

Basement High - Related Cretaceous Submarine Fans Growth in Southwestern Barents Sea

Yona Akbar

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Norwegian University of Science and Technology Department of Geoscience and Petroleum

Abstract

Deep marine sandstone deposit is one of favorable hydrocarbon reservoir in Norwegian Basin. However, it remains not being fully understood due to its variation in term of sedimentation process, distribution, and reservoir quality. Plenty of submarine fans system models were built as solutions to capture better insight regarding those challenges. However, the models are general version of real life example, thus it needs to be adjusted for each deep marine system. This study took place in southern Loppa High area where some of deep marine deposit reservoir were drilled and struck numerous failures, even though petroleum system is working on other plays in nearby areas. Possible causing factor is particular geological setting related to multiple uplift processes occurred in drainage source area of Loppa High. The goals of this study is to understand how deep marine deposit, in the form of submarine fans, growth in such distinctive geological setting. The result will be used in building submarine fans system model which later helps us conceive hydrocarbon prospectivity in the surrounding deep marine system.

In building the model, each of component defining the submarine fans need to be described one at a time. Straightforward and visible components including geometry, lateral distribution, formation thickness until accumulation location of the fans are some of the examples. Meanwhile, Any other components derived from combination of seismic and well data analysis, are paleo depositional environment, source condition, type of sediment transportation system, basin paleomorpholgy, slope gradient, number of feeder system, sedimentation mechanism, number of feeder system, and natural shape when the submarine fans was deposited initially. Combining all of available components, it is plausible to create new submarine fans model system particularly for Southeastern Loppa High area.

The result is model where most of the characteristics resemble closely to sand rich submarine fans, with some notable variation in several aspects. Multiple feeder system which conceptually related to slope apron and no direct lateral continuation between the end of conduit exit mouth and proximal fans body, are the significant variation which can be found on the model. Significant founding comes from present morphology of the fans, which is tilting toward updip direction. This current condition accommodate seal failure to develop and increase the risk of hydrocarbon prospectivity.

Preface

This thesis was made as a completion of two years master education in Petroleum Geosciences at Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, to complete an Master of Science (MSc) degree in Petroleum Geophysics. The study was performed under supervision and guidance from Professor Ståle Emil Johansen.

This study is an application in Barents Sea example for all concept described in my specialization project performed in Fall 2017 with the title "Relationship Between Sedimentation in The Deep Ocean and Basin Development. Examples from The North Atlantic And New Zealand"

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Chapter 1

Introduction

Loppa high is one of physiographic element, defining boundaries of Hammerfest Basin to the North (Rønnevik & Jacobsen, 1984). It was formed through rifting process at Late Mesozoic time (Dore & Lundin, 1996). Tectonically, loppa high suffered from several episodic uplift, after it was formed (L. T. Berglund, Auguston, Færseth, Gjelberg, & Ramberg-Moe, 1986). During each of uplift period, Loppa high was exposed sub aerially and became drainage source area for surrounding clastic deposit at the deeper marine part of the basin. one of the interval which has thick clastic deposit is between Jurassic and Early Cretaceous times (Faleide, Vågnes, & Gudlaugsson, 1993). Some wells were drilled to test structural and stratigraphical play of clastic deposit reservoir. Some of them successfully find hydrocarbon accumulation. However some dry hole wells was also encountered in the process. It was showing that there should be room to improve in understanding the existing petroleum system.

One way to improve the understanding of petroleum system is by studying reservoir models. In hydrocarbon exploration phase, models are used in predicting the location of reservoir accumulation, distribution and quality. Many submarine fans model have been constructed based on on the same illustration setting (Richards, Bowman, & Reading, 1998; Reading & Richards, 1994; Mutti, 1979). It has the same setting illustrating the relationship between shallow marine, shelf and slope condition. On the other hand, different setting which is basement uplift related have not been discussed on Loppa High area. The study on this kind of setting will certainly useful to post drill analysis and to support exploration concept on different part of the world.

The main objective of this Master's thesis is to understand submarine fan reservoir evolution phase and depositional sequences, related to basement uplift setting on Loppa High area. Numbers of 2D seismic lines and two 3D seismic cubes will be presented as the data input. For evaluating the submarine fan growth sequence, there will be performed seismic interpretation on the area of interest and more detail in seismic characteristic identification, related to stratigraphic sequence of the submarine fan.

Furthermore, additional objective is to classified the submarine fans system in Loppa High based on existing submarine fans model. Afterward, submarine fans model specifically designed for southeastern Loppa High will be constructed. The model will be generated by combining analysis from well log data, seismic interpretation along with the seismic internal character features. Additionally, the implication of the basement uplift setting toward the petroleum system of the area.

Key research question in this study include:

- What are depositional process involved in the reservoir deposition?
- How many source contribute to each submarine fan?
- What are the growth stages for each submarine fan?
- What type of clastic deep marine deposit occurs in Loppa high based on existing model?
- What are the implication of basement uplift setting toward the petroleum system on the reservoir?

Chapter 2

Theory

2.1 Deep Marine Deposit

2.1.1 Definition

The term deep marine deposit has been used in oil and gas industry, by both geologist and engineer in different understanding (figure 2.1. While engineer sees it based on present water depth level between 500 - 2000 meter, geologist conceives it based on its paleo depositional environment. Definition by (Slatt, 2006) which refers to sediment deposit in marine environment, under influence of gravity driven processes, at the depth below storm wave based area, is used in this study.

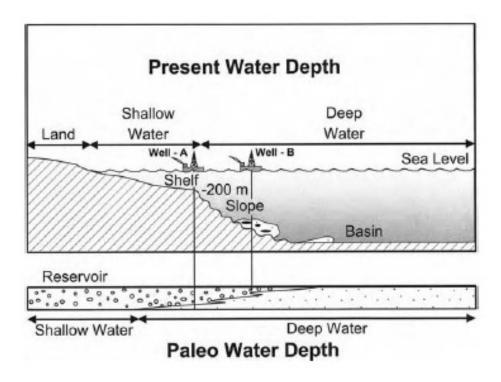


Figure 2.1: Illustration showing discrepancy in Deep water definition (Shanmugam, 2000)

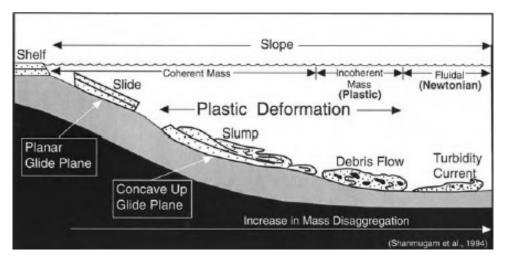
2.2 Gravity Driven Process

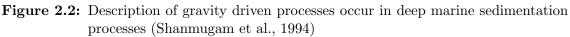
Sedimentation induced gravity process plays important role as the main factor in deep marine reservoir formation. Consistent to the definition at where deep marine deposit is located, gravity flow normally can be found in between the continental slope area, continental rise until it reaches basin floor. Several factors in triggering slope instability had been studied. Those are Eustatic changes in sea level (Daly, 1936), Earthquakes (Heezen & Ewing, 1952), High sedimentation, Tsunamis (Coleman & Prior, 1982), and Generation of gas (Dill, 1964).

Gravity driven process can be divided into two types which are mass transport deposit and sediment flow (Shanmugam, 2000) (Figure 2.2). Both types also contain two variations of process. In mass transport deposit, the process represent the same terminology as the end product, for example, slump deposit is a product of slump process. On the other hand, sediment flow uses different terminology than its process (i.e debrite). Types of gravity influenced process can be separated by the following description:

- Mass Transport
 - Slide
 - Slump
- Sediment Flow
 - Debris Flow
 - Turbidite

The following explanation will emphasize mainly on sediment flow. Dominant contribution of sediment flow to our deep marine deposit is the basic consideration, even though there is minor effect from the existence of mass wasting deposit nearby.





2.2.1 Sediment Flow

Middleton and Hampton (1973) defined sediment flow as gravity - induced interstitial fluid which is moving down slope. Fluid in this terminology, described as mixture of sediment grain and water with sundry composition, is used to differ its physical configuration from mass transport. Moreover, based on support mechanism types, rheology, and fluid state of the fluid, sediment flow can be divided into debris flow and turbidity flow. The first category is sediment support types, which illustrate the different condition of interaction between various grain sediment and water portion (figure 2.3 ((Slatt, 2006) Modified from Pyles, 2002). Turbidity flow occurs in less grain sediment fraction than debris flow, where fluid turbulence dominate the interaction of grain sediment and water.

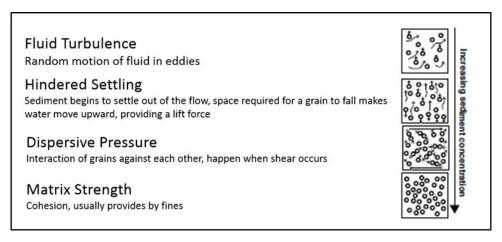


Figure 2.3: Sediment support type (Slatt, 2006) Modified from Pyles, 2002

The second category, introduced by Goddard (1980) as a study of the flow and deformation of matter (liquid or soft solid) under the effect of an applied force, is called rheology. Based on rheology, correlation between applied stress and rate of shear strain are used to differentiate type of sediment flow (Shanmugam, 2006). There are two kinds of rheology, which are Newtonian fluid and Bingham plastic. Newtonian fluid material is easier to be deformed, once stress has been applied. Mean while, it is slightly harder to alter Bingham plastic material, since the applied stress need to surpass its yielded stress. concrete is a good example for Bingham platic condition, while water is representing Newtonian fluid. From that example, concrete has more sediment portion than water. Thus rheology of material, similar to sediment support, is influence by mixture portion between sediment and water.

The last category is Flow state, which was based on Osborne Reynold experiment in 1883, when thin stream of dye was injected into flow of water through a glass tube. Turbulence flow and laminar flow are the type of flow state condition. turbulence flow is high rates flow, where the stream generated chaotic eddies, irregular fluid motion and macroscopic mixing across layers. Meanwhile, Laminar flow is low rate flow of fluid in parallel layers with no macroscopic mixing along the layer.

2.2.1.1 Debris Flow

Bingham plastic rheology and laminar fluid state are the characteristic of debris flow (Shanmugam, 2006). Most of identified debris flow characteristic (Fisher, 1971; M. A. Hampton, 1972; M. Hampton, 1975; Middleton & Hampton, 1973; Enos, 1977; Shanmugam & Benedict, 1978; Shanmugam & Moiola, 1994, 1995) can merely be used in core and outcrop identification. The following description are showing debris flow characteristic in larger scale which is suitable for our study purposes:

- Gravel to mud lithofacies to helps in predicting what kind of internal seismic pattern on debris flow deposit
- Irregular, sharp upper contact, and lateral pitchout geometries
- Lenticular to sheet like geometry
- Seismic pattern of Contorted, chaotic, and low amplitude reflection pattern
- Individual thickness of debris flow deposit can reach 80 m
- In some part of the world related to low sinuosity channel (deepwater elements will be discussed on the next chapter)

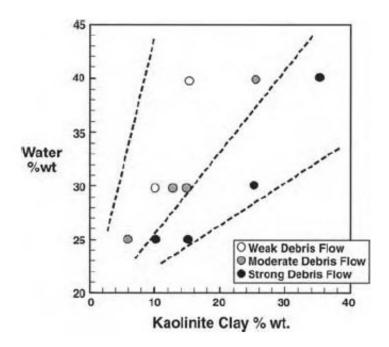
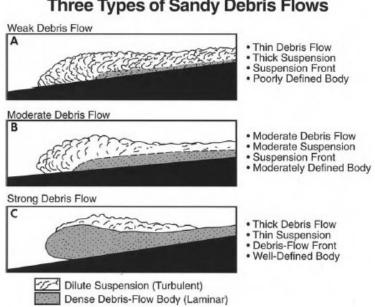


Figure 2.4: Plot showing the flow strength of debris flow (Shanmugam, 2000)

Based on timing of occurrence, in many cases, debris flow coincide at the same time with turbidity current. The illustrations shown in figure 2.4 describe different strength debris flow condition (weak, moderate and medium), which developed along with turbidity current. Turbidity current fraction, in each scenario, is influenced based on water and clay concentration mixture. The strength of debris flow is increasing as the clay content surpass the water portion. Instead of increasing, turbidity current portion is decreasing when clay content dominate the fluid mixture. The result will generate pronounced body of debris flow with thin suspension layer, influenced by turbidity current during the motion of the fluid mixture (Figure 2.5). On the other hand, weak debris flow can only be generated in a circumstance where less sediment grain mixed with large portion of water, creating thick suspension and poorly defined debris flow body. Moreover, the illustration itself can be modified into real life example by substituting the clay content with another type of grain such as sand, with similar expected end product.



Three Types of Sandy Debris Flows

Figure 2.5: Types of sandy debris flow (Shanmugam, 2002)

Since debris flow and turbidity current may be developed simultaneously, based on the flow strength, different location of suspension deposit may also varies. Weak and moderate strength of debris flow tend to accumulate suspension in more distal area than the debris flow body. Meanwhile, stronger debris flow deposits the suspension at the top of debris flow body, which then produces normal grading section (fining upward pattern). Normal grading is the signature pattern resembles both debris flow and turbidity current characteristic. However, debris flow is recognized by its floating clast fragment or granules in the final deposit product. Unfortunately, such differences are very difficult to be observed in seismic scales. More detail explanation of debris flow example will be discussed in further sub - chapter.

2.2.1.2**Turbidity Flow**

Turbidity flow is recognized by Newtonian rheology character, the sediment movement under turbulent state, which will deposited through suspension settling. Turbidity flow may be generated under single event where it occurs from sediment failure or a transformation during the debris flow process (Shanmugam, 2006) (Figure 2.6). Deposit which is produced from turbidity flow process is called turbidite which was introduced by Kuenen (1957) for the first time. Furthermore, Bouma (1962) developed the concept of turbidite by generating succession so called Bouma Sequences.

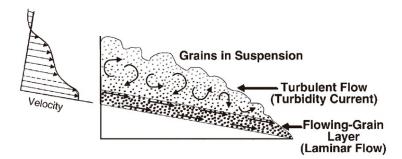


Figure 2.6: Illustration of turbulent flow current on top of laminar flowing grain layer (Modified after (Sanders, 1965)). It is similar illustration describing flow strength of debris flow on Figure 2.4, where at the same time generated turbidity current

Bouma sequences are based on five successions which are Ta, Tb, Tc, Td and Te, stacked respectively from bottom to top in vertical or lateral order (Bouma, 1962). The sequences are depicting details of turbidite as the result from turbidity flow process (Figure 2.7). The sequences has general pattern in forming upward normal grading alteration Kuenen and Migliorini (1950), where the grain size is decreasing as the sequences start to stack up vertically. Each sequence also has its own particular structures which differ one to another. While, Ta sequence has no structure, Tb and Tc has parallel laminae and homogeneous structure respectively.

	Grain Size	Bouma (1962) Divisions	
	← pnw	Те	Laminated to homogeneous
A CONTRACTOR	1	Td	Upper parallel laminae
	* Sand-	Тс	Ripples, wavy or convoluted laminae
		Тb	Plane parallel laminae
	 Sand (to granule at base) 	Та	Massive, graded

Figure 2.7: Bouma Sequences (Bouma, 1962)

In oil and gas industry, Bouma's turbidite model does not resembles turbidite definition when it is applied to hydrocarbon reservoir model. On the contrary, it is widely used in outcrop and core analysis. In reservoir model, turbidite is decribed as the whole Bouma sequence where it has normal grading vertically. However, the definition of turbidite is a deposit generated by turbidity current. The turbidity current itself may only transport fine grain sediment as their sediment support. Thus, the turbidite succession introduced by Bouma may come from more than a single turbidity current process. There is possibly influence from debris flow process or even bottom current reworking (Shanmugam, 2006). In this study, turbidite definition is used based on sediment flow process which has been discussed on the previous sub - chapter.

In this study, submarine fans will be analyzed in seismic scale. Therefore, the following characteristics, selected from Shanmugam (2006), are representing larger scale than core description scale in order to be applied on seismic scale:

- Fine-grained sand to mud
- Sharp or erosional basal contact
- Thin layers, commonly centimeters thick
- Sheet-like geometry in basinal settings
- Lenticular geometry may develop in channel-fill settings
- Laterally can extend for several kilometers in modern analogy (Atlantic Margin), but hardly preserved in the geological record
- Tend to bypass submarine canyon quickly due to rapid surges in short duration

As for summary for this sub - chapter for gravity driven processes, Figure 2.8 illustrates each depositional feature from Eocene and Paleocene, North Sea (Shanmugam, 2006). This information will be very useful to validate our seismic scale observation with the well data. Floating clast fragment feature is the most significant characteristic in observing debris flow deposit product in this study.

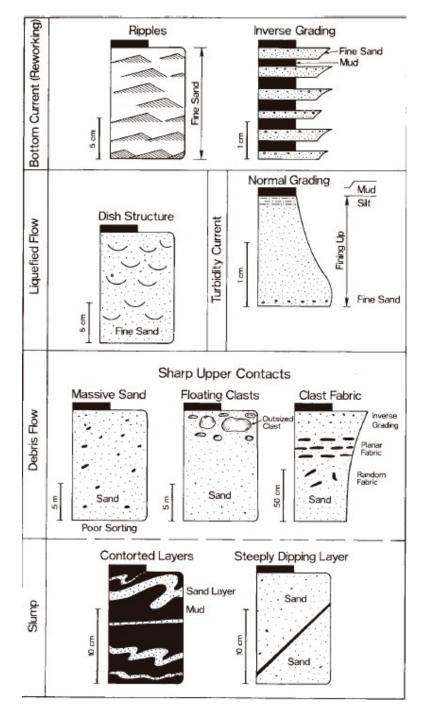


Figure 2.8: Depositional features in core for gravity driven process, Eocene and Paleocene, North Sea (Shanmugam, 2006)

2.3 Submarine Fan Models

2.3.1 Deep Marine Element

Deep marine environment is group of any possible area from the continental slope until basin floor area, which support the location of deep marine deposit accumulation. Deep marine environment is divided by the following area (Shanmugam, 2000):

- Submarine slope environments
- Submarine canyon and gully environments
- Submarine fan environments
- Submarine non-fan environment
- Submarine basin plain environment

Based on its suitability with our study example, submarine fan environment is selected to be discussed in much more detail in further discussion. Detail discussion will be focus on the characteristics defining deep marine environment, called as deep marine architectural element. In submarine fans environment, there are four elements which are are canyons, (erosional) channels, (aggradational) levee channels, and sheets or lobes (Chapin et al., 1994). In these four elements, potential reservoir quality and distribution are described in term of hydrocarbon prospectivity.

2.3.1.1 Sheet sandstone and reservoir

Based on its vertical geometry, fans lobes reservoir has a sheet - shaped form. It supports good vertical connectivity, tabular external flow and few erosional feature (Chapin et al., 1994). Due to that condition, (Chapin et al., 1994) thought that sheet sandstone reservoir to be best high rate reservoir. Sheet sandstone is using channel as its conduit system to deliver sediment from source drainage area into the basin floor. It is commonly developed at the end of channel mouth exit. Changes from narrow and confined area inside the channel into unconfined area on the basin floor , produces lobes feature as its lateral geometry. Based on net sand contained in the formation, sheet sandstone reservoir is divided into layered sand amalgamated sand (Chapin et al., 1994) (figure 2.9). Layered sand reservoir has more shale interbedded layer, since it has low net sand content in the whole sand body. On the other hand, amalgamated sand has higher net sand content due to sand - rich interval vertical stacking.

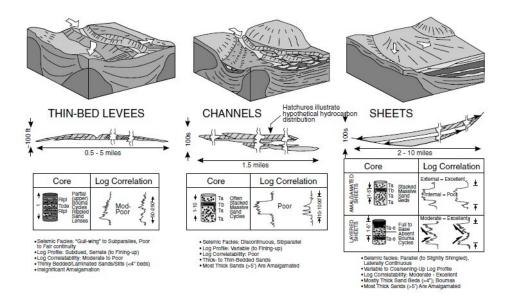


Figure 2.9: Classification of deep water element, Northern Gulf of Mexico. (Chapin et al., 1994)

Significant drawbacks are still occur in sheet sands element despite its character in having good continuity and connectivity. In some cases, channel might cross cutting the sheet sand body, leaving mud on its trail which leads to reduce in connectivity and continuity within the same sheet reservoir unit. The next factor is variation in external geometry which heavily depends on basin morphology condition at the time when the sediment is delivered (figure 2.10). Furthermore, vertical compartment tend to increase in the case when interbedded shale is dominating the layered sand, as the net sand content is decreasing.

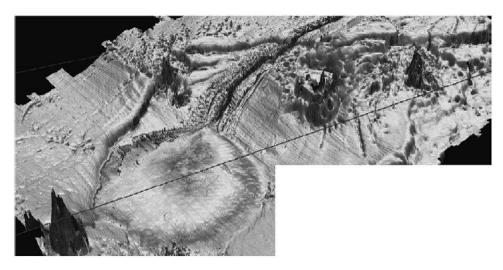


Figure 2.10: Isochrones map describing submarine fan on the seafloor, Nigerian Continental Slope (Pirmez et al., 2000)

2.3.1.2 Canyon and channel fill sandstone and reservoir

There are three types of channel fill classification. The first is channel fill from erosion of underlying sediment, the second is channel fill in between the levee and overbank succession, and the third is a mixture between the previous two types (figure 2.11) (Clark & Pickering, 1996; Mutti & Normark, 1987). The first type which is erosional commonly occurs in the updip slope where the sediment has sufficient velocity downward and created amalgamated channel sand (Slatt, 2006). Small scale of erosional channel can be generated by sediment flow processes, on the other hand, large scale erosional channel is formed by mass transport system. Erosional channel can be related also to low sinuosity of channel due to high velocity sediment movement within the channel. Type 2 is leveed related channel fill which is commonly occur in the lower gradient of slope. It is correlated with low energy and velocity during the deposition. Low velocity during the sediment transportation along the channel, caused high sinuosity of channel to be formed.

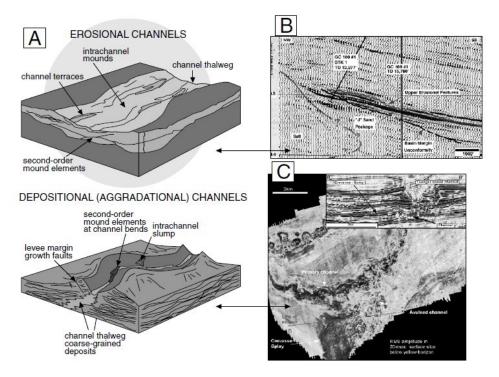


Figure 2.11: A is types of channel fill which are erosional and aggradational channel fill (Clark & Pickering, 1996). B is seismic feature example of erosional surfaces filled by shale (Holman & Robertson, 1994). C is horizon slice through aggradational channel fill (Mayall & Stewart, 2000).

2.3.2 Existing Submarine Fan Models

Throughout the history of hydrocarbon exploration, several submarine clastic deposit models have been generated by geoscientists. All of them have same common purposes. In exploration phase, it is used as prediction template on where is the potential location of submarine clastic deposit as hydrocarbon reservoir. Meanwhile, generating accurate geometry of reservoir unit, separate from non reservoir unit is the main goal on using the models in development phase (Richards et al., 1998).

Each model possesses different factors as the basic concept. Relation between coarse grain - canyon system and fine grain - delta system (Normark, 1974, 1978), fans geometry (Stow, 1986), efficiency of sediment delivery (Mutti, 1979), and number of source feeding system (Chann & Dott Jr., 1983), are some of the basic concept behind the existing models.

In this study, models based on grains size and feeder system is used as reference (Reading & Richards, 1994). The model was constructed by different grains size into four groups which are gravel - rich model, sand - rich model, mixed sand - mud model, and mud - rich model. Furthermore, each group will be defined by various scenarios based on number of feeder system available, which are single point source and multiple point sources.

A point source is normally an end point of canyon. Canyon itself is erosional incision acts as sediment transport pathway (Mitchum, 1985). In term of deep marine deposit, canyon normally lies from shelf to the toe of slope. Single point source is strictly related to the term submarine fans, while multiple point sources term is closely related to submarine ramps and submarine aprons. Figure 2.12 is showing classification framework for each grain size group using a triangle diagram. Each of the triangle corners defines different feeder system settings. Additionally, sediment supply mechanism was added into the framework.

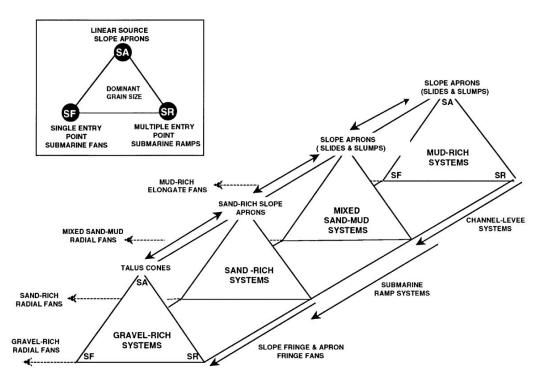


Figure 2.12: Classification of submarine - fans by sediment supply mechanism, dominant grain size, and number of entry points. Modified after (Reading & Richards, 1994)

From available grain size categories, only sand - rich group that will be discussed in further details due to its resemblance on our study data. Figure 2.13 illustrates sand

- rich system on different feeder system. Sand - rich system contains sand portion more than 70% with several common characteristics (Richards et al., 1998):

- Small lateral distribution (1-50 km)
- Naturally has structural trap as its hydrocarbon trapping mechanism
- Sediment source from incision, failure of sand rich shelves or canyon direct access of littoral drift

2.3.2.1 Sand-rich slope aprons

Slope aprons (figure 2.13a) accumulate sediment parallel against the slope, which forms continuous linear elongation. Common sediment source are coming from shelf - slope failure, mass wasting or by periodic flushing sand through basin margin incision (Reading & Richards, 1994). There was no existing well has been penetrated into sand - rich submarine aprons reservoir. However, some unpublished studies identified it in forming lobate geometry, aggradational pattern and wedged shape seismic pattern. In term of scale, it is normally small scale due to mass wasting sediment sources. In any case, it is possible to form larger scale deposit by reworking of topset system on the relative sea fall condition.

2.3.2.2 Sand-rich submarine fans

Sand-rich submarine fans (figure 2.13b) able to generate accumulation thickness ranging from 100 to 200 m. From sediment source point of view, it is related to single entry feeding system, where canyon delivers sediment from active sandy nearshore littoral drift to the deeper part of marine environment. Besides, reworking of deltaic and shelfal system are possible source drainage area for submarine fans system. Due to low efficiency transportation character (Normark, 1978), the end product deposit is commonly located adjacent to the end of the slope. Lateral distribution is normally related to the type of drainage area. localized, small accumulation is caused by nearshore littoral drift (Haner, 1971), while larger scale accumulation is a product from major slope incision and erosion of sand - dominated shelf (Heritier, Lossel, & Wathne, 1979).

Inner fan part of submarine fans is dominated by single feeder channel which linked down-dip with numerous branches of braided distributary channels. It is rare to find confined and stable channels on these system due to lack of fine grained sediment. As the result, braided character is imprinted on all over the fan surface which forms are sheet-like and lobate sand - bodies. Additionally, there is an dramatic changes from mid fan to basin plain (outer fan), where it goes into muddier system.

Sand - rich system can be a great reservoir where it has been proven on several North Sea Basin discoveries (Balder Fan by (Sarg & Skjold, 1982)). Seismically, submarine fan is shown as single, mounded to sheet-like interval. The internal character can be either opaque or poorly defined sub parallel reflectors (Richards et al., 1998). More detail explanation will be revealed on further discussion on seismic characteristic subsection.

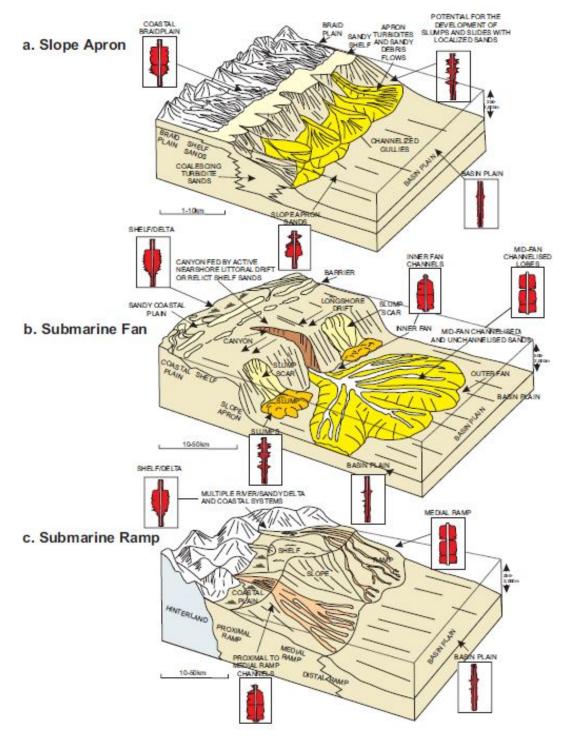


Figure 2.13: Schematic diagram showing sand-rich system along with the wireline log response. (a). slope apron, (b). submarine fan, (c). submarine ramp. Modified after (Reading & Richards, 1994)

2.3.2.3 Sand-rich submarine rams

Sand-rich submarine ramps (figure 2.13c) are deposited at the slope when sediment is transported along multiple incise feeder system through shelf - slope break. The drainage source can be in the form of coastal plain with narrow shelf or prograding sandy deltas. The sources provides a system with high rates of sediments input, allowing aggradational pattern to be developed as its end member product (Richards et al., 1998). It is difficult to directly discriminate aprons and rams. Both system has aggradational pattern as their deposit characteristic. However, the amount of sediment which is delivered basin ward is different. When aprons merely rely on small amount of sediment from mass wasting and slope failure, Rams have higher sediment supply due to its drainage source nature.

Based on its depositional model, sand - rich submarine ramps can be divided into three distinct physiographic elements which are proximal, medial and distal ramp (Chann & Dott Jr., 1983). Proximal ramp has short-living channel, covering rather small area (approximately 10 km) in the form of nearly elongated lobes. Meanwhile, medial and distal rams are recognized by the sudden increase in fine-grained sand rich turbidites accumulate on the basin plains mud (Richards et al., 1998).

Submarine ramps form linear, sheet-like geometry from shelf toward the basin area. Laterally, it has shape of elongate belt, parallel to the shelf-slope orientation. Similar to submarine fans, poor, low angle dipping, sub-parallel to parallel reflector may be found as internal seismic character. Additionally, combination of both structural and stratigraphical trap system are needed in order to achieve effective hydrocarbon trap mechanism (Boote & Gustav, 1987). Stratigraphic trap comes from abandonment process of a fan system, isolating particular fan aside from others.

2.3.3 Seismic Characteristic of Submarine Fans

Stratigraphic expression of submarine fans can be identified by its seismic characteristic. Based on seismic reflection profiles, canyon related fans system can be divide into four areas which are canyon, upper fan, lower fan and canyon fill (Mitchum, 1985). The rest of discussion for this sub-chapter will only discuss about upper fan and lower fan part which are the main part on submarine fan morphology. All of the terminology used in defining submarine fans is based on the submarine fans model from Sarg and Skjold (1982) (figure 2.14) modified from Mutti's outcrop model.

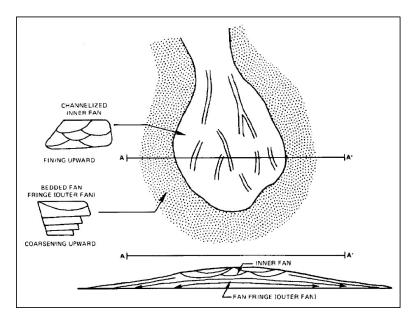


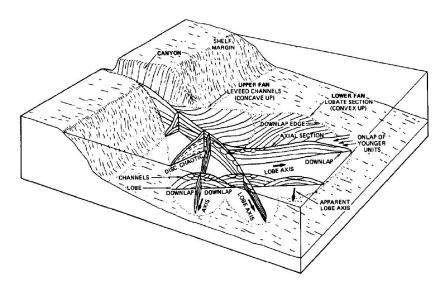
Figure 2.14: Lower submarine fan sedimentation model along with vertical grain size alteration pattern. After Sarg and Skjold (1982); modified after Mutti.

The bottom part of submarine fans is lower fan, where it is initially deposited at the beginning of fan sequence. It is covering the basin morphology especially depression near the slope - basin margin during the first sediment delivery into the basin. Stratigraphically, the lower fans are thought to be deposited during the low stand system and sea level fall. It has dominant coarse grained sand where most of hydrocarbon production from submarine fans play are came from (Richards et al., 1998).

Based on its sedimentation, lower fans can be divide by outer fans (fan fringes) and inner fans (Sarg & Skjold, 1982). Outer fans is formed on the base of the suprafan lobes. It has progradation pattern which resembles coarsening upward succession. On the other hand, Inner fan has retrogradation pattern, fining-upward sequences. It is due to channel system which eroding the underlying outer fan package.

On the contrary from lower fan, Upper fan is a product from low stand system and sea level rise (Richards et al., 1998). As the result, upper fan is normally formed as backstepping deposit and as canyon - filled deposit. Geologically, upper fan has unique character in the form of one or two large levee-channel system. On the proximal location, the size of levee is larger than on the distal part of the fans. Due to its small size, sometimes it is difficult to distinguish levee out of its channel. For the potential reservoir location, sand-prone deposit is concentrated on the channel filling, while silty and shale prone deposit is filling the levee interval.

Two indicators can be used in identifying stratigraphic expression, which are direct and indirect indicators. Direct indicators are features visibly appear on seismic reflection features. Those features are amplitude, continuity, termination pattern, and internal reflection pattern. Each of these feature is examined on different stack positions. The example of stack positions are pattern within the submarine fans and boundaries between submarine fans from the overlying and underlying layers. Furthermore, identified features will be correlated to each part of submarine fans (for example: lower fan and upper fan). Figure 2.15 is illustrating the summary of



direct indicators for canyon-fan system (Mitchum, 1985).

Figure 2.15: Seismic facies diagram of idealized canyon - fan system (Mitchum, 1985)

The whole body geometry of lower fans is mounded shaped structure. The internal character is dominated by bidirectional downlap at the base, which at the same time as part of outer fan interval. Reflection amplitude is commonly high and continuous with some and convex-upward features. However it sometimes chaotic and discontinuous amplitude near the upper surface due to channel stacking on the inner fan.

Internal reflection upper fan is concave-upward due to existence of levee-channel system. Bidirectional downlap is also occurs onto the upper surface of lower fan. Reflection amplitude is fairly continuous commonly on levee, but it can be discontinuous when dealing with levee complex. In some unmigrated seismic section, bow tie artifact will appear on the channel depression. While velocity pull up maybe appear below the channel position.

Chapter 3

Geology of Hammerfest Basin

3.1 Study Area

Barrents Sea Shelf is located on the southwestern part of Barrents Sea (figure 3.1). Geographically it is bounded by Atlantic Ocean on the west, Arctic Ocean on the north, Norwegian Mainland on the south and Urals folds belt to the east. The study area lies on the southern part of Barrents Sea Shelf, where several sub areas are located. These sub areas are Finnmark Platform, Hammerfest Basin, Tromsø Basin and Loppa High.

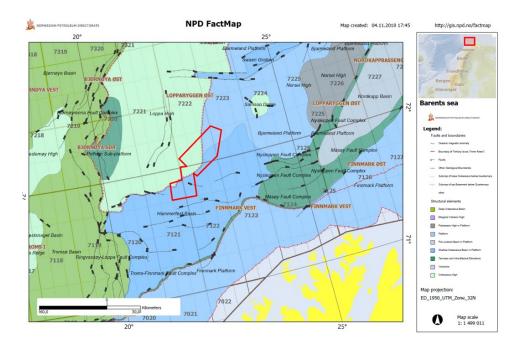


Figure 3.1: Location of study area in southwestern of Barents Sea. Outline, marked by thick red line, is 3D cubes outline used in this study. Norwegian Petroleum Directorate (NPD).

In general there are two fault complex trend on western Barrents Sea Shelf. There are NE-SW trend north (Svalbard Platform) (Rønnevik & Jacobsen, 1984), and NE-SW trend on the south which is separating Norwegian mainland from the shelf.

On the west part of the shelf, there are areas heavily disrupted by cross-cutting N-S and NNW-SSE-oriented faults. Those which being disrupted are mainly lies on area where boundary between Tromsø and Hammerfest Basin approximately occurred. In addition to present main fault trend, NW-SE fault trend was formed due to older tectonic activity before Hammerfest Basin was formed (Gabrielsen, 1984).

Structurally, there are 3 main fault complex features as boundaries in between each sub areas. Southern Loppa High Fault Complex, which later be known as Asterias Fault complex (AFC), is separating Loppa High from Hammerfest Basin (Dore & Lundin, 1996). Amidst the Hammerfest Basin and Finnmark Platform in the south, there is Trøms-Finnmark Fault Complex (TFFC). And the last is Ringvassøy-Loppa Fault Complex (RLFC) as a partition between Hammerfest Basin and Tromsø basin.

Based on fault geometries, each boundary has its particular type. Trøms-Finnmark Fault Complex (TFFC) is related to major listric fault type which created rollover structures and antithetic fault. On the other hand, Ringvassøy-Loppa Fault Complex is identically in the form of normal fault which suffered several reactivation times. Different from other two types, even if it is mainly represented by at least two major normal fault, Asterias Fault Complex had been influenced by compressional strike slip movement. Evidence of the respective movement is updoming and flower structure. The flower structure was then formed into normal faults when it collapsed (T. Berglund et al., 1986).

3.2 Geological Evolution of Hammerfest Basin

Loppa high structure formation is the result of multiple tectonic evolution prevailed on western Barents Sea shelf, including uplift, subsidence, tilting and erosion (Faleide, Vågnes, & Gudlaugsson, 1993). Since it is lies as the north boundary of Hammerfest Basin, it suffered from the identical tectonic activities happened on the adjacent Basin. On the next discussion, there will be three stages describing the formation of Loppa High structure as a part of Hammerfest Basin structural evolution.

3.2.1 Early Paleozoic - Triassic

The structural trend in the vicinity of Hammerfest Basin structure may be similar to the fault trend occurred as the consequences of compressional event when Iapetus Ocean was closing which started in Late Cambrian. The most noticeable result was Trollfjord-Komaglev fault zone which has WNW-ESE trend (B. Harland & A. Gayer, 1972). Major tectonic movement continued until carboniferous times, creating two structural trends which are NE-SW and NW-SE to WNW-ESE direction (Rønnevik & Jacobsen, 1984). NE-SW trend is located on structural depression limited to the north by Svalbard Platform and Norwegian mainland on the south. It is the same trend where the current western limit of Loppa High took place, although the trend on the particular area is almost N-S. NW-SE to WNW-ESE orientation was due to more local and compressional deformation, as the result of dextral fault due to wrench system along the Barents Sea (Ziegler, 1978). Furthermore, strike slip movement during Late Devonian to Carboniferous was followed by E-W extensional regime. It lead to structural tilting of Loppa High and Hammerfest Basin area, coincided with the reactivation of older basement fault trend.

Erosional process took place twice during each Permian time boundaries. It was intercepted by transgressed condition for all the highs in between two erosional time event. The latest erosion event long lasted from late Permian until Early Triassic, resulting in deep erosion of the top of high structure. The depocenters during this time period were located on the northeast and southwest of the present Hammerfest Basin (T. Berglund et al., 1986).

3.2.2 Triassic - Cretaceous

During Late Permian to Early Triassic, tectonic quiescence dominated western Barents Sea areas, with some slight tectonic reactivation of existing structure. It was shown by Lower Triassic isopach thickness map which indicate crestal erosion. Such erosion can only be done by reactivation of structural highs (T. Berglund et al., 1986). Moreover, Loppa High was started to be a depocenter from mid triassic period, which was due to north west normal faulting. It was shown by isopach of middle triassic sediment which thickened where the Loppa High lies. In some part of Loppa High, there was deeply cutting canyon shown as erosional line which appeared during Cretaceous post rifting stages where Loppa High was subaerially exposed.

Middle Triassic - Late Triassic period is dominated by sandstone, siltstone, shale and thin layer of coals. It is in the form of coarsening upward sequence, representing the changes from open marine environment into more continental deposit. It will be known as Fruholmen formation on the current Barents Sea lithostratographic chart (figure 3.5).

Tectonic activity during Late Triassic went back into stationary condition. It was when deposition was all over the Hammerfest Basin. During Late Triassic to Middle Jurassic, The deposition of Stø Formation was the outcome of several combinations between relative sea level rise, tectonic subsidence where Loppa High and Troms-Finnmark Platform were part of it, and local sediment input. Afterwards, relative sea level continued to rise, draping marine shales on top of Stø formation where Fuglen Formation is deposited. There is no evidence from seismic where the respective interval was being influenced by any tectonic activity. It can be examined from paralel reflector relationship in between each formation. It means that the depositional condition of Lower - Middle Jurassic deposit was not effected from tectonic activity leads to the formation of Hammerfest Basin. Moreover, during Late Jurassic, vast distribution of marine shale of Hekkingen Formation took place all over the areas. It was covering Hammerfest Basin along with the Loppa High area.

3.2.3 Cretaceous - Present day

Even though the shape of present Loppa High was controlled by mid-Carboniferous rifting, followed by tectonic uplift and tilting of the flank during Late Permian

until Early Triassic, the present configuration of Loppa High is a result of Late Jurassic until Early Cretaceous tectonism (Faleide, Vågnes, & Gudlaugsson, 1993; Henriksen et al., 2011; Wood, Edrich, & Hutchinson, 1989). The configuration of Loppa High started with the dextral strike slip movement during Late Jurassic period. The respective movement produced compressional system locally and positive flower structure along the western part of Southern Loppa High Fault Complex. The uplifted layer formed by flower structure was then collapsed during early cretaceous after deep erosion of the central part of the structure (figure 3.2 (T. Berglund et al., 1986))

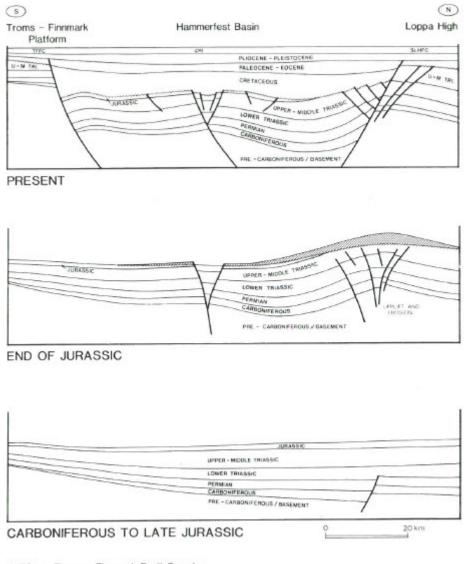




Figure 3.2: Schematic tectonic development of Loppa High and Hammerfest Basin. (T. Berglund et al., 1986)

Along the Cretaceous time, some topographic high as Troms-Finnmark PLatform and Loppa High were uplifted and eroded through several reactivation along the major fault. While on the southern of Loppa High, Cretaceous sediment was deposited, covering major parts of Western Barents Sea. It was occurred in the form of coastal onlap sequences into both structural high and filling of erosional valley cuts into Triassic sequences (T. Berglund et al., 1986). Additionally, there was tectonic uplift on Late Cretaceous time, followed by another subsequent erosion.

Even though Tertiary sediment covered major part of western Barents Sea, Paleocene to Eocene sediment is only concentrated on strutural depression like Hammerfest, Tromsø, Bjørnøya, and Senja Basin, and high for example Senja Ridge. However it was not deposited on top of Loppa High structure. Paleocene - Eocene sedimentation was followed by the early phase of sea-floor spreading to the west, causing tectonic uplift on Western Barents Sea. Furthermore, it was succeeded by westerly progradation of Eocene - Oligocene sediment, and final phase separation between Greenland and Spitsbergen. Lastly, Ice - sheet deposit loaded on top of thin-layered Upper Pliocene and Pleistocene sediment.

3.3 Petroleum System

One of the aim in this study is to find any relationship between the influence of submarine fans growth in the basement uplift setting toward the hydrocarbon prospectivity. Although Southwestern of Barents Sea is well known as hydrocarbon producing area, especially in Hammerfest Basin, numerous failures were encountered in several petroleum plays in the vicinity of Loppa High structure. Understanding basement uplift setting in Loppa High and its influence on submarine fans growth is expected to help us understand better concept of petroleum system risk in this area.

3.3.1 Source rock

In order to understand geological age and lithological summary of the following petroleum system element discussion, figure 3.5 is provided. Source rock is one of the element proven in Southwestern Barents Sea. There are three recognized source rock in Barents Sea which are Upper Jurassic shales, Upper and Middle Triassic shales. Middle Triassic shales, considered to be potential oil and gas source rock, is part of Botneheia member (Bjorøy, Vigran, & Rønningsland, 1978). It has diverse source rock quality which is believed to produce oil as hydrocarbon in Hammerfest and Nordkapp Basins (G. Dore, 1995). On the other hand, Upper Jurassic shales may contribute in producing hydrocarbon in Norwegian sector locally (Johansen et al., 1993). Among those source rock quality (G. Dore, 1995). Hekkingen shales has vast distribution and the best source rock quality (G. Dore, 1995). Hekkingen shales is considered to be mature at Hammerfest Basin margin in the west, and along the western fringe near Loppa High (G. Dore, 1995). In well 7122/2-1, Hekkingen shale is categorized as in immature to early mature condition (% Ro 0.47 - 0.75) (Sempre & Sørheim, 1993).

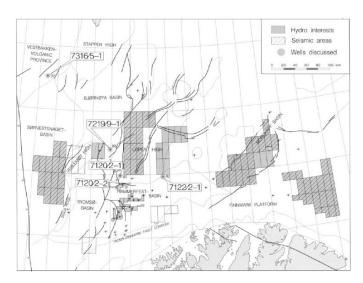


Figure 3.3: Barents Sea Exploration activity map in 1997. (Knutsen et al., 2000).

3.3.2 Reservoir rock

Several reservoir intervals have been tested during hydrocarbon exploration in Barents Sea. Some of them were successes and others struck by numerous failures. Both proven and potential reservoir intervals are summarized in figure 3.4. Stø formation along with the rest reservoir interval in Jurassic age, are prolific reservoir interval, in most of hydrocarbon producing fields in Hammerfest Basin (G. Dore, 1995). Stø formation was deposited in coastal marine environment (Dalland, Worsley, & Ofstad, 1988). The sandstone has good porosity and permeability which exceeded above 600 mD at well 7122/2-1 (Sempre & Sørheim, 1993). It is the same reservoir on the discovered producing field in Snøvhit, Albatross, and Askeladen. Beside Stø sandstone formation, sandstone from Kobbe formation is evident as good - hydrocarbon filled reservoir. It is penetrated at the top structure of Loppa High through well 7122/11-1 and 7122/11-2. Moreover some other interval such as Nordmela sandstone and Knurr submarine fans deposit are considered to have good porosity quality in a working petroleum system.

3.4 Exploration History

Specifically for surrounding Loppa High limit, Four petroleum plays have been tested at the reservoir age of Paleozoic to Cenozoic, in order to find hydrocarbon accumulation (Knutsen et al., 2000) (figure 3.3). Two of them were generated as prospects with stratigraphic trap at sandstone reservoir, while the other was fault bounded structural trap at sandstone reservoir and carbonate reservoir.

Well 7120/2-1 was drilled to test Paleozoic carbonates reservoir prospect at structural high which bounded both by rotated fault block as structural trap. It was dry but found more than 200 m of interval with paleo oil which later considered as heavy oil. The reservoir property has good porosity range in between 7 - 23 % based on core porosity. This particular play showed that the source rock element is working in the surrounding area, proved of good quality reservoir on the target interval but

somehow the trap failed. The other structural play, but in the sandstone reservoir, was penetrated by well 7219/9-1. It was testing the well known fault - tilted block of Triassic and Jurassic reservoir. The result was similar to well 7120/2-1, where 88 m column of palaeo - gas and 112 m column of palaeo - oil were found. The likeness was also occurred on reservoir properties as it encountered good reservoir both in quality and thickness (Knutsen et al., 2000). Post drill analysis summarized that trap failure was the reason for the dry condition.

Stratigraphic play was tested in two wells, which were 7120/2-2 and 7122/2-1. Since 7122/2-1 is the key well in this study, it will be discussed in more detail on the following chapter. Well 7120/2-2 was testing Lower Cretaceous sandstone wedge. The result was again dry with poor reservoir property. However, shows were found at the uppermost of the wedge and 300 m below the wedge itself. Accordingly, it was concluded that no palaeo - oil was found. Moreover, the same conclusion was drawn, which was trap failure occurred as the reason behind dry well condition. It was because the migration from Upper Jurassic source was thought to be possible.

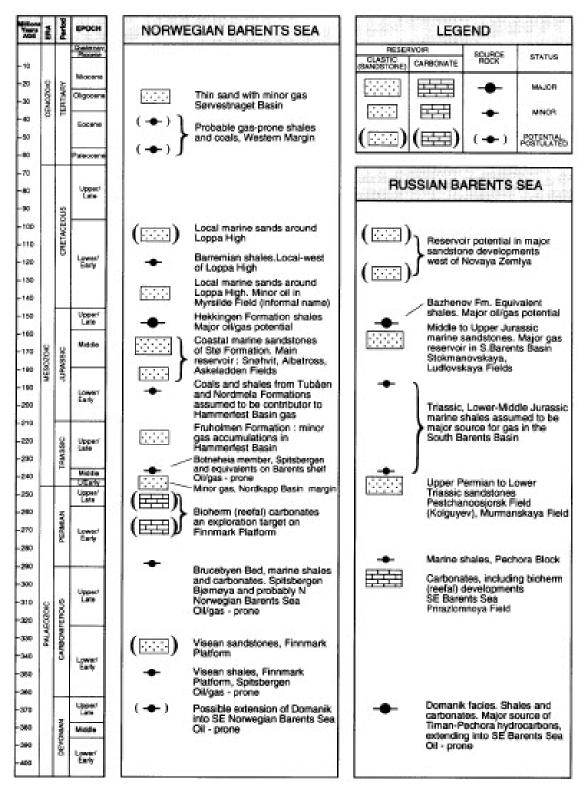


Figure 3.4: Summary of proven and future potential source in the entire Barents Sea covering Norwegian and Russian territory (G. Dore, 1995).

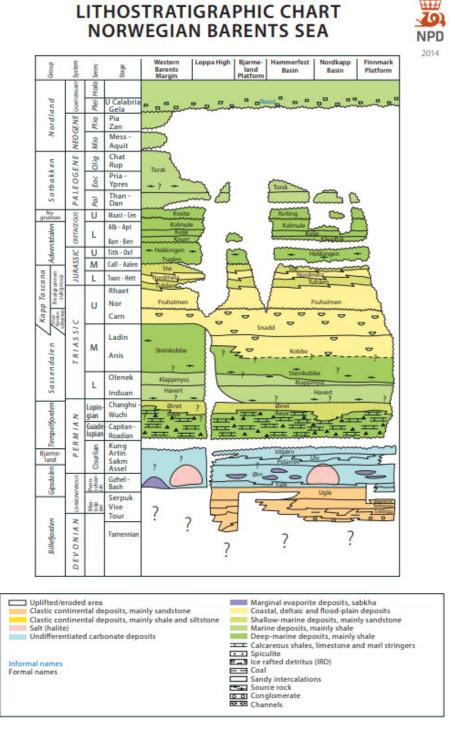


Figure 3.5: Lithostratigraphic Chart of Barents Sea. (Larssen et al., 2005)

Chapter 4

Data and Methodology

4.1 Data

The study takes place in block quadrant 7121-7123 until 7221 - 7223 of APA Block in Barents Sea Norway (figure 4.1. It is located approximately 150 km from Hammerfest and 60 km from Snøhvit field. The available seismic and well data are covering areas between the slope near Loppa High and the basin plain at the toe of the slope (figure 4.2). Several wells have identified on the vicinity of the study area. Some of them were directly used, while others were used merely for regional information purposes.

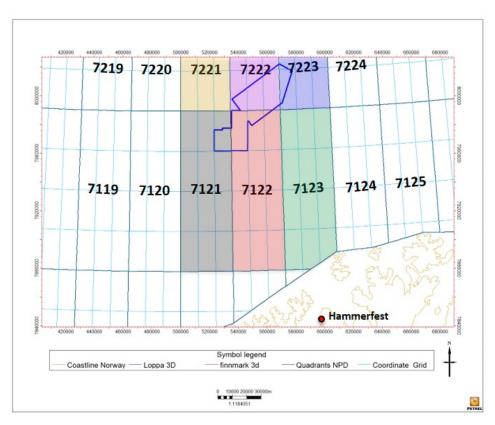


Figure 4.1: Area of study based on Norwegian Block Quadrant. Blue rectangle is 3D seismic outline used in this study. Norwegian Petroleum Directorate (NPD).

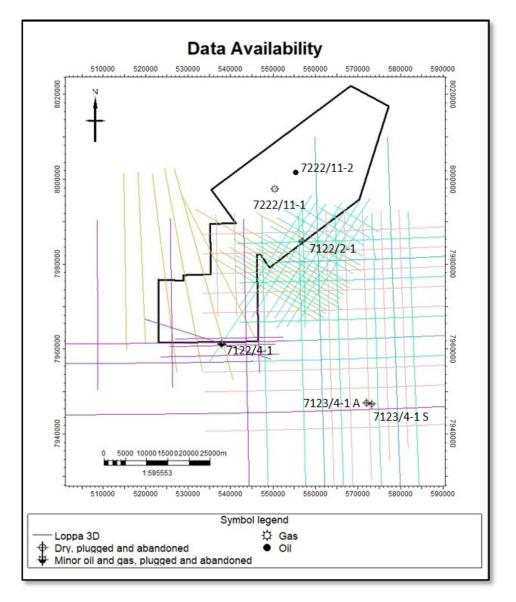


Figure 4.2: Data distribution map showing distribution of available seismic and exploration well used in this study.

4.1.1 Well Data

There are 6 exploration wells on the surrounding objective area (figure 4.2). two wells which are 7122/2-1 and 7122/4-1 will be used directly in well seismic tie process, while others were used in obtaining regional petroleum system. Different location were used as justification in using those two wells where both the wells are located just near the end of Loppa High Slope. Two wells are located way into the basin plain which are 7123/4-1A and 7123/4-1S. On the other hand, two wells which are 7222/11-1 and 7222/11-2, were drilled on top of Loppa High structure to penetrate Triassic age formation. Each of wells is using top formation markers provided by Norwegian Petroleum Directorate (NPD). the following information reveal more detail information regarding wells used in this study:

• 7122/2-1

7122/2-1 is a wild cat exploration well drilled in 1992. It was drilled to test Early Cretaceous stratigraphic sandstone prospect of Knurr Formation. It penetrated 123 ft of Knurr Formation clean sandstone, with water bearing zone on the most sandstone interval (figure 4.3). For the hydrocarbon shows, based on integrating data of gas reading, cuttings, side wall cores, and conventional cores, there is gas shows and no oil shows on Knurr Fm. On the other hand, source rock shows occur on Kolje Fm. And Hekkingen Fm. It was in the form of slow streaming cut fluorescence and pale - yellow residual fluorescence. Only sandstone from Sto gave same weak hydrocarbon shows at the depth of 2118 m. Core sample was taken from the depth of 1771 - 1931 m MD. 7122/2-1 well will be our main well where it was the only well penetrated exactly on the submarine fan model.

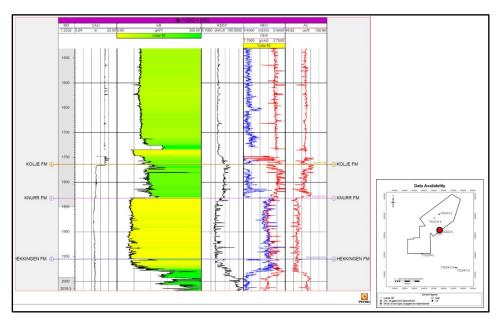


Figure 4.3: Well log response of well 7122/2-1.

• 7122/4-1

7122/4-1 well was a wild cat exploration well which is located at the tilted horst features and bounded by faults. The target was sandstone of Stø Fm at the South of Loppa High structure (figure 4.4). Hence, It It did not penetrate submarine deposit of Knurr Formation at the toe of the slope. The penetrated Stø and Nordmela Formation has good porosity and permeability. It was confirmed from core analysis and FMT result on each formation. Hydrocarbon shows were found at Knurr Formation and Hekkingen Formation which is a good source rock. Both interval of hydrocarbon shows only had weak shows, with no direct fluorescence and only very pale and slow cut appeared.

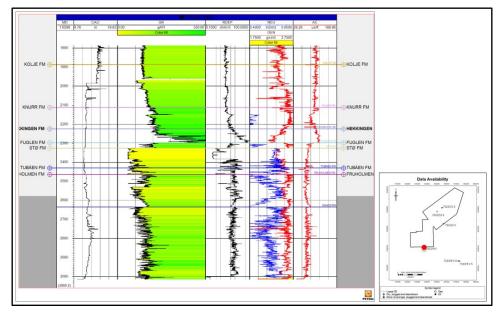


Figure 4.4: Well log response of well 7122/4-1.

• 7122/11-2

7122/11-2 is categorized as technical oil discovery well (figure 4.5. It was drilled to test the potential formation above Kobbe Formation which previously discovered oil and gas interval in well 7222/11-1 (Caurus Prospect). It is located on the crest of Loppa High structure where the large canyon system lies and became the sediment conduit on the deeper part of the areas. Due to erosional process, wells on this structural position lost most of the Jurassic interval (Stø, Fuglen and Hekkingen). There is no hydrocarbon shows above Kobbe Formation, however it encountered oil interval on the main channel of Kobbe Formation with 3.5 m of net pay and 19.1 % of core porosity

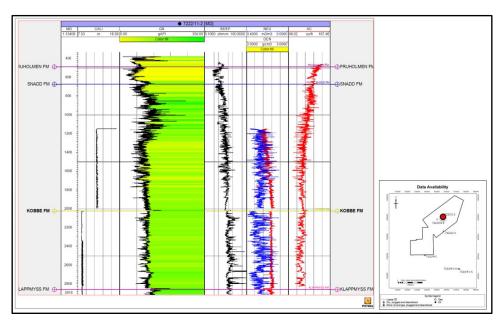


Figure 4.5: Well log response of well 7122/11-2.

4.1.2 Seismic Data

In this study, 82 2D seismic lines and 2 3D seismic cube were used (figure 4.2). Most of 2D lines have orientation perpendicular to the slope direction of Loppa High structure. The lines on the west has slight N-S and NWN-ESE orientation which defined the areas on the southern limit of our study. Meanwhile, Lines on the southeast has NW-SE and NE-SW orientation, which perpendicular not only to the slope direction, but also to the regional structural fault trend. Minimum distance between 2D line is 0.8 km while the maximum is around 1.5 km. Moreover, two cubes of 3D seismic were combined using Petrel. It was 3D PSTM seismic cube of SG9803, which is located on the south and OMV09M01 on the north.

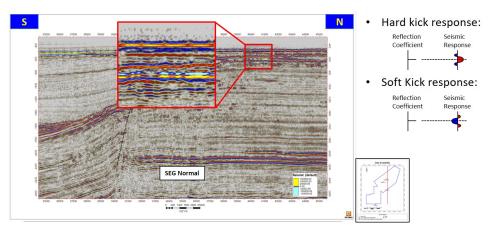


Figure 4.6: North 3D seismic cube

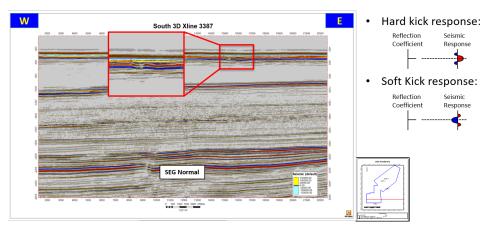


Figure 4.7: South 3D seismic cube

In term of year of acquisition, the available seismic lines are consisted with different years ranging from 82 to 90's. Due to that fact, different seismic quality are expected to be found in this study. Hence, quality control of available seismic data is important before starting an interpretation. Base on the seabed reflector response, north 3D seismic cube has SEG normal polarity where increase in acoustic impedance (positive coefficient reflection) is represented by peak / red colour (figure 4.6). Meanwhile, direct identification of the south 3D seismic polarity can result in misleading information. It is because there are several reflection on the seabed level (figure 4.7). However, by creating arbitrary line connecting the two 3D seismic (figure 4.8), it can be seen clearly that it has the same polarity as the north 3D seismic cubes which is SEG normal polarity. Moreover, 2D seismic lines has also SEG normal polarity based on same approach using sea bed reflection analysis (figure 4.9).

From seismic resolution point of view, it is obvious from figure 4.8 that OMV09M01 cube has higher vertical resolution compared to SG9803. on the main interest between the time interval 1450 ms - 1750 ms, it has dominant frequency around 26 Hz for OMV09M01 cube. With the average velocity around 3386 m/s, it has vertical resolution of 32 m on the main interest where the submarine fans lie. SG9803 has dominant frequency of 15 Hz on the same time interval. it has lower seismic resolution around 40 m when using velocity average of 3050 m/s.

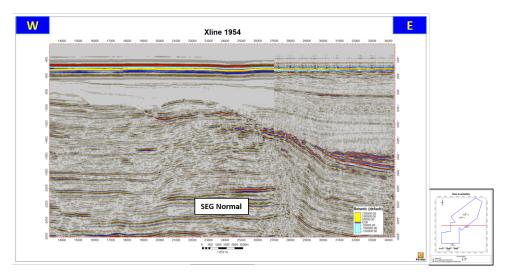


Figure 4.8: Merged 3D seismic cube

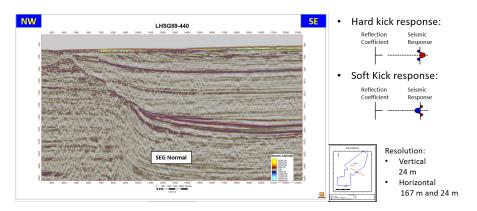


Figure 4.9: 2D seismic example for data quality check. The resolution calculations are using 30 Hz

for 2D seismic data lines, survey LHSG89 is used as benchmark for seismic resolution calculation. at the time interval of 1450 ms - 1850 ms, it has dominant frequency of 36 Hz with the average velocity of 3900 m/s. Hence, it can reach higher resolution than adjacent 3D seismic cubes with 23 m. Furthermore, based on qualitative observation, the quality of seismic data which include reflector continuity, 2D seismic lines used in this study can be categorized as good quality.

4.2 Methodology

4.2.1 Literature of Study

This study was started by extensive study of literature regarding any feasible theoretical concept and methodology which can contribute to achieve its purposes. Several starting topics were chosen contain the tectonic evolution of Hammerfest Basin in regard to Loppa High structure, the theory and concept of deep marine depositional processes, Deep marine depositional system models, and particular concept of seismic interpretation related to detail characterization of deep marine deposit features (morphology, facies and stages).

There have been massive numbers of literature discussing every geological and petroleum aspects in Western Barents Sea especially on Hammerfest Basin. The author selected several papers which directly related to the purposes of this study. Stratigraphic framework between pre - Cretaceous until present day interval was studied and summarized by Sattar, Juhlin, Koyi, and Ahmad (2017) for all areas near our study interest. Sediment transport pathways morphology, development, and contribution as sediment conduit from Loppa High crest into the deeper part of the basin was taken from Dicky et al. (2018) study incorporated by morphometry analysis of each canyons, gullies and slide scar. Moreover, study on submarine fans growth stages for each slope setting types in Triassic deposit, Hammerfest Basin (Hadler-Jacobsen et al., n.d.) was used as reference.

One of the main highlight on this study is related to the study of submarine depositional system model by Richards et al. (1998). Modification for depositional system related to uplifted basement was added as the result on our study.

4.2.2 Seismic Interpretation

Initial phase of seismic preparation was performed through two processes which are well to seismic tie and inter - seismic tie between 2D lines, and between 2D lines and 3D cubes. There is no well editing as the log data quality regarding well to seismic tie process is considered to have a good quality data. Well to seismic tie was performed along two wells near the toe of the slope which are 7122/2-1 (Figure (4.10) and (7122/4-1) (Figure 4.11). Main target interval for well (7122/2-1) is between 1500 ms - 1750 ms, while, it is between 1850 ms - 2000 ms for well 7122/4-1. Both of ties are showing good correlation on the main target interval. However, there is difference on the top of Knurr formation reflection response. On 7122/2-1 it has positive reflection coefficient on the boundary between Top Kolje and top of Knurr Formation. Meanwhile, it is showing the opposite reflection coefficient on well 7122/4-1. It is happened due to the existence of submarine fans deposit on 7122/2-1 which is not penetrated by 7122/4-1. Wavelets which was used in the well to seismic ties were extracted from interval interest in each well. vertical shifting was taken as necessary step at maximum shift of 15 ms from the initial time to depth relationship.

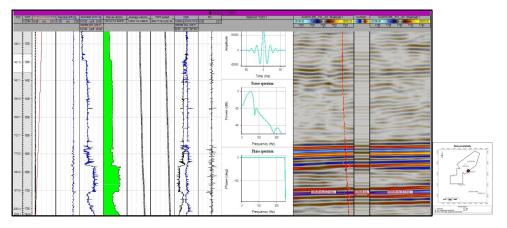


Figure 4.10: Well to seismic tie on well 7122/2-1.

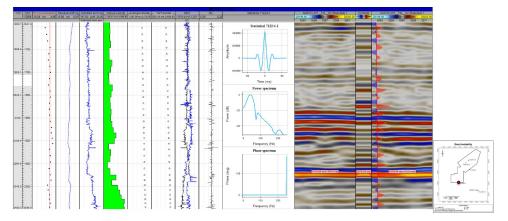


Figure 4.11: Well to seismic tie on well 7122/4-1.

Inter-seismic ties was conducted following the workflow on figure 4.12). This processes was done in order to reduce the mistie effect in between lines and cubes for our interval target. Due to difference in acquisition year, each of seismic survey has different frequency range and possibly different fold. It is effecting vertical and horizontal resolution quality for each seismic survey. Hence, it created sections of seismic which tie on certain interval yet not perfectly tie on the other interval (figure 4.13). Additionally, it could occur due to different interval velocity used in each processing year. As the consequences, the tie between 2D seismic lines will be focused mainly to tie the main interval target which between Cretaceous until Jurassic intervals. The 2D seismic tie was carried out by using automatic mistie analysis in Petrel 2016 and had been checked manually line by line during the interpretation process. Meanwhile 3D seismic cubes were tied and merged using Blue back Plugin in the same software platform. Example of merged 3D cubes section is already shown on figure 4.8. As a final step was the seismic tie between 2D lines and merged 3D cubes which was performed manually by shifting vertically the seismic 3D cube.

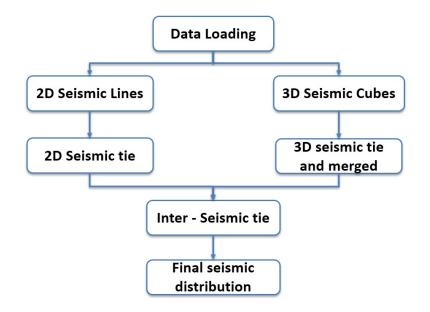


Figure 4.12: Workflow in generating tie between available 2D seismic lines and 3D seismic cubes.

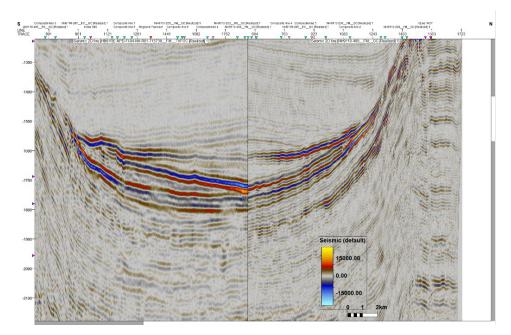


Figure 4.13: Composite seismic section showing mistie example between different acquisition year on 2D seismic lines. Medium to good correlation occurred at interval between 1500 ms - 1800 ms. Some of the mistie on this interval is probably due to different vertical resolution. On the other hand, the shallower interval at above 1400 ms, has poor correlation which probably due to different processing parameter.

Seismic interpretation was done mainly on 2D seismic data to define submarine geometry throughout the basin, and regional mapping to obtain complete basin morphology features as the base surface when the fans were deposited. Meanwhile, 3D seismic data was used to identify any features and relationship in between slope and basin floor. There are three top formation which picked on the seismic section, which are top Fuglen Formation, Top Hekkingen Formation and Top Knurr Formation. Each picked horizon was picked based on chrono stratigraphic picking instead of lithology picking in order to define the submarine fans whole geometry. Additionally, two horizon markers were picked where possible maximum flooding surface below top Hekkingen, and Flooding surface above top Knurr Formation were located. The later marker in some areas is corresponding to top Kolje Formation. Several faults were picked following the existing regional fault trend.

The first final product of seismic interpretation is structural map which are both in time and depth domain. Time to depth conversion formed using velocity model, created from available well marker and picked seismic horizons. Structural depth map was quality controlled by examining misfit for every picked horizon and marker.

4.2.2.1 Isochrone Map

From generated structural map, Isochrone map was constructed between top of Knurr Formation and Top of Hekkingen Formation. This Isochrone map was created in order to examine the distribution and morphology of Cretaceous submarine fans. The thickest area is representing interval with the thickest accumulation of submarine fans. The method used in obtaining the isochrone map was using surface attribute of isochrone thickness between two top surfaces.

4.2.2.2 Paleomorphology Map

Paleomorphology is basically came from the same method as Isochrone map. The difference is on the interval used in generating the isochrone map. In this study we generated isochrone map between top of flooding surface marker interval and top of Hekkingen formation. It is used to describe paleomorphology of top Hekkingen formation which became base surface before the deposition of submarine fans. It is a representation of paleo - condition around the age between 150 ma - 140 ma. The generated paleomorphology map is limited until at the edge of continental slope. It is due to the onlap of flooding surface marker as it went into the shallower depth on the slope.

4.2.3 Core Description

Core description was performed along conventional core data at well 7122/2-1. It is chosen due to the fact that the respective well penetrated precisely at the submarine fans deposit. Main interval of core description is between the depth of 1833 m - 1932 m MD. The analysis was based on core photos from the archive of Norwegian Petroleum Directorate (NPD). Description categories were focused on grain size

change and analysis, grain sorting, and biostratigraphy analysis which performed by Halliburton. The first two was intended to identify the sedimentation processes contributed to the deposition of submarine fans and also the sequences of sediment delivered into the basin, while the last one was used to obtain information about depositional environment of submarine fans deposit.

4.2.4 Log Pattern

Log pattern analysis is a method in examining the correlation between the wireline log pattern from logging process with another supporting data as conventional core and wireline log template from existing submarine fans system model. Gamma Ray log was used in determining the vertical grains size change on certain interval, where high value of Gamma Ray represents fine grain size and low value shows coarse grain size. Moreover, density log and sonic log were used in identifying possible porosity occurred on particular interval and grain sorting. Combining all of the analysis will result in identification of sediment delivery sequences, sedimentation process, and justification of depositional environment during the deposition of submarine fans.

Chapter 5

Result

In order to analyze and identify the growth stage of Cretaceous submarine fans in the toe of the slope of Loppa High, regional seismic study and detail seismic mapping had been performed at the Northern boundary of Hammerfest Basin with Loppa High. The following discussion will describe details each of the mentioned processes. Each of further figure is located as it shown on figure 4.2 regionally, however the specific location will be shown as map inset on each figure.

5.1 2D and 3D seismic Interpretation

2D and 3D seismic interpretation was conducted in regional scale from the southeastern slope of Loppa High until mid of Hammerfest Basin present depocenter to the south. It is including revisiting the interpretation made by Dicky et al. (2018) when investigating the morphometry of sediment conduit system. Six seismic horizons had been picked for the entire available seismic data. Three of them were picked based on markers on available key wells of 7122/2-1 (figure 5.1 and 5.2) and 7122/4-1, which from the oldest to youngest sequence are Top Fuglen Formation, Top Hekkingen Formation, and Top Knurr Formation.

Fuglen formation is described in the seismic as conformable planar reflection layer which is suitable with the depositional environment where relative sea level rise dominated and created deeper marine environment. The Fuglen formation in this area can be traced way back at least until the slope of present Loppa High Structure, since it was not being found on the well at the crest structure (figure 4.5) . It is also the base of eroded section on the slope area which formed the sediment conduit to the basin area. The top of Fuglen formation was picked at the positive coefficient reflection, showing the increasing density and velocity over the changes from Hekkingen to Fuglen formation due to compaction process and the existence of carbonate cemented mudstone (Riis & Halland, 2014). Hekkingen formation is described in the seismic also as conformable and planar reflection layer where it was formed on deep marine shale depositional environment. Although it was deposited until the crest of Loppa High paleostructure (T. Berglund et al., 1986), yet it does not appear on the present condition due to massive Cretaceous erosion. Hence, it merely can be traced until the slope of present Loppa High structure. Knurr formation is the key formation in mapping the submarine fans. The whole submarine fans body was identified in the seismic section as large lenses shape located at the end of the slope. It is most likely that this formation has no continuation until the slope of Loppa High structure. The thickness seemed to be thinning both toward the slope and further away from the slope. several internal pattern were recognized which will be discussed on the next sub chapter. The upper boundary of this deposit was marked by strong amplitude reflection which showing the changes from deeper marine dark brown to grey shale Kolje Formation. Moreover, termination pattern for example onlap of Kolje formation into the fans body, become another recognizable pattern, marking the upper boundary of Knurr formation. Additional horizons was picked based on the stratigraphic marker shown in Sattar et al. (2017) study, which are flooding surface near top Kolje formation and Maximum flooding surface below the Top Hekkingen formation.

Fault interpretation was done mainly on the Jurassic formation which are Fuglen and Hekkingen Formation and was concentrated on the basinal area where the submarine fans lie. Most of the interpreted faults are normal fault with two orientation trend which are NW-SE and NE-SW. It is confirmed by regional study which has been mentioned on the section 3.2. The distribution of the faults are located mainly on the northern part of well 7122/4-1 location. It happened due to the variation of Asterias Fault Complex displacement from east to west of Loppa High boundary during late Jurassic to Early Cretaceous (Sattar et al., 2017).

Furthermore, several attribute had been generated to help the interpretation process. Variance attribute was used in order to identify the channel feature along the submarine fans body. Meanwhile, several attributes which can help in tracing the continuation of reflector as instantaneous phase and cosine phase were used in determining the internal character of submarine fans.

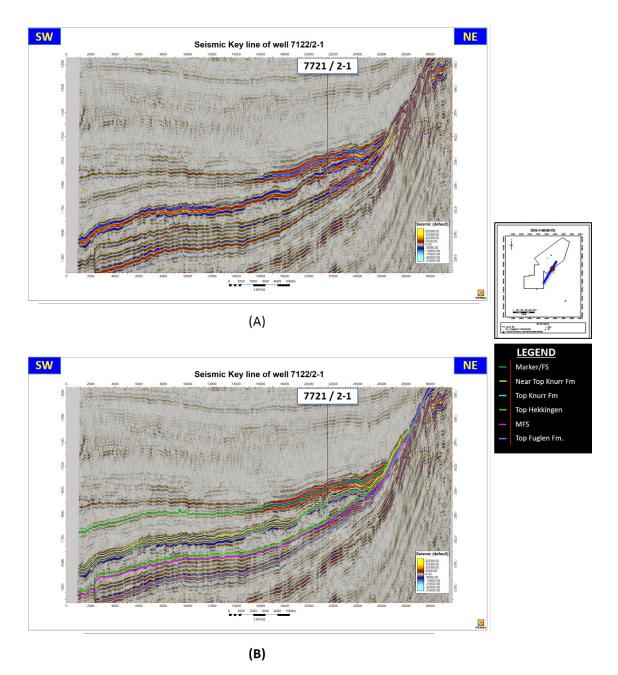


Figure 5.1: Seismic section of NH9110-206 which is key line where well 7122/2-1 well penetrated the submarine fans. The line is crosscutting submarine fans perpendicular to sedimentation direction. Vertical exaggeration on this display is 10. (A). uninterpreted seismic section. (B). Interpreted seismic section for several key horizons based on marker chosen from the well.

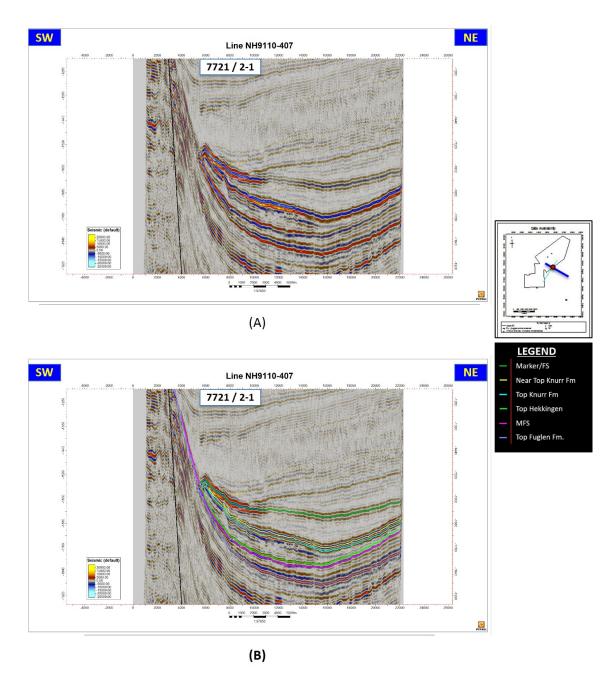


Figure 5.2: Seismic section of NH9110-407 which is key line where well 7122/2-1 well penetrated the submarine fans. The line is crosscutting submarine fans parallel to sedimentation direction. Vertical exaggeration on this display is 10. (A). uninterpreted seismic section. (B). Interpreted seismic section for several key horizons based on marker chosen from the well.

5.1.1 Structural Maps

From six seismic horizons picked for the entire section, three maps had been generated in order to understand the system involved in deposition of submarine fans. The generated maps are surface for top Fuglen Formation, top Hekkingen formation and top Knurr formation. The purposes in generating these three horizons into surfaces is to create isochrone and isopach map to analyze submarine fans deposition process.

Top of Fuglen formation has structural trend which dipping toward SW direction regionally (figure 5.3). The main factors controlling this kind of trend is the normal fault trending NW - SE which correlated with the opening of Hammerfest Basin. Most of the faults are located near the well 7122/4-1, where the play of fault bounded structural trap of St formation had been tested. Some isolated yet major displacement fault were found at the slope area. It is separating the end of canyon mouth directly against the basin floor. The other important morphology feature is the depression at the south of well 7122/2-1 which is formed by syncline dipping toward the SW and dies out toward the NE. It is probably occurred as an outcome from collapsing flower structure during the initial formation of Loppa High structure. Outline of Canyon contour were drawn in the top Fuglen formation surface map. The purposes is to marked the location of the Canyon feeder system on the rest of other two maps.

Hekkingen formation deposited overlying the existing Fuglen Formation (figure 5.4). Since the relationship between the two formation is conformable, there is no significant changes in term of structural features along the basin floor. Some faults have smaller throw gap for the same fault structure compare to Hekkingen formation. It is indicating that the collapsing structure was carried out during the Hekkingen formation far away toward the shallow part of Loppa High structure as it was washed away when the deep incision created Canyon feeder system (T. Berglund et al., 1986)).

On top of Hekkingen lies Knurr formation which filling available existing basin morphology (figure 5.5). Generally, the trend of the top structure is similar to the underlying formation. However, when Knurr formation was deposited, it filled the area especially where there is any depression near the end of the canyon. As the result, there is no trace of depression which have been found at the structure map of underlying formations. On the other hand, there are two narrow depressions recognized on top of Knurr formation surfaces which has trend of NE-SW for the larger scale depression and NE-SW trend for the smaller one. The large scale depression elongate until approximately 20 km, while the smaller one merely reach 6 km. Factor causing the depressions feature is possibly any erosional process which eroded the top of Knurr formation. More details analysis will be explain as we will see it on the seismic section.

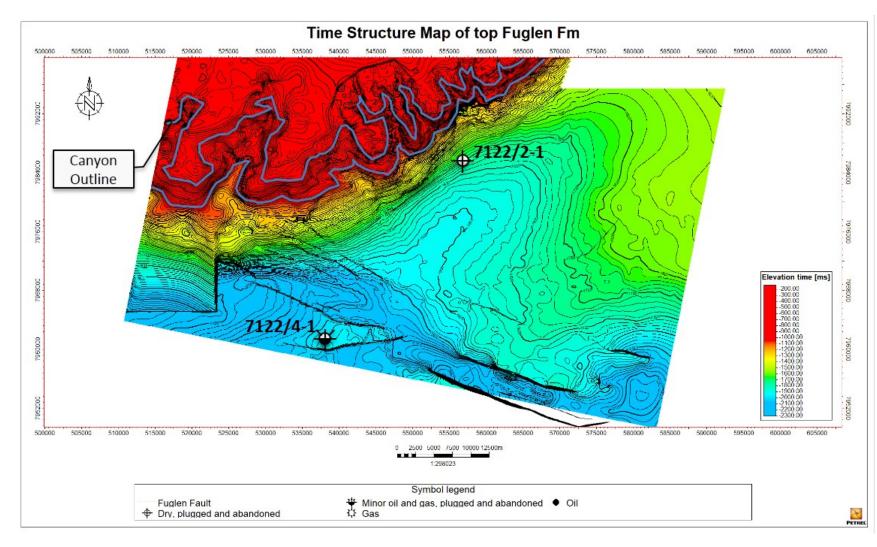


Figure 5.3: Time structural map of Top Fuglen Formation.

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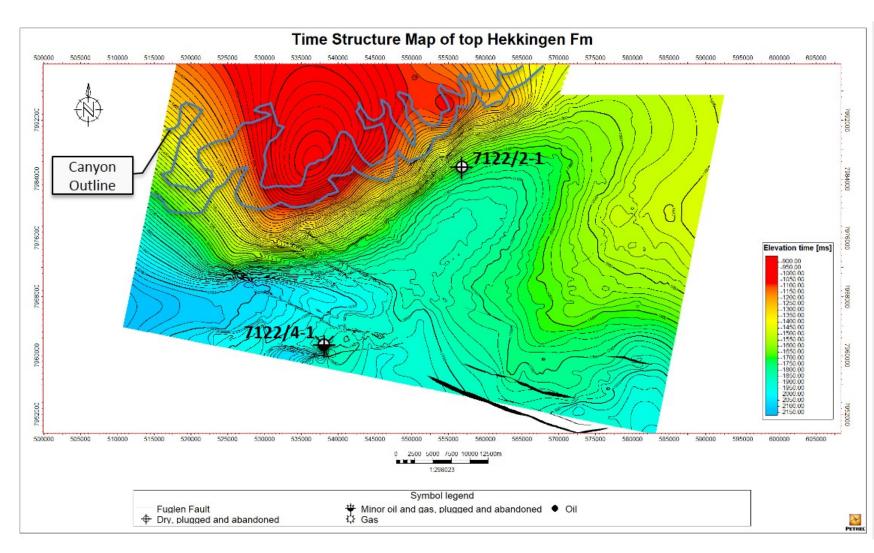


Figure 5.4: Time structural map of Top Hekkingen Formation

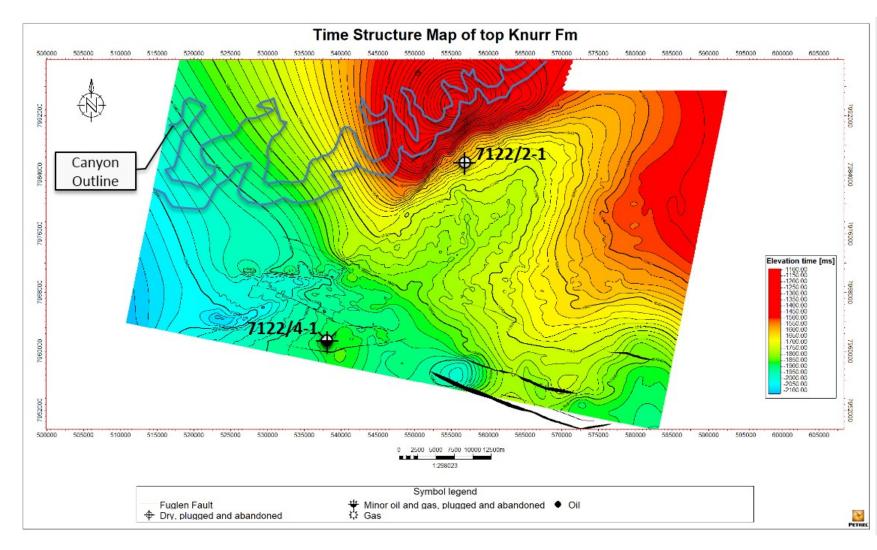


Figure 5.5: Time structural map of Top Knurr Formation.

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Master Thesis

5.1.2 Isochore Maps

Isochore (depth domain) is method to calculate vertical thickness of present structural position. It does not meant to describe any true vertical thickness of a layer formation. There are two isochore maps which had been generated in this study. The first isochore map was generated in order to define submarine fans morphology, distribution and submarine fans growth. Meanwhile, the second one in this study was meant to analyze the paleomorphology when the submarine fans were deposited.

The first isochore map was constructed between two surfaces of top Knurr formation and top Hekkingen formation (figure 5.6). Since Knurr formation resembles submarine fans deposit, it has to be pinched out somewhere away from the slope and toward basin direction, and downlaped into top of Hekkingen formation. The cut off used in the isochore map of Knurr formation is 0 ms. it means the purple colour is representing the area where the Knurr is pinched out toward the underlying top Hekkingen formation. Red colour on the north west is representing the slope and the crest of Loppa High structure.

The second isochore map is between the surface of top Hekkingen and the closest Flooding surface marker horizons above top Knurr formation (figure 5.7). The respective marker was chosen due to its nature which normally occurs in regional scale, thus it is continuous and can be traced throughout the whole basin area. Mean while, top Hekkingen Formation was the surface where it became the basin floor during Cretaceous submarine fans formation. by creating the isochore between these two surfaces, paleomorphology when the flooding surface marker event occurred, can be analyzed.

Large negative value of isochore is representing depression paleomorphology and vice versa. from figure 5.7, it can be seen that the paleomorphology is highly conformable with the top Fuglen formation and top Hekkingen formation structural surface map. The syncline depression located directly at the south of well 7122/2-1 was in the same location as well as the half - graben created at the north of well 7122/4-1. The similar features against underlying formation also showed that there is no significant tectonic event, in between the time of deposition on each formation from Fuglen formation until the deposition of flooding surface marker, which could create different structural morphology. Two additional lines were drawn at the paleomorphology map. Those two lines will be used on further analysis regarding the depositional timing between each submarine fans and any other deep marine deposit.

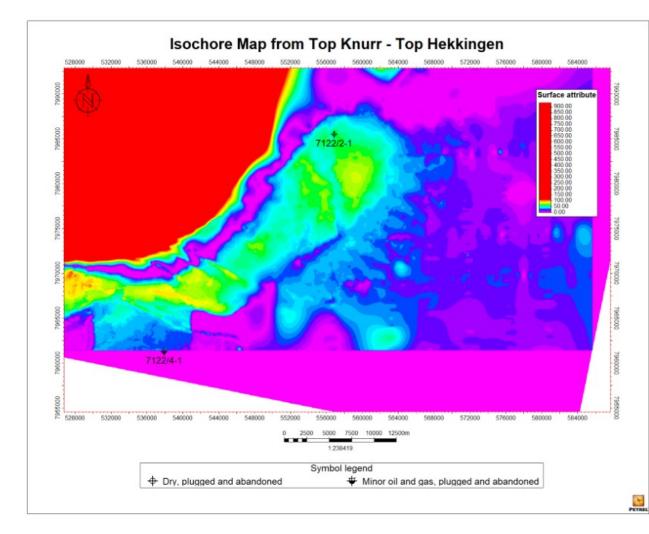


Figure 5.6: Isochore (depth domain) map of Top Knurr Formation until top Hekkingen Formation.

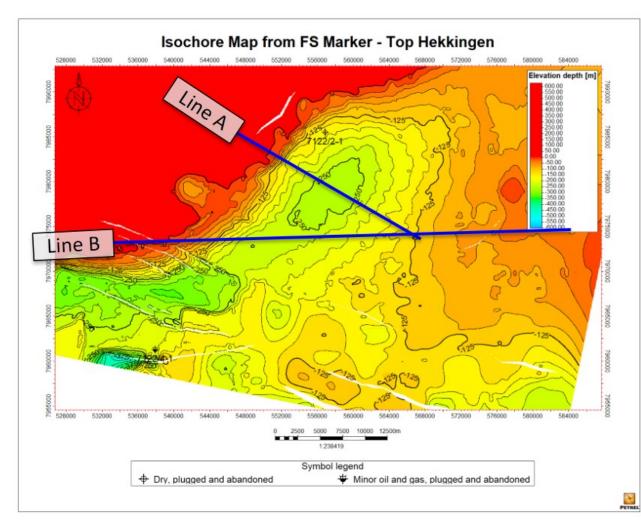


Figure 5.7: Isochore (depth domain) map of Top Flooding surface marker until top Hekkingen Formation. Line A is the location of figure 6.7, 6.8, and line B is the location of figure 6.11.

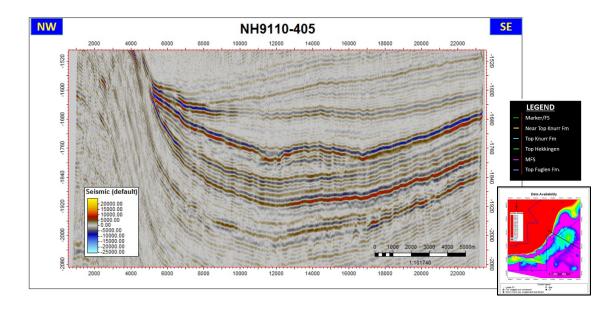
5.1.3 Internal Seismic Pattern

Internal seismic pattern identification was performed on several well representing the submarine growth in the study area (figure 5.8). Some of these lines were chosen due to its high vertical resolution and its location against the submarine deposit and any other deep marine deposit. There are two types of seismic internal configuration identified in this study, the first one was the termination pattern which resembled closely to the depositional process of each layer of submarine fans.

The first identified termination pattern on the proximal area was chaotic reflection. It is interpreted to portray deposit from depositional mechanism of sediment flow process which can be debris flow, turbidity flow or even both of the flow which was proven by Shanmugam (2002). moving toward basin ward direction, was mounded shaped bi - directional downlap feature which located near the base of the depositional surface. The amplitude strength of this feature is medium to weak reflection. It is interpreted to be the better sorting and finer grain of sandstone deposit compared to the deposit with chaotic pattern produced by sediment flow process. The next termination pattern is at the most distal location of the lower submarine fans layer which showed progradation pattern. The reflection strength of these features is relatively the same as the bi - directional downlap which is medium to weak reflection. It is interpreted as a possible finest grain size deposit compared to other deposit laterally which was deposited as a by pass sediment moving toward the basin ward.

There is another internal pattern which not considered as termination pattern. It is conformable and continuous pattern at the most proximal location. The anomaly has strong positive amplitude reflection. It is possibly related to initial deposit of sediment flow mechanism which has more immature deposit due to its position which is very close to the sediment conduit.

The second is the pattern which represented relationship from one layer against the another layer deposited before and after it. The pattern is in the form of small channel feature with the width of 1 km. The base directly below the channel has strong positive amplitude, while on the internal part of channel has low just about zero amplitude. the conclusion of categorizing the pattern as a result from channel erosional surface was deduced from discontinuity appears along two dashed yellow line (figure 5.8B). The dashed yellow line is interpreted to be a continuous line before it was being eroded by the channel feature came after. Another pattern is northwesterly onlap pattern toward the Loppa High structure at the top of the submarine fans surface. It becomes one of the limit defining the submarine fans geometry. Meanwhile, boundary on the opposite direction is downlap pattern on top of underlying submarine fans layer.



(A)

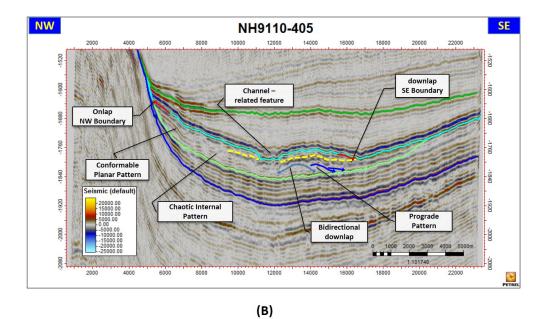


Figure 5.8: Internal seismic pattern characterization. (A). Uninterpreted section and, (B). Interpreted section along with the recognition internal pattern. Red arrows are showing the onlap feature toward the Loppa High, and downlap pattern toward the southeast direction. Dark blue arrows are showing progradation pattern and green is showing bi-directional downlap on two opposite direction.

5.2 Well Data Analysis

Data analysis from well was acquired to confirm the growth stage of submarine fans. The analysis included Log pattern identification and core analysis. These two methodology are closely related to each other, since one will confirm the other analysis. Detail scale of wireline log response and conventional core description, allows this study to analyze grain size growth sequence of submarine fans.

5.2.1 Log Pattern Identification

Log pattern identification was performed initially by looking at mainly on Gamma Ray log response in more larger scale (figure 5.9). In order to create an alignment against core analysis, log pattern analysis was conducted on the interval where conventional core was taken on the Knurr formation which is from the depth of 1833 - 1932 m MD. Gamma ray log was used in order to identify the grain size change along the vertical direction of submarine fans interval. High value of Gamma ray normally is used as shale indicator, nevertheless it can also be used in pointing out finer grain interval. On the other hand the low value of Gamma Ray indicates coarse grain interval. There are two groups of trend representing different vertical grains size change. The first is coarsening upward section represented by red diagonal arrows (figure 5.9), where Gamma ray log response is showing decreasing trend on the upward direction in a certain interval. Furthermore, second trend has the opposite trend than the first. It is showing increasing gamma ray log value upward in a vertical succession which resembles fining upward section.

Combination of several wireline logs pattern which are gamma ray, resistivity, density and sonic log was used in the second part of log pattern identification (figure 5.10). Several identified log pattern are:

- Base interval pattern (dark blue highlight area)
- Mid interval pattern (light red highlight area), and
- Top interval pattern (light green highlight area)

The base interval pattern is represented by dark blue highlight, showing an interval with relatively high gamma ray value, alongside with medium density log and medium sonic value. The lowest identified interval was at the depth of 1918.5 - 1923 m MD, while the similar pattern also appear between the depth of 1893.8 - 1895 m MD. Mid interval pattern lowest example depth was taken from the depth interval between 1908 - 1912 m MD. It was also found at several interval at the shallower depth until top of Knurr formation. Mid interval log pattern has relatively low gamma ray response, high density log value, and low sonic log reading (high velocity). The last group pattern is top interval pattern, defined as relatively medium gamma ray reading, medium density log response and medium sonic log value. It is spreading from the bottom log interval where the core was taken until the top of Knurr formation, but the lowest examined depth for this pattern emerged at the interval of 1900 - 1908 m MD. In order to create a distinct range on degree of log reading, the following table 5.1 is provided. Notice that medium value means

it is measured compared to overall trend value in Knurr formation. Mean while, if it measured between interval categories, medium value could also mean low log reading value.

Table 5.1:	Log reading	range value	e for log	pattern	identification.

Type of Log	Low	Medium	High
Gamma Ray (API)	40 - 45	56 - 62	75 - 95
Density Log $(g/cm3)$	2.15 - 2.2	2.25 - 2.35	2.45 - 2.65
Sonic Log (us/ft)	55 - 65	70 - 75	80 - 86

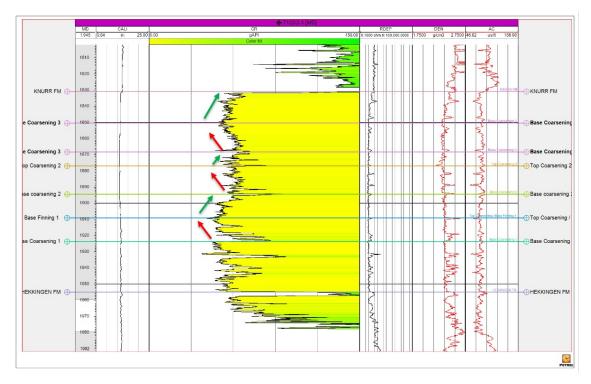


Figure 5.9: Grain size changing pattern identification from interval 1832 m to 1923 m MD (Knurr sandstone interval) from well 7122/2-1.

5.2.2 Core Description

Core description is an important method in validating the log pattern identified and discussed on the previous section. Any log responses and reading which corresponding particular pattern will be defined physically by correlating with the core description. Due to that matter, the description was executed at the same interval where the conventional core was taken. Any interval beyond the limit of core sample will be assumed to have same description core if it has same log pattern configuration. The analysis will be discussed following the sequence of ideal geological deposit which from the lower level interval.

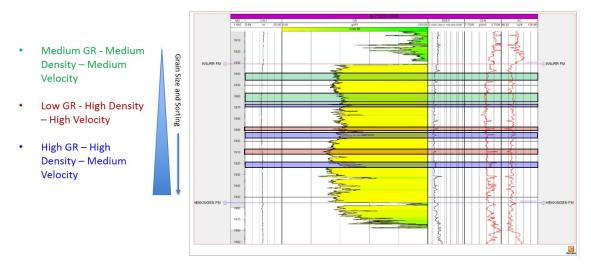


Figure 5.10: Log pattern identification from interval 1832 m to 1923 m MD (Knurr sandstone interval) from well 7122/2-1.

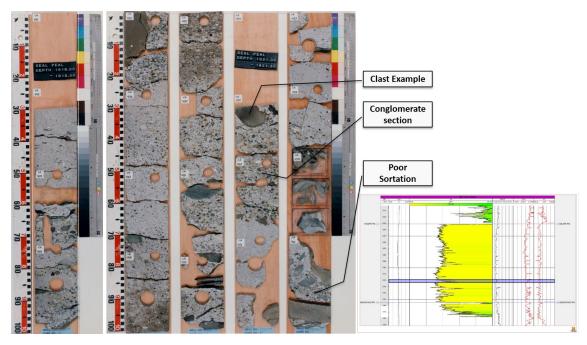


Figure 5.11: Core description from interval 1918.5 m to 1923 m MD (Knurr sandstone interval) from well 7122/2-1.

The first description is where the base interval pattern is located (figure 5.11). Based on core photos, the interval is composed generally by greyish colour. From sedimentation feature, there is no visible sedimentation structure obtained from this interval. It has poor grain sorting where the large grain and fine grain was deposited in irregular sequence at the most of the interval. Poor grain sorting condition on this interval leads to decrease in porosity since small grain mixed together along with larger grain and filling intergranular porosity. Hence, the density log reading of this interval is slightly high (medium density) due to poor sorting condition. On the other hand, sonic reading gives moderate or medium value compare to the other two pattern interval. It is possibly due to unconsolidated condition between grains on this interval, which is shown by grain debris pieces in most part of the core.

The large visible grain has the dimension between 5 - 10 cm at one of its axial length. It is interpreted as floating clast fragment from other rock as its original source. The respective condition with various range of grain size in one interval possibly yielded from gravity driven sedimentation process as debris flow or turbidity flow. From those two options, debris flow is chosen due to the existence of floating clast fragment from other rock source based on figure 2.8 from Shanmugam (2006). Some of visible clast are possibly from sandstone, mudstone and bio - clast. The presence of mudstone, claystone or any clay mineral in a floating clast fragment could create high gamma ray log value reading which is consistent with log pattern for base interval section. Moreover, there is intervals with medium grain size categorized as pebble grain size (more than 2 mm), forming conglomeratic rock interval.

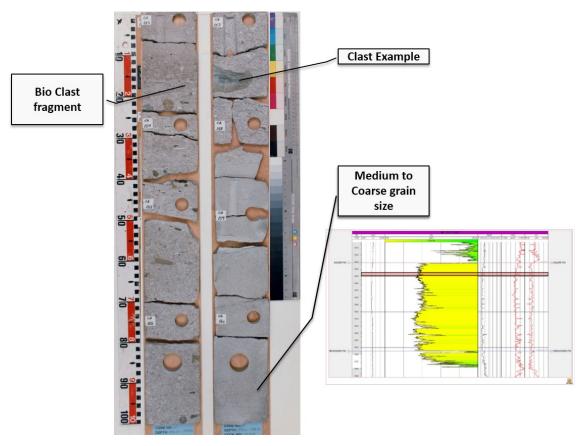


Figure 5.12: Core description example for mid interval pattern from the depth between 1846 m to 1848 m MD (Knurr sandstone interval) of well 7122/2-1.

The second description is on mid interval pattern, shown by the figure 5.12. It has light greyish colour with some dark brown colour in several centimeters of interval. There are some floating clast fragment scattered sparsely, surrounded by finer grain size. Finer grain size (coarse grain size in dimension) is dominated by clean sandstone interval in grey colour and minor mudstone with skeletal fragment on the brown colour interval. The Domination of clean sandstone interval created low value of gamma ray reading compare to the other two pattern interval. For sedimentation mechanism, even though the occurrence of floating clast fragment is not significant, debris flow process still influence the depositional process for this interval.

Generally, this interval has medium to good grain sorting, where the best sorting intervals are dominated by light grey colour. Better grain sorting normally generated

larger porosity. However, based on the core photos, this particular interval seems to be more solid than the base interval. This is probably the factor causing the density log reading is higher along with lower value of sonic log (increase in velocity).

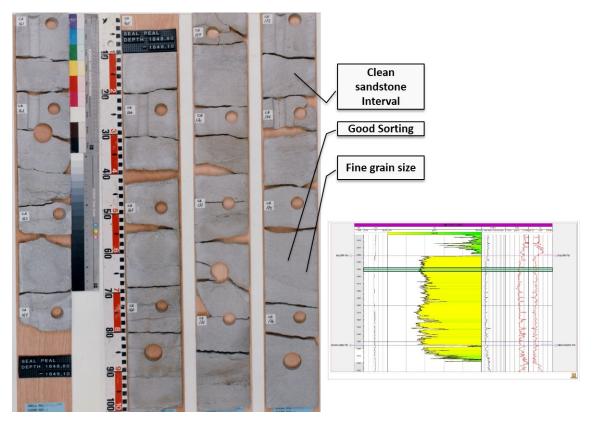


Figure 5.13: Core description from interval 1848 m to 1852 m MD (Knurr sandstone interval) from well 7122/2-1.

The last identified log pattern interval is top interval pattern (figure 5.13). Similar to the other underlying pattern, top interval section is dominated by grey colour interval. However, the difference is the domination of clean sandstone interval with no floating clast fragment. Due to that matter, it is sufficient to take initial interpretation that there is no influence of debris flow due to the absence of floating clast fragment. Although there is no evidence in debris flow, there is still possibility of having the influence from turbidity current mechanism. Clean sandstone interval created relatively low gamma ray reading compare to the other interval, yet it is consider to have medium log reading value if it compare toward overall gamma ray trend in Knurr formation. moreover, good sorting condition created more porosity which resulted in low density log value and low velocity log reading.

Chapter 6

Discussion

Seismic and well study presented on the result section have produced pieces of basic information in supporting several points of discussion on the following chapter. Seismic study gives regional description both from submarine fans growth point of view and paleomorphology reconstruction. Meanwhile, well data analysis provide validation on what have been seen on regional scale and give more detail scale of analysis.

The discussion chapter is divided into six sub chapters. In the first discussion, submarine fans geometry will be examined, therefore the analysis of lateral distribution will be defined. In the second discussion, depositional environment will be confirmed by combining several evidence with the existing study on Loppa High. In the third discussion, submarine fans growth will be constructed, thus combination of well data analysis and seismic interpretation will be used. In the fourth discussion, control of submarine fan growth will be discussed, hence basin floor morphology will be analyzed. The fifth discussion will focus on constructing submarine fans uniquely defined for Loppa High area, and the last discussion will talk about the implication on hydrocarbon prospectivity in Loppa High - type of geological setting.

6.1 Submarine Fans Geometry

Single submarine fans body visible in seismic fans may be constituted by multiple phases of depositional stage. Each of the phase possibly differ in term of lateral distribution across the basin floor. In order to visualize each of depositional growth along with its lateral distribution, submarine fans body geometry need to be defined as an initial step. Additionally, knowing submarine fans geometry will provide beneficial information in understanding hydrocarbon prospectivity, especially factors related to trap and seal component in petroleum system.

In establishing submarine fans geometry, component confining the limit of fans lateral distribution need to be explicitly described. It was done by interpreting certain signs available at every direction of fans distribution. The first identified sign came from thickness distribution which pictured by isochore map (figure 5.6). Thick deposit of submarine fans normally has concave downward - mounded shape. This ideal description of fans shape provide preliminary guess of how is fans distribution should look like in thickness map. It supposes to have thinner thickness both on proximal and distal area, while stacked of thick interval concentrates in the middle. Based on that illustration, numbers of fans body possibility are presented by figure 6.1 symbolized by the coloured dash lines.

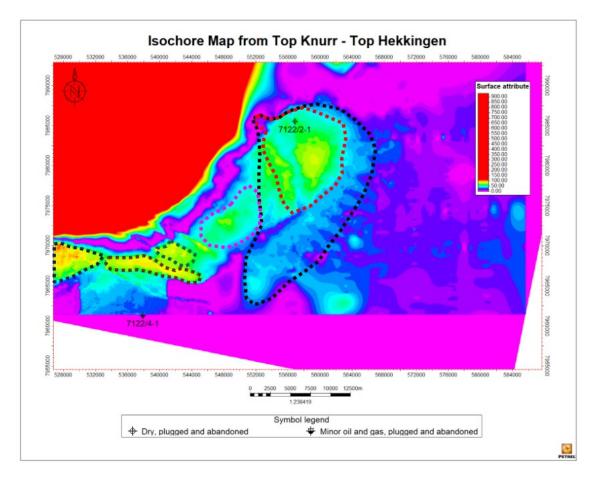


Figure 6.1: Isochore map between top Knurr formation until top Hekkingen formation. Coloured dash lines are representing possible submarine fans deposit along the south slope of Loppa High structure.

The second recognizable signs are combination of termination pattern on seismic section and changes in reflection amplitude laterally. Several termination pattern, especially those which located at the most proximal and distal area, have been identified in figure 5.8. Since one of the purpose in this study is to construct new submarine fans system model, the focus in mapping submarine fans geometry will highlight mainly the submarine fans deposit at the eastern side of our study area. Less fault influence in shaping both basin morphology and yet fans geometry was the main consideration focusing on this area. From the respective figure, it can be roughly divided two pairs of termination pattern which are bottom and top pair. Figure 6.2 gives additional remarks in describing termination pair location. furthermore, Each of point at the end of termination pattern pairs is marked on all 2D line section and map it on the isopach map. The result can be seen as two submarine fans geometry depicting bottom and top termination pair (figure 6.3).

In between top and bottom pair of termination pattern, there is void area where it

does not have obvious termination pattern as its distal boundary. Meanwhile, In the proximal area, it is bounded by conformable planar pattern onlaped into the slope of Loppa High structure. There is possibility that it might continue laterally way further from the slope merely from seismic line in figure 6.2. however, Figure 6.4B is showing seismic line with E-W orientation which has distinct thinning pattern of Knurr formation interval into basin ward direction. Although it might be caused by different vertical resolution between seismic line in figure 6.2 and figure 6.4, gradual thinning pattern toward the basin is clearly defined on the rest of regional 2D seismic line. As the consequences, there might be any vague sign, marking submarine fans distal limit on figure 6.2. One of the possibility is change in lateral reflection amplitude when Knurr formation went thinner and then pinched out into Hekkingen formation. Knurr formation layer thickness might go below vertical resolution limit, as it is very difficult to separate the reflection amplitude between top Knurr formation and top Hekkingen formation. By mapping some of these lateral amplitude change, limit of mid interval fans is described as yellow dash line in figure 6.3.

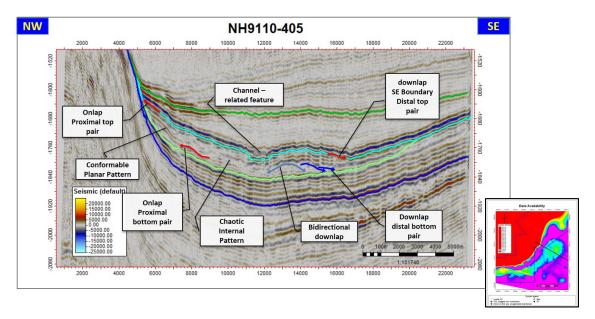
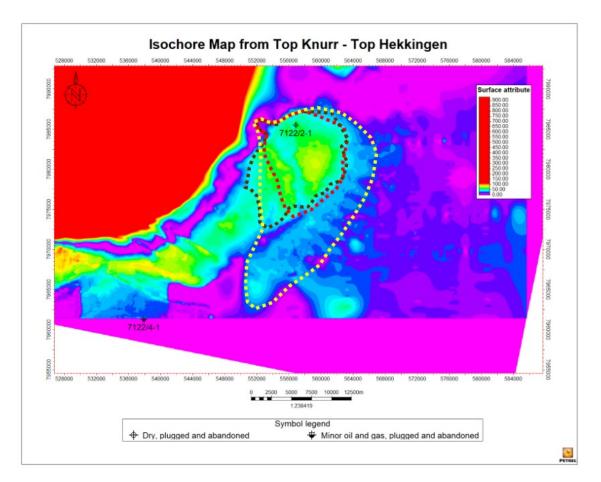


Figure 6.2: Identification of termination pattern on seismic section to define submarine fans geometry. For analyzing uninterpreted section of the same seismic line, please refer to figure 5.8A.

While NW-SE direction fans limit has been defined, there is uncertainty regarding boundary in between one fan body to another on NE-SW direction. figure 6.5 is showing the seismic line oriented in NE-SW direction which is parallel with the slope direction and perpendicular to initial sediment supply direction. As it is shown on the respective figure, NE boundary toward Loppa high slope structure is marked by the start of onlap termination pattern. Meanwhile, there is no obvious visible termination pattern on the SW boundary. In this case, lateral internal pattern change combined with thickness variation is used to delineate the SW boundary in between fans. Based on thickness map in figure 6.3, there is slight change in thickness which is thinning toward SW part of black dash line outline. It is consistent with the lateral change of internal seismic pattern which goes from chaotic pattern to strong continuous planar reflection toward the SW direction in figure 6.5. Moreover, this boundary will be validated with more evidence during the submarine fans growth



discussion on the next sub chapter.

Figure 6.3: Submarine fans geometry outline from bottom and top pair termination pattern, overlying Isochore map between top Knurr formation until top Hekkingen formation. Red dash line is representing top pair of termination pattern, while black dash line is portraying bottom pair termination pattern. Additionally, yellow dash line is depicting mid interval pair of termination based on change in reflection amplitude laterally.

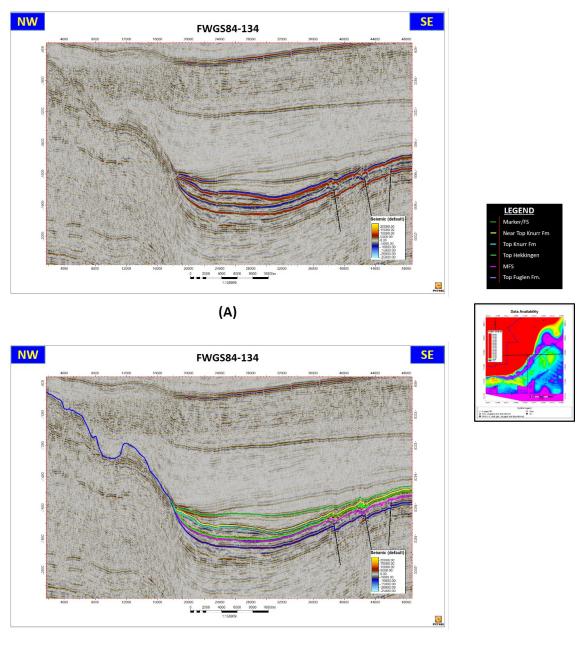
In conclusion for submarine fans geometry, Regionally, based on figure 6.1 there are two type of submarine fans geometries. The first type is accumulated on the western part of Loppa High structure where it is dominated by ideal fans shape deposit or simply a slight fan-shaped geometry of fans. Meanwhile, on the southern of Loppa high structure is dominated by fans which shape is elongated toward NW-SE until almost E-W trend direction.

6.2 Depositional Environment

Submarine fans deposit has particular depositional area which normally can be found on the deeper part of basin near the shelf slope break. The occurrence of these deposit are vast in time range, it means it can be deposited anytime. However, there is time when it is deposited and contains more high sandstone to shale ratio, which is during relative sea level fall condition (Posamentier & Vail, 1988). Moreover, relative sea level fall condition also support the accumulation to be concentrated at the end of shelf slope break area. Therefore, defining depositional environment for submarine fans is crucial to obtain prolific sand reservoir. In term of submarine fans growth sequence, depositional environment is important to justify sedimentation mechanism plays during submarine fans formation. By knowing the sedimentation environment and mechanism, submarine fans distribution and yet its overall stacking body can be defined in more detail fashion.

There are several existing literature which defined depositional environment of Cretaceous submarine fans in our study area. Nonetheless, the results are still divided into different depositional environment. Marin et al. (2017) interpreted the Knurr formation as coalescent fan deltas based on description from Dabrio (2009). Meanwhile, based on biostratigrahic report made by Halliburton in Sempre and Sørheim (1993), suggested that Early Cretaceous deposit was formed at the area between shallow marine inner shelf environment for the bottom level and marine shelf environment for the rest of Cretaceous interval. Analysis related to deep marine environment came from Sattar et al. (2017) who concluded that Early Cretaceous deposit was formed during relative sea level condition at the base of slope break. Furthermore, blocky gamma ray pattern along with sharp contact at the top formation indicating massive turbidite fan lobes deposit.

Based from core description on Knurr formation interval, there are plenty of evidence regarding floating clast fragment in some interval which sequentially occurred (figure 5.11, 5.12, 5.13). Floating clast fragment is evidence of one of sediment flow mechanism which is debris flow instead of turbidity flow (Shanmugam, 2006), and debris flow is one of sedimentation mechanism which acquired gravity influence during the process of deep marine sedimentation. Moreover, based on Shanmugam (2006), there is possibility of having influence from turbidity current mechanism in the deposition process, as both debris flow and turbidity flow may occur at the same time. Combining information both from Sattar et al. (2017) and core description, it can be confirmed that Early Cretaceous deposit near Loppa High slope break was deposited during relative sea level fall condition on deep marine setting.



- (B)
- Figure 6.4: Seismic section of older seismic acquisition year which parallel with the slope trend. It is showing thinning pattern of Knurr formation toward basin direction.

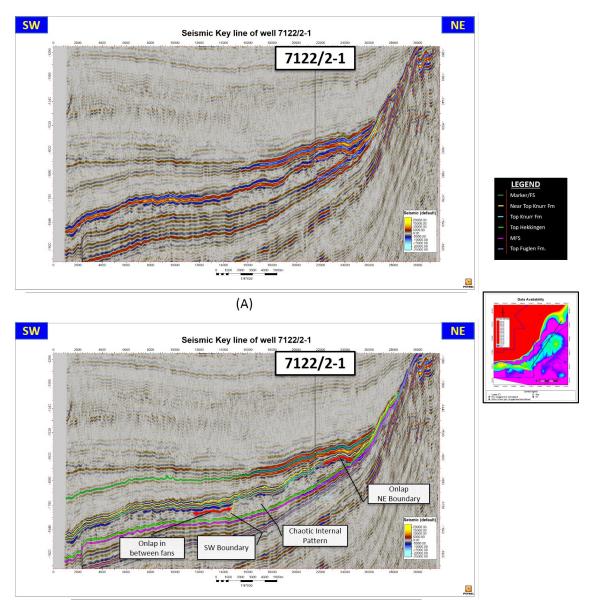


Figure 6.5: Seismic section which trend is perpendicular with the slope. It is difficult to separate the boundary between submarine fans and mass wasting deposit nearby, only based on termination pattern.

6.3 Submarine Fans Growth

Submarine fans commonly have at least three evolution sequences which are submarine fans initiation, growth and retreat (Gardner et al., 2003). In some of study, the evolution sequences framework covered a wide area from channel conduit in the proximal distance until unconfined channel area filled with lobe complex deposit at the distal basin floor (Hadler-Jacobsen et al., 2005). By understanding the evolution sequences will help to predict prolific reservoir accumulation location in a submarine fans system. Each evolution step happens due to combination of change in relative sea level, tectonic activity, and amount of sediment supply on drainage source area.

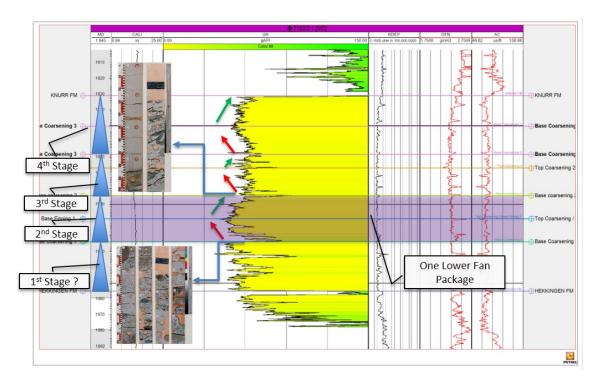


Figure 6.6: Well data analysis in understanding number of depositional sequence occurred in Knurr formation interval. Combination between core description and wireline log pattern are used in this analysis.

Initial step in defining evolution step in this study started by determining number of depositional sequence occurred based on combination between core description data and well log data. Figure 6.6 is showing compilation of both previous analysis. Based on submarine fans model from Sarg and Skjold (1982) (figure 2.14) on lower fan facies, it is comprises by two different log pattern. The base which is outer fan has coarsening upward log response, while the upper layer which is inner fan possesses fining upward succession. Combination between these two responses are forming a single lower fan sequence. The thickness which Sarg and Skjold (1982) used in describing lower fan facies are in between 30 - 50 m. Meanwhile, in this study, one single lower fan sequence has thickness between 30 - 40 m. Therefore, it is reasonable, in term of thickness scale, to use Sarg and Skjold (1982) model in our study.

Combining with core description, the location of interval which has significant floating clast fragment, coincided with the start of each lower fan sequence. It can be interpreted that in the beginning of each lower fan sequence, new sediment flow eroded the base of the canyon and produced large clast fragment as its initial result. The other possibility is that the floating clast fragment came from slope instability condition which occurred at the initial step of sediment delivery into the basin. From these analysis, can be concluded there are at least three sequence of lower fan facies constructing Knurr formation in between the interval where the conventional core was taken. Each of lower fan sequence has range of depth between 35 - 50 m. And at the beginning of a single lower fan sequence is marked by the occurrence of floating clast fragment deposit in considerable amount.

Further step will be analyzing sequence based on available seismic pattern. From

previous analysis on geometry, there are three pairs of layer packages based on termination pattern and change in amplitude reflection. Based on this analysis, sequences describing submarine fans evolution in Loppa High are constructed. The first sequence is depicting fans initiation process figure 6.7A. It is defined based on the bottom pair termination pattern. Fans initiation process was started by filling basin paleomorphology with initial sediment influx came from the canyon. The lateral distribution of this phase reach the distance of approximately 12.5 km in the direction parallel to the slope and 10 km at perpendicular direction of the slope. Sediment accumulated more in the same trend direction as basin depression near the slope which acted as barrier for the sediment to go further.

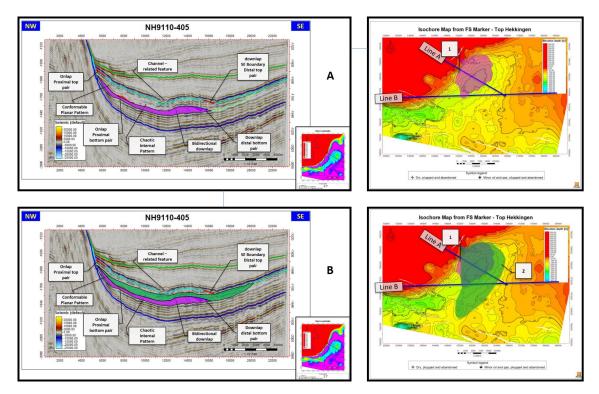


Figure 6.7: Illustration of submarine evolution stages derived from seismic pattern (left image) and plotted on underlying paleomorphology map (right image). A. Initiation phase. B. Growth phase. Note that the colour on seismic section is used on the same layer distribution when it is plotted at the map. For the uninterpreted seismic section please refer to figure 5.8. Number in each white box is showing the sequence order of when each deposit was formed instead of evolution order.

The second phase is growth phase where the limit is defined based on termination pattern on the limit toward the slope of Loppa High and change in reflection amplitude as the layer pinched out toward the basin direction. Accumulation of submarine fans during this stage expanded both in lateral direction and stacked vertically (figure 6.7B). However, lateral distribution showed more significant evolution compared toward vertical direction. It reached the radius of 25 km on the longer axis and 15 km on the shorter one. Similar condition occurred where the elongation trend of the growth phase tend to follow local depression near the slope. Factors controlling how far sediment distribution at this stage will be explained on further sub chapter.

The third phase is interpreted as submarine fans retreat and it is bounded by the

top pair of termination pattern, limited the boundary of the lobe (figure 6.8A). Retreat phase is determined since the distal downlap defining outer limit of the lobe, appeared closer to the slope than the outer limit of the growth phase. On this stage, the accumulation is stepping back toward the basin slope. The amount of sediment deposit seemed to be decreased in both lateral and vertical direction.

The fourth phase is the forming of initial process related to upper fan facies based on Mitchum (1985) model (figure 6.8B). It is marked by erosional feature formed by channel forming process (figure 6.9). However, due to seismic vertical resolution, it is difficult to predict whether the channel filled by any sand - rich deposit. There is possibility that the channel had not been filled by sand-rich deposit. It is due to non - existence of levee area formed at the edge of channel. Based on channel levee forming evolution sensu (Sylvester et al., 2011) (figure 6.10), the initial state will be marked by single channel form with no levee at the edge. Since the channel, leveed and channel fill have not had sufficient time to form, dramatic relative sea level rise possibly was the culprit in creating the respective condition.

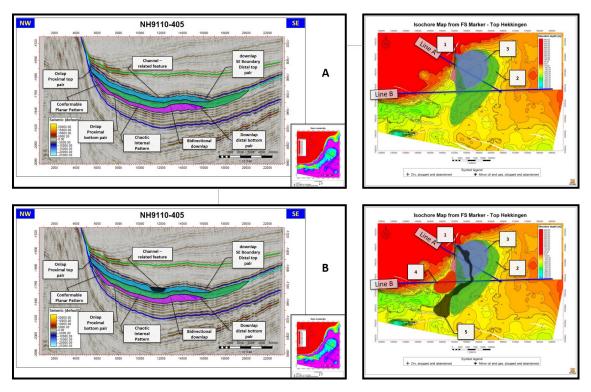


Figure 6.8: Illustration of submarine evolution stages derived from seismic pattern (left image) and plotted on underlying paleomorphology map (right image). A. Retreat phase. B. Erosional event as part of initial upper fan process. Note that the colour on seismic section is used on the same layer distribution when it is plotted at the map. For the uninterpreted seismic section please refer to figure 5.8.

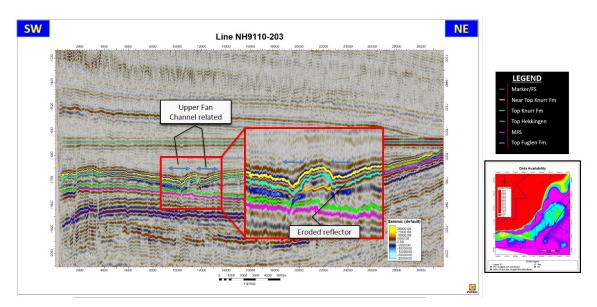


Figure 6.9: seismic section showing erosional feature created by channel forming process as part of Upper facies initial formation. The section is flattened at the flooding surface regional marker to illustrate paleocondition when the fans was deposited.

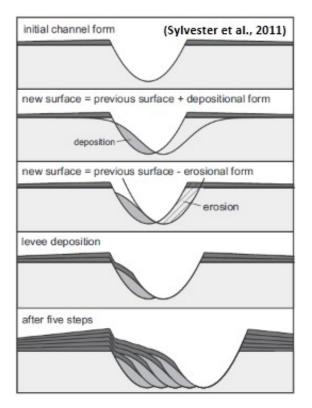


Figure 6.10: Model of channel levee evolution by Sylvester et al. (2011).

Beside submarine fans deposit, there is another adjacent deep marine deposit. It is marked by the number of 4 in figure 6.8, which is the number of deposition sequence order, not the number of evolution stages. It is interpreted as deep marine deposit which source came from slope instability that lead to slump process. Base on its deposition sequence order, it means that this deposit was formed after second deposition sequence order, which is the growth phase. The evidence of this concept is based on figure 6.11. In the mentioned figure, top of mass transport deposit (slump) is downlaped onto the top of growth phase. However, there is no clear evidence proofing slump deposition sequence order against another evolution stage (i.e retreat phase and erosional process). The location of the source of the slump will be shown later on the next sub chapter.

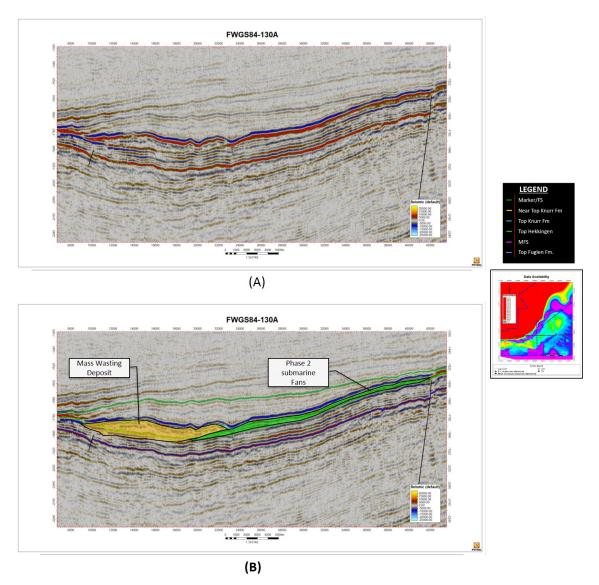


Figure 6.11: Seismic section showing sequence order between mass transport deposit occurrence toward phase 2 submarine fans evolution (growth phase). The location of this line also mentioned in paleomorphology map as line B (figure 5.7, 6.7, 6.8).

Finally, to summarize this sub chapter, it can be concluded that submarine growth can be explain by two sequence order. The first one is fan evolution phases which

order as following:

- 1. Initiation phase
- 2. Growth phase
- 3. Retreat phase
- 4. Erosional channel as part of upper fan facies initiation

The sequences above are possibly showing consistency toward the depositional sequences found from well data analysis. The first sequence from well, which is not covered by conventional core data may related to initiation phase, while the second and third sequence on the well may related to the growth phase, and the fourth sequence from the well may related to the retreat phase. There is no correlation against the erosional channel phase since the well used in this study did not penetrate the respective feature.

Meanwhile, from depositional sequence order point of view, the order are as following:

- 1. Initiation phase deposit
- 2. Growth phase deposit
- 3. It could be between retreat phase deposit or slump deposit
- 4. erosional channel

6.4 Factors Controlling Submarine Fans Growth in Southern Loppa High

6.4.1 Source condition

The factors controlling deposition of deep marine deposit such as submarine fans have been studied considerably. Some of the main factors are source condition, transfer system and morphology of the basin during the deposition (Lien, 2005; Færseth & Lien, 2002). Loppa High has been recognized as drainage area where the source sediment originally came for sediment accumulation on basin floor in the south since Late Jurassic to Cretaceous. Uplift - induced tectonic activity and relative sea level fall were the reasons exposing Loppa High structure which followed by deep cutting erosional channel (Faleide, Vågnes, & Gudlaugsson, 1993; Richardsen, Vorren, & Torudbakken, 1993; Miller et al., 2005). Additional information from this study is regarding how many sediment delivery sequence order occurred in forming the east submarine fans. Our previous discussion showed that at least four delivery sequences were performed during the deposition of Knurr formation.

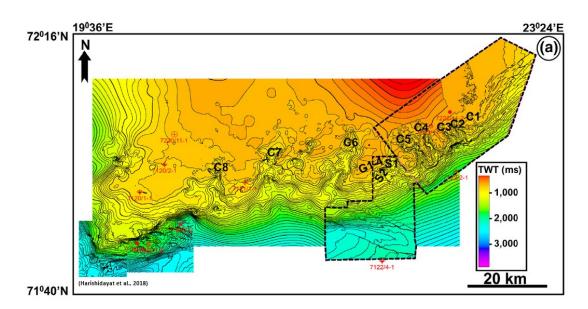


Figure 6.12: Time structure map of base sediment conduit system in south Loppa High (Dicky et al., 2018).

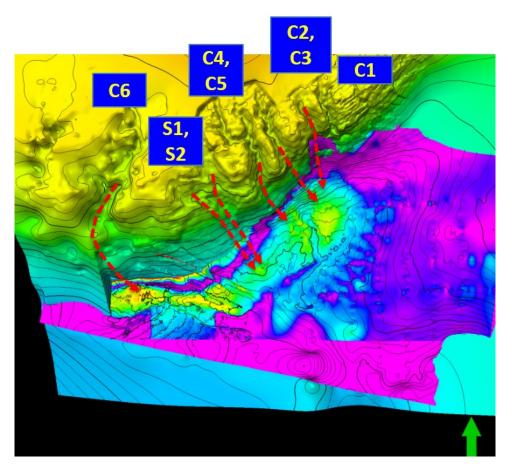


Figure 6.13: Time structure map of base sediment conduit system in south Loppa High from Dicky et al. (2018), overlaid by isochore map of Knurr sandstone. Red dash lines are showing sedimentation direction on each deep marine accumulation

6.4.2 Sediment transportation system

Large amount of sediment from Loppa High was transported down to the basin through Canyons, gullies and slide scars during Late Jurassic - Cretaceous (Faleide, Vågnes, & Gudlaugsson, 1993; Marin et al., 2017; Wood et al., 1989). All of sediment conduit in Loppa High suffered from three evolution starting from Late Jurassic until glaciation time on Late Pliocene - pleistocene. Dicky et al. (2018) have recognized, mapped and named all available sediment conduit type important in transportation system in Loppa High area (figure 6.12).

From available eight canyons, two slide scar and four gullies, our study area is intersected by six canyons and two slide scars (figure 6.13). Based on its proximity, it is interpreted that 6 canyons were responsible in delivering sediment which then became submarine fans. Submarine fans on the east was receiving sediment from C2, C3, C4, and C5, while fault oriented submarine fans on the south has sediment conduit from canyon C6. Using the same assumption, slide scars is interpreted as the source of mass wasting deposit (possibly as slump deposit) at the south of our main. Recognition of multi source conduit in this area is important in building submarine fans model particularly for Loppa High geology setting.

Additionally, multi source conduit origin is also identified from variance attribute time slice map between time at 1590 - 1650 ms at the top of submarine fans (figure 6.14). Multiple channels feature appear at proximal top surface of submarine fans whilst there is discontinuity of feature toward the end of canyon mouth. Later, the multiple channels possibly merged and formed large single channel as upper fan facies initiation process. Although there is uncertainty of this interpretation due to limited coverage of generated variance map on 3D seismic data.

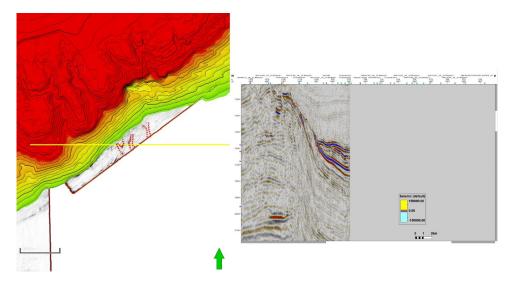


Figure 6.14: Time slice of Variance attribute at time 1590 - 1650 ms, underlying time structure map of base sediment conduit system in south Loppa High from Dicky et al. (2018) (Left). Seismic section intersected on the yellow line (right). Red dash lines are interpreted channel system formed near the end of canyon mouth.

6.4.3 Receiving basin morphology

Distribution of submarine fans in this area is greatly influenced by the combination of amount of sediment supply and receiving basement morphology. Lien (2005) showed that morphological basin evolution influenced the submarine fans geometry and lateral distribution. Furthermore, based on its lateral distribution, prediction of prolific sandstone reservoir location can be made.

In our study, The initial basin morphology had local depression in the trend of NE-SW adjacent to slope end (figure 6.7A). The respective feature became a barrier which prevented the arriving sediment deposited further away to the basin floor. As the result, the fans initiation phase is localized filled in the local depression. On the next phase, which is fans growth phase, the local depression had been filled by the previous sediment deposit and created flatter morphology. Due to that condition, it is interpreted that the following sediment could bypass and deposited further (figure 6.7B). However, the elongation bent following the depression trend to the SW soon after it reached the end of filled depression. The change in basin morphology was possibly the likely reason in further and bent deposition of the growth phase.

On the contrary, the retreat phase seemed to be influenced by the decreasing amount of sediment supplied to the basin (figure 6.8A). The interpretation was made due to the fact that, during this time, the basin morphology was no longer being restricted with the initial local depression due to previous sediment deposit. Yet, the sediment accumulated really closed to the toe of the slope which then supporting the idea of decreasing amount of sediment supply. Additionally, the last fans evolution phase, which is upper fan facies related channel, is interpreted as a product of rapid relative sea level rise due to non existing levee.

6.5 Submarine Fans New Model

Deep marine system in defining hydrocarbon reservoir has been heavily studied. The existing model came with different point of view, from grain sorting variation, different slope gradient, until number of source feeding system. However, there is no ideal model for each submarine system in the world (G. Walker, 1978; Richards et al., 1998). In this study, submarine fans depositional model is constructed in order to accommodate basement uplift related slope and source area. Unique character of Loppa High geological setting and its submarine product, generated submarine model figure 6.15 which was defined based using combination of several existing models by Richards et al. (1998); Mutti (1979); Sarg and Skjold (1982); Hadler-Jacobsen et al. (2005); Dicky et al. (2018).

Initial step in building submarine fans is identification of each character. Most of characters in southeastern Loppa High resemble sand-rich system submarine fans by (Richards et al., 1998). The first observed categories are related to its physical morphology which are lateral distribution, thickness and structural geometry. Submarine fans has thickness of 123 m on Knurr Formation. Lateral distribution of

the fans merely reached not more than 15 km. It is probably due to nearshore littoral drift as in Haner (1971) and low efficiency character in Normark (1978) which categorized near-slope submarine fans is caused by both factors mentioned. The previous characteristics are consistent by the model described by Richards et al. (1998), however, based on the present geometry position, it does not has natural structural trap as it has been seen at most of the examples.

From sediment feeder system, submarine fans deposited in our study area, have multiple source canyons (figure 6.13). It is does not resemble the similar character as the model in Richards et al. (1998) grouped sand - rich submarine fans as a product of single feeder system. Although the evidences of canyons contribution as sediment conduit is valid in this case, there is no evidence of continuation of any sediment conduit in between the end of canyon mouth with the proximal submarine fans body. As the result, it is interpreted that soon after sediment reached the end of the canyon, it fell and deposited from high gradient of slope into the basin, through debris flow mechanism. Evidence of debris flow influence was found in conventional core sample as floating clast fragment.

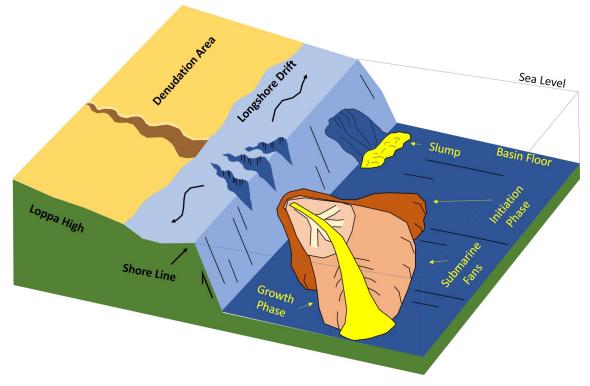


Figure 6.15: New submarine system model for southeastern Loppa High geological setting which related to basement uplift process. Modified from (Dicky et al., 2018).

Based on basin characteristic, Southeastern Loppa High has relatively high slope gradient. It became one of the factor, beside source drainage area, which determine the location of fans accumulation. Hadler-Jacobsen et al. (2005) identified several characteristic which similarly appear in this study:

• Submarine fans has three stratigraphical cycles, the first is a basinward stacking pattern filled in existing basin topography, the second id the most extensive distribution across the basin, and the third is shelfward stacking pattern. All of these cycles are considered as three evolution phase, consist of initiation phase, growth phase and retreat phase (Gardner et al., 2003).

- High shelf-to-basin-relief tend to have lack of slope and shelf progradation as its appears in submarine fans related delta.
- Prolific high sand to shale ratio accumulates at the toe of the slope.

As a conclusion, the unique setting of submarine fans system related to basement uplift in Loppa High, may close to what has been described as sand-rich submarine fans system based on Richards et al. (1998). However, there are some inconsistency in some of the classification as example in the number of feeder system which in this case has multiple source system instead of single source system. The other significant variation is the tilting present structure of submarine fans. It is probably due to continuous basement uplift occurred multiple time from Late Jurassic until Pliocene and Pleistocene (Dicky et al., 2018). At the end, the respective variation may have contribution to hydrocarbon prospectivity on this area.

6.6 Hydrocarbon Prospectivity Implication

Based on petroleum system, area at the south of Loppa High structure has prolific potential for hydrocarbon accumulation. Reservoir properties on Knurr formation in well 7122/2-1 are showing good and high sand to shale ratio sandstone reservoir. Although it is proven as water bearing reservoir, tested Knurr formation still hold good permeability of about 600 mD (Sempre & Sørheim, 1993). Beside the reservoir properties, significant thickness made Knurr sandstone to be a potential reservoir. Along with good quality of Hekkingen shale as source rock, Knurr sand - rich submarine sandstone should have been a potential area holding large amount of hydrocarbon accumulation.

However, Water bearing conclusion on Knurr sandstone interval clearly send a message that there is petroleum system element which is not working. (Knutsen et al., 2000) observed that the failure of well 7122/2-1 had something to do with the occupation of gas on Knurr formation before the Oil generated from Hekkingen shale migrated. Since gas has higher partial pressure than oil, it kept oil stay in Hekkingen formation even after secondary migration timing had ceased. Later on, the gas occupied in Knurr formation escaped due to seal failure on Kolje formation. The gas could be originally produced from Triassic source or migrated from Late Jurassic source rock in the west.

Meanwhile, Sattar et al. (2017) revealed the role of seal failure due to eroded seal layer of Hekkingen shale at the proximal area where the submarine fans are positioned updip toward the slope area. Moreover, there is another possibility in the form of sand thief of Kolje formation and by sand injectites feature directly above the Knurr formation.

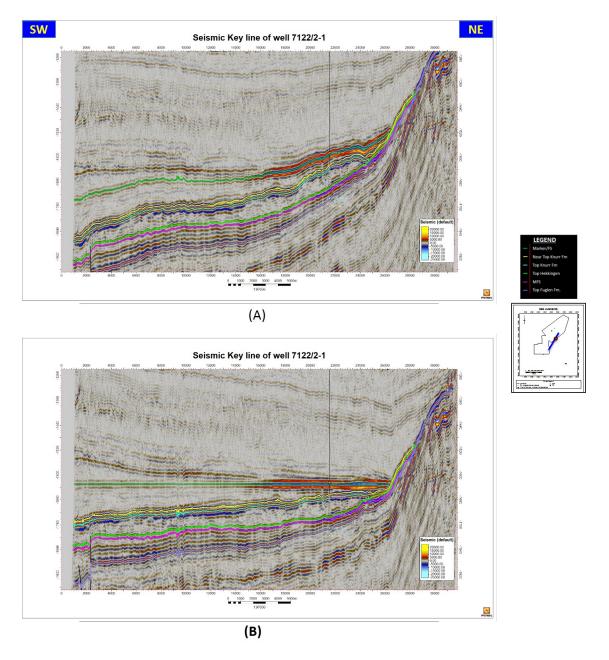


Figure 6.16: Seismic sections showing different structural condition. (A). Present structural condition experienced from uplift post deposition of Knurr formation. (B). Paleo structural condition, flattened at flooding surface marker just near top Kolje formation.

Post drill analysis both from Knutsen et al. (2000); Sattar et al. (2017) mentioned about the role of seal failure of petroleum system in 7122/2-1. In this study, the author wanted to make simple additional analysis regarding the seal failure condition. The following analysis will be very close related with the concept which Sattar et al. (2017) mentioned. Figure 6.16 is seismic section showing the same line with different time which intersected the well 7122/2-1 in SW-NE direction. on the A part, it is representing present structural condition where the submarine fans is tilted updip toward the slope area. However, on figure 6.16B, the section is flattened on flooding surface marker near Kolje formation, in order to examined paleo morphology just after the submarine fans was deposited. Based on the flattened section, the original geometry of top submarine fans was flat. Since the submarine fans is pinched out both on proximal and distal area, it is probably creating structural trap instead of stratigraphic trap. it is consistent with the observation from (Richards et al., 1998) which stated that sand-rich submarine fans, naturally has structural trap geometry.

The change in trapping system related to the evolving geometry through time, is possibly due to the tectonic activity, created several chapters of basement uplift in Loppa High structure. As we discussed earlier, the uplift processes occurred from Late Jurassic until Pliocene - Pleistocene. One of uplift event possibly made proximal Knurr sandstone geometry tilted toward the slope area. Afterward, the tilting position supported seal failure process to occur and reducing geological chance of success as the trap element in petroleum system is no longer favourable.

Chapter 7

Conclusion

7.1 Conclusion

The goals of this study is to understand submarine fans reservoir growth of Knurr formation, in term of evolution phase and depositional sequences in southeastern of Loppa High structure. In the further description, the conclusion will be presented based on our main objective and the main research questions, including additional finding regarding hydrocarbon prospectivity.

In understanding submarine evolution phase and depositional sequences, the following supporting findings are obtained:

- Submarine fans of Knurr formation in the southeastern of Loppa High structure was deposited in deep marine environment under relative sea level fall condition
- Sedimentation mechanism worked during deposition of submarine fans was dominated by debris flow with the possibility of turbidity current influence at the same time
- Identification of submarine fans geometry was done by combining sequence packages identified from well data analysis and termination patterns at submarine fans limit at both end of direction of landward and basinward.
- There are at least 3 identified sequence packages from well data analysis and one additional sequence was interpreted on the area where no conventional core was taken.
- At the beginning of each package is identified by floating clast fragment, representing debris flow process when sediment flow eroded the base of canyon as sediment conduit.
- From combination of internal seismic pattern and thickness map, there are at least four evolution phase which are initiation phase, growth phase, retreat phase (these events are considered as lower fan facies), and erosional phase related to upper fan facies.

- the lower fans facies are consisted of thick clean sand interval, while the erosional channel is interpreted to be filled by marine shale lithology as it still at the initiation phase of upper fan facies.
- each of evolution change is the result from the combination of source condition (including amount of sediment delivered to the basin), sediment transportation system, and basin morphology.
- Submarine fans deposit was receiving sediment influx from canyons as sediment conduit, delivering sediment from the crest of Loppa High
- Mass Transport deposit (slump) on the adjacent area, was a product from slide scars occurred at the western slope of the deposit.
- Based of depositional phase there are five sequences which are defined by the following order:
 - 1. Initiation phase deposit
 - 2. Growth phase deposit
 - 3. It could be between mass transport deposit or retreat phase deposit as the 3rd or the 4th order
 - 4. It could be between mass transport deposit or retreat phase deposit as the 3rd or the 4th order
 - 5. erosional channel

Generation of submarine fans system model, specifically for Loppa High geological setting has consistencies in the following characters, with the existing sand - rich submarine fans model by (Richards et al., 1998; Gardner et al., 2003; Hadler-Jacobsen et al., 2005):

- The thickness of submarine fans
- lateral distribution radius
- location of sand-rich accumulation at the toe of the slope
- Lack of shelf and slope progradation pattern
- The submarine fans is consisted by three evolution cycles which are fans initiation, fans growth, and fans retreat.

However, there are some unique aspects differ our submarine models against the existing model, which are described below:

- Southeastern Loppa High submarine fans are supplied by multiple source feeder system instead of single feeder system
- There is no visible connectivity between the end of mouth canyon and the proximal part of submarine fans
- There is no evidence in grain size changes on each growth stage of submarine fans

Regarding hydrocarbon prospectivity, It is concluded that basement uplift tectonic activity will reduce geological chance of success in trap system. It is because the uplift process made the submarine fans position tilted updip toward the slope area. It provided a condition which seal failure eager to occur.

7.2 Recommendation

In this part, several suggestions for further work will be provided. The overall concept and models discussed in this study, at the end, will support the understanding of hydrocarbon exploration. Therefore, the following suggestion will be related to further work which will both increasing the confidence of this study result and reducing uncertainty in hydrocarbon exploration:

- 1. In order to obtain more accurate concept in sediment transportation, detail seismic interpretation in between the end of canyon mouth and the proximal part of submarine fans need to be carried out
- 2. In order to convince the concept of seal failure, seal capacity analysis can be performed as further step
- 3. In order to achieve better understanding about seal failure on basement uplift reservoir, analogue case need to be compared from the same tectonic setting. In that way, it reduce hydrocarbon exploration uncertainty in southern Loppa High region.

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