Structural framework and its compartmentalisation within the associated uncertainties: A case study from the Statfjord Reservoir, Northern North Sea

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Abstract. The study to define the degree of compartmentalization along with the associated uncertainties has been done to aid the exploration sector to maximize its hidden potentials. Statfjord reservoir as the object of this study provides a robust clastic data which contains six different zones based upon petrophysical analysis. Seismic data interpretation is the core method to generate the structural and surface interpretation, followed by the structural framework modeling to define the juxtaposition along with the segmented fault system. The result shows moderate clay content (Effective Shale Gouge Ratio) ranging between 40% - 60% with 0.3 MD (millidarcy) permeability, which indicates moderately sealing faults. The compartments also considered having two different scenarios concerning its migration pathway. This is because of the limited well data at the reservoir system, therefore, two different Oil to Water Contact (OWC) value has been added (-2717m and -2617m).

1. Introduction

Defining the compartmentalisation is a major step to predict the play fairway of the reservoir system. This can be related to reservoir exploration and development through the production probability from the reservoir volume. This study focuses on the Statfjord – clastic reservoir of the upper Triassic Section at the Horda Platform area. The Horda platform lies in the North Sea region, formed by the combination of Maloy Slope and the Viking Graben [1]. Figure 1 reveals how the first rift occurred between the Late Permian into Early Triassic, having E-W direction of extension, followed by the secondary tectonic during Mid Jurassic to Early Cretaceous to have E-W, NW-SE, WNW-ESE or NNE-SSW. The secondary rifting produces pre-kinematic from the Early to Mid-Jurassic section, with a series of thickening reflection into the faults Late Jurassic [1] [2].

Bell et al. [2] described that in the first rift, the high value of the β factor situated in the Horda Platform which rises the level of extension, while in the second rifting, the β factor value decreases. The basement fault influences the first rift phase as it generates the basin shape, especially in the Nordfjord-Sogn detachment [3]. The tectonic continues to produce syn-kinematic during Early to Late Jurassic, followed by the post kinematic deposition in the Base of Cretaceous Unconformity (BCU) with the onlapping section at the seismic cross-section (Figure 1). Concerning the hydrocarbon implication, source rock is originated from the Draupne-Kimmeridge clay formation with Statfjord as
a clastic reservoir, having thin interbedded sand to shale lithology, while the Caprock is Dunlin formation [4] [5].

![Generalised geological map of the Horda Platform with the schematic cross-section along A-A'.](image)

**Figure 1.** Generalised geological map of the Horda Platform with the schematic cross-section along A-A'. Lines indicate the regional seismic section to show the regional extension trending along E-W with two different tectonic rifting regimes. The Viking graben extension explains the syn-kinematic, seen by the onlap geometry into the BCU (Base Cretaceous Unconformity) section.

### 2. Methods

3D Seismic interpretation is used as the primary input to predict the structural geometry of the Statfjord reservoir system [6]. It generates fault mapping and time structure which is then used to define the structural model and surface model, alongside with five well analysis [7] [8]. Four horizons have been picked based on the seismic observation and interpretation analysis which are Top Heather, Base Heather, Top Statfjord, and Basement. Those horizons are used to understand the play fairways analysis and how the structure and sediment interact within the extensional tilted blocks. To support the evidence, petrophysics analysis is used to reveal the hydrocarbon reservoir zone by correlating GR log, NPHI-RHOB logs to fine the sand line, shale line, hydrocarbon contact and water contact within the Statfjord reservoir formation.
This study uses both qualitative and quantitative analysis through the seismic interpretation, petrophysical analysis, and fault seal analysis prediction. There is a limitation of this study due to the lack of well data distribution across the field area, consequently, the double scenario of interpretation and modelling have been made. In addition to that, there are two different models of scenarios and interpretations to minimize the interpretation bias by giving the fault seal prediction through the Allan Diagram model. The reservoir compartmentalisation focuses on Top Statfjord, due to the oil discovery in 35/9-2 well. Those discoveries led to the potential secondary compartment in the vicinity of the prospect area, which then produces the double scenario of migration with fault seal analysis prediction.

3. Result and Interpretation  

3.1 Seismic Data Interpretation

The initial result comes from the well to seismic tie analysis, which is combining the time to depth ratio using check shot and wavelet extraction model.

![Figure 2](image)

**Figure 2.** (A) The well-seismic tie of 35/9-1 with a statistical model of wavelet extraction. Based on the log and velocity data (on the left section), it generates impedance to define the lithological borders and so it correlates with the synthetic seismogram (B) Time shifting based on picked of horizon interest, in order to match the real seismic data with the synthetic section (C) Mathematical analysis of wavelet extraction to creates the best curve of linear correlation, as the higher value of correlation, the better result will come (D) Plot of fairly match of synthetic seismogram and real seismic data in the Top Statfjord marker.

Well-tie analysis is applied as a guideline to pair two different seismic domain data (time-domain) and borehole data (depth domain) (Figure 2A). Well-tie is calculated using the wavelet extraction (frequency domain) on the seismic wiggle, multiplied with the impedance log from the well section to generate the synthetic seismogram (Figure 2A). Besides, the time-depth curve is used to determine the
interval velocity and sonic log correction to generate the synthetic and real seismic correlation, followed by seismic-well tie to digitize a certain horizon in an exact position (Figure 2B). The result is considered by various wavelet extraction with maximum dominant frequency around 25Hz, which then is used to create zero and negative polarity (Figure 2C).

**Figure 3.** 3D Visualisation of interpreted horizon interests with different trajectory lines. Toplines (above) corresponds with high structure magnitude with a huge displacement ratio compared to the below lines, while the displacement decreases towards the south. Potential reservoir compartments lie within the structural highs (footwall blocks) of the Statfjord formation.
Seismic Interpretation was performed with surface and structure model to generate a robust geological interpretation. However, as some of the areas are lack of data, the interpretation is then associated with the uncertainty, resulting in possible uncertain of compartmentalisation (Figure 3). In regard to the time-surface map, it is evidenced that high topography correlates to the hydrocarbon accumulation and potential trap location as it yields the four-way dip closure (Figure 3). The interpretation models show a consistent interpretation regarding with the horizon picking since the surface and faults are appropriately interpolated. Cross-section through 35/9-1 and 35/9-2 well section provides the potential compartments at the upper footwall section against the major bounding fault as a seal in the eastern of the section (Figure 3).

![Figure 4](image_url)

**Figure 4.** Petrophysical analysis of well 35/9-2 with assigned zones in the reservoir formation. The analysis is based on four different parameters: Lithology, Shale Volume (Volume of Clay), Porosity and Water Saturation. Those four parameters along with several log analysis (GR, NPHI, Porosity, and Density), creates the sediment log containing different lithology distribution.

Based on the petrophysical analysis on well 35/9-1, the Statfjord reservoir has a 2 meters sediment thick with having oil shown. However, due to the thickness below 5m, this reservoir cannot be divided into several parts as it also under the tuning thickness analysis. On the other hand, well of 35/9-2 has approximately 90m of thickness, creating 6 different zones, which are sandstone, siltstone and conglomeratic sandstone (Figure 4). Well 35/9-2 has 100% water saturation with 17% of effective
porosity and 31% total porosity, indicating the water-bearing reservoir, which potentially does not contain any hydrocarbon (Figure 4).

3.2 Structural Framework

The major faults which bound the Statfjord reservoir have a consistence interpretation with a major throw, separating the Statfjord reservoir to have communication to reservoir hangingwall (Figure 5A). Faults isolate the compartments into several parts, creating a seal to keep and accumulate the fluid within the compartments [9]. The overall geometry of the faults has N-S striking direction with a large steep dip around the tilted blocks [10]. Additionally, smaller faults within the compartment are assumed to baffle for fluid flow within the reservoir [11]. The major faults throw ranging from 0.8 to 1.2 km cut through the basement level and accommodate the high amount of sediments from pre to post kinematic section [12]. Kairanov [13] explained that most of the reservoir fault system is essentially planar with an average dip around 400-500 E. The throw around the major fault (Fault 5A) is approximately 850 m with bell-shaped geometry, dipping towards the east (Figure 5A). Reeve (2013) [1] explained that the fault throw model gives information on the maximum depocenter distribution with a negative linear correlation (Figure 5C). Based on that, the NE-SW striking faults (Fault A and B), initially have grown as isolated structures, and then as time goes, it evolved to have interaction with the adjacent faults. This result is evidenced by the empirical model on (Figure 5C) for the distribution of throw along the strike with lithology marks as a control parameter (Figure 5B).

To validate the structural model, cross-section to superimpose the previous model is necessary to apply. It shows how the interpretation is correct by combining with the previous interpretation or model in a similar geological area. Also, uncertainty relating to the interpretation bias could influence the main interpretation. This uncertainty makes an understanding of the potential assumption of fluid flow and top seal integrity [14]. In general, the geometry indicates a similar interpretation either in horizon or fault tip termination (Figure 5A). Regarding the Voorde [15], faults involved only within the Base Cretaceous Unconformity, due to the differential compaction from the overburden which creates distinctive fault exaggeration.
Figure 5. (A) Fault model distribution, representing the fault with distance and throw, possibly cutting from top Heather to the Basement. There is fault linkage between fault A and B, as the fault growth model. Those models started with isolated fault, interaction, and at the end creates the relay ramp geometry (B) Fault growth model from isolated normal fault to interaction and linkage fault based upon the displacement distance (D-X) plot. (C) Throw against depth relationship, showing the maximum depocenter from the Top Heather to the Top Basement.

3.3 Thickness Analysis and Amplitude Distribution
The isopach map is described by sediment thickness and distribution within the basin which is used to identify the environment of deposition and the source of sediment current (Figure 6A) [16]. Based on the thickness analysis, the isopach map has a variable thickness from 0 to 300 m, with the overall thickness surge towards the edge of the area (Figure 6A). The variation in thickness is due to the first rifting regime, creating a basement fault. The fault is then accommodating the sediment to be deposited afterward. According to Whipp [16], the changes in the environment of deposition from alluvial to fluvial correlates with the reservoir quality as the porosity might be varied as well.

Regarding with the seismic attributes, RMS amplitude with search window 35 ms below the top Statfjord formation has been done to examine high amplitude anomaly. This approach is used to show the sand dominated unit within the clastic zone of prospect (Top Statfjord formation) (Figure 6B). The importance of structural analysis is also calculated through the variance attribute, which describes the similar response of seismic reflector with low value and vice versa (Figure 6C). Therefore, the area with high variance will show the potential fault and deformation. The combination of isopach and attribute maps can be used to guide appropriately the facies distribution within the reservoir system.
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Figure 6. A) Top Statford to Basement isopach maps, showing the true stratigraphic thickness. The sediment package varies from 0 to 100 m, with the thinning packages seen in the top of the structure. This is possibly due to the pinching out geometry as the secondary tectonic (Syn Rift) brings the erosion afterward (B) RMS Amplitude map. (C) Variance amplitude map.

4. Discussion

4.1 Oil Water Contact and Migration Scenario
The reservoir is evaluated using the GR log and NPHI-RHOB log correlation, generating stratigraphic facies variation (zones) within the Statford reservoir. Oil down to analysis is used from well 35/9-1 with the contact at -2312m, while in 35/9-2 is a water-bearing zone with the contact approximately at -2730. Moreover, the OWC has been assumed in both model with -2717 m in model 1 and -2617 in model 2, resulting in 8 compartments and four compartments in model 1 and 2, respectively (Figure 7A and Figure 7B).

In addition, the factor that influences the compartment is the charge direction of hydrocarbon [11]. In this study, there are two different assumptions of migration direction, allowing the distinct hydrocarbon accumulation in the compartment. The first assumption is charge from below, which then makes the hydrocarbon to fill towards all of the compartments and spill out through the high permeability zone when the hydrocarbon exceeds the spill point (Figure 7C). The second assumption is charged from the north, giving the hydrocarbon filling the compartment A and B. Due to the fault length is less than the amount of hydrocarbon, the compartment A and B may combine to become one major compartment (Figure 7C).
Figure 7. A) OWC at model 1 with -2717 m, showing 8 compartments. (B) OWC at model 2 with -2716 m, having 4 compartments. (C) Schematic model of Hydrocarbon charge direction, filling the compartments

4.2 Juxtaposition and Fault Seal Analysis

Juxtaposition analysis indicates sealing fault within the reservoir by identifying sand-sand juxtaposition and sand-shale juxtaposition. Within the Statfjord formation, the reservoir divided into 6 zones which contain sand, shale, silt, and conglomerate based on the petrophysics analysis. Sand-shale juxtaposition appears in most of the fault, particularly in fault and with possible leaking zone located in the fault tip (Figure 8A). A simple schematic model using the Allan diagram is also used to define the fluid flow and assuming sand-sand sealing juxtaposition (Figure 8B).

Further study was performed to identify the area of compartmentalisation in the potential area where there is sand distribution. And as indicated in the same seismic interpretation section, faults bound the reservoir into 4 to 7 main compartments depending on its scenarios. However, to confirm this natural segmentation, fault seal analysis needs to be carried out to determine the fault integrity within the compartment areas. Fault seal analysis is used to define the possible sealing and leaking zone by calculating the clay content for rock property as well as permeability prediction for flow property (Figure 9). Overall, the clay content (ESGR) has 40%-60% with permeability about 0.3 mD, indicating moderate sealing faults (Figure 9). The main factor to define the sealing fault in sand-sand juxtaposition within the Statfjord formation is high clay content and low fault permeability. Regarding that, 13 numbers of fault are determined in model 1 with 11 sealing and 2 non-sealing, while 12 faults from model 2 are sealing (Figure 9).
Figure 8. (A) Juxtaposition Analysis, showing juxtaposition within the reservoir with possible sealing and leaking area. (B) The schematic model juxtaposition with pressure communication assumption and a rough sketch of Allan diagram model, modified from Brown (2003) [3].

Figure 9. Fault seal analysis model, showing the correlation between fault-throw calculation, Effective Shale Gouge Ratio and Permeability prediction. The schematic model has been produce in response to those analysis, showing the sealing and non-sealing fault map with under OWC zone.
5. Conclusion

This study favours scenarios of different degrees of compartmentalisation as the lack of well data which distributed within the reservoir system. It also creates two different models of interpretation in fault and OWC contact estimation. It resulted in two different migration scenarios, one from below of the compartments, and the other from the north domain. In addition to the structural juxtaposition, sub-seismic faulting may have an implication for compartments affecting the fault throw model and reservoir thickness variation which is also correlated to the reservoir quality distribution. The Statfjord reservoir has the value of ESGR ranging from 40% to 60%, and 0.3mD of permeability, indicating the moderate sealing faults. The Stratigraphic compartmentalisation is more considered upon the structural compartmentalisation allowing the Statfjord to be more compartmentalised in the crestal zone. The compartments are controlled by the huge fault displacement, which minimizes the potential fluid flow communication within the reservoir. The critical risk of this study is to the degree of sealing along the major and minor fault.

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Reference

[1] Reeve M, Bell R Duffy O, Jackson C, and Sansom E 2015 The growth of non-colinear normal fault systems, What can we learn from 3D seismic reflection data. Journal of Structural Geology. [Online]. 70 pp 141-155.
[2] Bell R., Jackson C, Whipp P and Clements B 2014 Strain migration during multiphase extension: Observations from the Northern North Sea. Tectonics. [Online] 33(10) pp 1936-1963.
[3] Brown A 2003 Capillary Effect on Fault-Fill Sealing. American Association of Petroleum Geologist Bulletin 87, no 3 381-396.
[4] Catterall J J 2012 Structural Framework of the Statfjord Formation (Rhaetian-Sinemurian) in the Oseberg South Field Norwegian North Sea MSc Thesis Norwegian University of Science and Technology.
[5] Cowie P A, Underhill J R, Behn M D, Lin J, Gill, C E, 2005 Spatio-temporal evolution of strain accumulation derived from multi-scale observations of Late Jurassic rifting in the northern North Sea: a critical test of models for lithospheric extension. Earth Planet. Sci. Lett. 234, 401e419.
[6] Dalrymple M 2001 Fluvial Reservoir architecture in the Statfjord Formation (Northern North Sea) augmented by outcrop analogue statistics Petroleum Geoscience [Online] 7(2), pp 115-122.
[7] Duffy O, Bell R., Jackson C, Gawthorpe R and Whipp P 2015 Fault growth and interactions in a multiphase rift fault network: Horda Platform, Norwegian North Sea. Journal of Structural Geology [Online] 80, pp 99-119.
[8] Factpages Norwegian Petroleum Directorate, Wellbore.
[9] Faerseth R.B 1996 Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea Journal of the Geological Society 153(6) pp 931–944 doi: 10.1144/gsigs.153.6.0931.
[10] Fraser S I, Robinson A M, Johnson, H.D., Underhill, J.R., Kadolsky, D.G.A., Conell, R., Johannesen, P. & Ravnås, R. (2003) Upper Jurassic. In: The Millenium Atlas: Petroleum Geology of the Central and [10] Northern North Sea (Ed. by D. Evans, C. Graham, A. Armour & P. Bathurst), pp. 157–189. The Geological Society, London.
[11] Gautier D L 2005 Kimmeridgian Shales Total Petroleum System of the North Sea Graben Province: U S Geological Survey Bulletin 2204-C 24 p.

[12] Johannesen J, Hay S J, Milne J K, Jebsen C., Gunnesdal, S C and Vayssaire, A. 2002 3D oil migration modelling of the Jurassic petroleum system of the Statfjord area Norwegian North Sea. Petroleum Geoscience 8(1), pp 37-50.

[13] Kainarov B 2013 Reservoir Characterization of Sognefjord and Fensfjord formation across Gjoa Field North Sea Norway MSc Thesis University Stavanger.

[14] Smalley P, and Hale N 1996 Early Identification of Reservoir Compartmentalization by Combining a Range of Conventional and Novel Data Types SPE Formation Evaluation. [Online] 11(03) pp 163-170

[15] Voorde M, Ter Faerseth R B, Gabrielsen, R H and Cloetingh, S A P L 2000 Repeated lithosphere extension in the northern Viking Graben: A coupled or a decoupled rheology? Geological Society, London, Special Publications. 167 (1). pp. 59–81. doi: 10.1144/gsl.sp.2000.167.01.04.

[16] Whipp P, Jackson C, Gawthorpe R, Dreyer T and Quinn D 2014 Normal fault array evolution above a reactivated rift fabric a subsurface example from the northern Horda Platform, Norwegian North Sea. Basin Research. [Online]. 26(4), pp.523-549.