University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Petroleum Engineering	Spring semester, 2022 Open
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Title of master's thesis: Controls and Distributions of Tertiary Sandstones in Southern Viking Graben, North Sea	
Credits (ECTS): 30	
Key words: Rogaland Group Hordaland Sands Hordaland Group Utsira Formation CO_2 Storage	Number of pages: 97 Stavanger, 15/06/2022

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Acknowledgements

Special thanks to my supervisor Dora Luz Marin Restrepo, for her weekly guidance, encouragement, support and feedback. Words alone cannot express my gratitude.

To all the professors of the Petroleum Geoscience department, I thank you for the knowledge you imparted to me.

To my parents, siblings and Yemi, thank you for always encouraging and believing in me. My friends Obinna, Imran and Edward, for always offering to help me, I deeply appreciate.

Finally, to God, the author and finisher of my faith without whom this master's degree would not have been possible. You make all things beautiful in your time.

Abstract

The Tertiary succession in the Ve Sub-basin, Sleipner Terrace, Utsira High and Ling Depression is studied to understand the lateral and vertical distribution of Tertiary sandstones, to know if Tertiary tectonics had an effect on the deposition of the Tertiary sandstones and to describe the opportunities and challenges of the Tertiary sandstones for CO_2 storage by using 3D seismic data and well logs.

Four intervals of interest namely Rogaland Group, Hordaland sands (named for this study), Hordaland Group and Utsira Formation are mapped and interpreted.

Tectonic uplift, sea-level fluctuations, and post-depositional processes played major roles in the lateral distribution of the Tertiary succession. The East Shetland and Scotland platforms, and the Norwegian landmass served as the source of the sediments in the Tertiary.

The faults present in the Rogaland Group showed little to no displacements. The lack of growth strata across these faults suggests that they were inactive during the deposition of the group. Late salt mobilization of the Zechstein Group created the folds in the Rogaland Group, Hordaland sands and Intra-Hordaland Group. However, the movement of the salt is suggested to have stopped after the deposition of the Hordaland sands. Polygonal faulting is mapped within the Hordaland Group and is considered mainly as seals based on recent studies and observations from this study. Mud diapirs that disrupted the lateral variation of sediments within the Hordaland Group are responsible for the multiple folds within the interval and for controlling the segmented depocenters. Thickness variations within the Utsira Formation that is caused by the underlying mud diapirs suggest that the mud diapirs were active during the deposition of the Utsira Formation.

Great opportunities exist for CO_2 storage within the Tertiary succession.The Tertiary succession in this study is considered as saline aquifers due to their low resistivity values. The Utsira Formation which is currently being used for CO_2 storage holds the most potential although challenges exist because of the poorly defined stratigraphic trap and the possibility of up dip migration to areas not suitable for CO_2 storage. The Hordaland sands is also a promising prospect because of its thick sandy unit, good porosity and sufficient depth, however, uncertainties in the integrity of its seal and its poorly defined stratigraphic trap exists. The sandy portions of the Rogaland and Hordaland groups may also serve as potential storage sites. Several intraformational seals exist within the Tertiary succession and their presence is desirable as they cause slow migration of the CO_2 which may lead to chemical trapping.

1. Introduction

Tertiary sandstones have been proven to be important in the North Sea because they are significant hydrocarbon reservoirs in fields like Balder, Sleipner East and Grane (Ahmadi, Sawyers et al. 2003, Dreyer, Bujak et al. 2004, Brunstad, Gradstein et al. 2013, McKie, Rose et al. 2015). The Paleocene is probably the most important Tertiary reservoir and hydrocarbon reservoirs of Paleocene age were first discovered in the North Sea in 1967 (Brunstad, Gradstein et al. 2013). Recent production from the Martin Linge field has identified oil in a reservoir of the Eocene Frigg Formation and the Miocene Skade Formation is the reservoir in the recent Liatårnet discovery (NPD 2021). Yet, despite its importance, only a few studies have been published characterizing the controls and distributions of these sandstones in the Norwegian North Sea.

Previous studies focused more on the effects of tectonics in sedimentation on a regional scale and established that post-rift thermal subsidence with superimposed periods of uplift affected the North Sea during the Tertiary (Ahmadi, Sawyers et al. 2003). The distribution of the sediments in the Tertiary was influenced by basin physiography, underlying Mesozoic and Paleozoic structures, syn-depositional tectonics and local halokinesis (Ahmadi, Sawyers et al. 2003, Brunstad, Gradstein et al. 2013). Remobilized sands, polygonal faulting, seismic chimneys and channels have been mapped in 3D seismic dataset covering the study area (Løseth, Rodrigues et al. 2012) but the lateral variations of the Tertiary sandstones, their distributions and the role of active tectonics controlling their deposition still remains unclear in the study area.

The Norwegian North Sea covering approximately an area of 142 000 km^2 has the most discovered and produced hydrocarbon on the Norwegian Continental shelf (NPD 2022a). The Viking Graben is a part of the North Sea graben system. The study area (Figure 1) is part of the southern Viking Graben. It extends from the Sleipner Terrace to parts of the Ve Subbasin, the southwestern Utsira High and west of the Ling depression (NPD 2022).

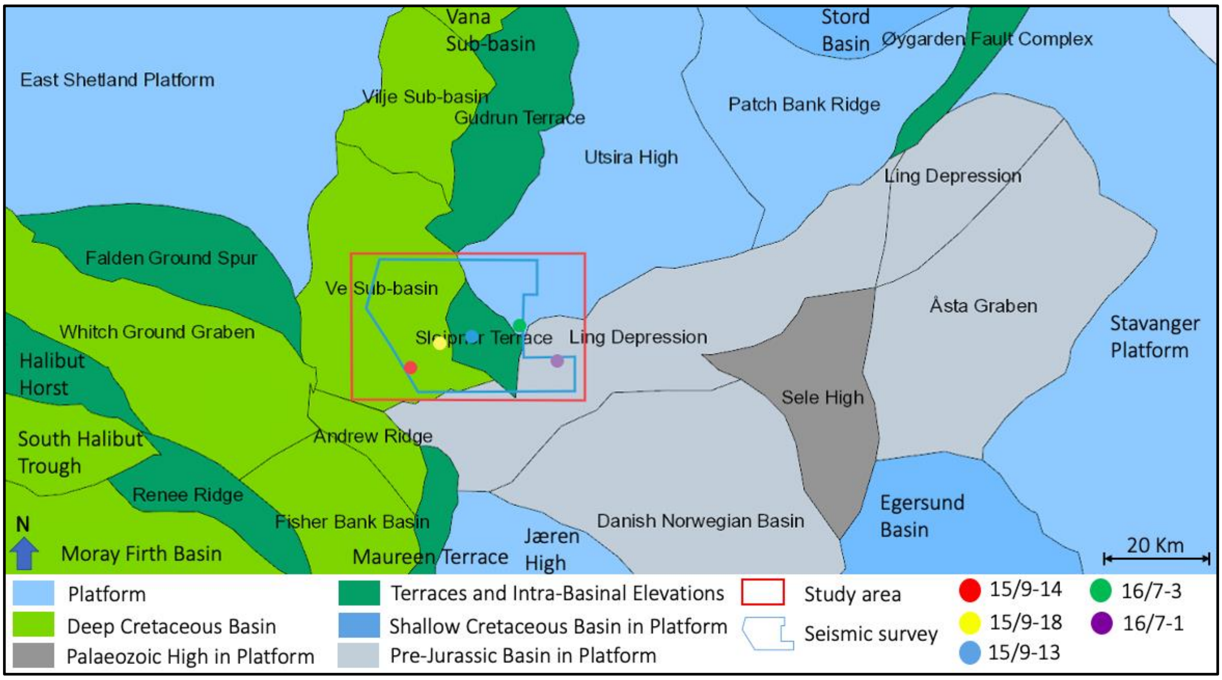


Figure 1: The location of the study area with structural elements situated near and inside the study area. Note the location of the wells used in this study. (Modified after NPD, 2022).

To investigate the Tertiary sandstones in the study area is important because:

1) In the Sleipner field, located in the Sleipner Terrace, the Tertiary Utsira Formation has been used for CO_2 storage since 1996 (Aminu, Nabavi et al. 2017, Tomić, Karović-Maričić et al. 2018). Thus, a thorough understanding of the geological evolution of an area, a comprehension of the lateral variation of facies and a literature revision about the challenges associated with the CO_2 storage in the Sleipner Field, can contribute to recognize CO_2 storage opportunities in the different Tertiary sandstone units.
2) The characterization of Tertiary sandstones can contribute to find future reservoir opportunities in near-field exploration areas.
3) This study contributes to improve the Tertiary geological evolution of the southern part of the Viking Graben.

The following research questions will be answered in this thesis:

- How do the Tertiary sandstones vary laterally and what is controlling this variation?
- Do opportunities for CO_2 storage exist within the Tertiary successions in the study area?

Thus, this study aims at characterizing the controls and distribution of the Tertiary sandstones by combining seismic and well log data. The objectives of this thesis are :

- To understand the lateral and vertical distribution of Tertiary sandstones in the study area.

- To know if Tertiary tectonics had an effect on the deposition of the Tertiary sandstones in the southern part of the Viking Graben.
- To describe the opportunities and challenges of the Tertiary sandstones for CO_2 storage in the study area.

1.1 Current Knowledge on CO_2 Storage

1.1.1 Geological Elements for CO_2 Storage

With the current need for the mitigation of greenhouse gases emissions, the geological storage of CO_2 is one of the key technologies recommended by the Intergovernmental Panel on Climate Change (Pachauri, Allen et al. 2014). Four major geological elements are needed to successfully store CO_2 in the subsurface (Table 1).

Table 1: Geological Elements Necessary for CO_2 Storage.

Geological Elements	Characteristics
Reservoir	- Saline aquifers or depleted hydrocarbon reservoirs or unminable coal seams, or other storage options (e.g., basalts). - Good reservoir properties (Porosity, Permeability) - Thickness (>50 metres) - Homogeneity
Depth	>800 metres
Seal	- Homogeneity/Lithology - Thickness (>50 metres) - Seal by-pass - Lateral extent
Trapping Mechanism	- Physical trapping (Stratigraphic, Structural or a combination of both) - Chemical trapping (Residual, Solubility or Mineral)

Reservoir: The CO_2 storage units should possess good reservoir qualities such as good porosity and permeability to allow the injection and migration of CO_2 within the rock. They should also be homogenous in nature and large in size to allow injection of large volumes of CO_2. Saline aquifers, depleted hydrocarbon reservoirs and unmineable coal seams are the three main options for the geological storage of CO_2 (

1) *Figure 2*) (Michael, Arnot et al. 2009, Tomić, Karović-Maričić et al. 2018). Other options still under consideration are organic rich shale, basalt formations, ultramafic rocks (Rosenbauer and Thomas 2010), salt caverns and abandoned mines (Metz, Davidson et al. 2005, Niemi, Bear et al. 2017). However, the potential of these other storage options has not been studied in detail (Niemi, Bear et al. 2017, Tomić, Karović-Maričić et al. 2018).

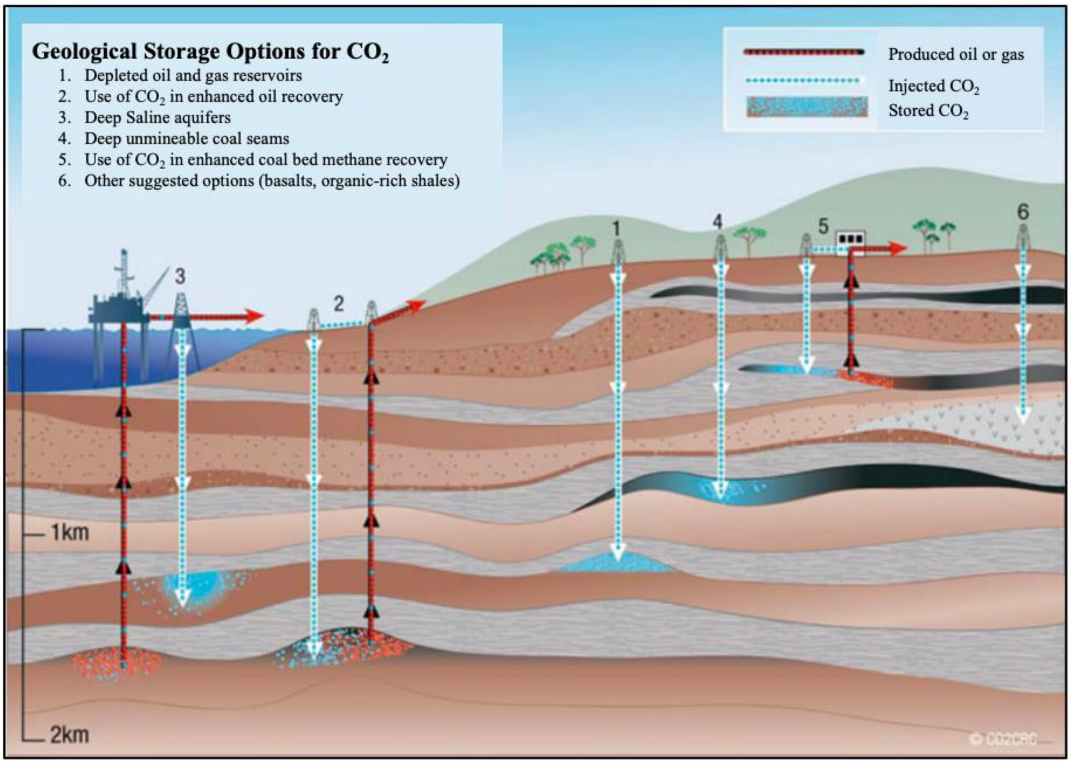


Figure 2: Overview of Geological storage options for CO_2. (Modified after Aminu, Nabavi et al. 2017).

Saline aquifers are geological formations having water-permeable strata filled with brine. They are important potential CO_2 storage units because they are generally large and usually laterally continuous aquifers (Rosenbauer and Thomas 2010) that may be capable of storing large volumes of CO_2 estimated to vary between 1000-10000 Gt CO_2 (Rosenbauer and Thomas 2010). Although reservoir properties and large storage capacities are favorable, there are still uncertainties in their flow regimes and capacities (Rosenbauer and Thomas

2010). Also, their lack of infrastructure (such as injection wells) makes them less favorable as a storage option (Wang, Wang et al. 2016).

- Depleted hydrocarbon reservoirs are formations that have previously produced hydrocarbons. They are important potential CO_2 storage units (although gas fields hold more storage potential than oil fields) because most of their pore volume is available for CO_2 storage due to the depletion of the in-situ fluids (Metz, Davidson et al. 2005). According to Global CCS Institute 2014 (Tomić, Karović-Maričić et al. 2018), their storage capacity is estimated to vary between 675 and 900 Gt CO_2. When compared to other storage options, they are considered most suitable (Tomić, Karović-Maričić et al. 2018) because of confidence in their great seal integrity as they have housed hydrocarbon for a long time (Bentham and Kirby 2005, Halland, Riis et al. 2013). Also, there is sufficient knowledge of the reservoir and already in place infrastructure (Aminu, Nabavi et al. 2017). However, when compared to saline aquifers, depleted hydrocarbon reservoirs may be penetrated by many wells which may have fractured the reservoir or seal thus the well integrity requires detailed study (Bentham and Kirby 2005, Halland, Riis et al. 2013).
- Unminable Coal Beds are geological formations made up of mainly coals. Coal beds attractive for CO_2 storage should have sufficient permeability and may be too deep or with thin beds that make them unsuitable for mining because the CO_2 will get released if they were ever mined (Niemi, Bear et al. 2017). Coal bed storage depends on the adsorption of significant amount of CO_2 due to the large amount of micro-pores on the coal matrix (Aminu, Nabavi et al. 2017). Compared to saline aquifers and depleted hydrocarbon reservoirs, storage in unminable coal beds may take place at shallower depths (Metz, Davidson et al. 2005). Storage capacity of 3-200 Gt CO_2 is estimated for unminable coal beds (Metz, Davidson et al. 2005).

  Unlike saline aquifers which have been rarely considered for economic resources (Rosenbauer and Thomas 2010), depleted hydrocarbon reservoirs and unminable coal beds have a value-added economic benefit (Metz, Davidson et al. 2005, Rosenbauer and Thomas 2010) due to enhanced oil recovery (EOR) and coalbed methane recovery (ECBM) respectively that injection of CO_2 aids. However, because of supercritical CO_2's reaction with organic matter and caprock seals, high environmental risks are prone (Rosenbauer and Thomas 2010).

- Organic-rich shale is similar to unminable coal beds as it provides an adsorption substrate for CO_2 (Nuttall, Drahovzal et al. 2005, Vermylen, Hagin et al. 2008). Abundance of shales may suggest large storage capacity (Metz, Davidson et al. 2005) although this may not be the case if minimum depth is considered for CO_2 storage. As at 2018, there was still no data on storage capacity in organic shales (Tomić, Karović-Maričić et al. 2018).
- Basalt formations and ultramafic rocks may be potential CO_2 storage units because of their ability to convert CO_2 to a solid mineral (carbonate minerals) (Rosenbauer and Thomas 2010). However, uncertainties exist because of the leakage possibilities through fractures in the caprocks of basalt rocks. Alternatively, the CO_2 that migrates through the fractures may undergo mineralization before reaching the surface (Aminu, Nabavi et al. 2017).
- Salt Caverns storage are potential storage options because of their efficiency, flow rate during injection and high storage capacity when measured per unit volume but they pose challenges to the environment because the brine has to be disposed from the solution cavity and the CO_2 may be released if the system fails (Metz, Davidson et al. 2005).
- Abandoned mines maybe potential storage options depending on their sealing capacity. Sedimentary rock mines such as potash mines, salt mines or lead deposits may have some potentials unlike heavily fractured igneous and metamorphic rocks whose sealing would be difficult (Metz, Davidson et al. 2005). Abandoned coal mine in Colorado, USA has been successfully used for natural gas storage (Metz, Davidson et al. 2005), thus abandoned coal mines offer the opportunity for CO_2 storage (Piessens and Dusar 2004).

Previous studies have established that when compared to all the storage options, saline aquifers have the highest worldwide capacity for CO_2 storage (Dooley, Davidson et al. 2009, Michael, Arnot et al. 2009, Rosenbauer and Thomas 2010, Halland, Riis et al. 2013, Niemi, Bear et al. 2017) because of their occurrence in all sedimentary basins worldwide (Bentham and Kirby 2005).

2) Depth: A second factor is the depth at which the CO_2 should be stored (Figure 3). It should be stored relatively deep (greater than 800 m) to ensure that it exists in a super-critical state. This is important as a higher density means more storage efficiency and also for storage security to avoid the CO_2 seeping to the surface (Halland, Riis et al. 2013, Ringrose 2020).

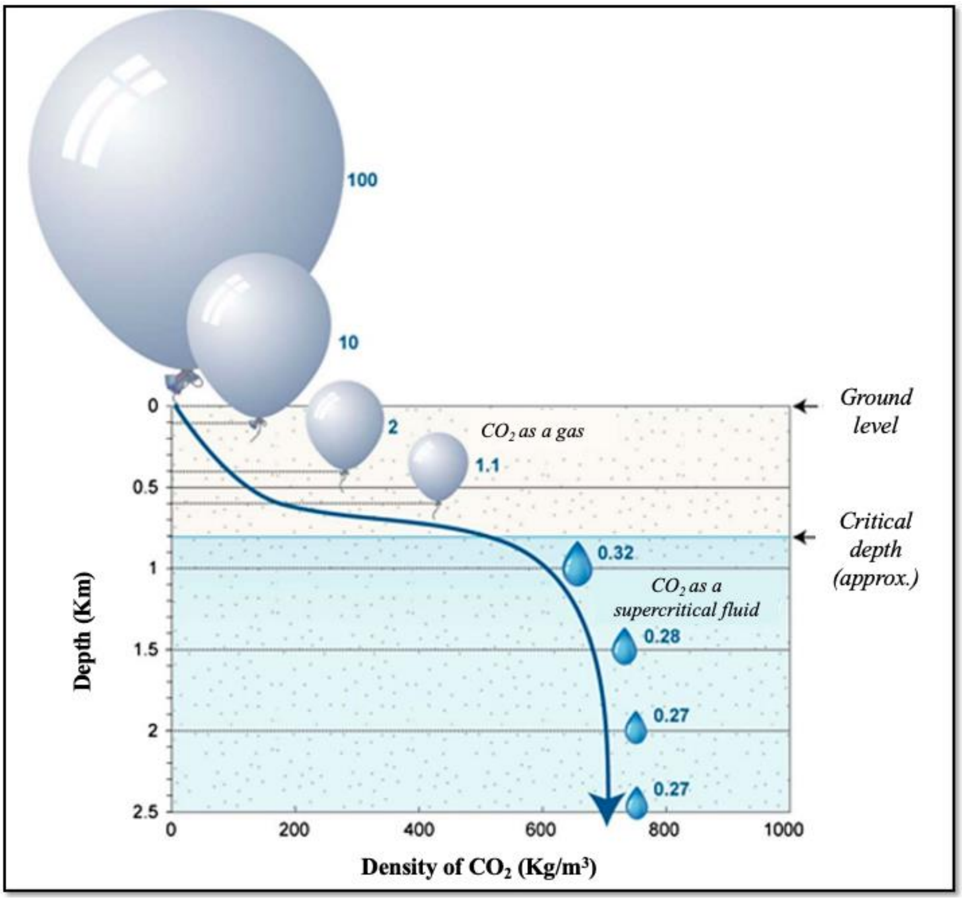


Figure 3: Depth at which CO_2 exists as a supercritical fluid. (Modified after Aminu, Nabavi et al. 2017).

3) Seal: The third factor is the seal. The CO_2 storage reservoir would be overlain by an impermeable caprock preventing the migration of the CO_2 to other formations or areas (Figure 4). Good seal integrity is needed for a successful CO_2 storage thus, a homogenous seal, thick seal and a seal not damaged by drilling activities or tectonics provides great confidence (Halland, Riis et al. 2013, Chadwick, Williams et al. 2017, Ringrose 2020). If multiple heterogeneities exist in the seal, the seal may be breached thus allowing the CO_2 to flow to other areas. The most common 'seal by-pass' features are: geological faults, chimneys or pipes and injected bodies of sedimentary or igneous material (Chadwick, Williams et al. 2017).

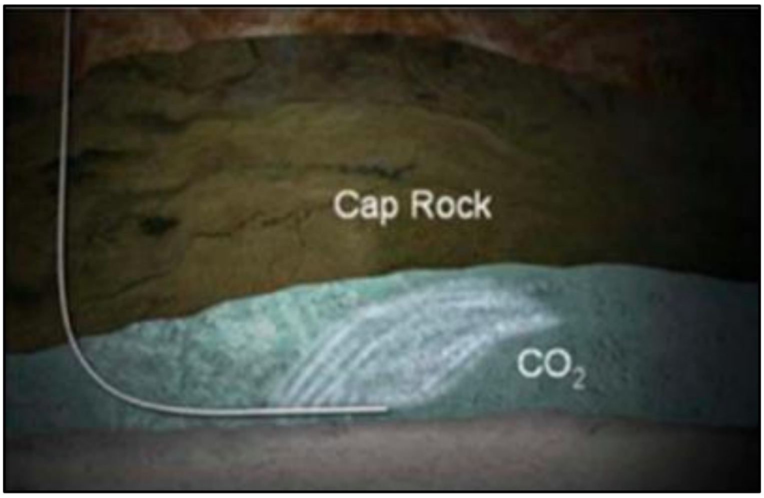


Figure 4: Caprock/Seal. (Tomić, Karović-Maričić et al. 2018).

4) Trapping mechanisms: These are responsible for holding CO_2 in place in storage reservoirs. They can be divided into physical trapping (Figure 5) (stratigraphic, structural or combination of both), and chemical trapping (residual, solubility, and mineral trapping) (*Figure 6***Error! Reference source not found.**) (Shukla, Ranjith et al. 2010, Halland, Riis et al. 2013, Zhao, Liao et al. 2014, De Silva, Ranjith et al. 2015, Aminu, Nabavi et al. 2017).

   - Physical trapping is the dominant trapping mechanism (Halland, Riis et al. 2013). It involves stratigraphic, structural or combination of both trapping mechanism that holds the injected CO_2 in place making it immobile and unable to diffuse into adjacent lithologies (Aminu, Nabavi et al. 2017).

     A) Stratigraphic trapping: These traps are formed because of rock type changes caused by changes in depositional environment (Metz, Davidson et al. 2005). In this mechanism, injected CO_2 migrates vertically along the permeable host rock until it is obstructed by the impermeable caprock. It later migrates laterally due to buoyancy to structurally higher areas around the reservoir-caprock boundary (Rosenbauer and Thomas 2010). Various stratigraphic trapping mechanisms exists such as impermeable top seals or pinchouts (Figure 5A) (Metz, Davidson et al. 2005). Stratigraphic trapping mechanism is most effective in lateral unconfined aquifers (typical of saline aquifer) (Bentham and Kirby 2005, Rosenbauer and Thomas 2010) with large storage capacity, low flow rates, minor structural traps and low groundwater (Rosenbauer and Thomas 2010).

     B) Structural trapping involves trapping of CO_2 by geological structures such as folds (Figure 5B), salt domes or sealing faults (Metz, Davidson et al. 2005).

C) Combination of both trapping mechanism: In this mechanism, both stratigraphic and structural trapping acts to hold the CO_2 in place.

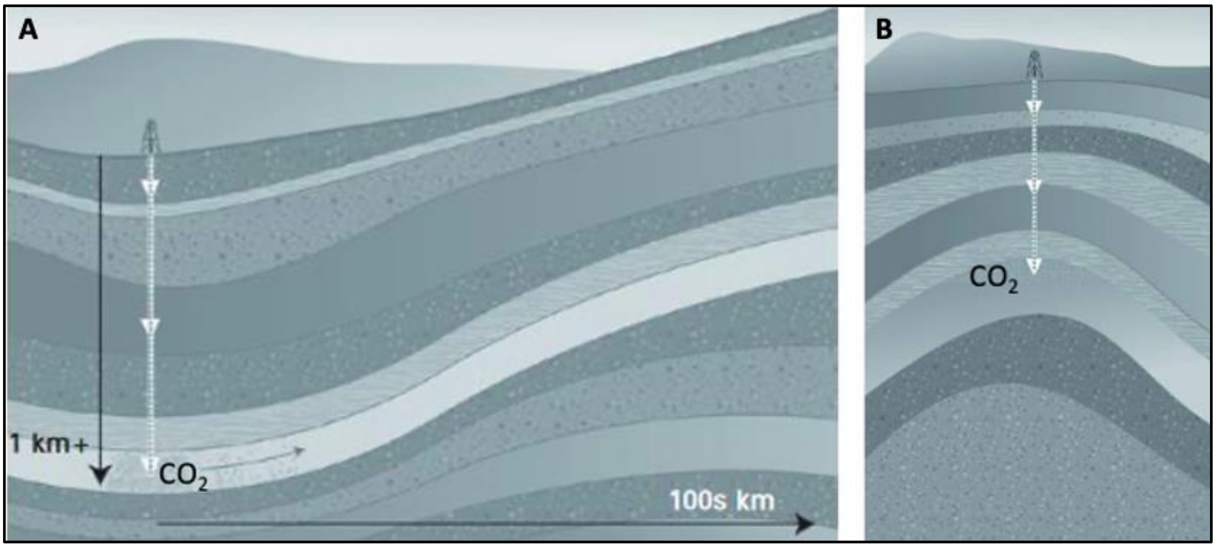


Figure 5: Physical trapping mechanism. A) Stratigraphic trapping; the CO_2 moves vertically till it encounters the impermeable bed above, it then moves laterally driven by buoyancy till it is stopped by an impermeable bed. B) Structural trapping; the CO_2 is trapped by the folded bed and juxtaposed against impermeable beds. (Modified after Rosenbauer and Thomas 2010).

- Chemical trapping: A sequence of chemical processes occurs between the host rock, formation water and CO_2 during CO_2 storage (Metz, Davidson et al. 2005). Chemical trapping is divided into:

  A) Residual trapping: This involves the injected CO_2 displacing the insitu fluids as it moves through the porous host rock. The displaced fluids later return and trap the remaining CO_2 within the pore spaces in the host rock (*Figure 6*A) (Aminu, Nabavi et al. 2017).

  B) Solubility trapping: Here, CO_2 dissolves in formation water thus eliminating its buoyancy forces by reducing its free-phase quality. Next, the dissolved CO_2 further dissolves with the host rock causing an increase in pH due to the formation of ionic species (*Figure 6*B) (Metz, Davidson et al. 2005, Aminu, Nabavi et al. 2017).

  C) Mineral trapping: In this trapping mechanism, the CO_2 reacts with the formation water and minerals in the rock causing precipitation of carbonate minerals (*Figure 6*C). Mineral trapping mechanism is relatively very slow but the permanent trapping of the CO_2 makes it a more desirable mechanism (Metz, Davidson et al. 2005, Sundal, Hellevang et al. 2014, Aminu, Nabavi et al. 2017, Hellevang, Haile et al. 2017).

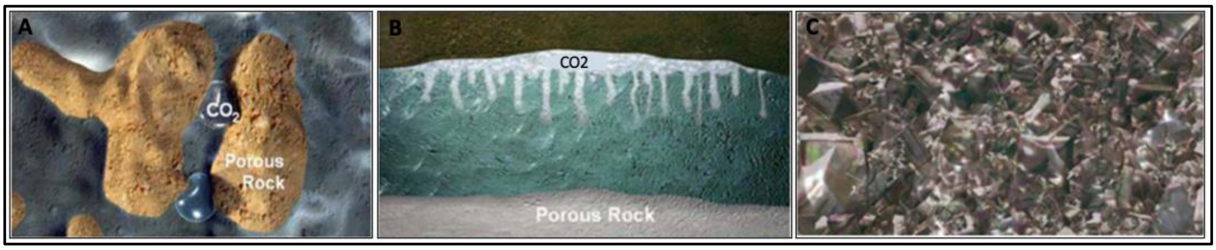


Figure 6: Chemical trapping mechanism. A) Residual trapping, B) Solubility trapping, C) Mineral trapping. (Modified after Tomić, Karović-Maričić et al. 2018).

1.2 CO_2 Storage in Tertiary reservoirs in the North Sea

Currently, the CO_2 storage potential of Tertiary sandstones is being explored in the Norwegian North Sea (Halland, Riis et al. 2013). Some potential prospects are the deep-water sandstones of the upper Paleocene Fiskebank Formation in the Norwegian-Danish Basin. The Paleocene Fiskebank saline aquifer is located in a depression overlying the top of the Shetland chalk Group. It is assessed due to the good sealing capacity of the Paleocene caprocks and the high porosity and permeability of the sandstones. Also, the abandoned Frigg gas field in the central North Sea with reservoirs located in the huge Frigg-Heimdal Formation has potential due to the huge reservoir size and remaining gas in the field (NPD 2010). Evidence of the remaining gas in the field suggests that the reservoir has been pressure depleted (beneficial for pressure management (Ringrose 2020)) possibly due to production, thus the reservoir is being considered as a depleting gas reservoir for CO_2 storage. Additionally, the Miocene Utsira Formation has been successfully used for CO_2 storage for up to twenty years in the Sleipner Field which is located in the study area (Furre, Eiken et al. 2017). The formation is a saline aquifer that possess all the factors necessary for CO_2 storage. It has good porosity (30-40%), good permeability (1-3 darcies) and the regional extent of the Utsira Sand renders it potentially attractive for storing large volumes of CO_2. The Utsira sands are 200-250 m thick and lies at depths between 800-1000 meters below the seafloor and are overlain by an impermeable caprock of 200-300 m known as the Nordland Group shales (Aminu, Nabavi et al. 2017). Stratigraphic lap-outs define its limits to the east and west. At the southwest, this sandy units laterally becomes shales while at the north it occupies a narrow channel that is deepening (Chadwick, Holloway et al. 2004). Due to the lack of well-defined closures, challenges of CO_2 migration may occur.

The Nordland Group shales act as a top seal for the Utsira reservoir and is presently an effective seal, however, an accurate assessment of caprock sealing capacity has not been studied in detail (Chadwick, Holloway et al. 2001, Chadwick, Holloway et al. 2004). Studies have shown that the eight intra-formation mudstones identified within the Utsira Formation before the CO_2

injection in the Sleipner area did not properly seal as expected thereby not slowing migration as CO_2 was observed at the top seal (Nordland Group shales) within three years of injection (Cavanagh and Haszeldine 2014, Lloyd, Huuse et al. 2021). The cause of this seal by-pass has been suggested to be a result of microfractures, sand injectites, carbonate cement dissolution, lateral discontinuities, chimney excavation or hydro-fracturing of thin shales due to fluctuating ice loads from Quaternary glaciations (Cavanagh and Haszeldine 2014, Chadwick, Williams et al. 2017, Lloyd, Huuse et al. 2021). By the end of the injection, the intra-formation mudstones may have failed as sealing units as some of the CO_2 would be drained to the top of the Utsira Formation while about 40% will be residually trapped (Hermanrud, Andresen et al. 2009, Lloyd, Huuse et al. 2021).

Another challenge is possibly be related to the presence of a regional dip mapped towards the west, which suggests that in the long term there is a risk that injected CO_2 will migrate updip to levels that are too shallow to be accepted for storage (Halland, Riis et al. 2013).

More opportunities may exist in the Utsira Formation located at the left and right sides of the UK-Norway boundary because it is part of a larger sandy deltaic complex (Hutton Sands) but the communication between the different sandy formations is still uncertain (Halland, Riis et al. 2013). Studies suggest that large volumes of CO_2 can be stored approximately 750 m below the Utsira Formation due to the presence of many structures that could house the CO_2 and prevent upslope migration (Halland et al., 2013). The northeast part of the Utsira Formation which has high porosities because the sediments are closer to the eastern Sognefjord source area (Halland, Riis et al. 2013, Lloyd, Huuse et al. 2021) has not been evaluated for storage. Additionally, the outer part of the Utsira-Skade Formation that has middle Miocene shale as the seal and possibly clay diapirism structures as the traps has also not been evaluated for storage (Halland, Riis et al. 2013).

2. Geological Setting

The North Sea has been affected by a long extensional history that started as a result of the extension of the Caledonian crust during the Devonian times. However, the present day structural framework of the North Sea is largely a result of the Permo-Triassic and the Late Jurassic to Early Cretaceous rifting phases (Zanella, Coward et al. 2003). Thermal cooling and subsidence followed after each of these rifting phases. The North Sea Basin was deformed by tectonic inversion during the Late Cretaceous to Cenozoic and the basin margins were affected by significant uplift during Cenozoic times (Zanella, Coward et al. 2003). The North Sea Basin present day configuration is characterized by an average maximum horizontal stress oriented north-west to south-east, that is consistent with the active stress field in north-western Europe (Zanella, Coward et al. 2003).

2.1 Cenozoic

The North Sea Basin subsided as a regional post-rift sag when extension ended in the Early Cretaceous (Head, Riding et al. 2004). This rapidly subsiding epicontinental basin is bounded to the west and east by the British and Scandinavian land–shelf zones respectively (Gregersen and Johannessen 2007). During the Cenozoic time, these bounding areas underwent up to six stages of relative uplift, which also influenced the North Sea Basin (Galloway, Garber et al. 1993, Head, Riding et al. 2004). According to Galloway et al. (1993), these uplifts were followed by major episodes of siliciclastic sedimentation, which was interpreted as onlap-defined mega sequence primarily during the Palaeocene, Eocene, Oligocene, and Miocene. However, sequence geometries and the location of some depocenters indicate that Cenozoic structures in the North Sea Basin may have been inherited from pre-existing underlying Mesozoic and Paleozoic structures (Figure 7) (Copestake, Sims et al. 2003)

2.1.1 Paleocene

During the Paleocene, the pattern of deposition in the North Sea changed from basin-centered to basin- margin (Ahmadi, Sawyers et al. 2003). This change was as a result of a combination of Atlantic European tectonic events, oceanic patterns, eustasy, differential tilting and subsidence, climate, and changes in sediment supply. Basin physiography and underlying Mesozoic and Paleozoic structures, syn-depositional tectonics and local halokinesis influenced lithofacies distribution (Ahmadi, Sawyers et al. 2003, Brunstad, Gradstein et al. 2013).

Paleogene tectonic activity which was as a result of the development of the Iceland Plume caused regional uplift that affected the Scottish Highlands and the East Shetland Platform close to the North Sea and the Norwegian landmass (which experienced less uplift) (Brunstad, Gradstein et al. 2013). This tectonic activity also caused the North Sea basin to enclose and isolate from the Atlantic Ocean. Stresses that occurred along the line of the future north-east Atlantic Ocean created major volcanic activity (Brunstad, Gradstein et al. 2013). Simultaneously, regional subsidence affected the Viking Graben and its flanks in the North Sea Basin (Loseth, Wensaas et al. 2003). Erosion of the uplifted areas gave rise to input of thick Paleocene siliciclastic deposits into the subsided areas thereby causing the cessation of calcareous deposits that was prominent during the Late Cretaceous in the North Sea (Loseth, Wensaas et al. 2003). Thus, the Scotland-Shetland area is suggested as the primary source of the thick Paleocene siliciclastic deposits (Figure 7) (Ahmadi, Sawyers et al. 2003, Brunstad, Gradstein et al. 2013) but the Norwegian landmass may have also acted as a minor provenance because of the less uplift (Brunstad, Gradstein et al. 2013). The uplifted areas created drainage patterns that trended in the southeast direction and deposited prograding shelf systems on the western margins of the Viking and Central grabens while interbedding of deep water turbidites and hemipelagic mudstones gradually filled the basins above the Mesozoic grabens (Copestake, Sims et al. 2003).

A compressional deformational phase which has been interpreted as a result of the first pulse of Alpine orogeny affected the central North Sea although not as pronounced as the Southern North Sea. This deformation reactivated the Late Jurassic rift elements giving rise to salt-related features that were caused by compressional reactivation of the Triassic to Late Jurassic diapirs and minor compressional inversion structures (Copestake, Sims et al. 2003). The initiation of this late movement of salt is the combination of compressional tectonics and gravity-induced halokinesis. Upturned beds are seen against the flanks of the diapirs (Copestake, Sims et al. 2003).

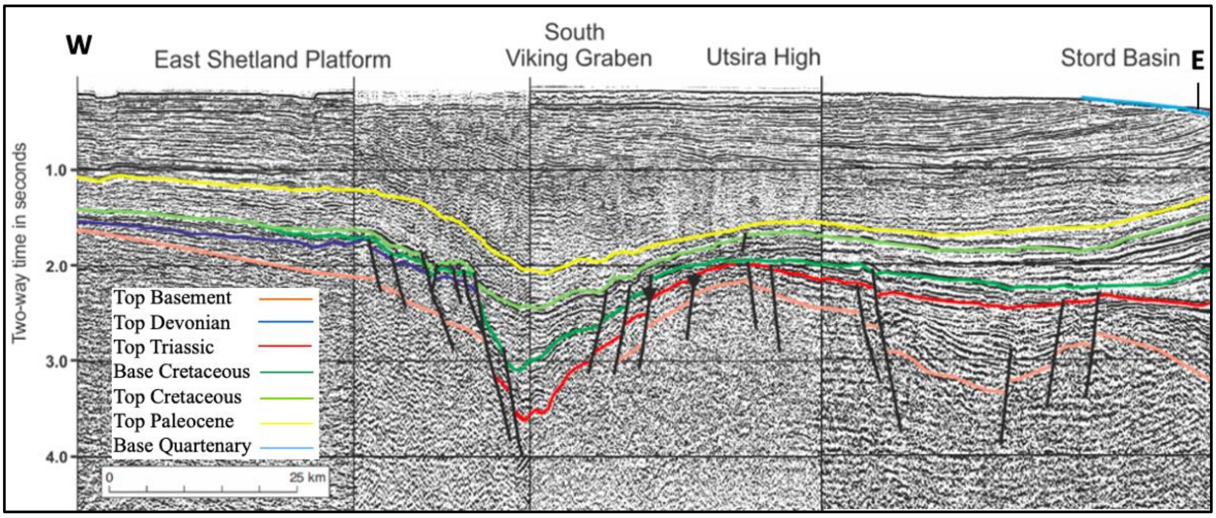


Figure 7: Regional seismic line. Note how the Paleocene pattern of deposition follows underlying patterns and how the interval thins from west to east indicating that the East Shetland Platform was the prominent source.(Færseth 1996).

2.1.2 Eocene

The structures of the top Eocene surface show similarities with that of the underlying Paleocene reflecting the continuation of post-rift subsidence (Copestake, Sims et al. 2003) which was due to the wanning of the Island plume (Anell, Thybo et al. 2010).

The post-rift deposits are mainly mud prone, with small but essential sand input that decreased because sediment supply reduced throughout the Eocene. On the western and eastern margins of the basin, marginal- to shallow-marine deposition dominates while deep-marine sedimentation dominates in the basin's center above the Viking and Central grabens (Copestake, Sims et al. 2003). Volcanism associated with incipient North-east Atlantic spreading ended around 52 Ma in Eocene times. Throughout the Eocene, the sediment supply, particularly coarse-grained clastics dwindled, causing a different deposition pattern from the large Paleocene submarine fans. Early Eocene submarine-fan systems had smaller and localize fan deposits whereas mid-to-late Eocene deposits became channelized (Copestake, Sims et al. 2003).

Overall, the pattern of deposition progrades from the west to the east as the North Sea Basin was filled. The position of major rivers and deltas influenced the amount of coarse-grained clastics brought from the East Shetland Platform and the Scottish Highlands into the basin during the early Eocene. (GABRIELSEN, JORDT et al. 2002). Due to a shortage of available accommodation space, the deeper-marine reservoir sandstones of the Eocene were frequently point sourced, produced by sediment bypass. The Eocene sediments in the study area thins eastwards towards the central North Sea indicating that there was less input of coarse-grained sediments from the east. This was possibly as a result of the regional subsidence that occurred in Norway (Jordt, Thyberg et al. 2000). The North Sea's regional stress regime changed to one of east-west extension toward the end of the Eocene (Copestake, Sims et al. 2003).

2.1.3 Oligocene and Miocene

Southern Norway and the eastern flanks of the northern North Sea basin was uplifted during the Eocene-Oligocene transition (GABRIELSEN, JORDT et al. 2002). The uplift and units that prograded from the East and West created a shallow marine environment in the northern North Sea, which separated deeper waters to the south and north of the basin and later connected the deeper Central North Sea with the Norwegian-Greenland Sea during the Miocene (Copestake, Sims et al. 2003). Across most of the study area, polygonal normal faults have been recognized in the lower Cenozoic strata which were active during sedimentation and early burial (Zanella, Coward et al. 2003, Head, Riding et al. 2004). They are considered to be a result of compaction and loss of water in fine grained, mud dominated sediments. The faults serve as dewatering conduits and may be migration pathways burial (Zanella, Coward et al. 2003, Head, Riding et al. 2004). Sedimentation on a marine, subsiding passive margin overprinted by intermittent regional phases of tectonic movements and uplift on the Norwegian continental margin dominated the Oligocene and Miocene (Copestake, Sims et al. 2003). Seismic and biostratigraphical data suggests that the North Sea, Norwegian Sea and surrounding mainlands experienced a regional uplift and erosion before the late-middle Miocene phase of compression related to the regional Alpine shortening (GABRIELSEN, JORDT et al. 2002). The regional uplift and a mid-Miocene fall in glacio-eustatic sea level caused erosion and the creation of a prominent unconformity. The unconformity is from the latest Oligocene (c. 25 Ma) to late Miocene time (c. 8-9 Ma) but it is locally interrupted by upper Oligocene and lower to Mid-Miocene age deposits (GABRIELSEN, JORDT et al. 2002). The regional uplift increased the influx of sand (Utsira Formation) in the North Sea Basin, more proximal to the mainland. The formation was sourced from the Shetland Platform in its southern and middle part, while its northeastern sediments were derived from the Sognefjorden/Nordfjord source areas (Rundberg and Eidvin 2005, Eidvin, Riis et al. 2014). Regional mapping of the Utsira Formation shows that it occupies two depocenters in the north and south areas in the center of the northern North Sea. At the southern depocenter which corresponds to the Sleipner area, the formation is revealed to be about 300 m thick (Zweigel, Arts et al. 2004) while the north thickness reaches 200 m (Chadwick, Holloway et al. 2004).

2.2 Stratigraphy

The Tertiary in the Southern Viking Graben is divided into three groups namely; Rogaland, Hordaland, and Nordland groups (Figure 8) (NPD 2014). The formations of these groups have been described in detail (Deegan and Scull 1977). For this study, only four intervals in the Tertiary stratigraphic succession are studied. These intervals are; the Rogaland Group, the lower Hordaland sandstone unit (Hordaland sands), the Hordaland Group and the Utsira Formation from the Nordland Group.

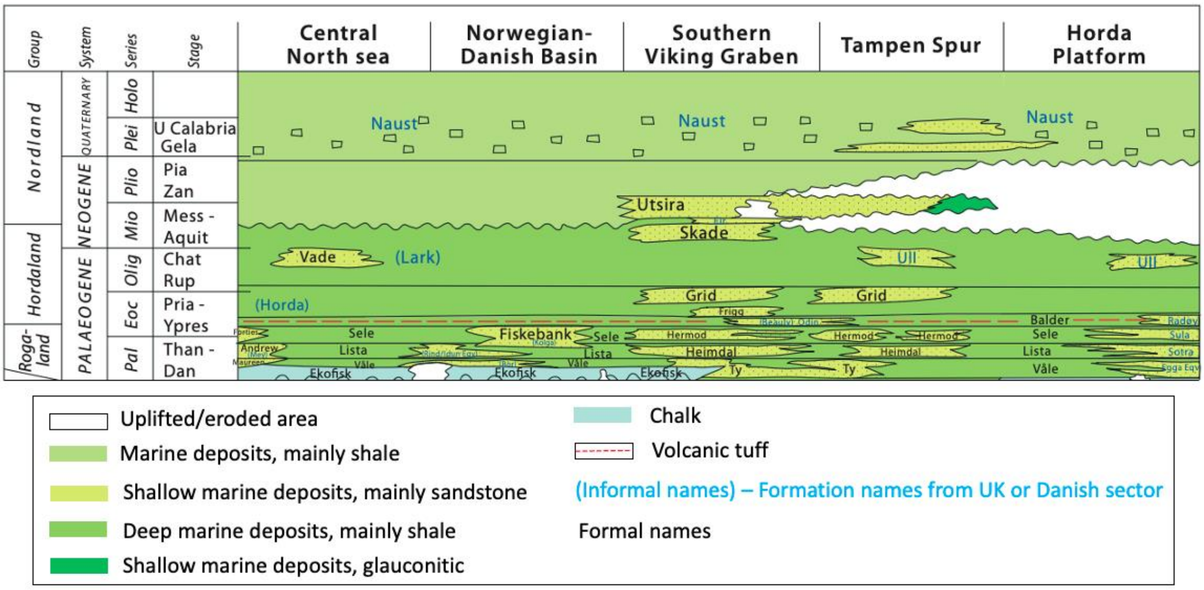


Figure 8: Stratigraphy of the study area (Modified after NPD 2014)

2.2.1 Rogaland Group

The Rogaland Group was named after the county of Rogaland in southwest Norway (NPD 2004). The Rogaland Group dates from the Paleocene to the early Eocene. A deep marine environment having submarine fans from the west and possibly southeast prevailed in this group. It is divided into formations namely; Ty, Våle, Lista, Sele, Heimdal, Hermod, and Balder in the southern Viking Graben (Ahmadi, Sawyers et al. 2003).

The lithology mainly consists of sandstones and shales with minor amounts of coal, tuff, volcaniclastic rocks, marls and reworked carbonate sediments (NPD 2004). In the northern North Sea, the group is bounded at the base by the chalks of the Shetland Group and at the top by irregularly bedded sediments that are substantially less tuffaceous (NPD 2004).

2.2.2 Hordaland Group and Hordaland Sands

The Hordaland Group was named after the county of Hordaland in Norway (NPD 2004). The group is Eocene to early Miocene in age with marine sediments mainly deposited in deep water. The group is found across the North Sea Tertiary Basin, however, it is sparse near the basin's margins due to erosion or non-deposition. Its maximum thickness in the southern Viking Graben is approximately 1400 m. The group consists of marine claystones with minor sandstones, thin limestones and streaks of dolomite. The sandstone content which increases to the east is generally very fine to medium-grained sandstones and often interbedded with claystones (NPD 2004). In the North Sea, the group is bounded at the base by laminated tuffs of the Balder Formation (Rogaland Group) and at the top by undifferentiated claystones of the Nordland Group or sandstones of the Utsira Formation. When bounded at the top by undifferentiated claystones, the top of the group indicates an early to middle Miocene age unconformity (Eidvin and Rundberg 2007) and this can be difficult to spot in some wells (NPD 2004).

In the study area, part of the Hordaland Group shows severe deformations by polygonal faulting and soft sediment mobilization (Zweigel, Arts et al. 2004).

Four sandstone formations (Frigg, Grid, Skade and Vade) are now recognized in the Hordaland Group (NPD 2004). In the study area, there exist sandstones at the base of the Hordaland Group that cannot be attributed to any of these four formations because these sandstones are more continuous than the four sandy formations, and for this study would be called the Hordaland Sands. Claystone intervals between sandstones are not classified as formations and stay as nameless units of the Hordaland Group (NPD 2004).

2.2.3 Utsira Formation

The Utsira Formation was named by Deegan and Scull in 1977 after the Utsira High (NPD 2004). The Utsira Formation forms part of the Nordland Group. It is middle to late Miocene in age and was deposited in a shallow marine shelf. The formation consists of marine sandstones, claystones and occasional lignite. The formation is found in the Viking Graben, but it pinches out towards the northeast between the Oseberg and Troll fields. The Utsira Formation generally thins and increases in clay content eastwards implying that the majority of the sediment came from the west, but local sources in the east are also possible (NPD 2004).

It is bounded at the base by the underlying Hordaland Group or in some cases mid-Miocene shales while at the top by the Nordland shales. On seismic, the lower part of the formation shows sub-parallel mounded reflections caused by sandy clay and may represent mud volcanoes (Ahmadi, Sawyers et al. 2003). Local thickness variations generally observed in the formation are as a result of the presence of mud diapirs and mud volcanoes at the base of the formation (Zweigel, Arts et al. 2004).

2.3 Structural elements of the Study area

The study area consists of four main structural elements; the Ve Subbasin, Sleipner Terrace, Utsira High and Ling Depression (Figure 1).

2.3.1 Ve Sub-basin

The Ve Sub-basin is located in the southern part of the Viking Graben. It is bounded to the North by the Vilje sub-basin and Gudrun Terrace, the West by the East Shetland platform and Falden Ground Spur, the South by the Andrew Ridge and Ling Depression and the East by the Sleipner Terrace and Utsira High (NPD 2022).

2.3.2 Sleipner Terrace

The Sleipner Terrace is located in the southern part of the Viking Graben. The Gudrun Terrace and Utsira High are located at the North of the Sleipner terrace. The Ve Sub-basin, Ling Depression and the Utsira High respectively surround its west, south and east. (NPD 2022)

2.3.3 Utsira High

The Utsira High is a basement high bounded to the South by the Ling Depression, west by the Viking Graben and east by the Stord Basin. The structural evolution experienced in Utsira High is linked to the South Viking graben's rifting and sagging (Jenssen, Bergslien et al. 1993).

2.3.4 Ling Depression

The Ling Depression separates the Utsira High in the north from the Sele High in the South. The tectonic features of the Ling Depression are of great importance because it helps to study the changes in structural styles observed in the Central North Sea. The Ling Depression and the Åsta Graben mark the northern boundary for the Zechstein salt (Heeremans and Faleide 2004).

3. Data and Methodology

The data set includes two 3D seismic cubes (ES9401 and ST98M3) with several wells. However, five wells were chosen for the study area (Figure 9). These five wells were chosen based on their locations to represent the structural elements in the study area. Two of the wells are located in the Ve Sub-basin while each of the remaining three are located in the Sleipner Terrace, Utsira High and Ling Depression.

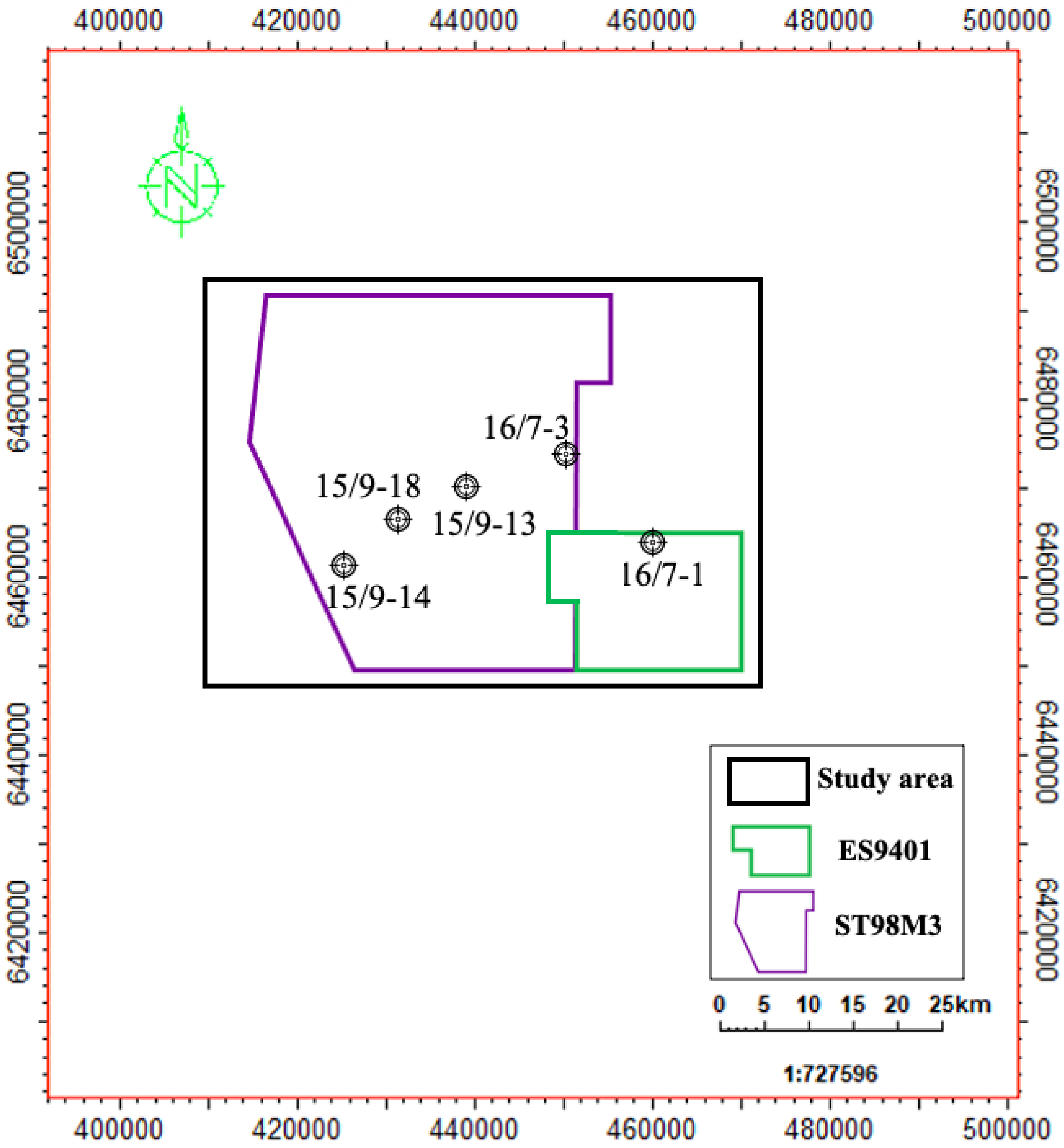


Figure 9: The 3D dataset and the location of the five wells used in this study.

3.1. Well data

The well data are used for understanding and interpreting the lithological variations and in some cases for depositional or structural understanding. All the five wells used in this study have gamma ray logs. Well 15/9-14 sonic log, density, neutron and resistivity logs, well 15/9-13 has neutron and density logs, and resistivity log that only covers the Utsira Formation. Formation well tops from the Norwegian Petroleum Directorate (NPD) are loaded into the dataset and these formation well tops can be connected to the seismic data using a seismic-well tie process. A summary of the five wells used in this study are presented (Table 2).

Table 2: Details of wells used in the study (NPD 2022b)

Well	**Depth (M)**	**Oldest Age**	**Oldest Formation**	**Structural Element**	**Drilling operator**	**Year**
16/7-1	2781	Late Permian	Zechstein	Ling Depression	Esso Exploration and Production Norway A/S	1967
15/9-14	3563	Triassic	Smith Bank	Ve Sub-basin	Den Norske stats oljeselskap a.s	1982
15/9-13	3280	Late Permian	Zechstein	Sleipner Terrace	Den Norske stats oljeselskap a.s	1982
16/7-3	3141	Early Permian	Rotliegend	Utsira High	Esso Exploration and Production Norway A/S	1982
15/9-18	3622	Triassic	Smith Bank	Ve Sub-basin	Den Norske stats oljeselskap a.s	1983

3.2. Seismic Data

The ST98M3 3D cube is the main seismic survey as it covers all parts of the study area except the Eastern edge of the Ling Depression. The ES9401 3D cube covers the Ling Depression. A summary of the two 3D seismic cubes used in this study are presented in

Table 3.

Table 3: General description of the two seismic dataset used in this study.

	ES9401	ST98M3
Size (GB)	4.6	47.5
Seismic type	3D	3D
Inline length (m)	12187.85	38087.97
Crossline length (m)	22625.04	38037.51
Size (Km2)	276	145
Inline interval	25.5	12.5
Crossline interval	12.5	12.5
Maximum depth (TWT)	5500	5400
Polarity	Positive	Positive

The seismic dataset has positive (American) polarity meaning that there is an increase in acoustic impedance (hard kick) with depth because of increasing density and velocity. Polarity was interpreted using the reflector of seafloor since seismic velocity and density increases from seawater to sediments. Seismic to well-tie (Figure 10) was done in order to link the well data and seismic data together for better interpretation.

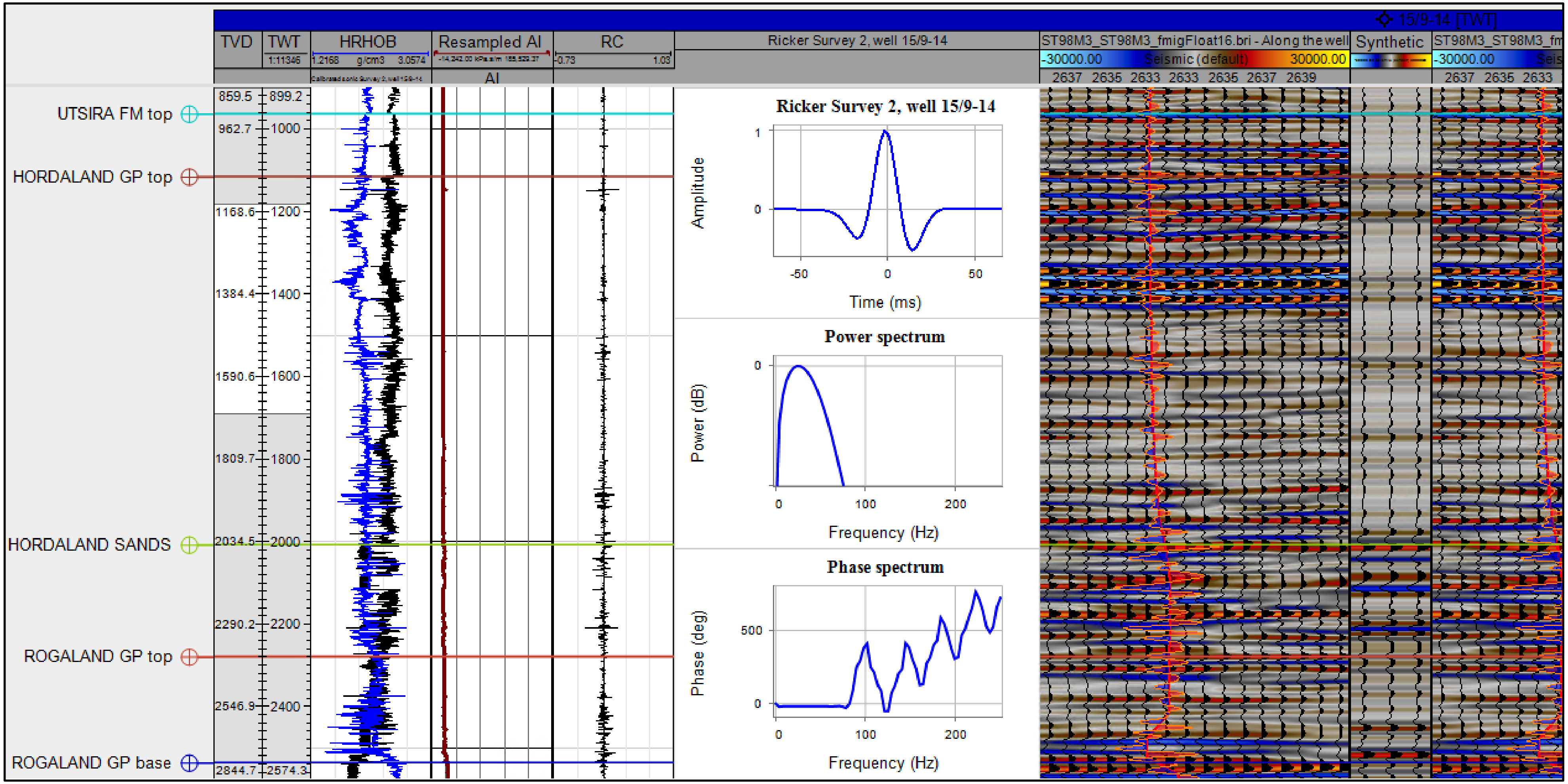


Figure 10: Seismic to well tie for well 15/9-14 used in this study

3.2.1 Seismic Attributes

- Variance (Edge method): Variance (Edge method) is amplitude invariant as either in low or high amplitude, the seismic response and signature are the same. Variance helps to map either structural discontinuities or stratigraphic terminations (Petrel 2015).
- RMS amplitude The RMS amplitude calculates the root mean square (RMS) over a specified window. Using amplitude variations and density changes, it can be used to detect channels (Petrel 2015).

3.3 CO_2 Storage Potential

The characterization and ranking procedure created for storage sites in the Nordic region (Anthonsen, Aagaard et al. 2014) and the methodology from the CO_2 storage atlas of the Norwegian part of the North Sea is being employed (Halland et al., 2013). These procedures have been modified to capture the factors of interest outlined in subchapter 1.1.1 and will be analyzed using well log analysis, seismic interpretation and literature review.

After the type of reservoir has been established, reservoir qualities such as porosity, permeability, heterogeneity, thickness and the factors depth and traps will be considered based on the criteria in Table 4. Seal criteria will include thickness, seal by-pass, lateral extent and lithology of the primary seal (

Table 5).

Further conclusion will be made by transforming the criteria values into points from 1-3 where 3 is given to the preferred, 2 is given to the questionable and 1 is given to the hazardous. The total points that can be gotten is 27.

Table 4: Criteria for potential Reservoir properties (Halland, Riis et al. 2013, Anthonsen, Aagaard et al. 2014).

Reservoir properties	Preferred	Questionable	Hazardous
Depth	>800m-2500m	600m-800m	<600m
Porosity	>20%	10-20%	<10%
Permeability	>100mD	10-100mD	<10mD or no data
Heterogeneity/Thickness (Net sand)	>50m	15-50m	<15m
Traps	Defined trap structures	Poor definition of traps	Lack of traps

Table 5: Criteria for potential seal properties (Halland, Riis et al. 2013, Anthonsen, Aagaard et al. 2014).

Seal properties	**Preferred**	**Questionable**	**Hazardous**
Thickness	>50m	20-50m	<20m
Lithology of the primary seal	Homogeneous clay, mud or evaporites	Chalk	High content of silt or sand
Seal by-pass	None	Uncertain	High Risk
Lateral extent	Continuous	Unsure about existence of continuous seal. Seal locally thinner than 20 meter	Not continuous

4.0 Results

4.1 Seismic Facies

Seven main seismic facies and structures have been identified and interpreted within the study area (Table 6). Identification and interpretation of these seismic facies and structures is important in understanding the lithofacies variation and strata continuity, tectonic and depositional processes, and CO_2 storage potential within the Tertiary succession.

Although diapirs and polygonal faults are not seismic facies, they are labelled as facies for uniformity.

In this subchapter, the first paragraph describes the identified seismic facies while the second paragraph gives the interpretation.

Facies A: Medium to high amplitude continuous reflectors

Seismic facies A exhibits medium to high amplitude continuous reflectors. They have higher amplitudes than the surrounding reflectors. Small mounds are also observed (Table 6).

Based on the geometry of the Facies A and the size, it is interpreted as a submarine fan. The presence of submarine fans has been previously discussed by various works such as Copestake, Sims et al. (2003).

Facies B: Wing like reflectors

Facies B exhibits high amplitude wing like reflectors that cross-cut underlying and overlying reflectors (Table 6). They are often seen to also cross-cut or connect with each other. Generally, when they occur, they occur as a package of 30-100 ms thick reflections and often cover a vertical area of about 200 ms.

Based on their geometry, facies B are interpreted as post-depositional sand injectite features that may have been formed during sand remobilization. Their crosscutting and connection relationship with each other may indicate that there were repeated stages of injection through burial. Several authors have discussed their presence in the study area (Huuse and Mickelson 2004, Duranti 2007, Hurst and Cartwright 2007).

Facies C: Faults with polygonal patterns

Facies C exhibits faulted high amplitude reflectors. The faults are normal faults and they display multiple directions. They show very little to no displacements. Variance amplitude map displays polygonal patterns (Table 6).

From the facies description and polygonal network pattern in map view, facies C indicates polygonal faulting. (Zanella, Coward et al. 2003, Head, Riding et al. 2004, Zweigel, Arts et al. 2004) have documented the presence of polygonal faults which were active during sedimentation and early burial in the study area.

Facies D: Wavy low amplitude reflectors

Facies D exhibits low amplitude reflectors that are wavy and consistent (Table 6). On well logs, they show high gamma ray readings.

Based on the well control, facies D is interpreted as fine grained sediments, possibly shales.

Facies E: Fold with chaotic internal low amplitude reflectors

Facies E are observed to have folded overlying reflectors and then distorted underlying reflectors. They show internally chaotic low amplitude reflectors (Table 6).

Based on the seismic geometries and description of the facies, facies E are interpreted to be mud diapirs. The presence of mud diapir have been documented by several authors. (Ahmadi, Sawyers et al. 2003, Zweigel, Arts et al. 2004).

Facies F: High to Medium amplitude parallel to subparallel reflectors

Facies F display high to medium amplitude reflectors that are parallelto subparallel (Table 6). Facies F occurs as a group of reflectors that are laterally continuous unless when disrupted by seismic facies. On well logs, facies F have low gamma ray readings.

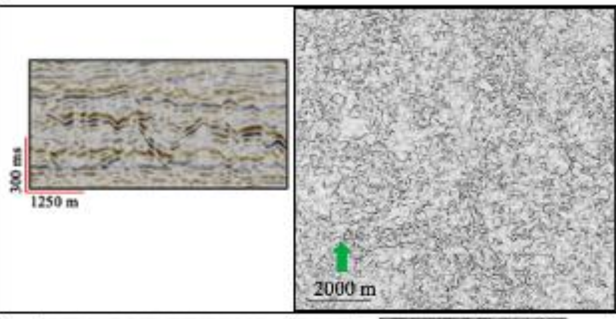
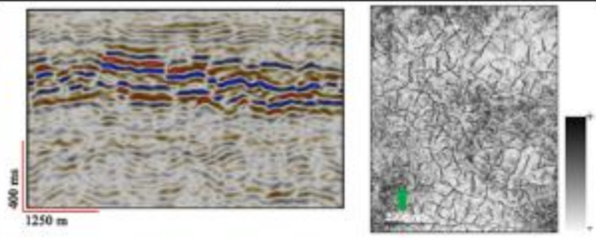
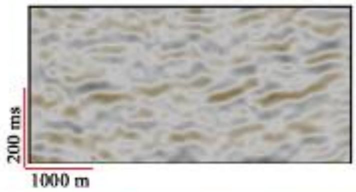
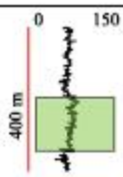
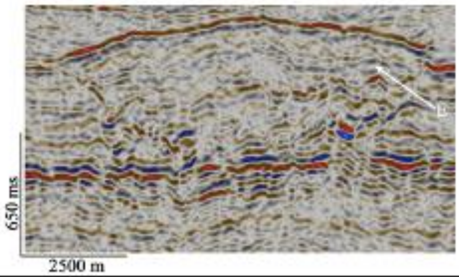
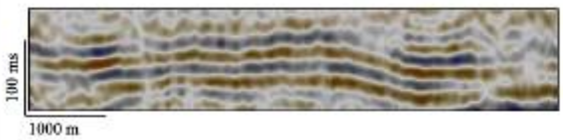
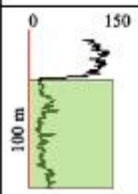
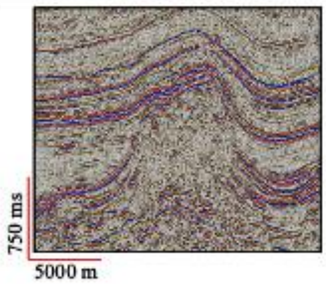
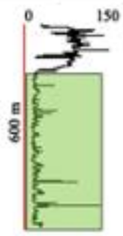
Based on the well control, facies F are interpreted as coarse grained sediments (sandstones).

Facies G: Fold with chaotic semi-transparent internal reflectors

Facies G are observed to have folded reflectors above and the reflectors by the sides are upturned and pulled up to the top of the folds. The internal reflectors are chaotic and semi transparent. On well logs, facies G show very log gamma ray readings (Table 6).

Based on the geometry, upturned reflectors against the flanks of the fold and pull up, facies G is interpreted to be salt diapir. Although facies G does not occur within the intervals of interest, it underlies the folds of the Rogaland Group and Hordaland sand and it plays a role in the folding. Facies G has been documented by Copestake et al., 2003.

Table 6: Summary of seismic facies and structures identified in this study.

Facies Description	Interpretation	Seismic Example	GR Pattern (gAPI)
A: Medium to high amplitude continuous reflectors	Submarine fan		N/A
B: Wing like reflectors	Sand injectites/ Remobilized sands		N/A
C: Faults with polygonal patterns	Polygonal faulting		N/A
D: Wavy low amplitude reflectors	Fine grained sediments		
E: Fold with chaotic low amplitude internal reflections	Mud diapir		N/A
F: Medium to high amplitude parallel to sub-parallel reflectors	Coarse grained sediments		
G: Fold with chaotic semi-transparent internal reflectors	Salt diapir		

Seismic Unit Description

The seismic surveys are divided into seismic units based on the different formations of interest. Thus, four units are interpreted in this study: the Rogaland Group, the Hordaland Sands, the Hordaland Group and the Utsira Formation. The tops mapped in the seismic volumes are:

- The base of the Rogaland Group
- The top of the Rogaland Group
- The top of the Hordaland sands
- The top of the Hordaland Group
- The top of the Utsira Formation

To illustrate the lateral distributions and outline of the seismic units, seismic lines that cover the study area are shown in Figure 11.

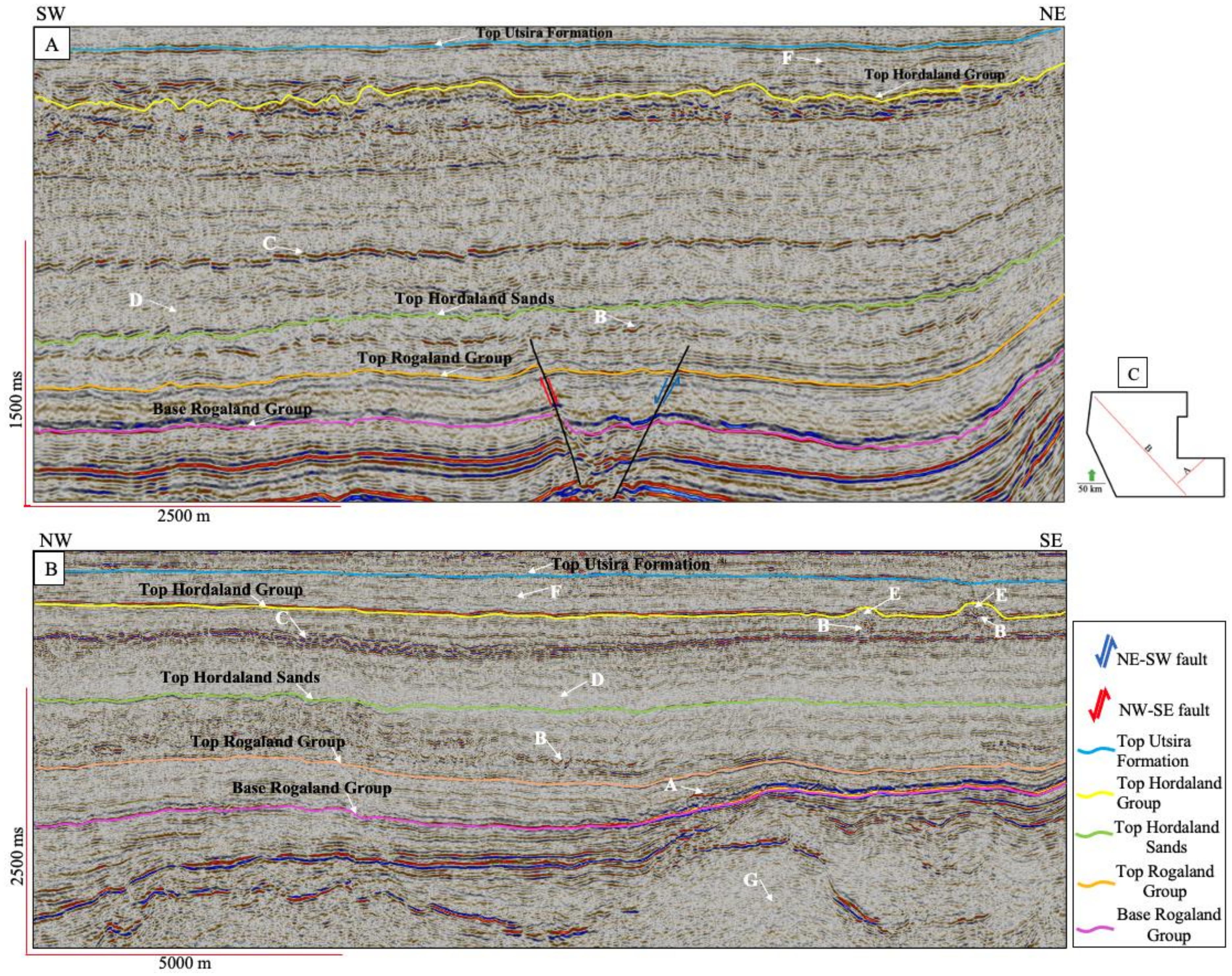


Figure 11: Seismic lines of the study area showing the interpreted units. A: Seismic line of ES9401 showing faults and seismic facies B (sand injectites), C (polygonal faulting), D (fine grained sediments) and F (coarse grained sediments). B: Seismic line of ST98 M3 showing the seismic facies A (submarine fans), B (sand injectites), C (Polygonal faulting), D (fine grained sediments, E (mud diapir), F (coarse grained sediments) and G (salt diapir). C: Location of seismic lines A and B.

4.2 Rogaland Group

4.2.1 Well log

The Rogaland Group interval is laterally continuous throughout the correlated wells and generally found at average depths of 2109 m with shallowest depth of 1670 m in well 16/7-1 (Ling depression). It gets thicker towards the West reaching a maximum thickness of 411 m in the Ve Subbasin (well 15/9-18) and a minimum thickness of 186 m in the Ling depression (well 16/7-1). The gamma ray response towards the west displays a serrated-blocky shape typical of sandstones and shale intercalations (Figure 12). However, it appears more serrated as it moves towards the East. Generally, the sandy content of the Rogaland Group increases laterally towards the East while the shales appear to thin out (Figure 12).

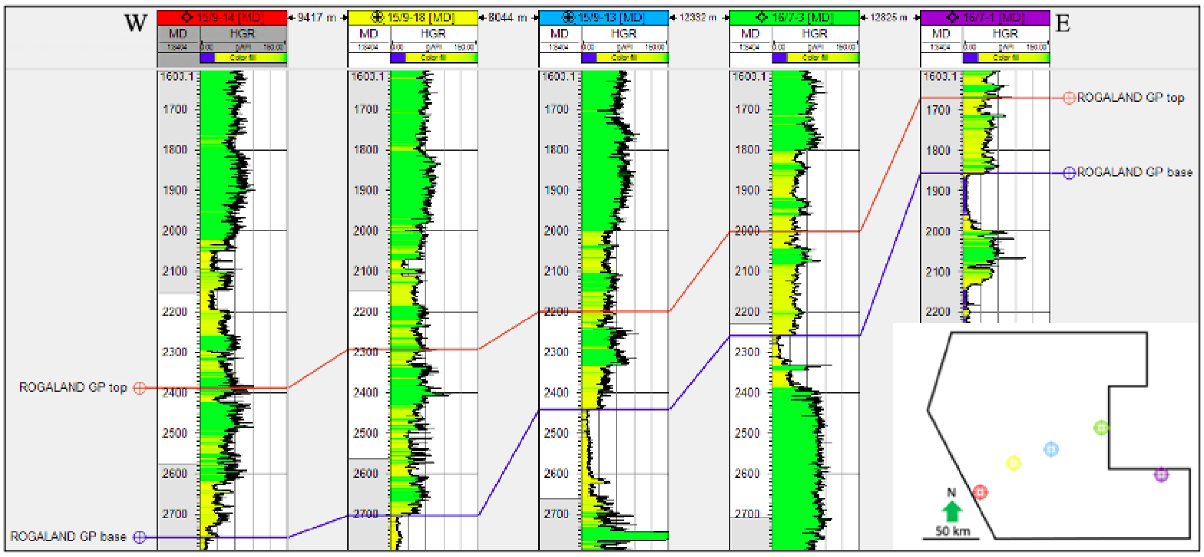


Figure 12: West to East well correlation of the Rogaland Group.

4.2.2 Seismic Descriptions

The Rogaland Group is present throughout the study area. The group is observed to have similar dips and folds with the units below and above it. The folded area is located in the southeast edge and it is as a result of the underlying salt diapir (facies G). Thickness variations are observed within the interval as the interval is thicker at the flanks than at the crest of the fold (Figure 13). Medium to high amplitude continuous reflectors (facies A) are observed within the interval reflectors (Figure 14). These reflectors are continuous although they are only displayed as high amplitudes in some areas. Wavy low amplitude reflectors (facies D) are also present within the unit They constitute the rest of the unit where there are no facies A. Normal faults often offset the Rogaland Group to a small extent. These faults strike in either the NW-SE direction or NE-SW direction (Figure 15). The NW-SE strike faults usually have throws of 2-10 ms or lack displacement while the NE-SW strike faults have throws ranging from 20-50 ms.

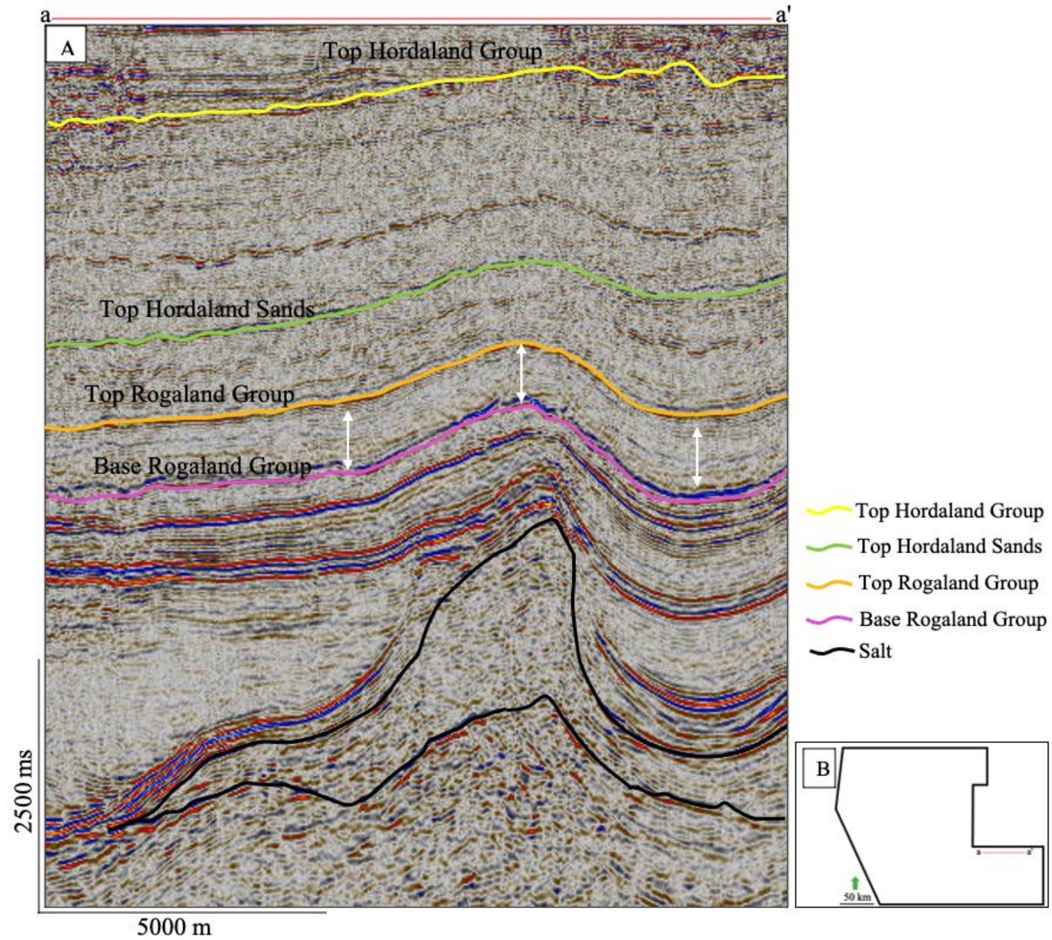


Figure 13: A: Seismic line showing the Rogaland Group interval. The white arrows (1.2 cm) are used to measure the thickness variation. Note how thickness reduces over the crest of the fold. B: Location map of seismic cross section.

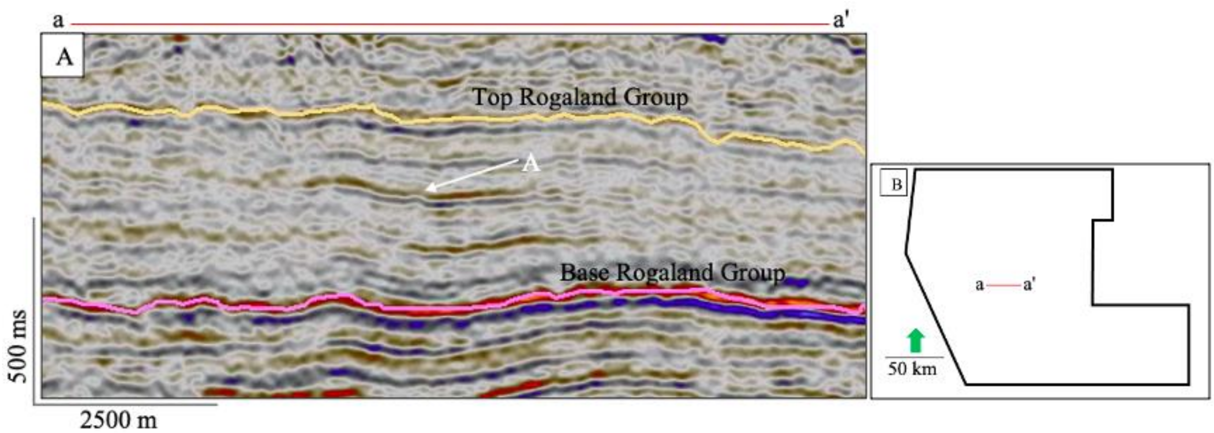


Figure 14: A: Seismic cross section of seismic facies A located within the Rogaland Group. B: Location map of seismic cross section.

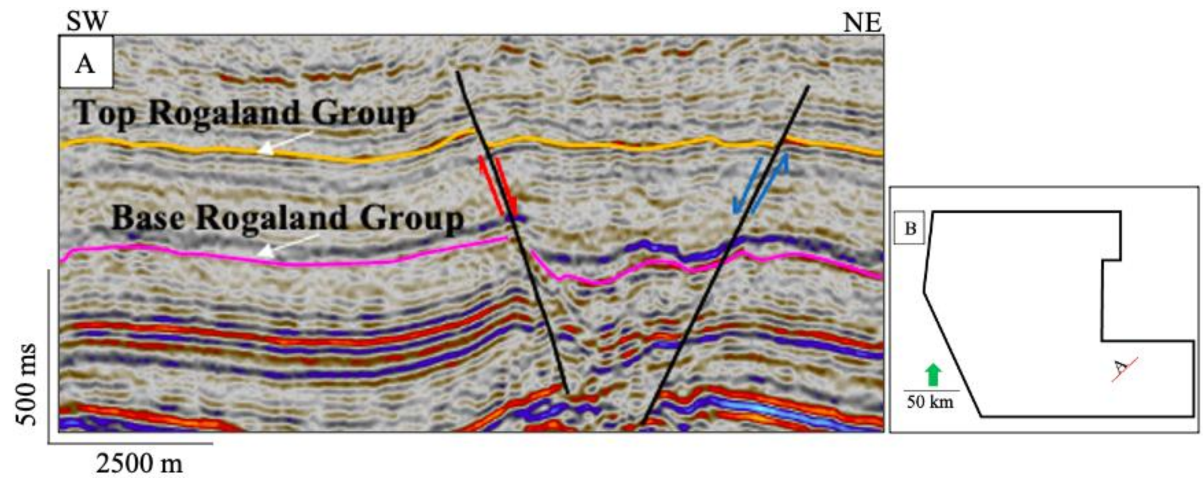


Figure 15A: Seismic cross section of faults trending in NE-SW direction (blue arrows) and NW-SE direction (red arrows). B: Location map of seismic cross section

4.2.3 Maps and Attributes

In the Ling Depression, the Rogaland Group is penetrated by faults (Figure 16). The faults that penetrate the structural high at the southeastern edge of the Ling Depression show no displacements as the same depth (1850 ms) is maintained across the faults while some other faults show minor displacements.

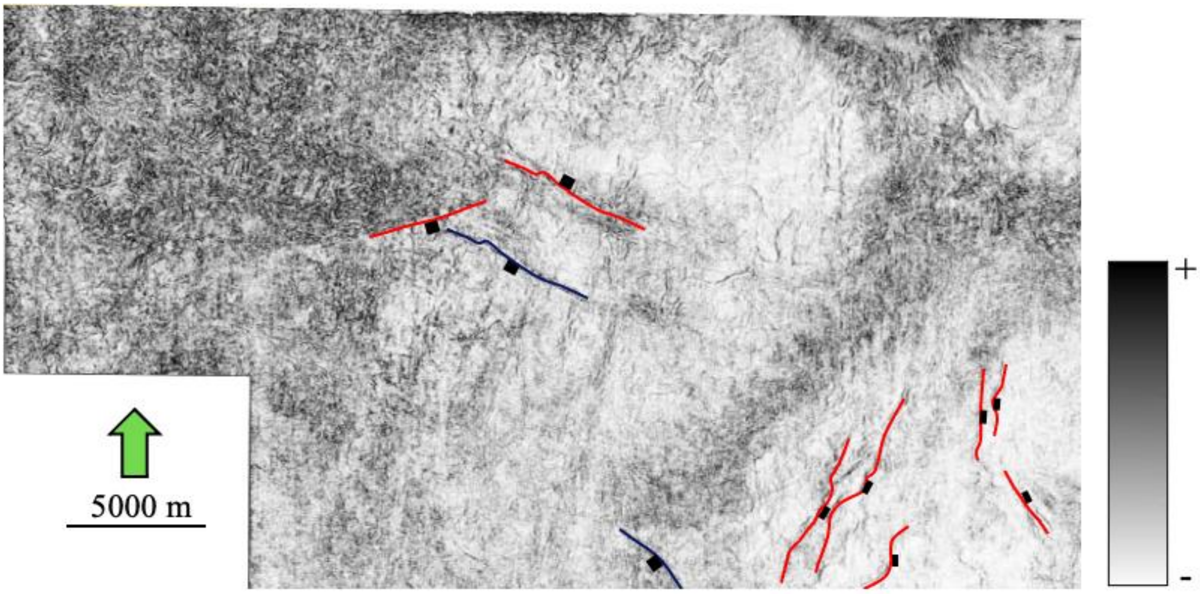


Figure 16: A: Uninterpreted variance amplitude map of the Ling Depression area where the faults are present. B: Interpreted variance amplitude map. The faults are colored according to their direction. Blue is trending in the NE-SW direction while Red is trending in the NW-SE direction. Variance amplitude map of the other seismic cube is poor and no fault was mapped in the seismic lines of the other cube.

The deepest areas within the Rogaland Group are located in the southwestern edge of the Ve Sub-basin (Figure 17). A sequential increase in thickness is observed from the southeast to the northwest until a maximum thickness of 480 ms in TWT is reached at the Ve Subbasin (Figure 17). The faulted areas show no thickness variations across the faults.

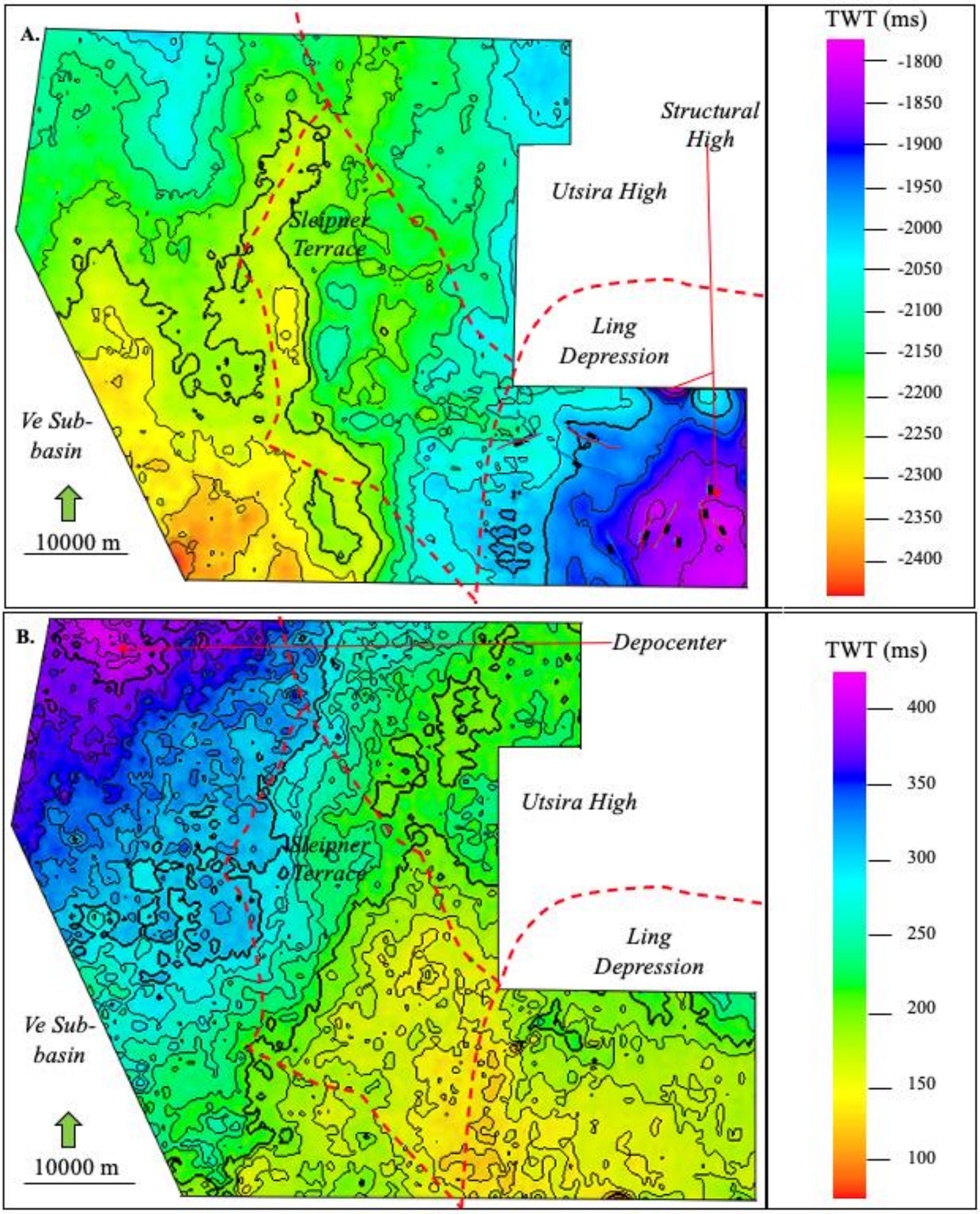


Figure 17: A: TWT structural map of the Rogaland Group. Note the location of the structural high in the southeast. B: TWT thickness map of the Rogaland Group with depocenters in the north.

Two seismic facies are observed within the Rogaland Group while one is identified to underlie the unit and fold it. They are facies A; medium to high amplitude continuous reflectors, facies D; wavy, low amplitude reflectors and facies G, fold with internal chaotic semi-transparent reflectors (Figure 18).

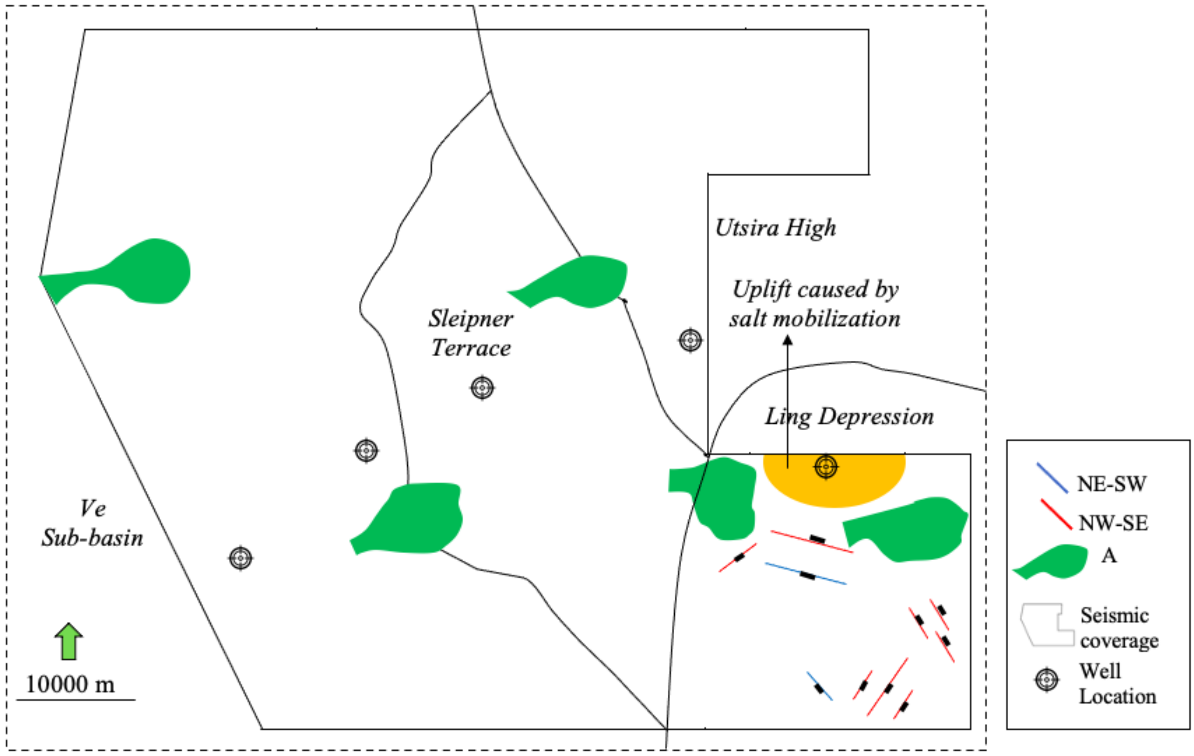


Figure 18: The Rogaland Group seismic facies map. Facies A: Submarine channel. The white parts within the seismic coverage are interpreted as the background sediments.

Facies A occur as medium to high amplitude continuous reflectors in parts of the Rogaland Group interval. They occur mainly at the eastern parts of the Rogaland Group. The wells (16/7-3 and 16/7-1) located within or around facies A are sand-rich. Based on the geometry observed on seismic and well control, facies A is interpreted as sand-rich submarine fans.

Facies D occurs laterally throughout the interval unless when interrupted by facies A. The wells located within facies D are shalier (well 15/9-14). Based on well control, facies D is interpreted as fine grained sediments (shale). The lateral continuity of the facies suggests that it is the background sediments of the Rogaland Group.

Facies G are folds with internal chaotic semi-transparent reflectors. They occur mainly in the Ling Depression and are the cause of the folds in the unit above. Based on the geometry observed, they are interpreted as salt diapir. The evidence of growth strata suggests that they were active during the deposition of the Rogaland Group.

4.3 Hordaland Sands

4.3.1 Well logs

The Hordaland Sands overlay the Rogaland Group and it is laterally continuous throughout the correlated wells. It is found at an average depth of 1881 m with shallowest depth of 1580 m in the eastern well 16/7-1 (Ling depression). Maximum thickness (347 m) among the correlated wells is observed in well 15/9-14 (Ve Sub-basin) and the thickness progressively decreases towards the east with thickness of 90 m in well 16/7-1 (Ling depression). Clear packages of high gamma ray values (green colour) are present both laterally and vertically across the interval (Figure 19). Also, two packages of low gamma ray values (yellow colour) and a blocky pattern are observed in the well at the western edge (15/9-14) while a package of low gamma ray value is observed in well 15/9-18 after which the Gamma ray appears as serrated responses towards the east (Figure 19) showing consistent behavior as sandstones interbedded with shales.

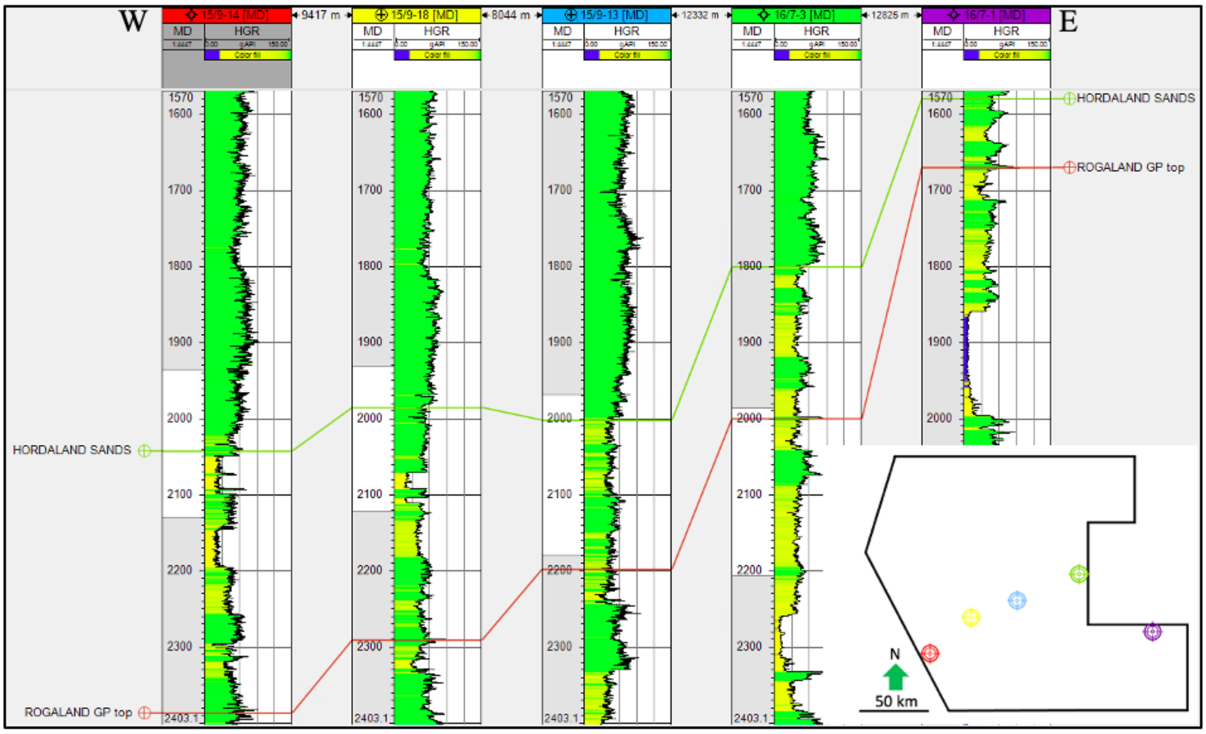


Figure 19: West to East well correlation of the Hordaland Sands. Location map showing the location of the wells.

4.3.2 Seismic Descriptions

The Hordaland Sands are present throughout the study area. Wavy, low amplitude reflectors (facies D) are observed to occupy this interval laterally and vertically (Figure 20). However, at the western area, they are interrupted by medium to high amplitude continuous reflectors (facies A) and wing like reflectors (facies B) (Figure 20). Facies B covers a lateral distance of about 3 km. Individual wing-like reflectors of facies B within this interval range in length from 20 ms to 50 ms and are observed to cross cut overlying and underlying reflectors. Facies A and B thin as they move towards the east of the interval while facies D continues laterally. Just like the Rogaland Group, the Hordaland sands follow the pattern of the underlying unit and it is also folded (Figure 21). This folded area is located in the southeast edge and it is located directly above the underlying salt diapir. Thickness variations are observed within the interval as the interval is thicker at the flanks than at the crest of the fold. However, it generally thins significantly towards the east.

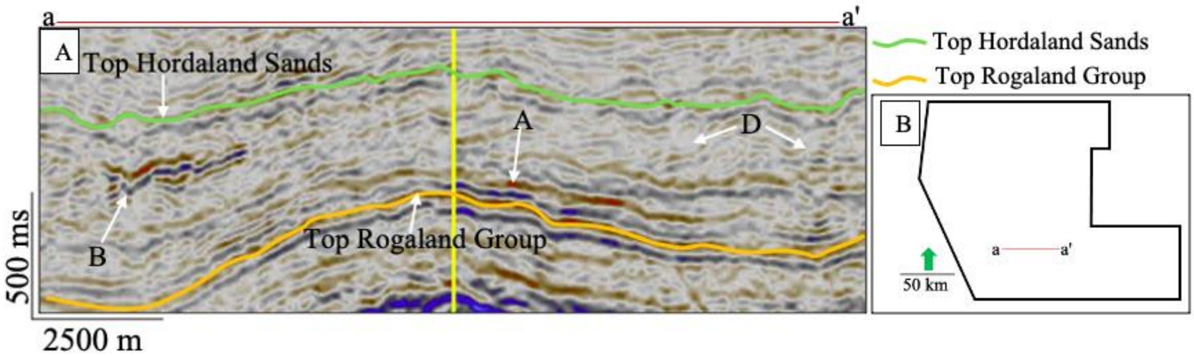


Figure 20: The Hordaland Sands interval showing seismic facies A (medium to high amplitude continuous reflectors), B (wing like reflectors) and D (wavy, low amplitude reflectors). See Figure for location of seismic cross section. Yellow line is an error in the seismic.

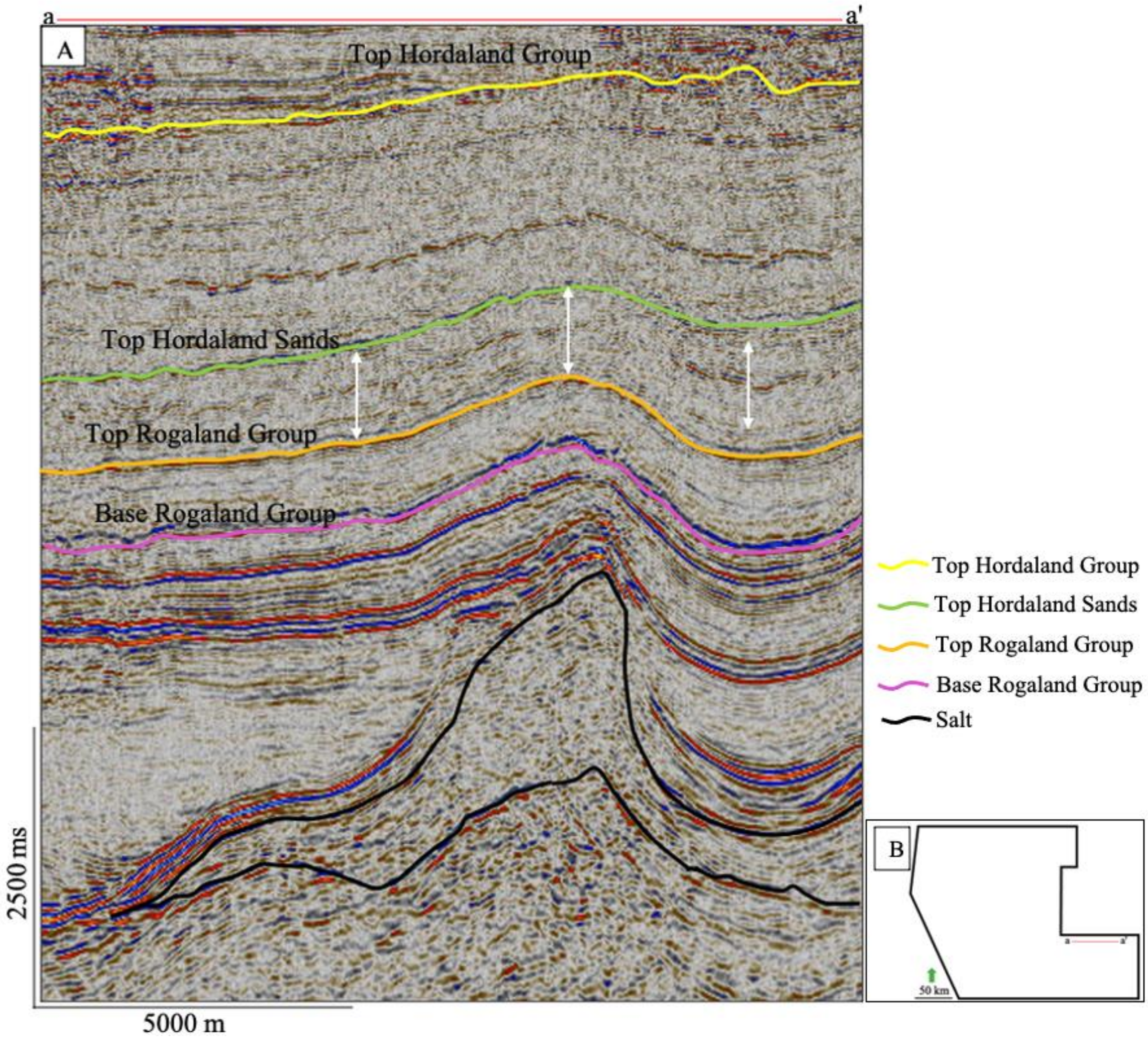


Figure 21: A: The Hordaland sands following the pattern of the underlying formations with the fold located above the salt diapir. The thickness variations between the crest and the flanks is measured with 1.6 cm white arrows. Note how thickness reduces over the crest of the fold. B: Location map of seismic cross section.

4.3.3 Maps and attributes

From the time structural map (Figure 22), the Hordaland sands has two structural highs that reach a depth of 1600 ms; one in the southeastern part of the Ling Depression and the other in the northwestern edge of the Ve sub-basin. The southeastern structural high corresponds to the area folded by the underlying salt diapir. The maximum thickness is 500 ms and it pinches out progressively to the east until it reaches 100 ms at the southeast (Figure 22),

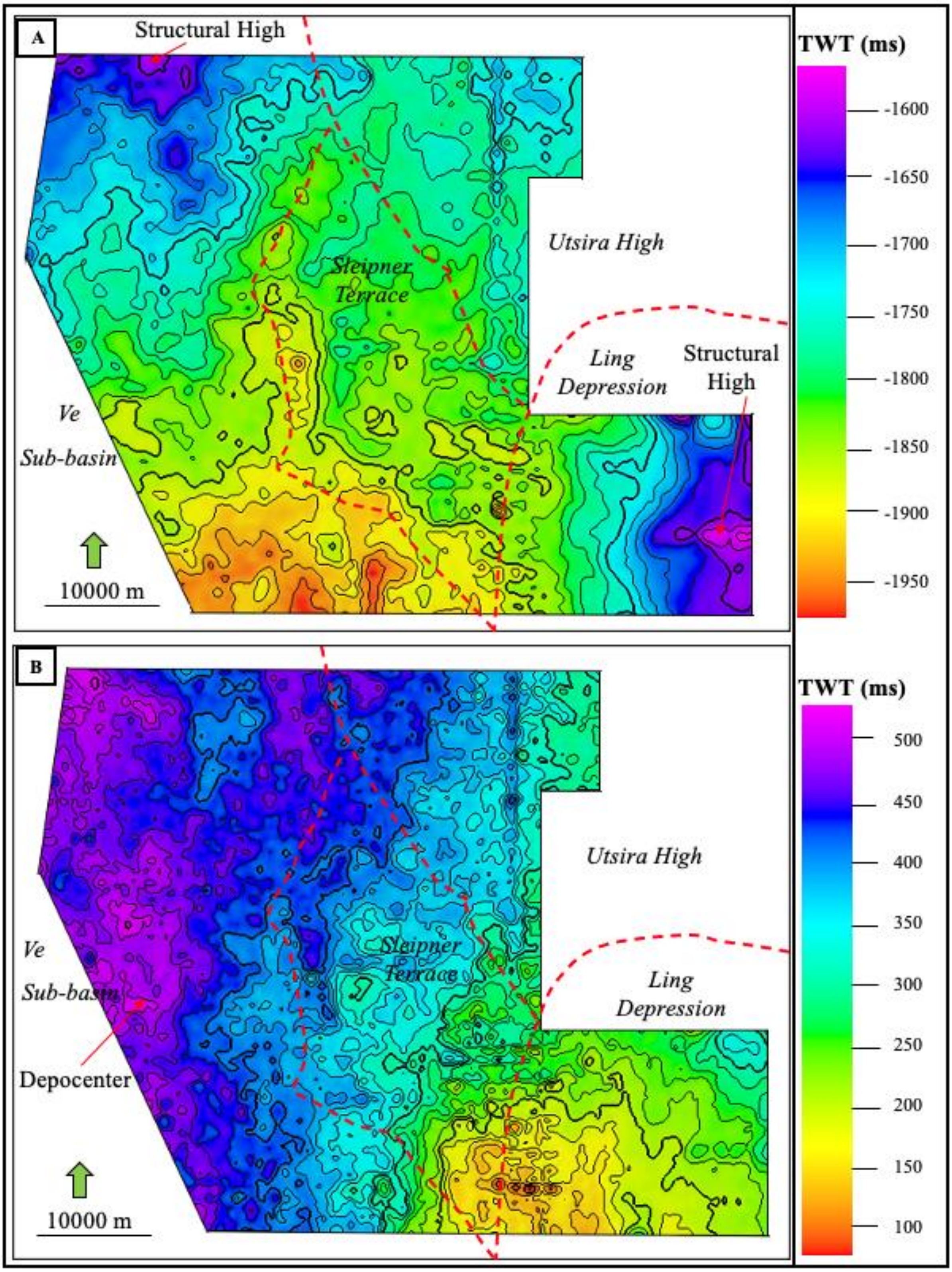


Figure 22: A: Hordaland sands TWT structural map. Note the locations of the structural highs. B: TWT thickness map with large depocenter in the west.

Three seismic facies are observed within the Hordaland Sands (Figure 23). They are facies A; medium to high amplitude continuous reflectors, facies B; Wing like reflectors and facies D; wavy, low amplitude reflectors.

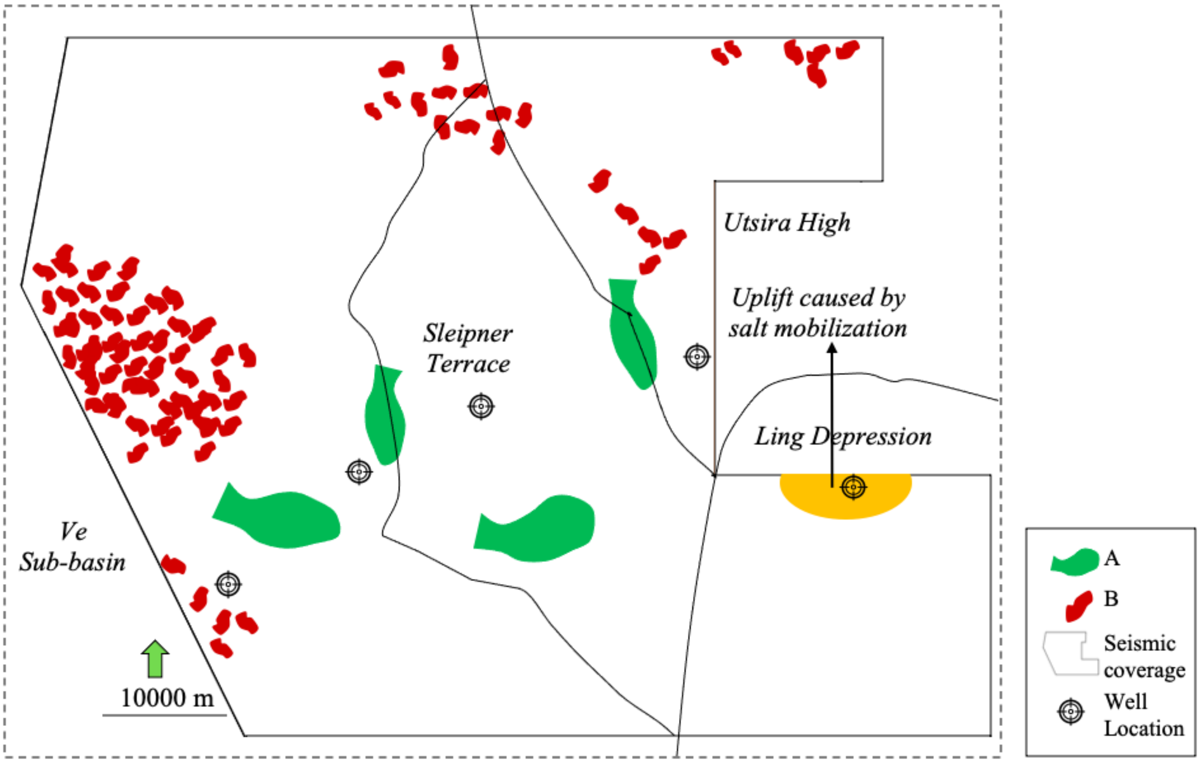


Figure 23: The Hordaland Sands seismic facies map. Facies A: Submarine channel, Facies B: remobilized sands. Note the uplifted area caused by the underlying salt diapir (facies G). The white parts within the seismic coverage are interpreted as the background sediments of facies D

On the RMS attribute map, the bright amplitude areas correspond to areas interpreted to consist of facies A and B. Facies A and B occur mostly in the west and pinch out towards the east. Based on the geometry observed on seismic, facies A is interpreted as submarine fans while facies B is interpreted as remobilized sands. Well log data supports the interpretation as the wells within the bright amplitude areas are sandier than wells outside the bright amplitude areas (Figure 24). The presence of remobilized sands within the study area have been documented by Hurst et al, 2007 and Duranti 2007 while submarine fans have been documented by Jones et al., 2003. The blue amplitude areas are interpreted as the background sediments which corresponds to facies D. On seismic, facies D appears as wavy, low amplitude reflectors. Based on well control gotten from NPD, facies D is interpreted to be fine grained sediments (shales) (NPD 2022).

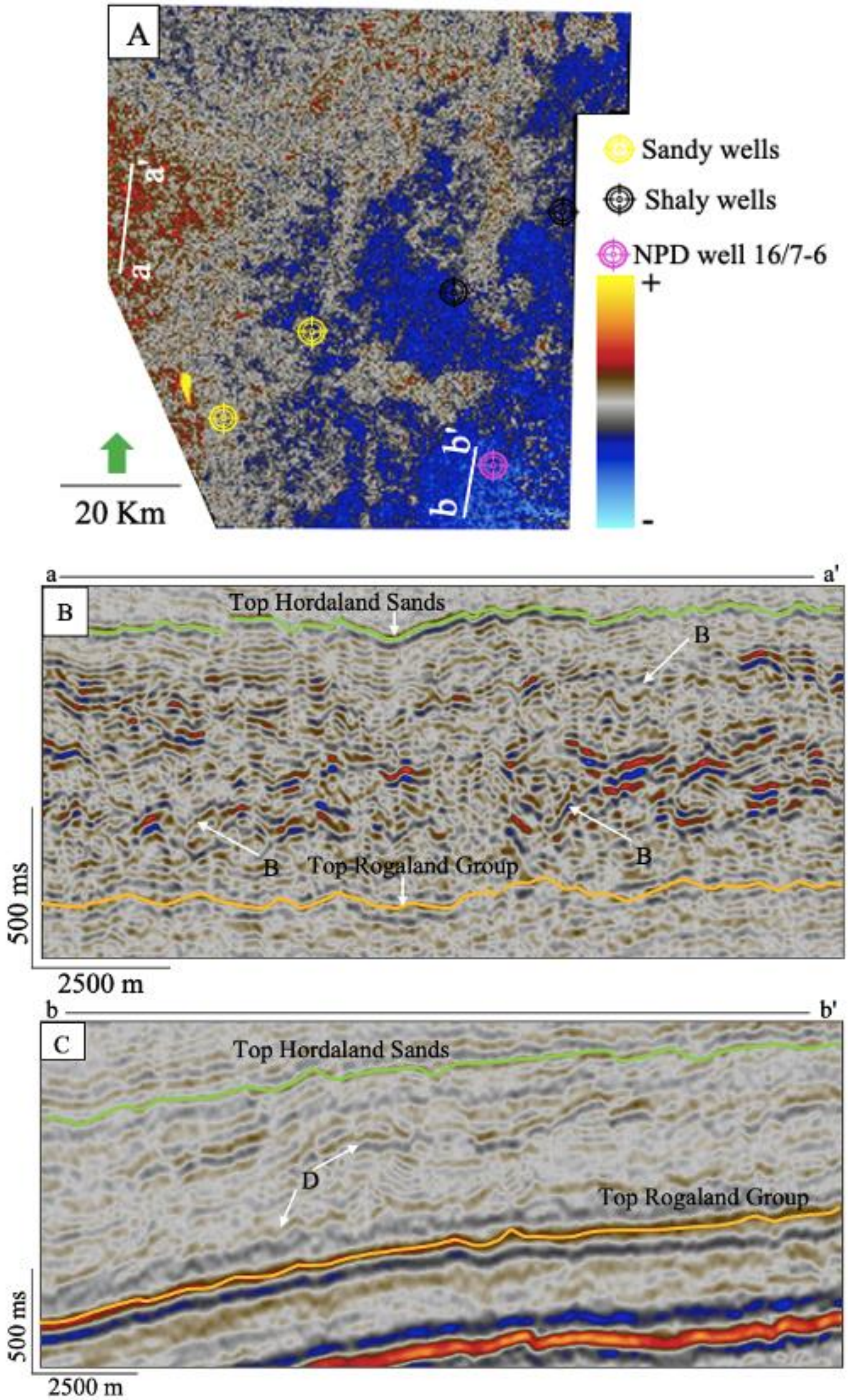


Figure 24: A: RMS amplitude extraction at 50 ms below top Hordaland Sands. B: Seismic cross section with seismic facies B within the Hordaland sands interval. Note how seismic facies B distorts the interval. C: Seismic cross section with seismic facies D within the Hordaland sands interval.

4.4 Hordaland Group

4.4.1 Well logs

The Hordaland Group interval overlies the Hordaland Sands and it is laterally continuous throughout the correlated wells. It is found at an average depth of 1108 m with its shallowest depth at 1017 m (Well 16/7-1). It has its maximum thickness of 962 m in well 15/9-14 (Ve Subbasin). The Gamma ray (Figure Figure 25) response is in general high (green colour) and spiky with a blocky pattern indicating a fine-grained succession. Minor low gamma ray values (yellow colour) are also observed within the interval and are interpreted as sandstones. In the western well (15/9-14), four sandstone packages are observed and these packages get thinner to the east while some of them pinch out.

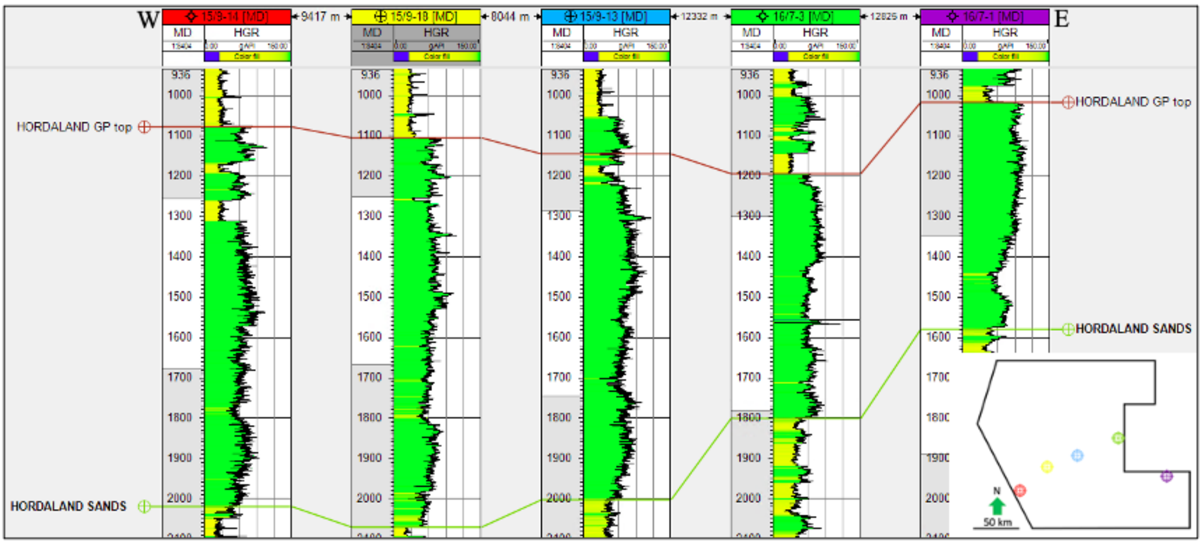


Figure 25: West to East well correlation of the Hordaland Group.

4.4.2 Seismic Descriptions

The Hordaland Group is present throughout the study area. From the seismic, the interval is the thickest of all the four intervals reaching a thickness of approximately 550-700 ms in the ES9401 survey and 700-800 ms in the ST98M3 cube. Generally, the interval thins towards the east and it has a great variation of seismic facies. The Hordaland Group can be divided into 2 intervals by a high amplitude reflector (Figure 26). The base part of the Hordaland Group is characterized by low amplitude reflectors (facies D), the reflectors are wavy but coherent and occupy an area of about 200-300 ms in length, extending laterally within the interval. The amplitude and continuity of the reflectors increases upwards until the highest amplitude reflectors within the interval are reached in the middle. These high amplitude reflectors are heavily faulted (facies C). The faults are normal faults and they display multiple strike directions with little to no offset. Above these high amplitude reflectors, wavy, low amplitude reflectors (facies D) and medium amplitude parallel reflectors that are fairly continuous (facies F) except when interrupted by seismic facies are observed. Within these facies D and F, chaotic low amplitude reflectors (facies E) are observed to distort their lateral continuity. The chaotic low amplitude reflectors create almost circular geometries and often fold the overlying reflectors and cause mild depressions in the underlying reflectors. The folds created by facies E1 usually range from 34-158 m and onlapping reflectors are observed against the flanks of these folds (Figure 27). Small size (10 ms) wing like reflectors (facies B) often occur beneath or around facies E (Figure 27). Intra Hordaland Group interpreted as it folds over underlying salt diapir (figure). Same thickness is measured at the flanks and the crest of the fold with the intra Hordaland Group (Figure 28).

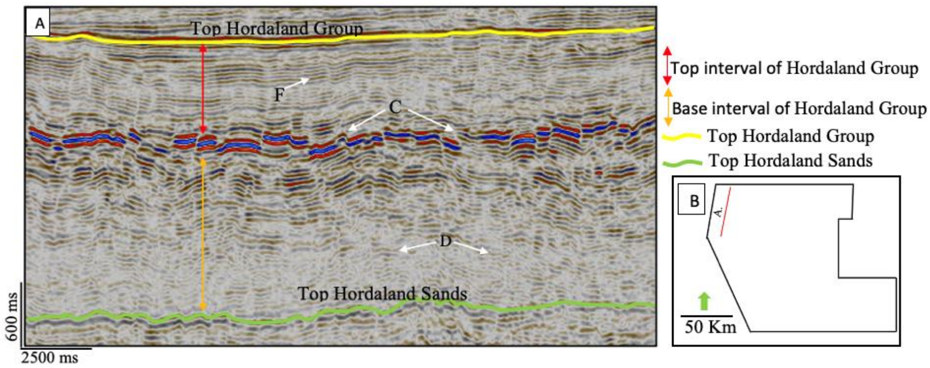


Figure 26: A: Hordaland Group interval showing seismic facies C, D and F. Note the bright amplitude reflectors (facies C) that separate the top and base parts of the Hordaland Group. Also note the normal faulting and multiple strike directions of facies C. B: Location map of seismic cross section A.

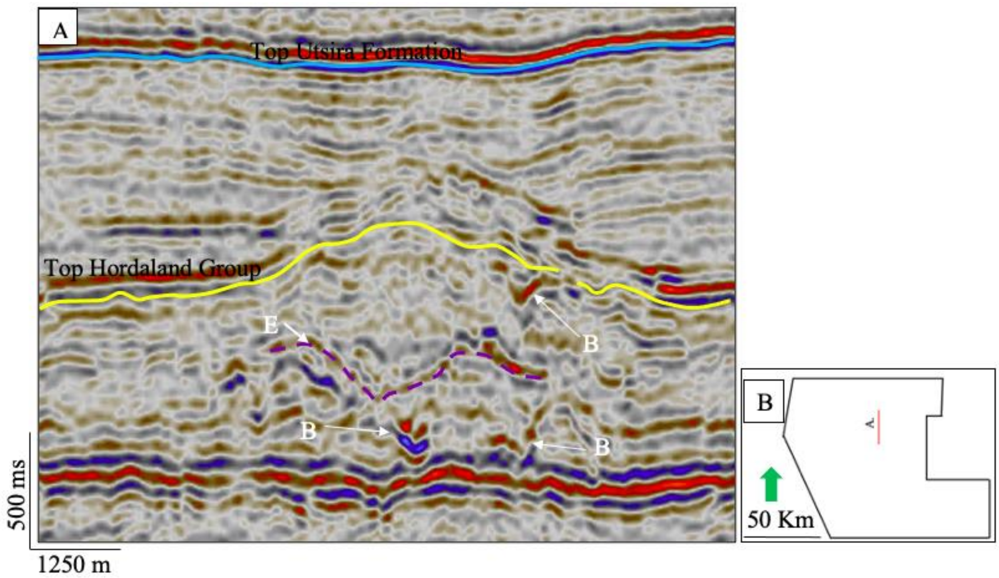


Figure 27A: Seismic line showing facies B and E1 within the Hordaland Group. Note the fold created by facies E1 and the presence of facies B around/below facies E1. B: Location map of seismic line A

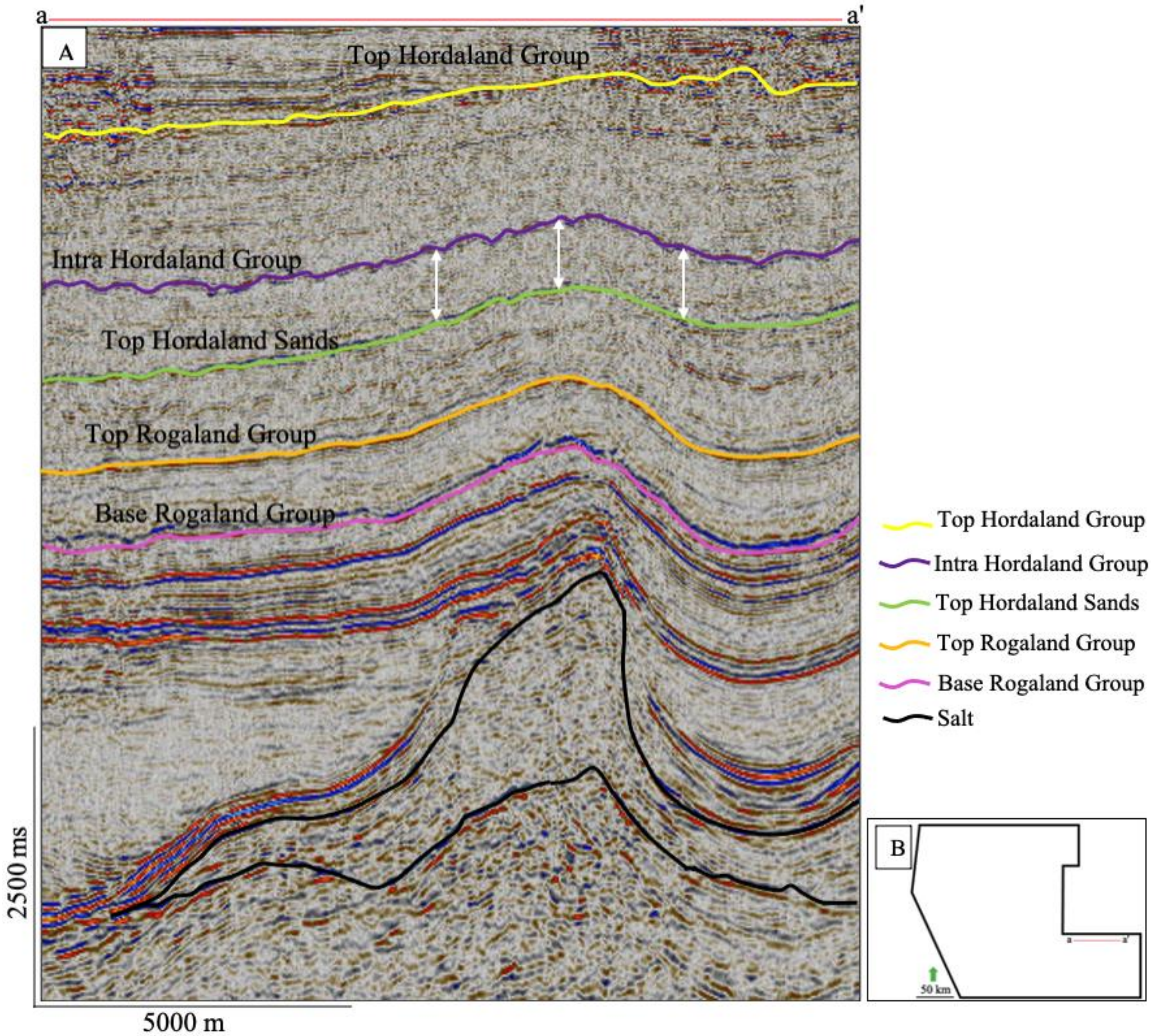


Figure 28: A: Intra Hordaland Group following the pattern of the underlying formations with the fold located above the salt diapir (black polygon). Note how the white arrows (1.4 cm) measure same thickness at the crest and the flanks. B: Location map of seismic cross section A.

4.4.3 Maps and Attributes

From the time structural map (Figure 29), the closely spaced contours typical of steep slopes and related to the many folds are observed to cover majority of the area. Seismic cross section of these closely spaced contours shows that they are related to facies E (Figure 30). The unit has three minor structural highs and one major structural high. The three minor structural highs reach a maximum elevation of about 1000 ms and are observed at the northwestern edge (Ve sub-basin) and eastern edge (Utsira High) while the major structural high is found at the southeastern edge (Ling Depression) and reaches a maximum elevation of above 1000 ms. From the time thickness maps (Figure 29), the unit is seen to thicken towards the south until it reaches four segmented depocenters at the southern edge of the Ve Sub-basin. Seismic cross section of these depocenters, show that facies E occur at the locations of these depocenters.

These depocenters reach a thickness of 900 ms. The area with the smallest thickness of about 550 ms corresponds to parts of the southeastern structural high in the Ling Depression.

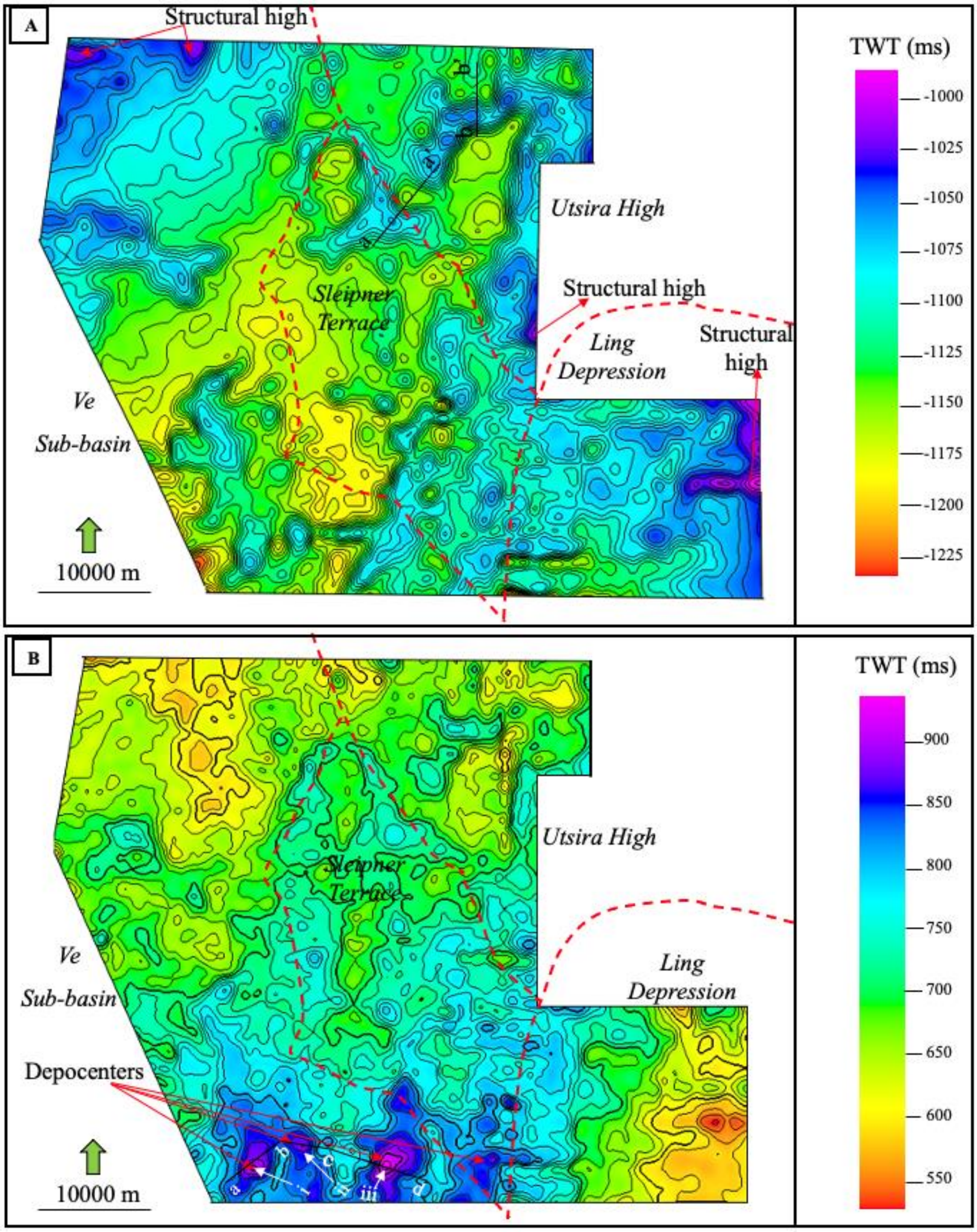


Figure 29: A: TWT structural map of the Hordaland Group. Note the locations of the structural highs. B: TWT thickness map with depocenters in the south.

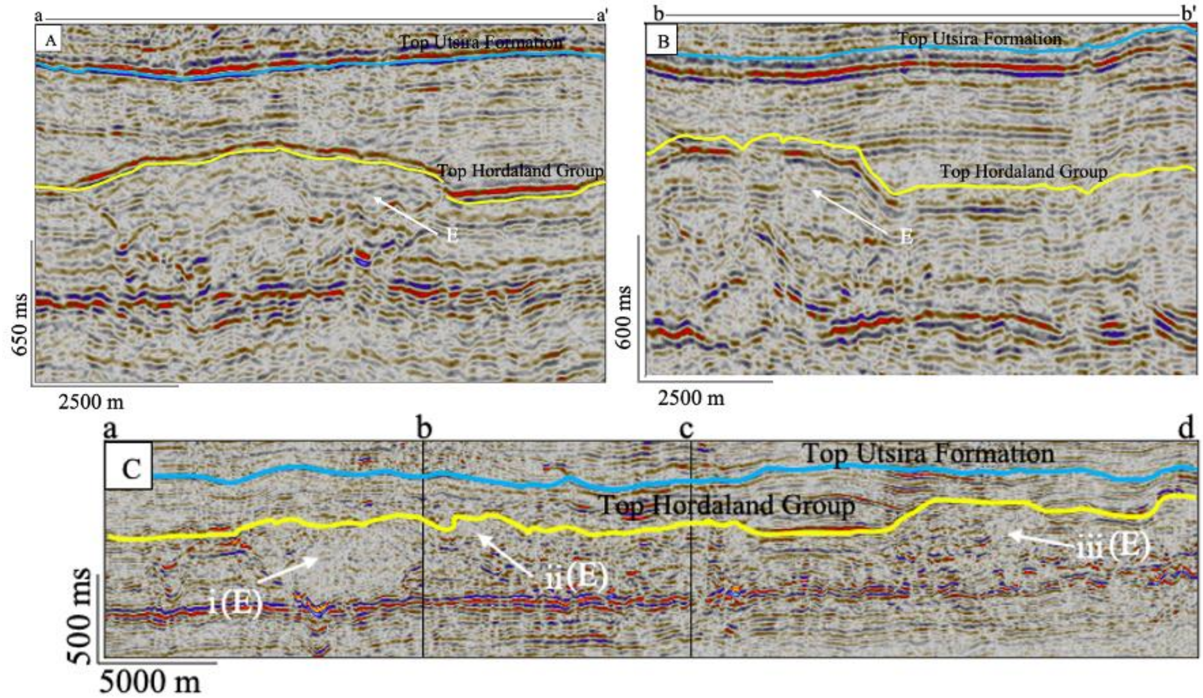


Figure 30: A and B: Seismic cross sections of the close contour spacings in the time structural map. Note how the facies E are related to these close spaced contours. C: Seismic cross section showing the depocenters i, ii and iii marked in the time thickness map. Note how facies E1 is related to these depocenters.

Five seismic facies are observed within the Hordaland Group (*Figure 31*). They are facies B; Wing like reflectors, facies C; faults with polygonal patterns, facies D; wavy, low amplitude reflectors, facies E; fold with low amplitude chaotic internal reflectors and facies F; medium-high amplitude parallel-subparallel reflectors.

Facies C is characterized by a series of discontinuities that create a network of bounded normal faults with a polygonal geometry (Figure 32). Based on the series of faulted segments, reflection patterns observed and the polygonal geometry, facies C is interpreted as polygonal faulting. They are further interpreted as non-tectonic structures possibly affected by post-depositional processes based on their lack of systematic strike direction which occurs in tectonic related faulting. The presence of facies C within the Hordaland Group has been properly documented by (Zweigel, Arts et al. 2004).

Facies D has been previously interpreted as fine grained sediments (shales) and this is supported by well control. Facies D are the background sediments that occupy the base area within the Hordaland Group.

Based on observations from well logs, facies F is interpreted as coarse grained sediments (sandstones). Also, based on the fairly lateral continuity of the reflection pattern, it is further interpreted as background sediments that occupy the top area within the Hordaland Group. The presence of facies E within facies F acts as discontinuities that offset the lateral continuity of facies F.

Based on the folds and internal chaotic reflectors observed, facies E is interpreted as a mud diapir. The mud diapirs greatly deform the background sediments. The presence of mud diapirs within the study area has been discussed by Ahmadi et al., 2003 and Zweigel et al., 2004. The wing like reflectors (Facies B previously interpreted as remobilized sands often found at the base of the mud diapirs suggests that they are genetically related and this has been discussed in detail (Loseth, Wensaas et al. 2003, Huuse and Mickelson 2004, Løseth, Rodrigues et al. 2012)Løseth et al., 2003, Huuse et al., 2004, Huuse (2008), Rodrigues et al. (2009) and Løseth et al. (2012).

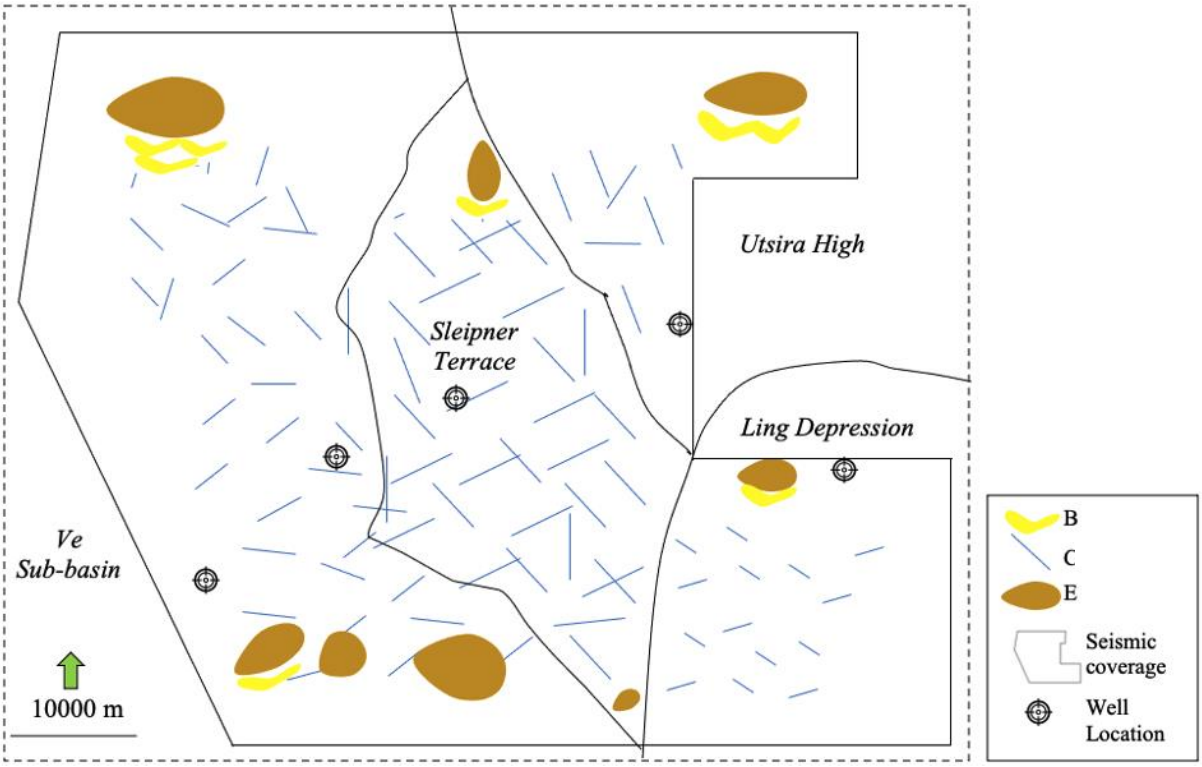


Figure 31: The Hordaland Group seismic facies map. Facies B: remobilized sands, facies C: polygonal faults, facies E: mud diapirs. The white parts within the seismic coverage are interpreted as the background sediments of facies D and F. Note the various directions of the blue lines indicating the lack of specific strike direction in the polygonal faults.

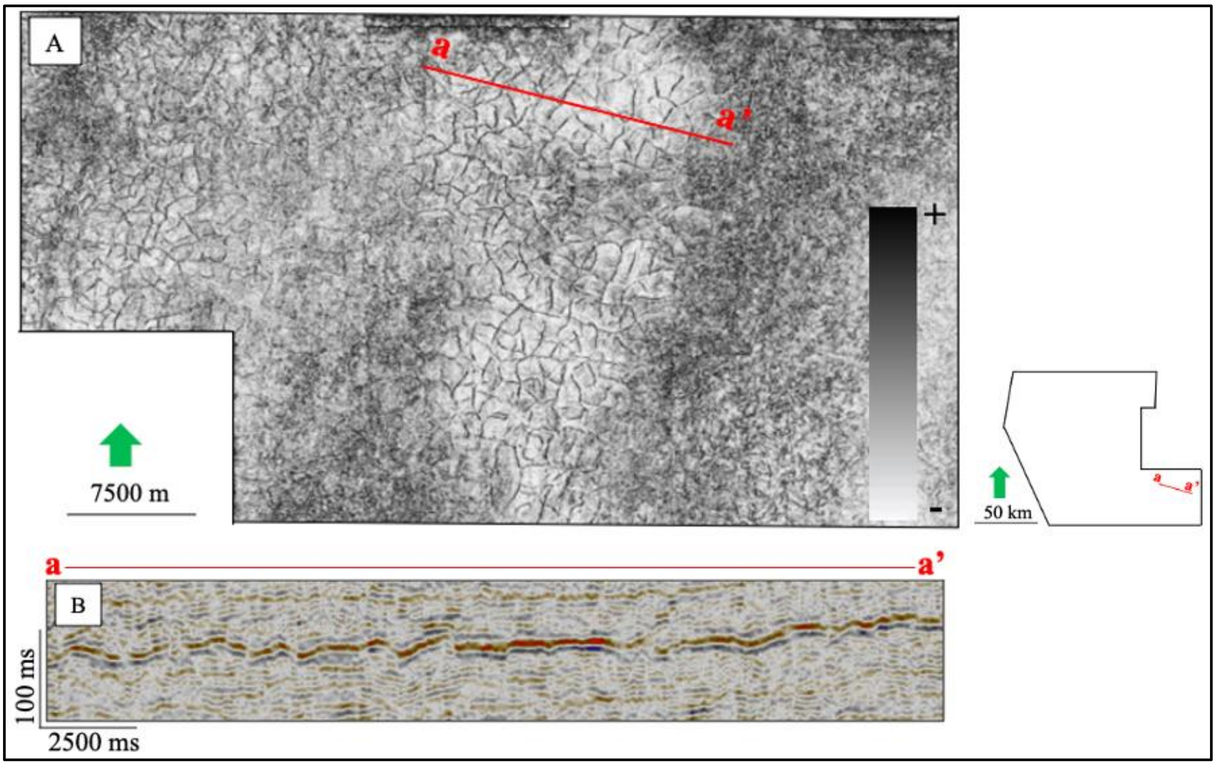


Figure 32: A: Reflection amplitude map of seismic facies C at depth 1580 ms (TWT) in the Ling Depression. Note the pattern of the polygonal fault. B: Seismic cross section of facies C.

4.5 Utsira Formation

4.5.1 Well logs

The Utsira Formation is laterally continuous throughout the correlated wells. It is found at an average depth of 861 m. It tends to become shallower towards the East with its shallowest depth at 808 m (Well 16/7-1 (Ling Depression)) and deepest depth at 925 m in well 15/9-14 (Ve Sub-basin). It has an average thickness of 227 m. The Gamma ray response (Figure 33) exhibits a serrated character with generally low gamma ray readings (yellow colour) and minor spiky high values (green colour). This log character is interpreted as a thick sandy unit with interbedded shales. The Shaly interbeds thicken towards the East and becomes more frequent within the formation.

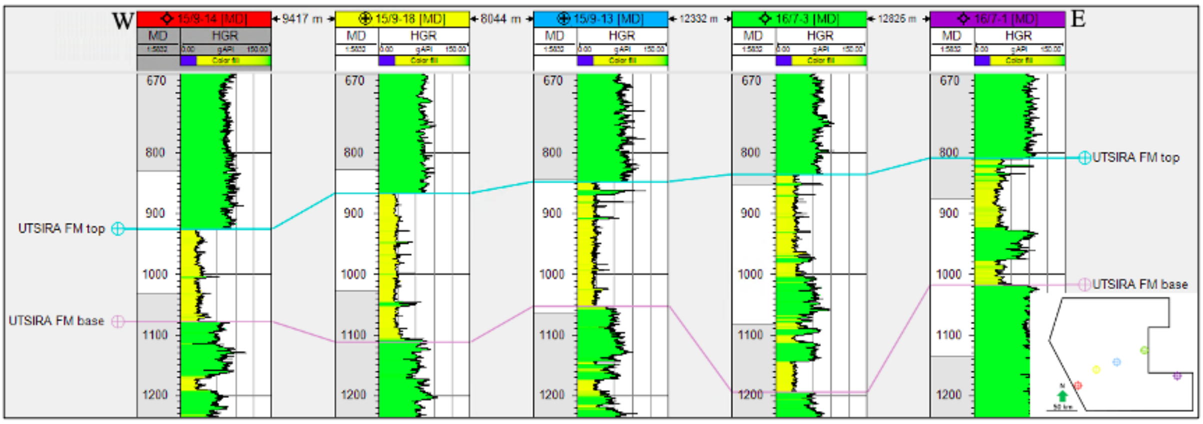


Figure 33: West to East well correlation of the Utsira Formation.

4.5.2 Seismic descriptions

The Utsira Formation is present throughout the study area. The top of the interval often has gentle folds while the base is distorted with several folds and depressions. Within the interval, medium amplitude parallel seismic reflectors (facies F) Figure 34) are observed to be laterally continuous except when they are interrupted by seismic facies. The chaotic low amplitude reflectors of facies E disrupt the continuous nature of facies F and are also responsible for creating the gentle folds observed at the top of the interval. Isolated high amplitude reflectors (facies G) occur within the interval and often terminate against the flanks of facies E. Most times, the reflectors towards the base of the unit onlaps onto the underlying unit of the Hordaland Group marking the mid Miocene unconformity (Figure 35).

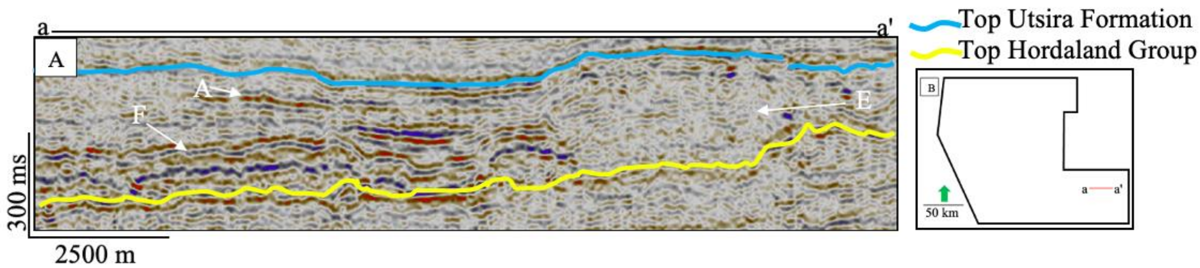


Figure 34: Facies D and F in Utsira Formation

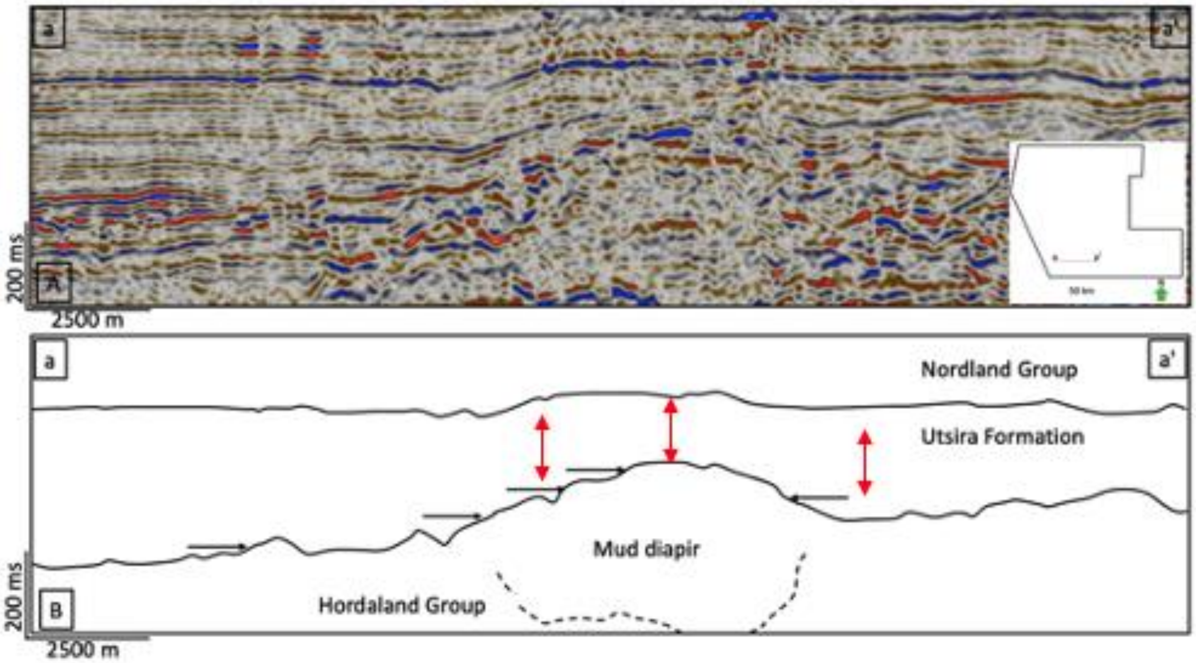


Figure 35A: Seismic cross section typical of the Utsira Formation in the study area. B: Interpreted seismic line a-a'. Horizontal arrows indicate onlap. Note the underlying mud diapir (dashed black line) that may have caused the uplift at which the reflectors towards the base of the Utsira Formation onlapped. Equal vertical red arrows (0.9 cm) are used to measure thickness variations at the flanks and crest of the mud diapir.

4.5.3 Maps and Attributes

From the time structural map (Figure 36), a gradual increase in elevation is observed in two directions; from the south to the north and from the south to the southeastern edge. In general, the unit dips towards the South. The steepest areas correspond to the structural high area at the southeastern edge of the Ling depression where an elevation of 650 ms is reached. From the time thickness map (Figure 36), thick areas are located at the North, Center and southeastern edge of the formation. However, the depocenter is located at the southeastern edge and corresponds to the structural high (Ling Depression) where maximum thickness of 400 ms is reached.

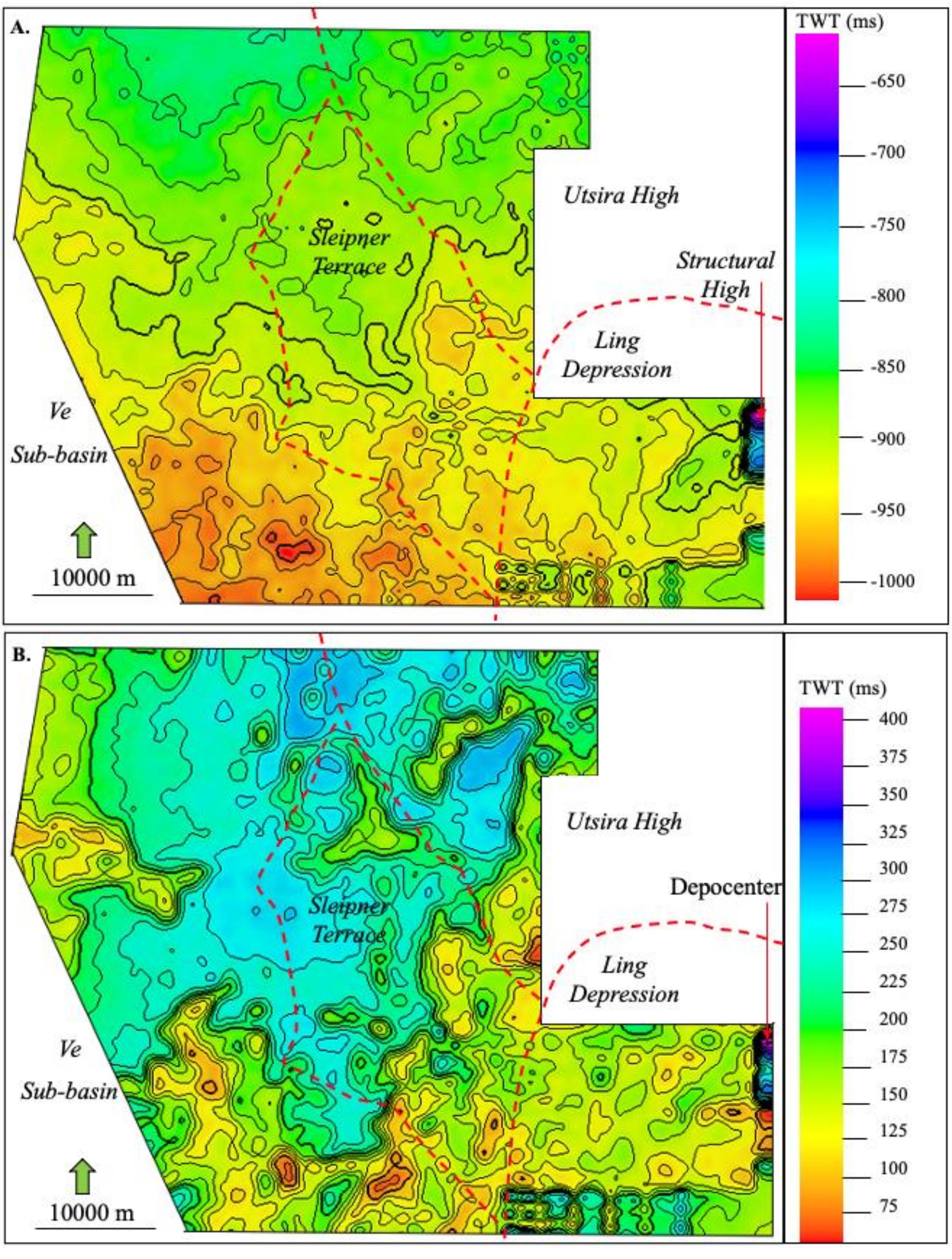
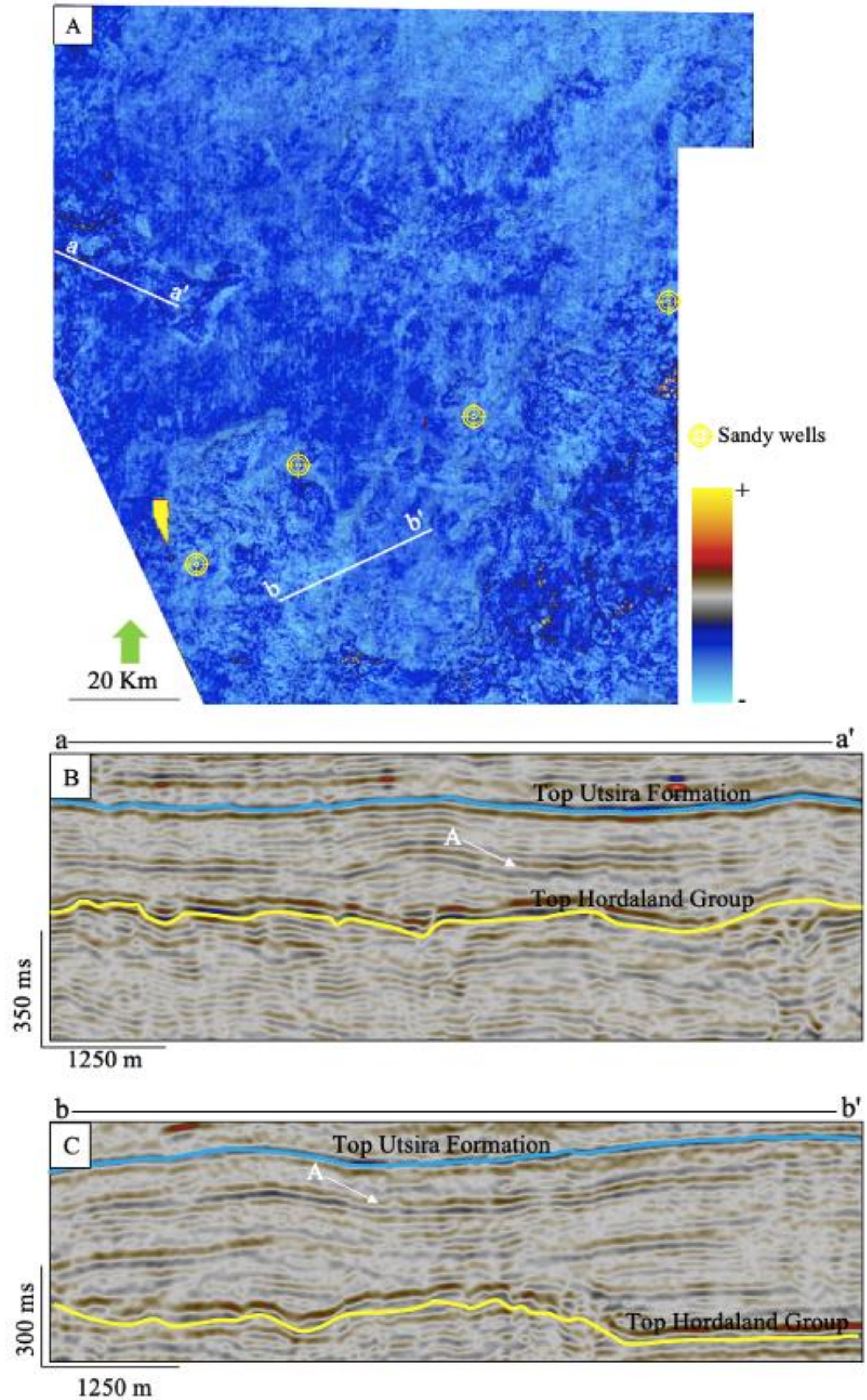


Figure 36: A: S4 TWT structural map with structural high at the eastern edge of the Ling Depression. B: Time thickness map showing a minor depocenter at the eastern edge the Ling Depression coinciding with the structural high.

Three seismic facies are mapped and interpreted within the Utsira Formation (Figure 37). They are facies A; medium-high amplitude continuous reflectors, facies E; folds with low amplitude chaotic reflectors, facies F; medium-high amplitude parallel-subparallel reflectors.
Facies A occurs at the western, center and southeastern part of the Utsira Formation (RMS map).
Based on the geometries observed in the seismic, facies A is interpreted as submarine fans.
Seismic Facies E (fold with internal low amplitude chaotic reflectors), occur as the south eastern edge, they are bounded by the medium-high amplitude reflectors of facies A. Based on the geometry observed in seismic, facies E may represent mud diapirs. The presence of mud diapirs has been discussed by Ahmadi et al., 2003 and Zweigel et al., 2004 but no relationship to the submarine fan has been observed. Figure 38.
Facies F occurs mostly throughout the interval. Its continuity throughout the interval suggests that it is the background sediment of the Utsira Formation. Based on well control, facies F are interpreted as coarse grained sediments (sandstones).

Figure 37: (Utsira Formation) seismic facies map showing facies A: Submarine channel and E: Mud diapir. The white parts within the seismic coverage are interpreted as the background sediments.



A
a
a'
b
b'
Sandy wells
+
-
20 Km
B
Top Utsira Formation
A
Top Hordaland Group
350 ms
1250 m
C
Top Utsira Formation
A
Top Hordaland Group
300 ms
1250 m

Figure 38: A: RMS amplitude extraction 10 ms below top Utsira Formation. The wells are sand filled. B and C: Seismic cross section showing submarine fans within the Utsira Formation.

4.6 Elements for CO2 Storage

General classification of the study area is done based on well 15/9-14 (Figure 39). The factors necessary for CO2 storage are presented for each of the Tertiary succession of interest.

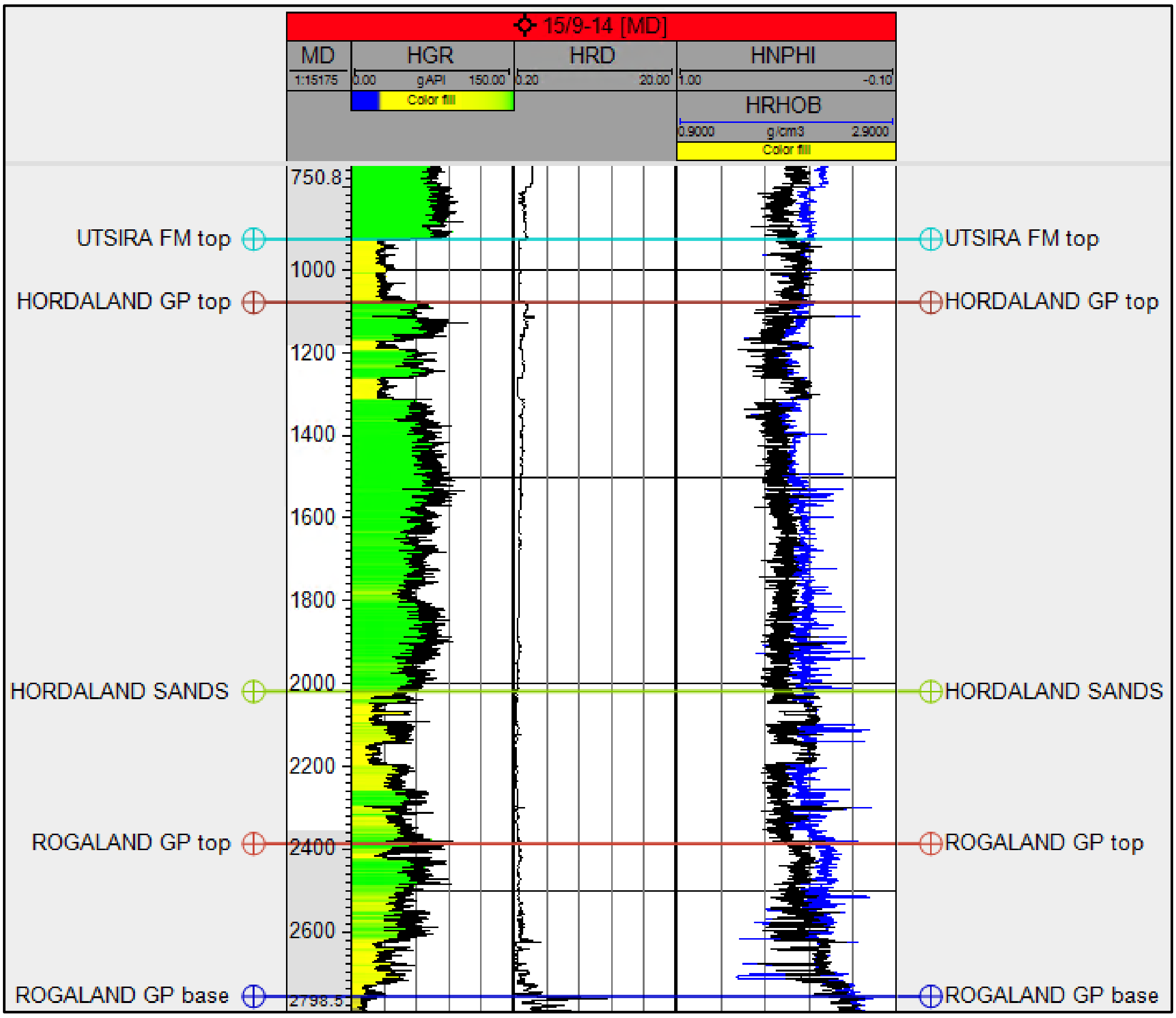


Figure 39: Well 15/9-14 displaying well logs used to classify the type of reservoir.

4.6.1 Rogaland Group

Reservoir**:** The base of the Rogaland Group shows resistivity log ranges of 0.49 to 3.4 ohm-meter and often corresponds to about 23-34 gAPI of gamma ray values and areas with an overlap between neutron and density logs with minor gap between them. Towards the top, the resistivity values are observed to range from 0.2-0.5 except in areas that corresponds to slight high values of gamma ray (about 59 gAPI) (Figure 40). However, the average resistivity reading of the Rogaland Group is about 1.4 ohm-meter.

At the base of the Rogaland Group, the overlap between density and neutron logs suggests hydrocarbon shows. In addition, the minor gap between the overlap suggests oil fill and this is supported by NPD 2022. The observed slight high values of gamma ray are interpreted as interbedded sands and shales while the low resistivity values when corresponding with low values of gamma-ray can be interpreted to be brine filled sands.

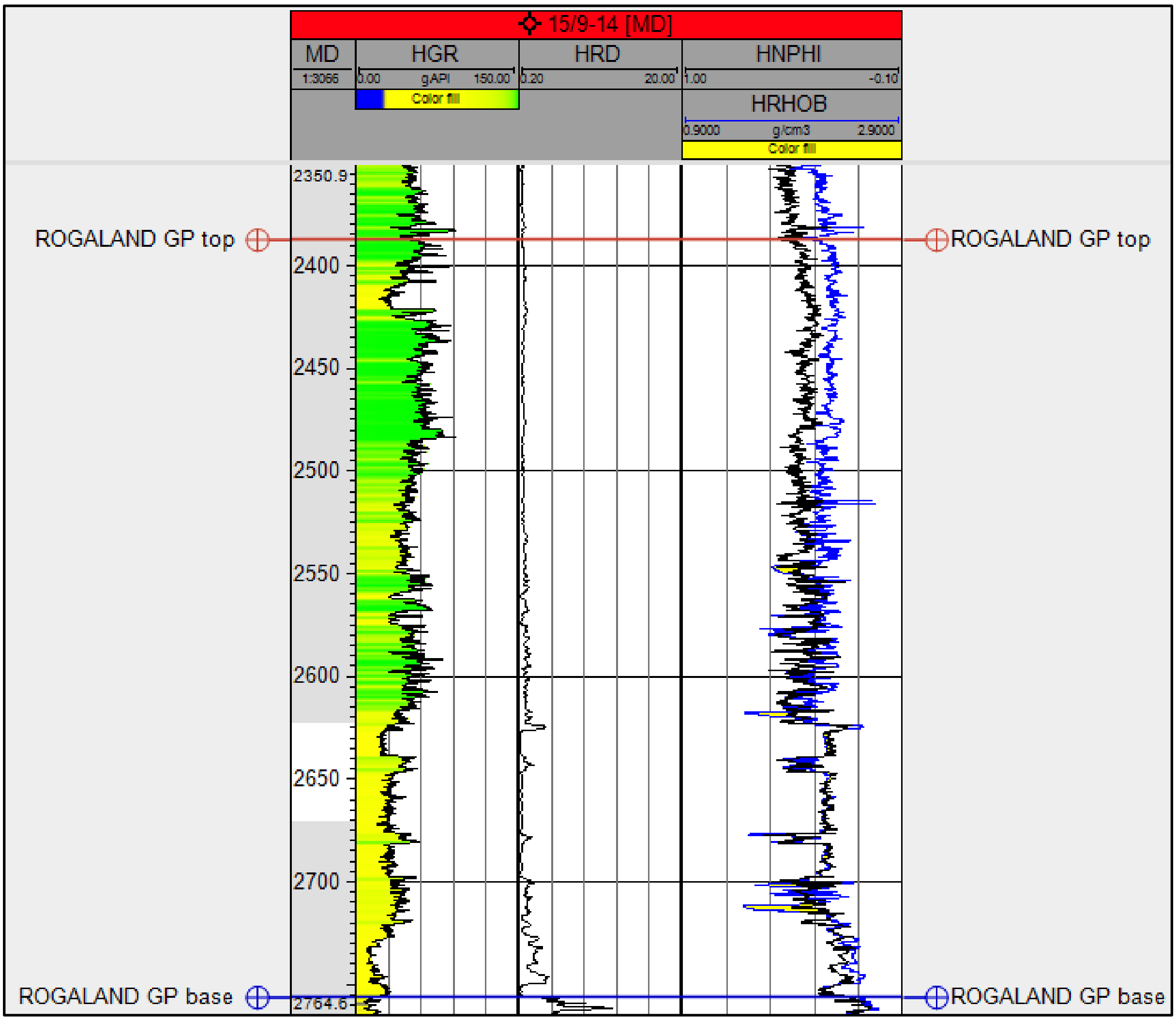


Figure 40: Zoomed view of the Rogaland Group logs. Note the areas of overlap between the density and neutron logs that have yellow colour fill.

Porosity and permeability: From wells such as 15/9-13, the Rogaland Group has been documented to have porosities ranging from 25.7 to 26.9%. (NPD 2022b). Permeabilities of

16 millidarcies to 10 darcies have been recorded in fields of Paleocene age (Ahmadi, Sawyers et al. 2003).

Homogeneity/ thickness (Net sand): The unit changes from low gamma rays with thin peaks of high gamma rays at the base (140 m thick) to an interbed of high and low gamma rays (65 m thick), mainly low gamma rays (50 m thick), to mainly high gamma rays (80 m thick), low gamma rays (25 m thick) and high gamma ray values at the top (12 m thick) (Figure 40).
Based on the gamma ray readings, the low gamma ray readings which are interpreted as sands are observed at three intervals and have net thickness ranging from 25-140 m. The interbedded and high gamma ray values which are interpreted as interbedded sands and shales and shales respectively are observed at three intervals within the unit and have thickness ranging from 12-80 m. The sandy intervals can serve as the reservoirs within the unit while the interbedded and shaly intervals can serve as intra formational seals.
Average formation thickness and depth: Its average thickness is 300 m and it is found at average depths of 2109 m. It is most shallow at the Ling Depression where it reaches a depth of 1670 m.
Seals: The Rogaland Group is directly overlain by the Hordaland Sands. From the well logs, the Hordaland sands are described as a generally sandy unit with some shaly intervals. The unit is laterally continuous and has an average thickness of 229 m although they thin towards the east reaching thickness of 90 m. Seismic facies description have interpreted the presence of remobilized sands, shales and submarine fans within this unit. The tip of the faults that cut the Rogaland Group are observed to cut the base of the Hordaland sands.
Traps: Seismic interpretation of the Rogaland Group shows that the Rogaland Group consists of faults an anticline structure and stratigraphic trapping.

4.6.2 Hordaland Sands

The Hordaland Sands shows very low resistivity values of about 0.2-0.3 ohm-meter corresponding with generally low values of gamma-ray. The resistivity values of 0.3 correspond with areas having gamma ray readings of around 65 gAPI and wider separation between the neutron and density logs. In general, the average resistivity values of the Hordaland sands are very low (0.25 ohm-meter). No overlap is observed between the density and neutron logs (Figure 41).
Generally, the Hordaland sands is interpreted to be brine filled sands based on the low resistivity values corresponding with the low gamma ray values. Areas corresponding with

high gamma ray values are interpreted as shales. The lack of overlap between the density and neutron logs suggests no hydrocarbon shows within the unit.

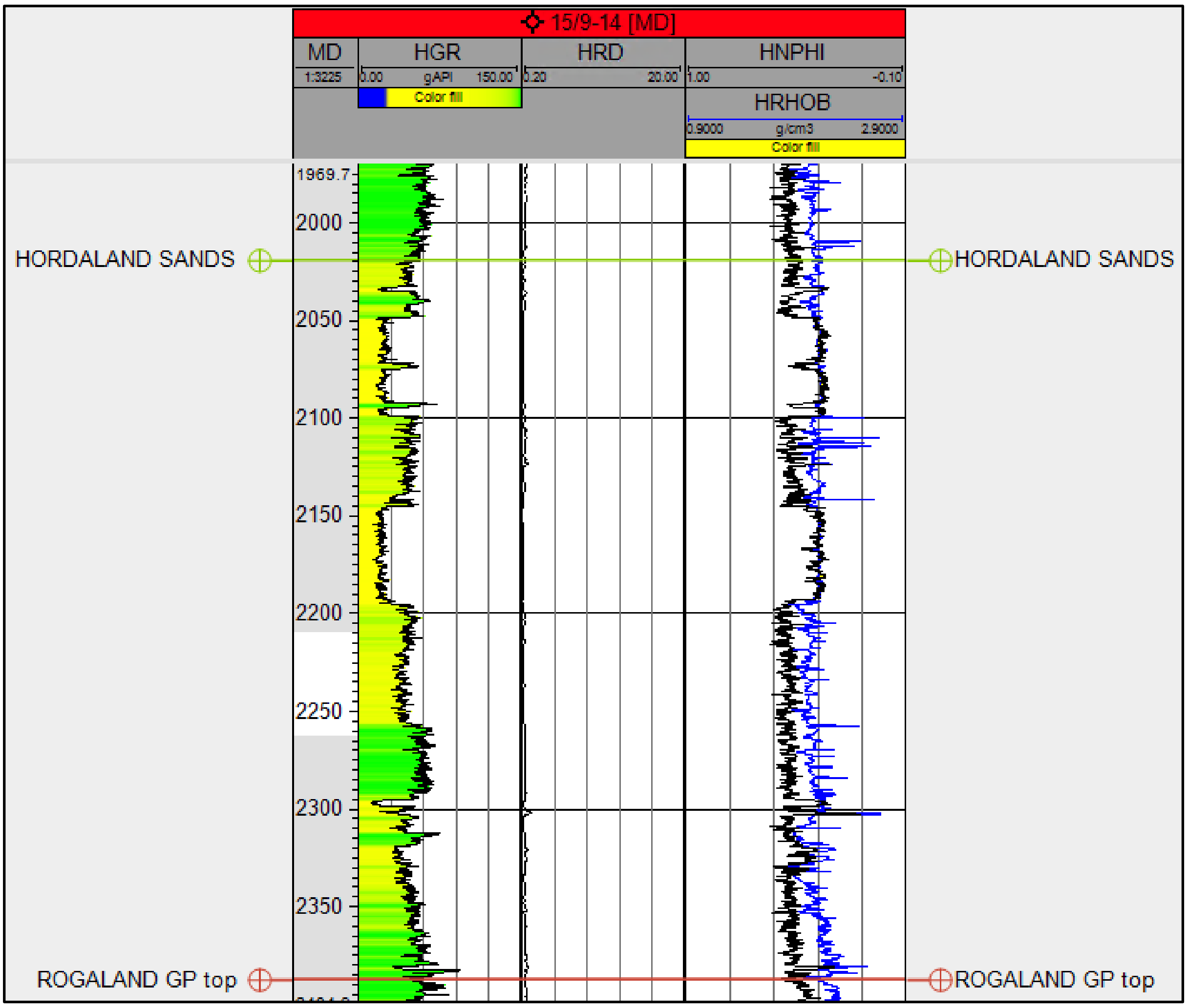


Figure 41: Zoomed view of the Hordaland sands logs. Note the general low gamma ray readings that corresponds to very low values in the resistivity log. The unit also has no hydrocarbon shows.

Porosity and permeability: Sand injectites have been observed to get porosities and permeability values from their parent material (the sandstones of the Rogaland Group) although they may be 2% lower but still maintaining high porosities (Hurst, 2011). Thus, for the sake of this study, the porosity values for the injectites are 23-24 % (NPD 2022) while permeability remains 16 mD – 10D (Ahmadi et al., 2003).

Homogeneity/thickness (Net sand): The unit consists of high and low gamma ray reading at the base (35 m thick), followed by low gamma ray (50m), mainly high gamma ray (37 m thick) and low gamma ray values (220 m thick).

From the gamma ray readings, the low gamma ray values are observed at two intervals within the unit and have net thickness ranging from 50 m – 220 m. Two intervals of interbedded gamma ray values and high gamma ray values interpreted as interbedded sand and shale and shale respectively have been observed to range from 35 – 37 m in thickness and they may serve as seals to the underlying Rogaland Group or as intra-formational seals.

Average formation thickness and depth: Its average thickness is 229 m and it is found at average depths of 1881 m. It is most shallow at the Ling Depression where it reaches a depth of 1580 m.

Seals: The Hordaland sands is overlain by the Hordaland Group. Based on the well logs, the unit consists of mainly shales with thin interbeds of sands within some intervals. The Hordaland Group is laterally continuous and with an average thickness of 773 m. Thickness is observed to reduce sequentially till thickness of 563 m in the Ling Depression is reached. Seismic facies description has interpreted the presence of polygonal faults, sand injectites and mud diapirs.

Traps: Sand injectites and shales have been mapped within the Hordaland sands unit. Studies have classified sand injectites as intrusive traps (this is different from structural and stratigraphic traps) (Bergslien et al., 2005). Also, possibility of stratigraphic trapping exists.

4.6.3 Hordaland Group

The Hordaland Group generally has resistivity values of about 1.8 ohm-meter which corresponds to gamma-ray values of 85-100 gAPI. The area of the group that displays resistivity readings of 0.5 ohm-meter corresponds to low gamma ray readings of 28-29 gAPI. No overlap is observed between the density and neutron logs, however, closer spacing of the logs is observed in areas that correspond to low value of gamma rays than areas with higher values (Figure 42).

Based on the general high values of gamma ray, the Hordaland Group is interpreted to be mainly shale. The lack of overlap between the density and neutron logs suggests no hydrocarbon show within the unit and the low gamma ray area which corresponds with 0.5 ohm-meter resistivity is interpreted to be brine saturated sands.

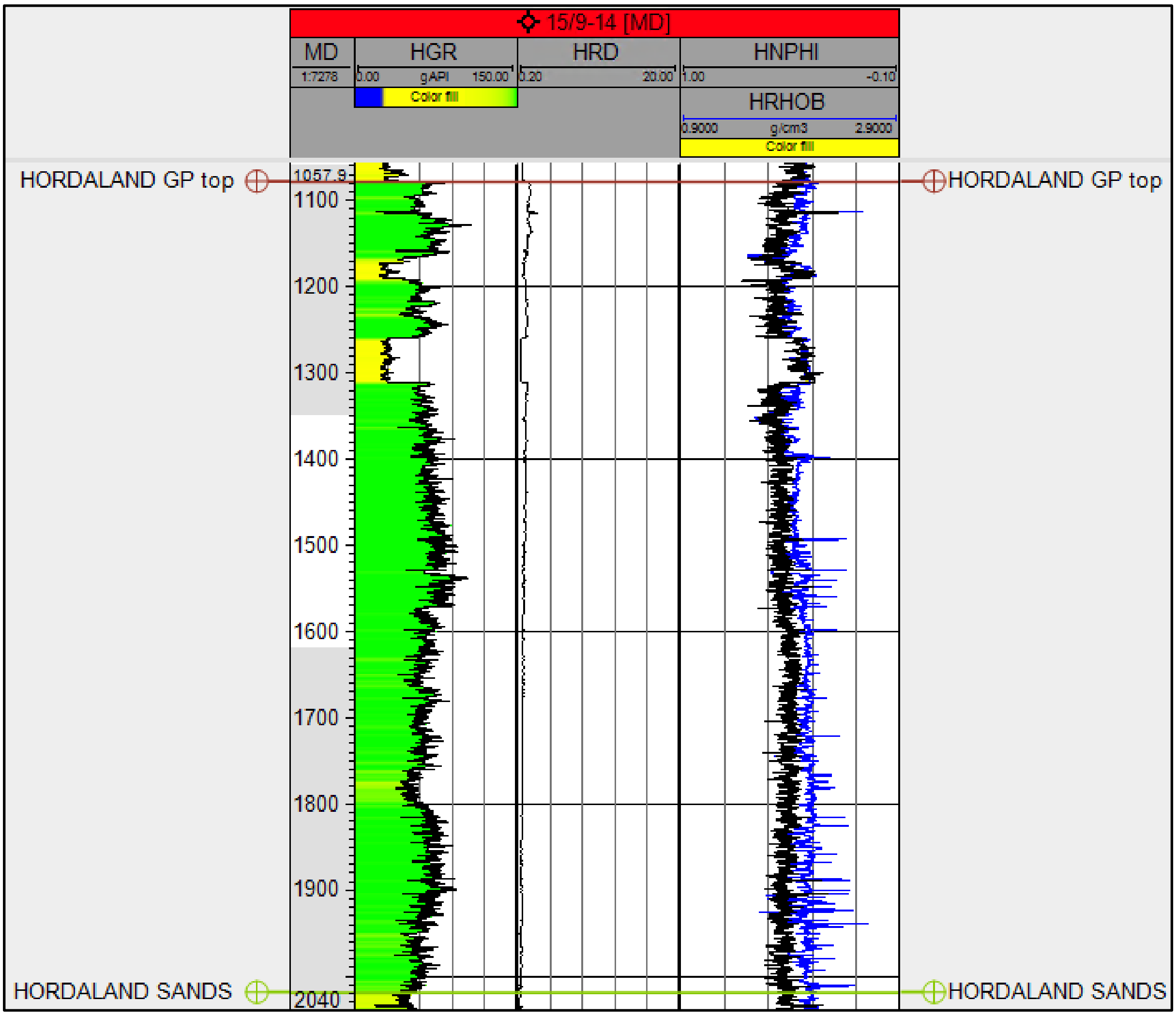


Figure 42 Zoomed view of the Hordaland Group logs. Note the low gamma ray reading at depth 2060 m that corresponds to a deduction in resistivity. The unit also has no hydrocarbon shows.

Porosity and permeability: The sandy part of the Hordaland Group has porosity values of 35% with unknown permeability values (Anthonsen et al., 2014).

Homogenity/ thickness (Net sand): The Hordaland Group consists mainly of high gamma ray values with thickness ranging from 60-470m.The high gamma ray values are separated by four intervals of low gamma ray values having thickness of 20 m, 30 m, 50m and 20 m from the base (Figure 38). Based on the gamma ray logs, the unit contains generally high gamma ray values interpreted as shales. The low gamma ray intervals interpreted as sandstones have thickness ranging from 20m-50m.

Average formation thickness and depth: Its average thickness is 773 m and it is found at average depths of 1108 m. It is most shallow at the Ling Depression where it reaches a depth of 1017 m.

Seals: Shales of the Hordaland Group overlie the sandstones observed within the unit. These shales above the sandstones are about 70 m and 90 m thick.
Traps: Stratigraphic pinch out of the sandstones of the Hordaland Group and possibility of chemical trapping.

4.6.4 Utsira Formation

The Utsira Formation has mainly low gamma ray readings of about 24-28 gAPI corresponding with resistivity readings of 0.8 ohm-meter. A thin peak of gamma ray reaching a value of 60 gAPI corresponds with a resistivity of about 1.82. No overlap is observed between the density and neutron logs. (Figure 39). Based on the low gamma ray and resistivity readings, the unit is interpreted to generally consist of brine saturated sandstones. A gamma ray peak observed at depth 1005 m suggests an interbed of very thin shale. No hydrocarbon show is observed as the density and neutron logs do not overlap.

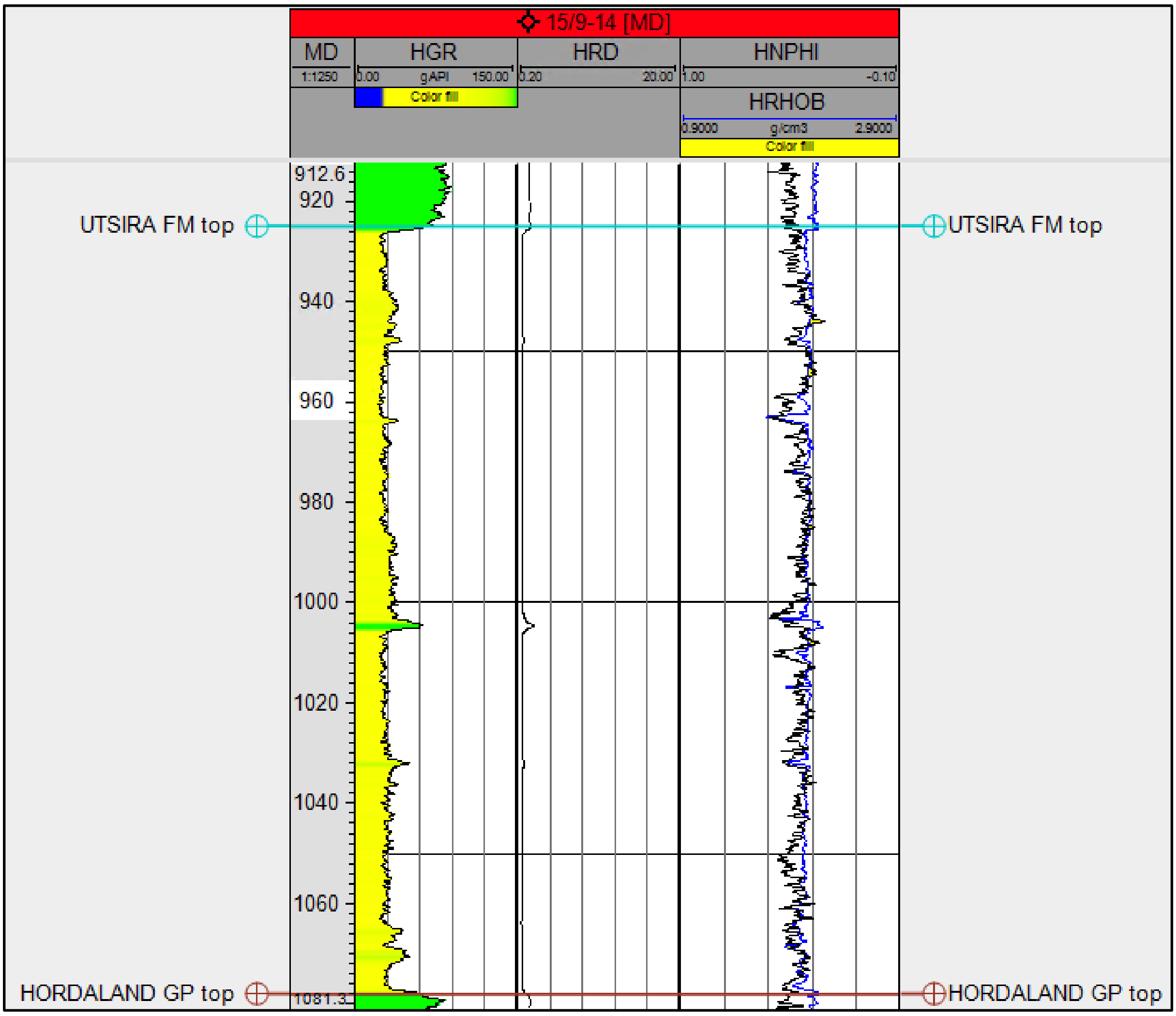


Figure 43: Zoomed view of the Utsira Formation logs. Note the gamma ray peak at depth 1005 m that corresponds to a slight increase in resistivity. The unit also has no hydrocarbon shows.

Porosity and permeability: The Utsira Formation has been recorded to have porosity of 30-40% and good permeability of 1-3 darcies.

Homogenity/thickness (Net sand): The Utsira unit consists of low gamma ray value from 925-1080 m depth. A meter thick high gamma ray value is observed at depth 1005 m (Figure 39). The unit is generally made up of sandstones based on the low gamma ray readings and the sands are 115m thick.

Average formation thickness and depth: Its average thickness is 227 m and it is found at average depths of 861 m. It is most shallow at the Ling Depression where it reaches a depth of 808 m.

Seals: The interval above the Utsira Formation has not been analyzed in this study. However, according to Aminu et al., 2017, the Utsira Formation is overlain by impermeable caprock of 200-300 m known as the Nordland shales (Aminu et al., 2017). It is located at shallow depths and therefore less affected by faults due to its ductile rheology (Angeli et al., 2013).

Traps: Mud diapirs have been mapped within the Utsira Formation and they may serve as traps. Possibility of mud diapirs serving as traps have been discussed (Halland et al., 2013).

5.0 Discussion

5.1 Tectonostratigraphic evolution

5.1.1 Tectonostratigraphic evolution of the Rogaland Group

The Rogaland Group sediments based on observations from the seismic data, RMS amplitude and well logs have been interpreted as sand-rich submarine fans interbedded with shales (background sediments). The time thickness map shows the thickest deposit (400 ms) of the Rogaland Group at the northwestern edge. Minor thickness of 200 ms is also observed in the east. Based on this, it is suggested that the primary source of the Rogaland Group deposits is probably from the East Shetland Platform as the thickest deposits are found adjacent to the Platform while minor input came from the Norwegian landmass. This interpretation is consistent with that of Ahmadi et al., 2003 and Brunstad et al., 2013 who suggested that tectonic uplift and erosion of the Scotland-Shetland platform and less magnitude of uplift of the Norwegian landmass during the Early Paleogene led to the deposition of shales and sand-rich submarine fans (which were transported by gravity flows) in a deep marine environment)figure 44

The lack of significant growth strata observed across the faults that penetrate the Rogaland Group suggests that the faults were probably inactive during the deposition of the group and are thus remnant from underlying units

Salt diapirism is suggested to have deformed the Rogaland Group. Evidence of this is seen from the seismic as the Rogaland Group follows similar topography with the underlying intervals below. Also, the fold observed in the Rogaland Group sit directly above the underlying salt diapir. Further evidence of the timing of the salt deformation is observed as the Rogaland Group thins over the crest of the salt diapir while it is thicker at the flanks of the salt diapir. This variation in thickness suggests that the salt diapir was active during the deposition of the Rogaland Group. This interpretation is in line with the interpretation of Copestake et al., 2003 and Jones et al., 2003 that the Zechstein salt remobilization which was possibly due to the first pulse of Alpine orogeny which occurred during the Late Cretaceous to Cenozoic and folded the overlying strata such as the Chalk Formation, Rogaland Group and the Eocene sediments. As a result of the folds (uplift) created by the salt diapir, Dreyer et al (2004) and Brunstad et al., 2008 report that a shallow marine may have been created within the deep marine deposits of the Rogaland Group.

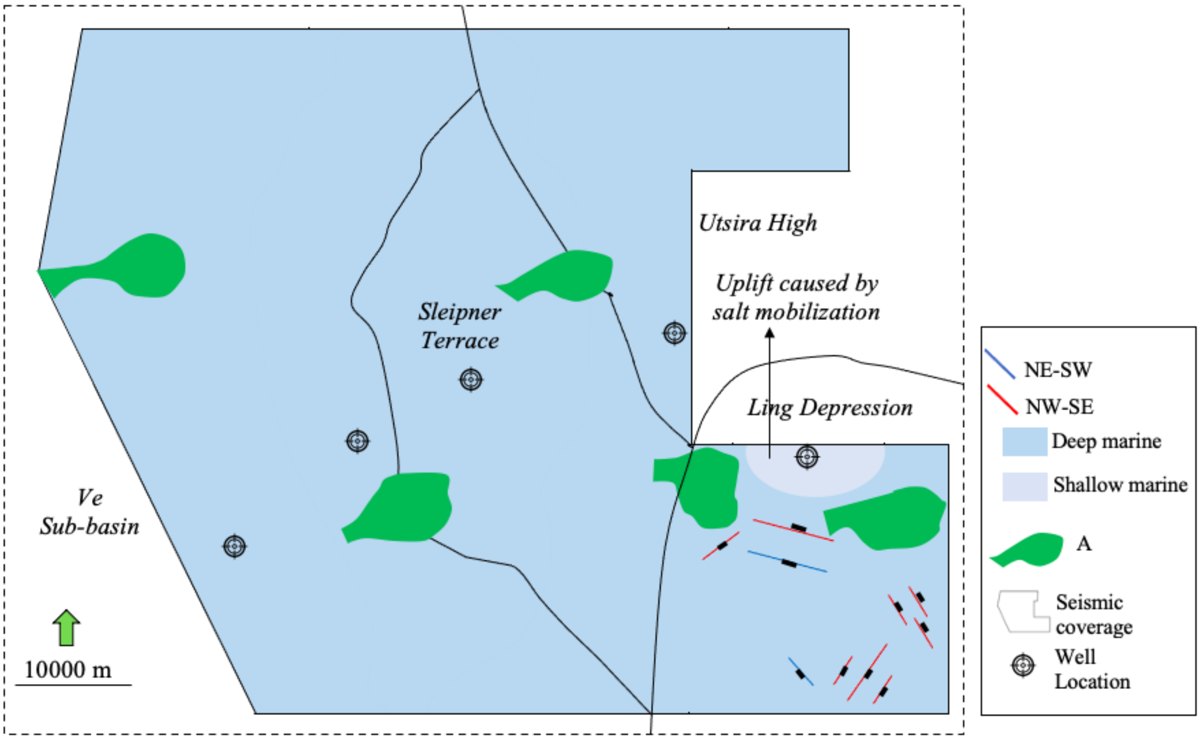


Figure 40: Paleogeographic map of the Rogaland Group. The uplift caused by salt mobilization created a shallow marine environment.

5.1.2 Tectonostratigraphic evolution of the Hordaland Sands.

The deposits of the Hordaland sands based on seismic data, attributes and well data are interpreted as submarine fans, shales and remobilized sands. Further interpretation based on the lateral continuity of the shales observed in the well logs and facies description from seismic data suggests that they may be the background sediments of the unit. The time thickness map (figure) clearly shows that the depocenter of the Hordaland sands is located at the west. This evidence suggests that the East Shetland Platform may have acted as the primary source. Just like the Rogaland Group, the submarine fans and the shales of the Hordaland sands are suggested to be sourced from the uplifted Scotland-Shetland platform and transported in a deep marine environment (fig of paleomap)(Ahmadi et al., 2003 and Brunstad et al., 2013). Although the Scotland-Shetland platform acted as the primary source, it is suggested that the Norwegian landmass contributed as a source although with less input of sandy sediments. Evidence of this is seen as the sandy submarine fans thin towards the east. This lack of submarine fans towards the east, minor input from the Norwegian landmass or far distance from the primary source is probably the reason why thickness at the east is reduced as observed in the time thickness map (figure). Jordt et al., 2003 suggested that the eastward thinning of the coarse-grained sediments was probably as a result of the regional subsidence of Norway.

The folds in the Hordaland sands lie directly above the salt diapir indicating that the Hordaland sands were deformed by the salt diapir. The greater thickness in the crest of the folds when compared to the flanks of the fold shows that the salt diapirism was probably active during the deposition of the Hordaland Sands. This interpretation is in line with the interpretation of Copestake et al., 2003 and Jones et al., 2003 just like discussed in the Rogaland Group interpretation.

The remobilized sands in the Hordaland sands interval have been interpreted as post depositional sand mobilization based on the work of Huuse and Mickelson (2004). They proposed that the rapid sedimentation rate of the Rogaland Group increased lithostatic pressure, compaction and vertical fluid flow thereby causing the sands to be remobilized into the Hordaland Sands interval.

In summary, it is suggested that the background sedimentation of shales and the submarine fans were sourced from the uplifted East Shetland platform and deposited in a deep marine environment. The shales spread laterally within the unit as it is suspected to have source input not only from the west but from the east while the submarine fans pinched out towards the east. The shales and submarine fans were intruded by remobilized sands from the underlying Rogaland Group. The fold (uplift) created by the salt diapir may have created a shallow marine environment within the deep marine deposits of the Hordaland Sands (Paleomap).

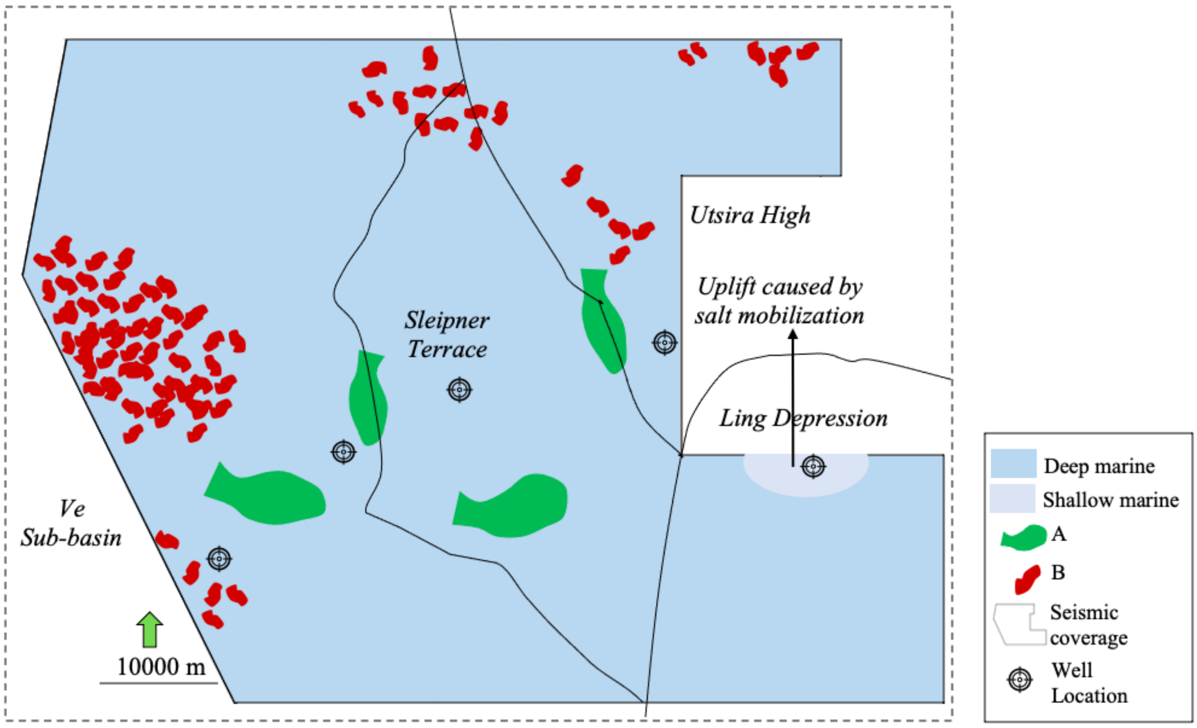


Figure 45: Paleogeographic map of the Hordaland Sand. The uplift caused by salt mobilization may have created a shallow marine environment.

5.1.3 Tectonostratigraphic evolution of the Hordaland Group

From the time structural map, the Hordaland Group is interpreted as being heavily folded and these folds are caused by the mud diapirs that distort the unit. These mud diapirs create thickness variations and are also responsible for controlling the segmented depocenters located in the south. These areas of maximum thickness observed in the south suggests that the deposits of the Hordaland Group were probably sourced from Southern Norway. Gabrielsen et al., 2002 documented that Southern Norway was uplifted during the deposition of the Hordaland Group and deep waters were created to the north and south while a shallow marine environment was created in the East and West direction during this deposition.

Post depositional process such as remobilized sands, polygonal faulting and mud diapirs have been interpreted to modify the unit.

Observations from the seismic and well log data suggests that the base part of the Hordaland Group consists of shales. Lack of visible intrusion in both seismic and well data suggests that these shales at the base are homogenous and can be correlated laterally. This is collaborated by Rundberg and Eidvin (2005) who interpreted the unit to be mainly shales. The shales continue vertically until they get to the middle of the Hordaland Group where they become affected by polygonal faulting. These polygonal faulting is interpreted to be non-tectonic due to the lack of systematic strike direction and the modest throws of faults (figure of polygonal faults). This interpretation is consistent with that of Zanella & Coward, (2003), Head et al, (2004) and Zweigel et al., (2004) who interpreted the polygonal faults to be related to sediment compaction during early burial. The upper part of the Hordaland Group as indicated by wells is interpreted to consist of shales and sandstones. Eidvin and Rundberg (2007) support this interpretation by stating that the top part of the Hordaland Group consists of mainly shales with sands in some wells and Rodrigues et al. (2009) found about 100 m of irregular shaped sand in the top Hordaland Group. These sandstones have been observed to pinch out towards the east indicating a possible secondary source of the Hordaland Group from the west. Sediment thickness of about 650 ms – 750 ms is also observed at the west (Figure) thus, the secondary source is suggested to be the East Shetland Platform. This interpretation is in line with the findings of Eidvin et al., 2014 that the upper Hordaland Group is suggested to have been sourced from a delta system in the west prograding rapidly to the east during the mid-Miocene. The top part of the Hordaland Group is deformed to a large extent by mud diapirs. The Mud diapirs have been interpreted to have an almost-circular shape possibly suggesting a point source. Beneath most of the diapirs, the wing like facies interpreted as remobilized sands were identified (figure) and this may suggest that the remobilized sands and the mud diapirs may be genetically linked. This interpretation is in line with Huuse (2008), Rodrigues et al. (2009) and Løseth et al. (2012) who proposed that the presence of the mud diapirs and remobilized sands are as a result of pressure build up from the massive gas expulsion during the Oligocene that caused fluidization and sand remobilization. These gases may have come from the Upper Jurassic source rocks and the pressure increase caused hydro fracturing that allowed the passage of gas, oil and formation water into the overlying formations (Johannesen et al., 2002; Løseth et al., 2003). The passage may have been through the polygonal faults (when oriented favorably) and into the overlying Hordaland top. Johannesen et al., 2002 and Løseth et al., 2003 also proposed that the mud diapirs were formed as a result of gas injection via feeder pipes from Paleocene or even deeper formations. However, the lack of visible feeder pipes from the seismic (probably due to poor seismic quality) fails to agree with this suggestion.

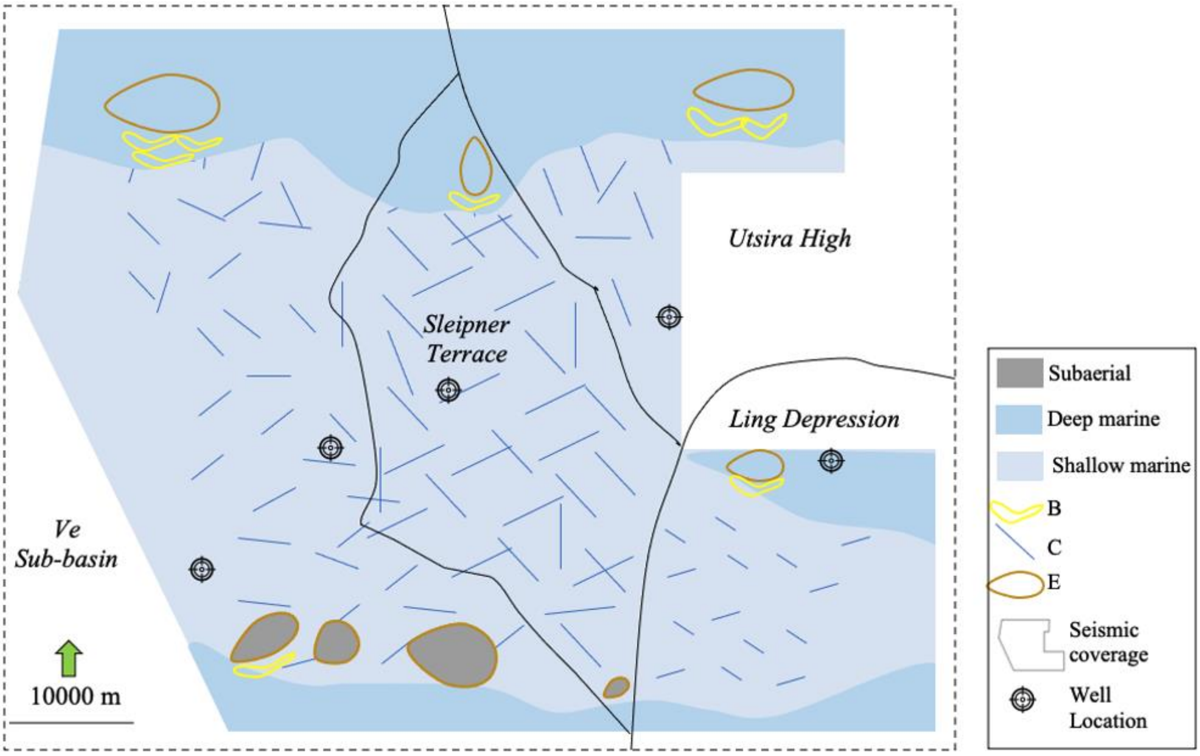


Figure 42: Paleogeographic map of the Hordaland Group. The uplift of Southern Norway created the shallow marine environment. The folds caused by the mud diapirs may have created a subaerial exposure when they occur within shallow marine environment.

5.1.4 Tectonostratigraphic evolution of the Utsira Formation

Well logs and interpretations from seismic facies suggests that the Utsira Formation is made up of predominantly sandstones. The Utsira Formation is often distorted by the underlying mud diapir which causes the folds at the top of the Utsira Formation. Thickness variations are observed as the flanks of the mud diapir are thicker than the crest. This suggests that the mud was probably moving at the time the Utsira Formation was deposited. The submarine channels found by the sides of the mud diapir suggests that the movement of the mud diapir may have controlled the deposition of the submarine channels

A small depocenter is located at the east while other thick areas are observed in the center and northern parts. Based on this, it is suggested that the sediments of the Utsira Formation were sourced mainly from the Norwegian landmass while minor inputs came from the East Shetland platform. Several authors documented that the formation derived its southern and middle sediments from the Shetland Platform while its northeastern sediments were derived from the Sognefjorden/Nordfjord source areas (Rundberg and Eidvin 2005; Eidvin 2014). It is suggested that a regional uplift which affected the North Sea, Norwegian Sea and surrounding mainlands, and a mid-Miocene fall in glacio-eustatic sea level increased the influx of sand into the North

Sea basin and led to the deposition of the Utsira Formation (Davidson et al., 2000; Gabrielsen et al., 2002).

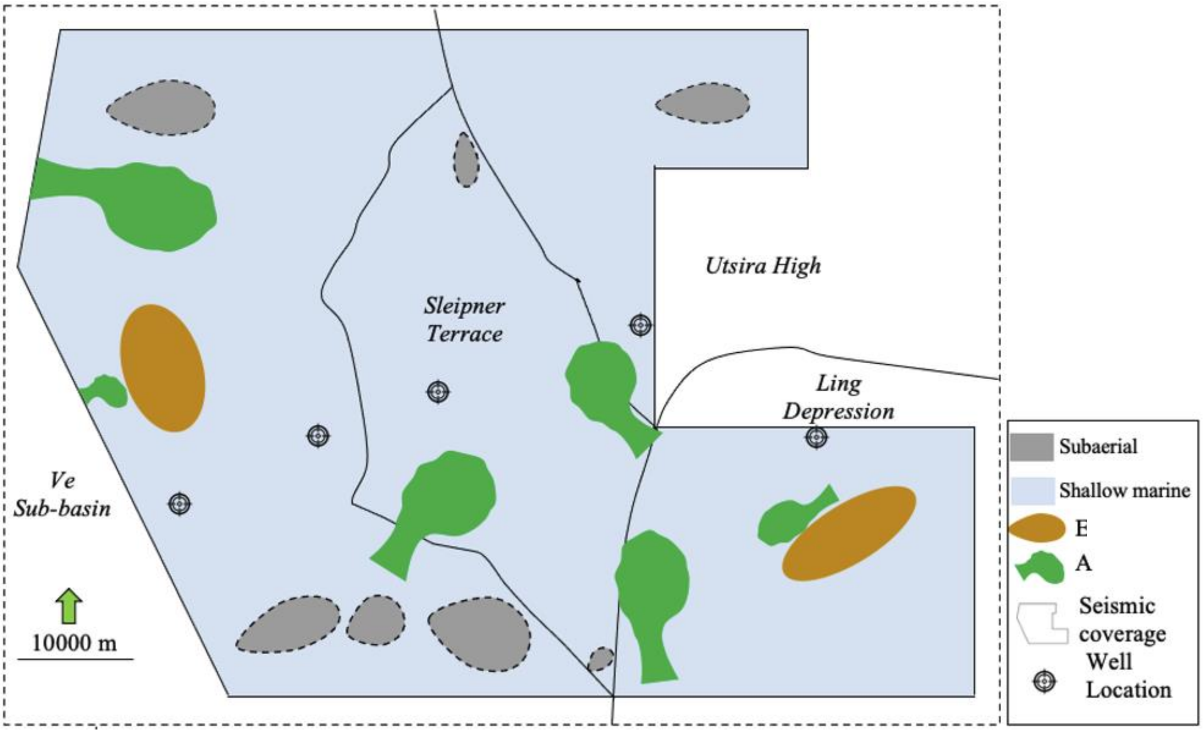


Figure 43: Paleogeographic map of Utsira Formation. Dashed lines represent onlapping reflectors on the uplifted areas caused by underlying mud diapirs which suggests subaerial exposure. Note how the channel forms a tidal dominated delta towards the south.

5.2 CO2 storage potential

A summary of the factors necessary for CO2 storage is summarized in table. The criteria values are transformed into points from 1-3 where 3 is given to the preferred, 2 is given to the questionable and 1 is given to the hazardous. The highest point that can be achieved is 27.

Table 7: Summary of the factors necessary for CO2 storage.

Factors	Points	Rogaland Group	Hordaland Sands	Hordaland Group	Utsira Formation
Reservoir Depth	3	2100 m	1881 m	1108 m	861 m
	2				
	1				
Porosity	3	25.7-26.9%	23-24%	35%	30-40 %
	2				
	1				
Permeability	3	800mD-1D	800mD-1D	500mD-1D	1-3 D
	2				
	1				
Reservoir homogeneity /Thickness	3		50-220		115 m
	2	25-140 m		20-50 m	
	1				
Traps	3				
	2	Faults and folds	Folds, Stratigraphic (pinch out, Remobilized sands).	Stratigraphic pinch out	Stratigraphic pinch out
	1				
Primary Seal thickness	3		60-470 m	70-90 m	200 – 300 m
	2	35-37 m			
	1				
Main lithology of Group/Formation above	3		Mainly shales	Mainly shales	Mainly Shales
	2				
	1	Sand			
Seal by-pass	3				Effective seal
	2		Mud diapirs and Polygonal faulting as a by-pass is uncertain	Possibly affected by mud diapirs	
	1	Remobilized sands			
Lateral extent of seal	3				Continuous
	2	Fairly continous	Fairly continous	Fairly continous	

	1				
TOTAL	27	19	24	23	26

5.2.1 Rogaland Group

Although the Rogaland Group contains of oil shows, it is suggested to be a saline aquifer based on the average salinity observed within the unit. The Group has an average thickness of 300 m. The average depth of the unit is 2109 m suggesting that the CO2 stored in it can exist in a super critical state provided the temperature and pressure conditions are favorable. It also has its shallowest depth at 1670 m which is still a sufficient depth therefore risks of the injected CO2 migrating upwards to areas outside the super critical phase is unlikely. Studies have shown that the unit has excellent porosity (25.7 to 26.9%) (NPD 2022) and permeability properties (800mD to 1000mD) (Ahmadi 2003). From the well logs, sandy intervals within the unit exisits although with some thin shales. These sandy intervals have thickness ranging from 25-140 m. Faults and anticlinal folds have been mapped within the unit. The faults have been observed to have little to no displacements (less than or equal to 50 ms (TWT). The faults are juxtaposed againt the Hordaland sands (which have been mapped to consist of remobilized sands, shales and submarine fans) when slightly displaced thus they may serve as migration pathways. More studies are needed for proper analysis of the faults. The anticlinal folds available within the unit have been suggested to be caused by the mobilization of the underlying salt. This anticlinal fold may form a structural trap for CO2 storage, however, possibility of the fold not being an adequate trap is suggested as the sides of the crest are juxtaposed against the permeable Hordaland sands. The Rogaland Group have been mapped to reduce in thickness towards the east, a minor possibility of further reduction in thickness may cause the group to pinch out thereby forming a stratigraphic trap that may successfully hold injected CO2.

The unit is overlain by the Hordaland sands (229 m thick). The Hordaland sands unit have shale intervals ranging from 35-37 m which serve as the primary seal of the Rogaland Group. However, the presence of remobilized sands within the low permeability shales compromises their seal integrity. This is because the remobilized sands may serve as seal by-pass within the shales. Seal by-pass nature of sand injectites have been documented by several authors such as Zweiget et al., 2004; Hermanrud et al., 2010 and Lloyd et al., 2021. The Hordaland Group that overlies the Hordaland sands may serve as a secondary seal to the Rogaland Group. The efficiency of the Hordaland Group as seals is discussed later.

The intervals of shales ranging from 12-80 m interbedded into the high porosity layers of the Rogaland Group as observed from the well logs may serve as intraformational seals thereby slowing down the rate at which the injected CO2 would get to the reservoir and seal boundary. Efficiency of intraformational seals would depend on some factors such as its thickness, faulting and lateral continuity (Zweiget et al., 2004; Hermanrud et al., 2010 and Lloyd et al., 2021). Based on these factors, the observation from the study suggests that the intraformational seals may be able to trap the CO2 as it has sufficient thickness of 12-80 m (greater than 10 m), and the shales within the unit have been mapped to be laterally continuous. Therefore, the intraformational seals may act as barriers to the flow of CO2 and possibility of the CO2 being affected by chemical trapping mechanisms may exist before it reaches the overlying seal.

5.2.2 Hordaland Sands

From the analysis of the well log, the Hordaland sands is interpreted to be a saline aquifer. Based on the interpretation in this study, the unit consists of remobilized sands, shales and submarine fans. The presence of these remobilized sands and submarine fans encased within shales makes it a potential storage option. This is because the unit has an average thickness of 229 m sandy intervals having thickness of 50 – 220 m. The porosity and permeability values are 23-24% (NPD 2022) and 800mD to 1000mD (Ahmadi et al., 2003). The average depth of the unit is 1881 m which is suitable for CO2 storage in a super critical state provided the temperature and pressure conditions are favorable. Its shallowest depth is at 1580 m which still supports the super-critical state therefore risks of the injected CO2 migrating up-dip is unlikely. Remobilized sands are known to have high porosity and permeability and this would allow the free flow and migration of CO2 within the unit (although this quality is subject to diagenesis) (Hurst et al, 2007).

The presence of the sand injectites within the unit also serves as a trap. Sand injection serving as intrusive traps (different from structural and stratigraphic traps) has been documented by Bergslien et al., 2005. However, the trap definition may be poor because of their complex connectivity and because of the lack of parallel contacts with the top seal. These observations in this study are in line with findings by Bergslien et al., 2005. The remobilized sands have also been identified on seismic and well data to thin towards the east into more shaly sediments which may probably serve as stratigraphic traps, however, the eastern extent of the remobilized sands has not been mapped with great confidence in this study.

The Hordaland sands are overlain by the Hordaland Group which serves as the seal. The Hordaland Group is made up of mainly shales and has been mapped to be laterally continuous with average thickness of 773 meters. Seismic facies interpreted as polygonal faulting and mud diapirs have been mapped within the Hordaland group and these play a major role in the sealing ability of the Hordaland Group. It is widely accepted that the presence of polygonal faults found within shales increases the permeability of the shales (Gay et al., 2004; Faulkner et al., 2010; Ilg et al., 2012; Xia et al 2022), and from findings that this study proposes, they may have served as migration pathways for fluidization in the Oligocene. However, recent studies suggests that even when the faults are favorably oriented, the permeability they create may not be large enough to allow the injected CO_2 to flow smoothly (Xia et al 2022). On geology time scales, the rate of migration through polygonal faults is low and thus, it has been documented that the presence of polygonal faults alone cannot give rise to extensive migration (Cartwright et al., 2007, Xia et al 2022). Also, the sealing ability of the faults can be improved with time as clay from the shales gets smeared along the faults (Turrini et al., 2017 and Xia et al 2022). In addition, the thickness of the unit affected by the polygonal faults (400-600 ms) is so great that the possibility of the injected CO_2 being trapped by chemical processes before it gets to the top of the seal exists. Based on these, the Hordaland Group even with the polygonal faults within the study area may act more as seals than migration pathways. Seal by-pass within the seal is most likely to be related to the mud diapirs interpreted in the study. However, the mud diapirs are located at the top of the sealing unit and are less likely to be in contact with the injected CO_2. 35-37 m thick of shales present within the Hordaland sands may act as intraformational seals. These intraformational seals are laterally continuous with sufficient thickness. No major faults are observed within them, however; they may be intruded by the remobilized sands hence their seal integrity may be compromised. Table presents a summary of the criteria discussed

5.2.3 Hordaland Group.

The Hordaland Group is interpreted to be a saline aquifer with an average thickness of 773 m. The group has been interpreted to consist mainly of shales although intervals of sands with 20-50 m thickness have been observed. The average depth of the unit is 1108 m suggesting that the CO_2 stored in it can exist in a super critical state provided the temperature and pressure conditions are favorable. It also has its shallowest depth at 1017 m in the Ling Depression which is still a sufficient depth therefore risks of the injected CO_2 migrating upwards to areas outside the super critical phase is unlikely. Studies have shown that the sands within the unit has excellent porosity and permeability properties.

No defined trap has been mapped within the unit however, the sandy intervals within the unit thin significantly towards the east and they may pinch out eventually.

The sands within the Hordaland Group are overlain by shales within the Hordaland Group. These shales range from 70-90 m in thickness. The large thickness and lateral continuity makes the Hordaland Group shales a potential effective sealing unit.

5.2.4 Utsira Formation

The Utsira Formation is interpreted to be a saline aquifer with an average thickness of 227 m. The group has been interpreted to consist mainly of sands with good porosity (30-40%) and good permeability (1-3 darcies). The average depth of the unit is 861 m suggesting that the CO2 stored in it can exist in a super critical state provided the temperature and pressure conditions are favorable. However, challenges with the depth may exist as the shallowest depth of 808 m is located in the Ling depression and the possibility of the injected CO2 migrating to depths too shallow for super critical phase to exist is possible. This challenge has also been documented by Halland et al., 2013 who observed and up dip migration towards the east.

No defined trap has been mapped within the unit however, it is proposed that as the thin towards the west, they may pinch out thus creating a stratigraphic trap.

The overlying formation has not been accessed in this study however, studies have documented that the overlying Nordland impermeable shales of 200-300 m thick currently provides an effective seal for the Utsira Formation (Chadwick et al. 2001b, Chadwick et al. 2004). The presence of the 1m thick intraformational shales which should act as a seal may not sufficiently seal or reduce the rate of flow mainly because of its insufficient thickness (< 10 m).

6. 0 Conclusion

- The lateral and vertical distributions of the Tertiary sandstones of the Southern Viking Graben have been affected by salt mobilization, polygonal faulting and mud diapirs.
- The late salt mobilization folded the Rogaland Group, Hordaland sands and Intra Hordaland Group units. This salt activity may have ended after the deposition of the Hordaland sands.
- Mud diapirs within the Hordaland Group created numerous folds and controlled the segmentation of the depocenters within the Hordaland Group.
- The mud diapir that folded the overlying Utsira Formation was active during the deposition of the Utsira Formation and may have controlled the distribution of the submarine fans within the formation.
- Based on the findings in this study, the Utsira Formation holds the most promise for CO2 storage although challenges exist in its stratigraphic trap and shallow depth observed in the Ling Depression.
- Great opportunities for CO2 storage also exist in the Hordaland sands mapped specifically for this study. Due to its sand thickness, good porosity and permeability values, sufficient depths and possible intrusive trap, it is desirable as a storage option. However, challenges exist in its poorly defined traps and uncertainty in its seal.
- The Hordaland Group is considered as a potential storage option because of its seal thickness and thickness and sufficient depth of its reservoir.
- The Rogaland Group is also considered as potential option because of the sand thickness and sufficient depth. The presence of intraformational seals also makes them desirable. Major challenges are in their lack of seals with impermeable lithologies and their lack of defined traps.

- Major challenges for CO2 storage within the Tertiary succession are in trap definitions as most of the traps within the intervals of interest are poorly defined stratigraphic traps.

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