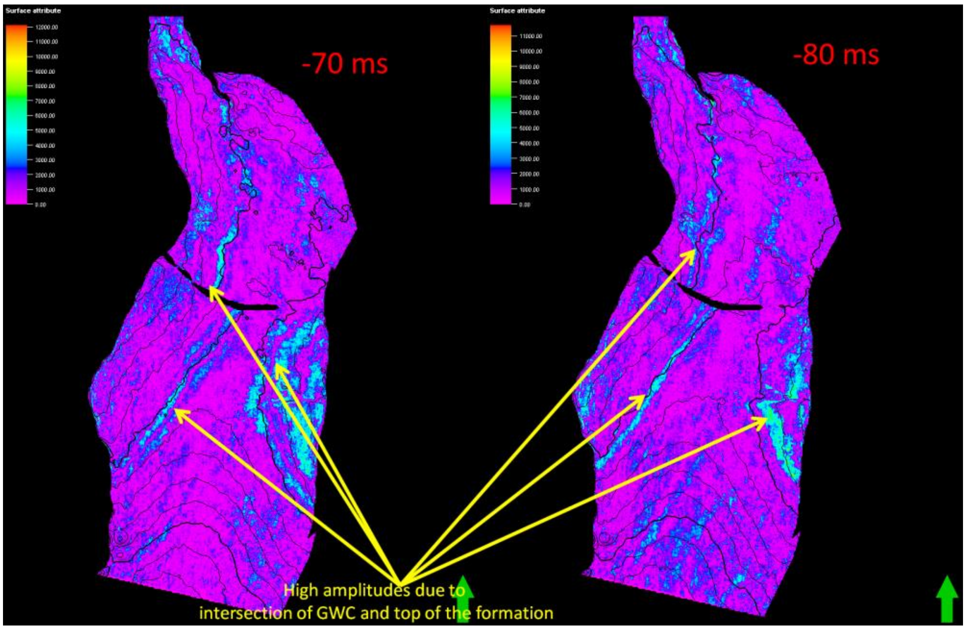


Figure 6.17: Amplitude slices at 70 and 80 ms showing the match between high amplitudes and intersections of GWC and top of the formation

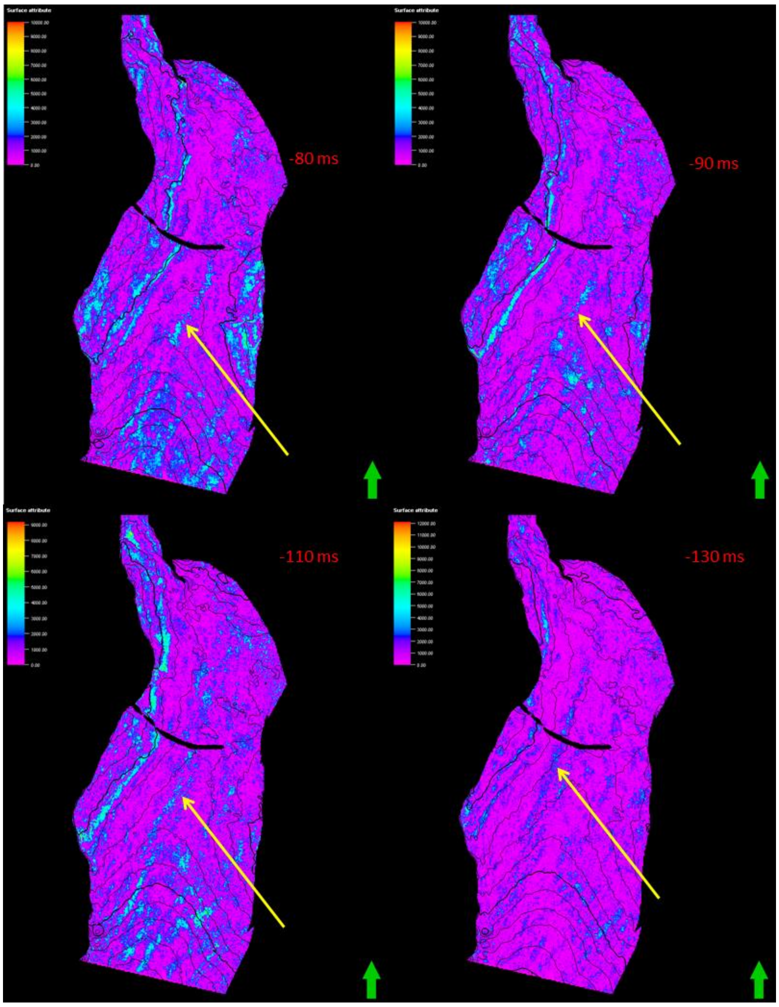


Figure 6.18: Horizontal slices showing the flat westwards prograding feature

Unfortunately, seismic data within the Sognefjord Formation is dramatically affected by fluid contact. It makes impossible to follow the lateral distribution of the formation. However, the observed prograding shoreline can be a good evidence of transgressive regime of the sea level.

The resulted geological model together with thickness map, wells correlation and attribute slicing study may be helpful in further understanding of Sognefjord Formation. However, to understand a later distribution of the formation, data should be reprocessed because of a large amount of limitations such as poor data quality, multiple, pulldown.

7. CONCLUSION

The main aim of this study was a detailed interpretation and characterization of reservoir Sognefjord Formation using data from 2D regional seismic and 3D detailed seismic surveys to understand tectonic and depositional patterns of reservoir formation and its seismic impression.

Interpretation of 2D survey summarized in tectonic – sedimentalogical table and basin development figure which suggest that sand development and distribution was controlled by tectonics. During the stages of rifting sand was locally distributed because of topographic trapping. The relative distribution of sand and mud ratio depended on sand availability and drainage patterns.

The upper Jurassic Sognefjord Formation is a shallow-marine sandstone tongue which forms a reservoir in the Troll East field. Regionally, the formation pinch out into offshore shales of Heather Formation westwards.

The analysis of seismic and well data provided slightly different results but proved the west-east, wave-dominated shoreface deposition environment due to sigmoidal shapes and observation of transgressing shore line in the attribute slicing study. The lateral distribution of the formation is hardly observed because of the data quality. Different seismic impressions of Sognefjord formation above the GWC and below in the aquifer are decribed. In addition, the multiple was observed which complicates the interpretation of seismic.

For future studies, the 3D survey should be reprocessed to get rid of the multiple. In addition, the velocity study should be produced to avoid the pull down effect appearing in the survey.

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