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Play based evaluation of the eastern margin of Nordland Ridge, Norwegian Sea

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Abstract

Play based evaluation of the eastern margin of Nordland Ridge, Norwegian Sea

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The University of Stavanger, 2016

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The main objective of this study is produce a petroleum system evaluation of potential plays along the eastern margin of the Nordland Ridge. The area of study consists of two major tectonic structures; the Nordland Ridge and the Trøndelag Platform to its east. Significant discoveries along the western flank of Nordland Ridge have generated interest in furthering exploration of the central and eastern parts. The tectonic evolution of both, the Nordland Ridge and Trøndelag Platform began during the Permo-Carboniferous rifting episode but on Nordland Ridge, it has been overprinted by the subsequent mid Jurassic to mid Cretaceous tectonic activity. During this time the region was influenced by three distinct crustal extensions and a compressional phase resulting in a complex tectonic history. It was subaerially exposed which caused erosion of almost all of Cretaceous and some Jurassic strata from the uplifted highs and footwall crests. Upper Cretaceous and Paleogene deposits are quite thin with major hiatuses due to sea level variations.

Previous studies reveal that the Paleocene and Cretaceous sediments are thin and high in clay content. The Upper Jurassic contains oil prone organic rich but immature shales on the Trondelag Platform. Middle and Lower Jurassic sandstone units are also found on Trondelag Platform but are absent in parts on the Nordland Ridge due to erosion. The earliest deposits of these Lower Jurassic units are interbedded with coal layers which are also immature on the Trondelag Platform. The late Triassic deposits have good sand content and they overlie thick late Upper-Middle Triassic evaporites. Late Permian, has shown east Greenland equivalent carbonate buildup and organic rich shale deposits that have a good source rock potential. The primary targets have been defined as the Lower- Middle Jurassic sandstone units while Permian shales have been proposed as a notional source rock. Due to complex tectonic history, trap formation and retention is a risk for any petroleum system in the area. In addition to significant uncertainty tied to retention, one of the major geological risks is the migration of charge from the Trondelag Platform to the traps within the Nordland Ridge.

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1. INTRODUCTION

The Nordland Ridge is a structural high offshore on the mid Norwegian Continental Shelf. It was formed during multiple rifting episodes in the Late Permian- Early Triassic and Middle Jurassic- Early Cretaceous (Gowers & Lunde, 1984)). Consequently, it is characterized by large normal faults with with NE-SW orientations. The Trondelag Platform is located on the eastern flank of the Nordland Ridge and originated as a subsiding basin during the Early Permian (Larsen & Skarpnes, 1984).

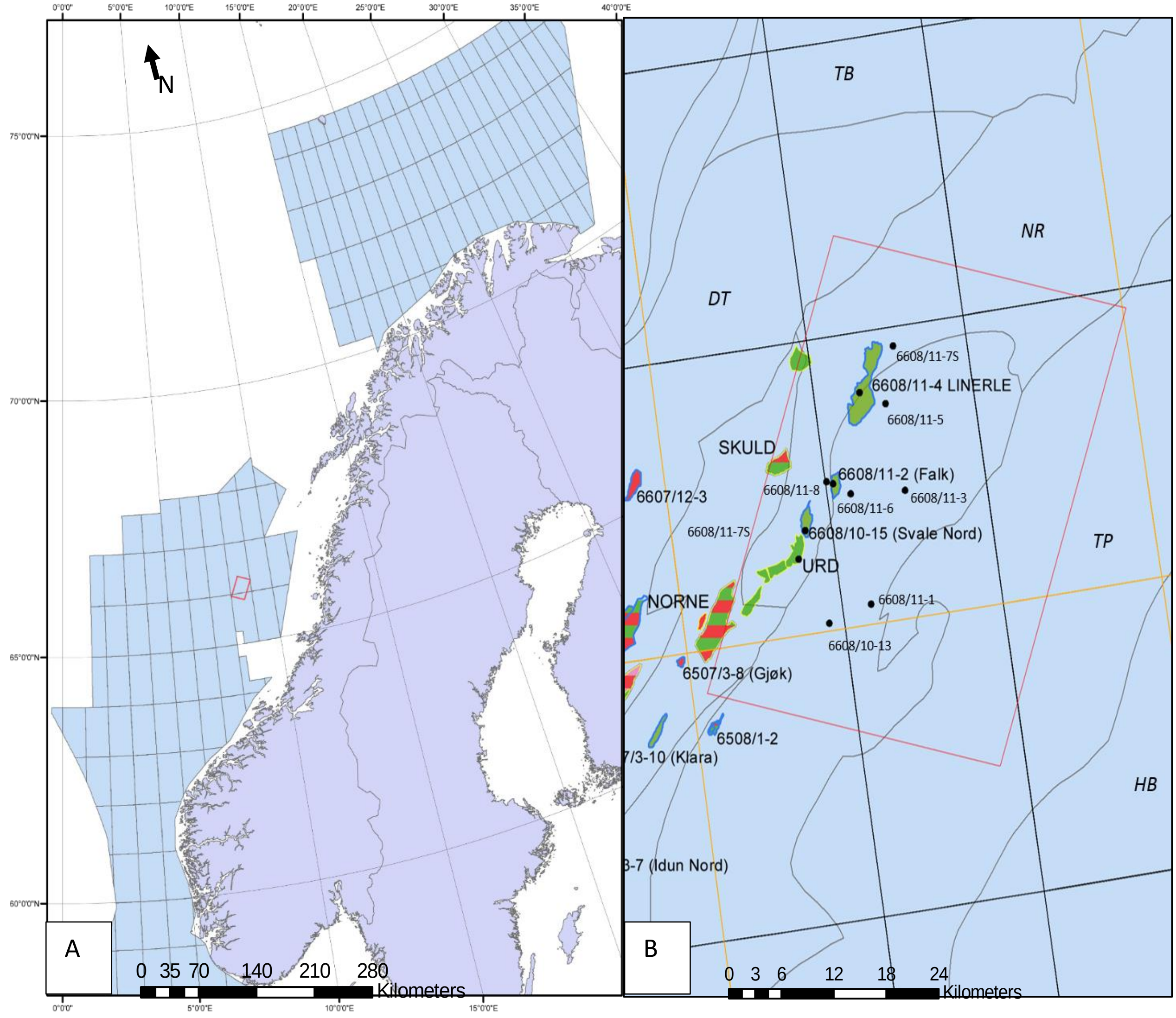


Figure 1: (A) Location of the study area (in red) on the Norwegian Continental Shelf. (B) Structural map of the study area with 6608/10 and 6608/11 as can be seen from, well nomenclature. The producing fields of Norne, Urd and Skule are higlighted with yellow border while the discoveries, which are called by their well name are highlighted in blue. The wells provided with the data set are marked within the study area.DT-Dønna Terrace; HB-Helgeland Basin; NR-Nordland Ridge; TB-Træna Basin; TP-Trøndelag Platform (structural elements defined by NPD).

Hydrocarbon Exploration efforts in the Nordland Ridge started in the 1980's and have yielded positive results like Norne, Urd and Alve fields along with Falk and Linerle discoveries (Figure 1B). Most of these accumulations are structural traps along the western margin of the ridge charged by Lower and Upper Jurassic source rocks from within the Haltenbanken (Stefatos et al., 2014). Due to differential subsidence these source rocks are immature towards the eastern edge of the Nordland Ridge and as a result, exploration activities have been relatively less intense on the eastern side. However, with the discovery of Permian organic rich shales, there is a renewed interest in the region.

1.1 Objectives

The aim of this study is to investigate the hydrocarbon potential on the eastern margin of the Nordland Ridge and the adjoining Trøndelag Platform by conducting a play based petroleum system evaluation. This evaluation builds on some key concepts:

- Investigate basin framework to improve the understanding of the development of trap mechanisms.
- Examine regional source rock maturation to determine the extent of the hydrocarbon charge.
- Analyze possible migration risks due to complex tectonic history of the region.

2. GEOLOGICAL SETTING

The Nordland Ridge can be subdivided into three structural highs; the Rødøy High, the Grønøy High and the Sør High, bounded by normal faults to the north-west (A) and south-east (B) (Figure 2).

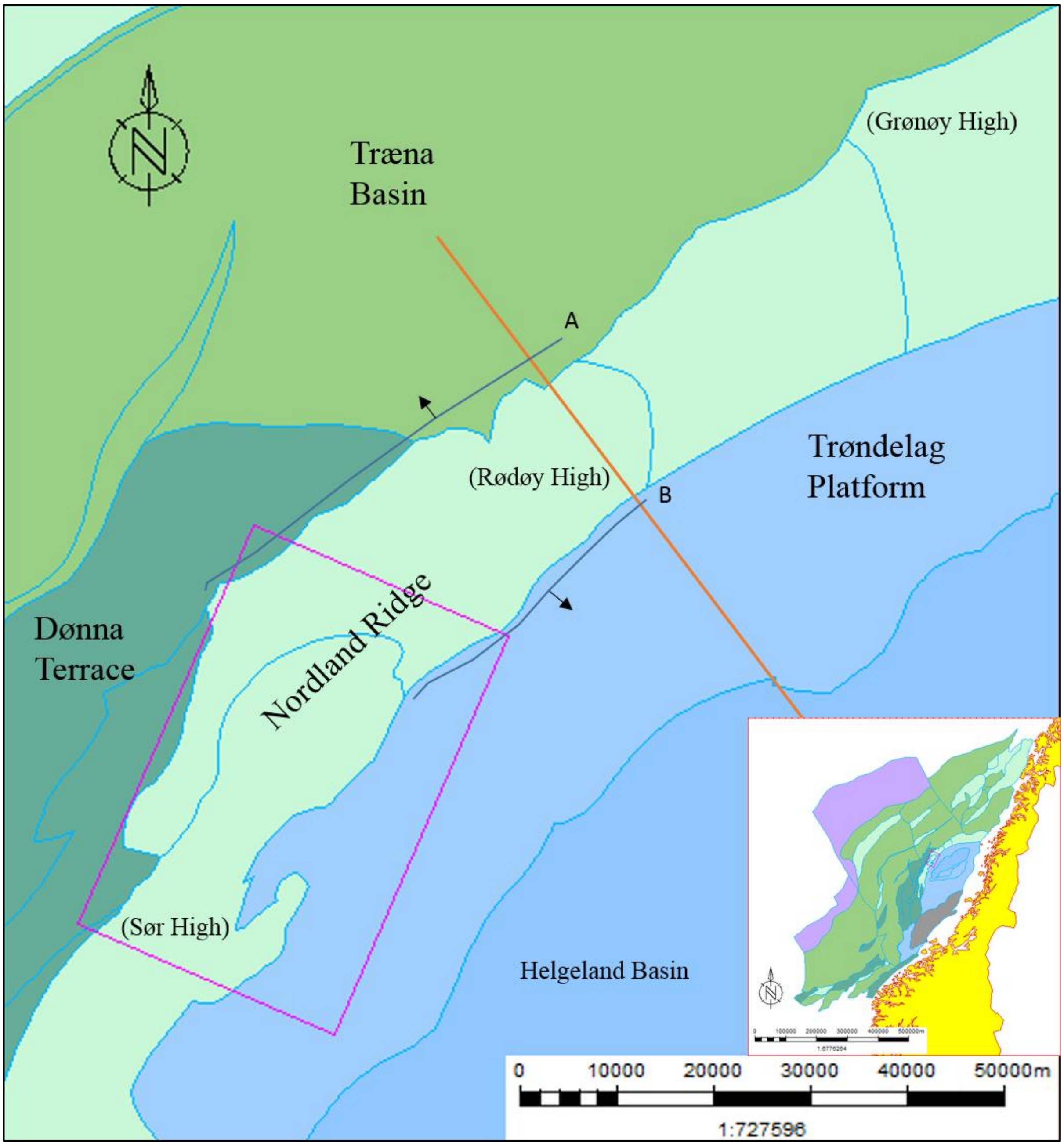


Figure 2: Structural map of Nordland Ridge and its sub elements. The purple box display the extent of the area of interest. (See figure 2 for cross section along the line).

2.1 Tectonostratigraphic setting.

2.1.1 Paleozoic

The oldest strata in the region has been identified to be Cambro-Silurian, mainly deposited during the Caledonian orogeny from 450-500 M.a. (Gowers and Lunde, 1984). This collision lasted until Early Devonian, when the tectonism changed from compressional to extensional (Larsen and Skarpnes, 1984). During the Devonian the remaining uplifted regions in the central horst-structure underwent intense erosion. The initial development of fault A (Figure 1) in the region happened during this phase as a sinistral strike-slip fault. This fault arguably accelerated the regional subsidence, later become the Træna basin (Gowers and Lunde, 1984).

2.1.2 Carboniferous.

During Early Carboniferous, the region was a part of a continental landmass. The knowledge of this period is limited due to lack of data, but from studies conducted off the east coast of Greenland, it is assumed that the change in tectonic stress regime led to the formation of small parallel basins (Figure 3, highlighted in red) that were filled with eroded sediments from the Caledonides (Ramberg, 2008). This supports the continuation of Devonian erosional activity of the highs in the Trøndelag Platform (Gowers and Lunde, 1984).

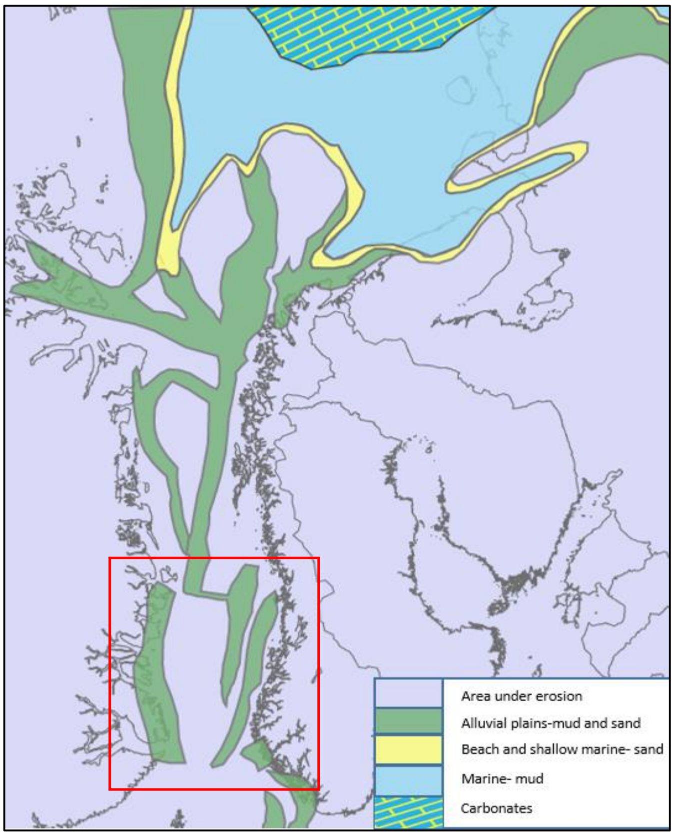


Figure 3: Regional paleogeography of the Norwegian Sea during Early Carboniferous. Highlighted area in red shows parallel basins. Modified from (Ramberg, 2008)

The Mid-Carboniferous shows an abrupt climate change from humid to arid conditions. This led to the transformation of alluvial plains into arid deserts. Ephemeral but heavy rainfall transported the wind-sorted sediments into localized depressions (Figure 4). These conditions continued throughout the Late Carboniferous all the way to Early Permian, amid extension and subsidence, even as the northern parts of the landmass such as present day Barents Sea were undergoing transgression (Ramberg, 2008). This progression can be observed by the increase in spatial extent of carbonates from early to middle Carboniferous. The whole region experienced removal of large amounts of strata from Devonian, Carboniferous and possibly some from Cambro-Silurian, forming an unconformity that was covered in Permian (Gowers and Lunde, 1984).

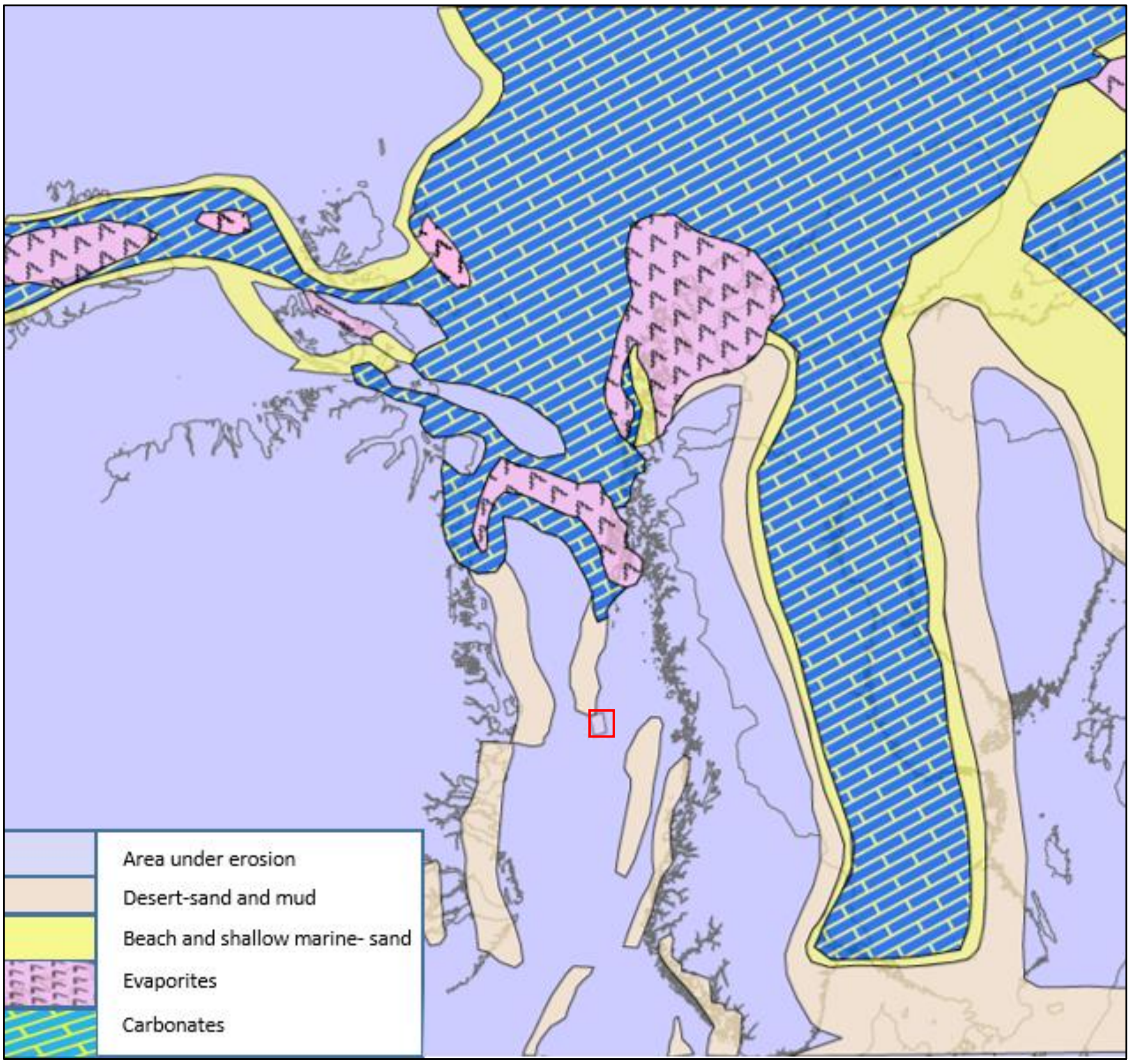


Figure 4: Regional paleogeography during mid Carboniferous. The highlighted region in red shows the area of interest. Modified from(Ramberg, 2008)

2.1.3 Permian

The Permo-Carboniferous unconformity that had developed by now, faulted in Late Carboniferous to Early Permian the on-going transgression inundated Mid-Norway during Late Permian and a seaway existed in the place the Norwegian Sea is located today. This period experienced an hiatus in the rifting, but still underwent subsidence (Gowers and Lunde, 1984). These faults have a North-South trend due to an East-West extensional regime during this period. During this period, a horst started developing towards the west of the region, followed by the development of a basin towards the east (**Error! Reference source not found.**). The horst developed in the west is known today as the Rødøy High (**Error! Reference source not found.**) and the basin is the precursor of the Helgeland Basin. (Larsen and Skarpnes, 1984). The newly developed basin was filled with gray colored marine mudstones and sandstones that are found on top of red sandstones in the Helgeland Basin. The Nordland Ridge was in very shallow waters and has shown evidences of limestones and possible reef structures which are similar to that found on the east coast of Greenland, showing that these two areas were in close proximity at that time (Ramberg, 2008).

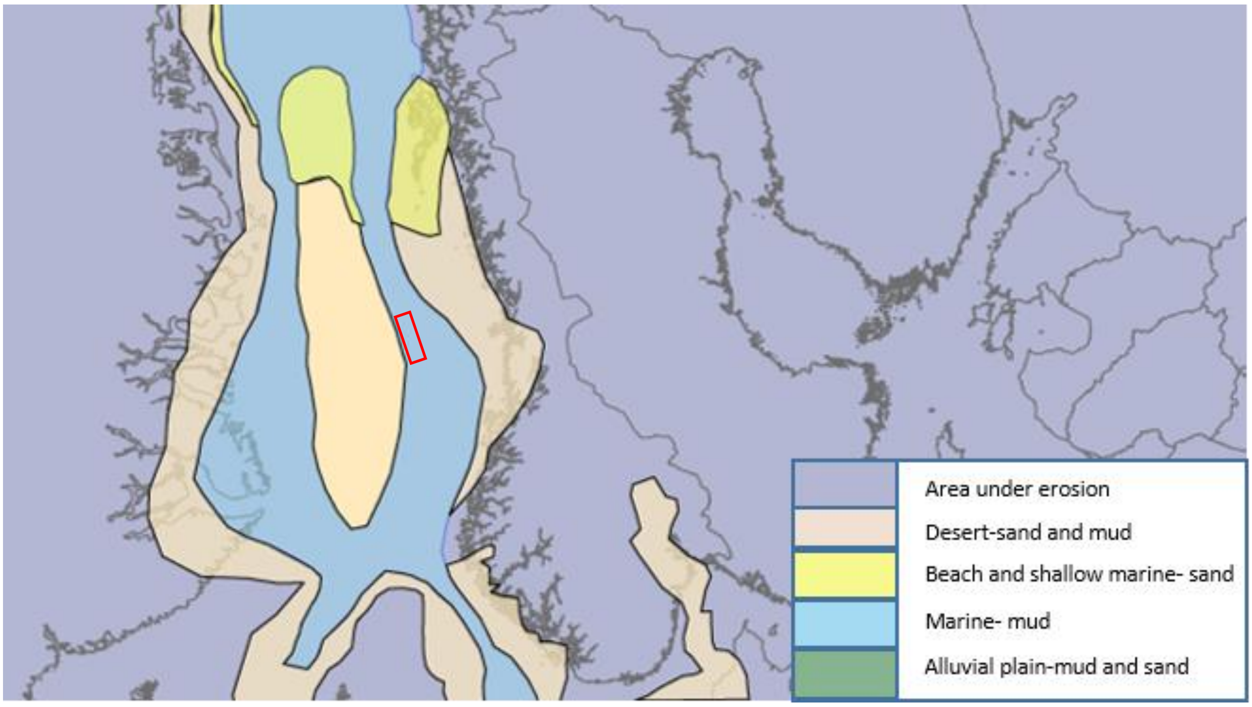


Figure 5: Regional paleogeography during Late Permian. Highlighted in red denoted the area of interest. Modified from (Ramberg, 2008)

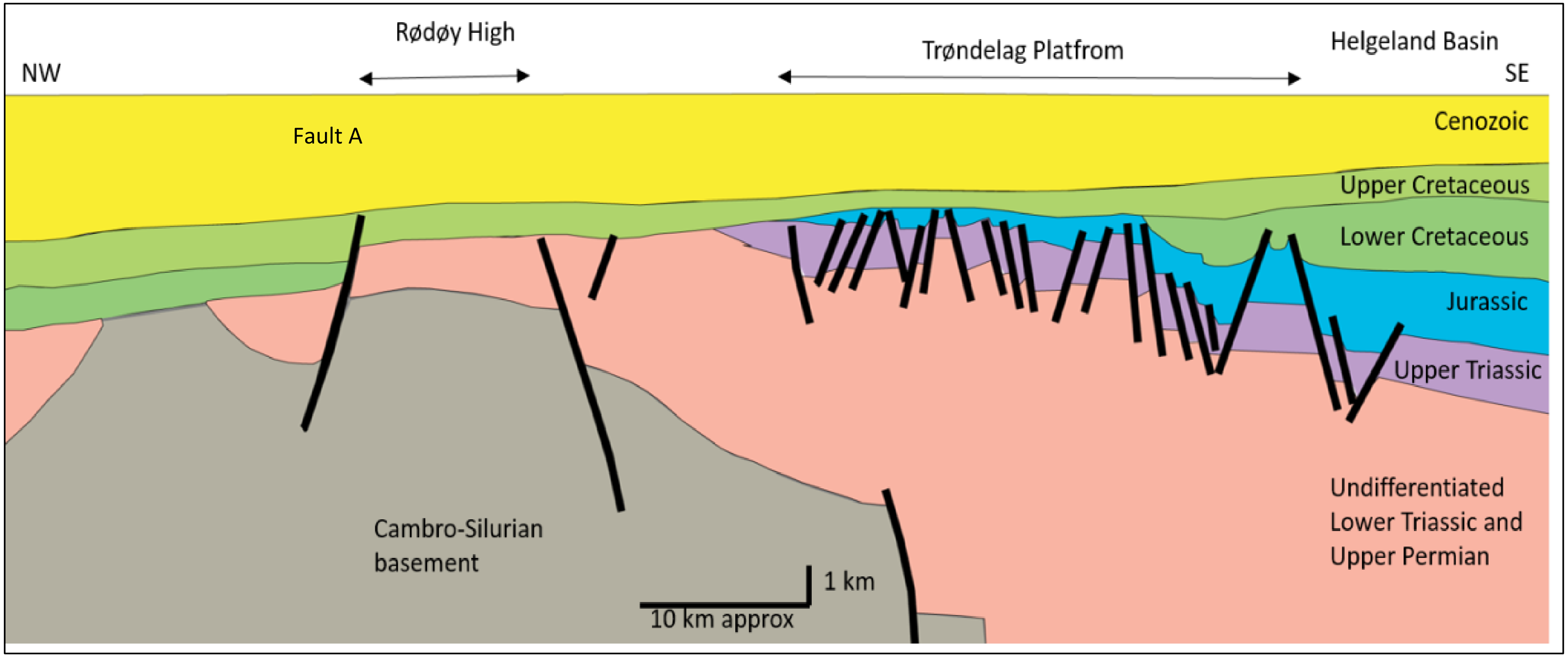


Figure 6: Schematic cross Section of the Rødøy High , modified from ((Gowers and Lunde, 1984))(See figure 1 for map location).Note the subcropping of Upper Cretaceous strata by Jurassic, Triassic and Permian deposits along with the basement. The Lower Cretaceous sediments were deposited after the rifting episode in Upper Triassic-Jurassic and can be seen only in the basins on the either side of the structural high

2.1.4 Triassic

Early Triassic saw the continuation of the extensional tectonic regime that began in Late Permian. Crustal extension led to the formation of rift basins between Norway and Greenland, marking the onset of the breakup of Pangaea. Rifting also continued across the Rødøy high along with subsidence of the Helgeland Basin. (Brekke et al., 2001; Gowers and Lunde, 1984; Larsen and Skarpnes, 1984; Ramberg, 2008). During this period the Helgeland Basin acted as an embayment with restricted water entry (**Error! Reference source not found.**A). This led to frequent evaporation of seawater in the hot Triassic climate leading to a cyclic deposition of thousands of meters of salt and evaporites. The onset of earliest Middle Triassic was a period of reduced rifting, and the seaway from Permian began receding and had left the region exposed by the Middle Triassic (**Error! Reference source not found.**B). During this time the basins from earlier were filled with sediments and broad alluvial plains were formed resulting in dry land for most of the remaining Triassic (Ramberg, 2008).

Late Triassic was a period of tectonic quiescence. The sea level rose again and flooded the alluvial plains (Figure 7C) (Gowers and Lunde, 1984; Larsen and Skarpnes, 1984; Ramberg, 2008).. Gradual increase in rainfall during this time also led to the formation of lakes, one of which extended from present day Trøndelag coast to Nordland Ridge, replacing the saline sea that existed earlier (Figure 7D). Rainfall also increased the formation of rivers and along with crustal uplift in mainland Norway resulted in transportation of large amounts of deposits in the low lying Norwegian-Greenland area (Figure 7D). These deposits are the Åre formation and it extends to early Jurassic. Continental low relief persisted throughout this period. (Larsen and Skarpnes, 1984; Ramberg, 2008).

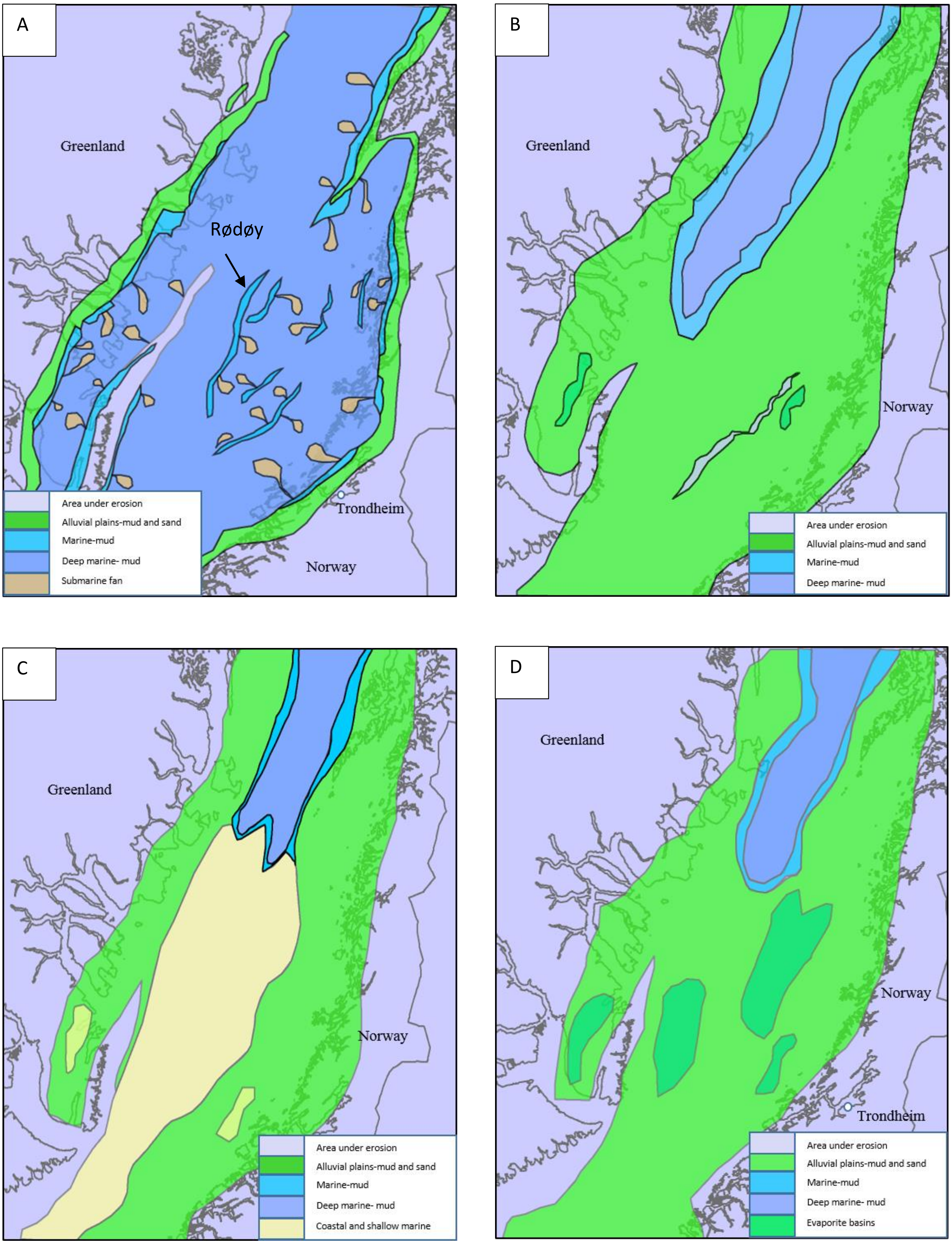


Figure 7: Regional paleogeography during Triassic. (A) Early Triassic. (B) Middle Triassic. (C) Late Triassic. (D) Latest Triassic Modified from (Ramberg, 2008)

2.1.5 Jurassic

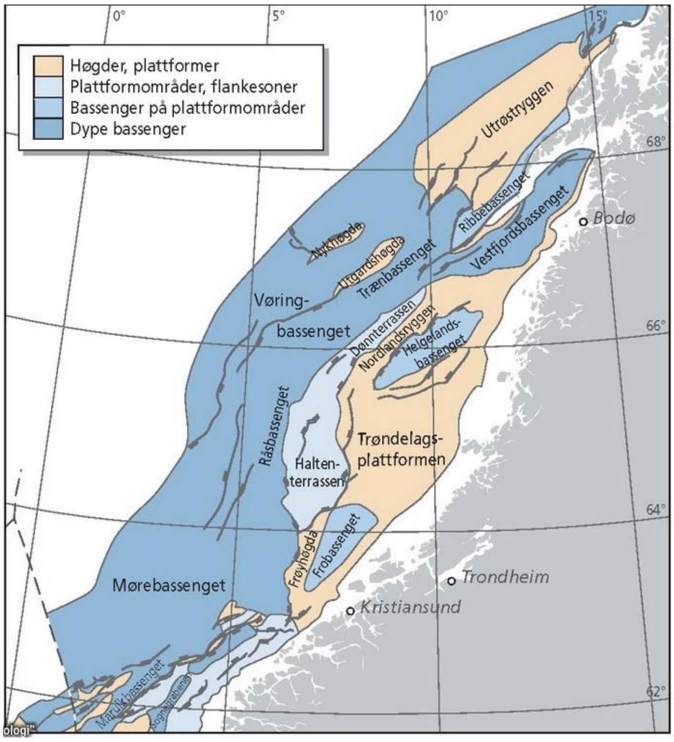


Figure 8: Structural elements of the Norwegian sea during Jurassic.((Ramberg, 2008))

During Early Jurassic most of the Norwegian Sea was occupied by humid swamplands as can be deduced from the large number of coal seams in the deposits of those times (Ramberg, 2008). The stress regime also changed during this period, from a W-E to NW-SE direction. This gave rise to a new fault system trending NE (Larsen & Skarpnes, 1984). On a regional scale, tectonic subsidence was taking place, affecting the local depositional environments. Gradual subsidence led to periodic encroachment by seas. Shallow lakes developed between fluvial channels. Towards the end of Lower Jurassic and early Middle Jurassic, the region was mostly characterized by alternating shallow marine and coastal plain environment confirming that the sea level was on the rise. This period also saw some the basin flanks getting uplifted (Figure 8). Marking the beginning of formation of the Nordland Ridge with an updoming event and the end of Middle Jurassic (Ramberg, 2008). The relative sea level kept on rising and eventually connected the northern Boreal Sea to the southern Thethys Sea. From the end of Middle Jurassic began a major rifting episode for the region. The rifting exposed footwalls to suberial exposure while the rest of the Norwegian sea region was submerged, resulting in the formation of islands, one of them being the Nordland Ridge (which now includes the Rødøy high). These exposed islands were heavily eroded forming syn rift deposits between them and removal of most of the Jurassic and parts of the Triassic sections. Basin wide subsidence led to rifting and development of several fragmented basins and highs. The Rødøy high, now a part of the Nordland Ridge underwent an uplifting phase during the Late Kimmeridgian due to a SE-NW compressional stress. This reactivated the old Triassic faults with dextral strike slip movement due to their N-S trend (Gowers & Lunde, 1984)

2.1.6 Cretaceous.

Norwegian Sea continued to rift during the Early Cretaceous. After the Kimmeridgian compressional event the stress regime reverted to NW_SE extensional trend (Larsen & Skarpnes, 1984). Normal extensional faulting along the same trend as earlier continued along the flanks of the Nordland Ridge throughout the Early Cretaceous. During this time the region also subsided towards the NW which can be seen by the SE onlap of lower Cretaceous (Gowers & Lunde, 1984)

The Early Cretaceous development of the region is quite complex and can be divided into three major phases (Gowers & Lunde, 1984).

- Berriasian-Valangian: The eastern faults on the Nordland Ridge were active during this period and led to a gradual subsidence in the Helgeland Basin.
- Valangian-Barremian: Due to subsidence a flexure zone developed along the Rødøy High, and as a result it is subaerially exposed to erosion.
- Aptian-Albian: The region underwent an extensive transgression which submerged most of the highs and halted erosion.

Major development of the Ridge and Helgeland basin took place during the Early Cretaceous (Figure 9) (Gowers & Lunde, 1984; Larsen & Skarpnes, 1984; Ramberg, 2008)

Hereafter, the faulting activity along the southeastern flank of the Ridge gradually decreased while it continued at the same pace along the northwestern flank the resulting in a higher subsidence rate for the western basins as compared to the Helgeland basin.

At the beginning of Late Cretaceous, marine shales were getting deposited in the region due to high transgression. These were later removed due to another subaerial exposure in Turonian times, followed by the deposition of formations

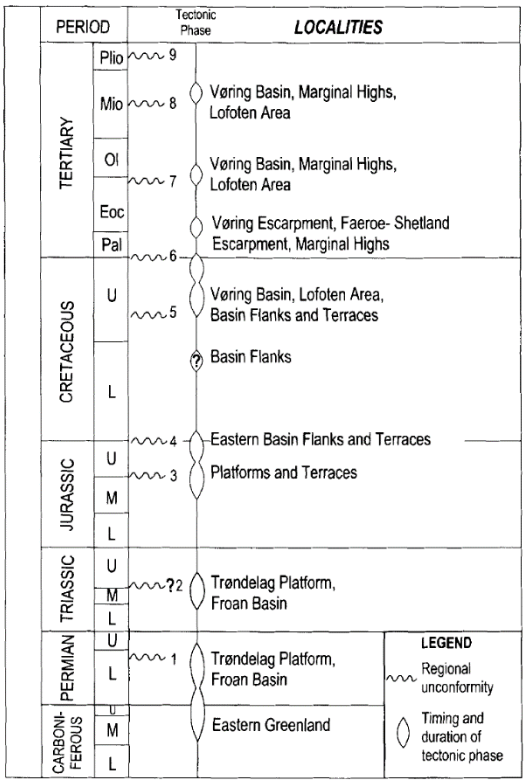


Figure 9: Summary of tectonic activity of Norwegian Sea, modified from (Brekke et al., 2001)

belonging to the Shetland Group towards the end of Late Cretaceous. The Helgeland basin also underwent a minor phase of subsidence, but that is generally attributed to compaction of the underlying Jurassic sediments, though some movement has been observed in some Early Cretaceous faults (Larsen & Skarpnes, 1984).

2.1.7 Cenozoic.

Late Cretaceous and Paleocene mark an important event in the evolution of the Norwegian continental shelf (NCS). The final splitting of the Norway-Greenland continental plate and development of oceanic crust happened during this time. The Norwegian Sea, as we know today, had begun its formation (Ramberg, 2008). Throughout this time the western flank of the ridge acted as a hinge line between actively subsiding basins and the stable Trøndelag Platform (Gowers & Lunde, 1984).

Splitting of the continental crust between Norway and Greenland caused an isostatic rebound during Paleocene. The NCS experienced a regional uplift and subaerial exposure resulting in increased sediment transport (Eidvin et al., 2007). Most of the sediments came from the eastern coast, but stratigraphic records suggest some sediment inputs from East Greenland before the seafloor spreading commenced. Towards the beginning of the seafloor spreading, the area experienced an increase in volcanism caused by the commencing of the rift (Ramberg, 2008).

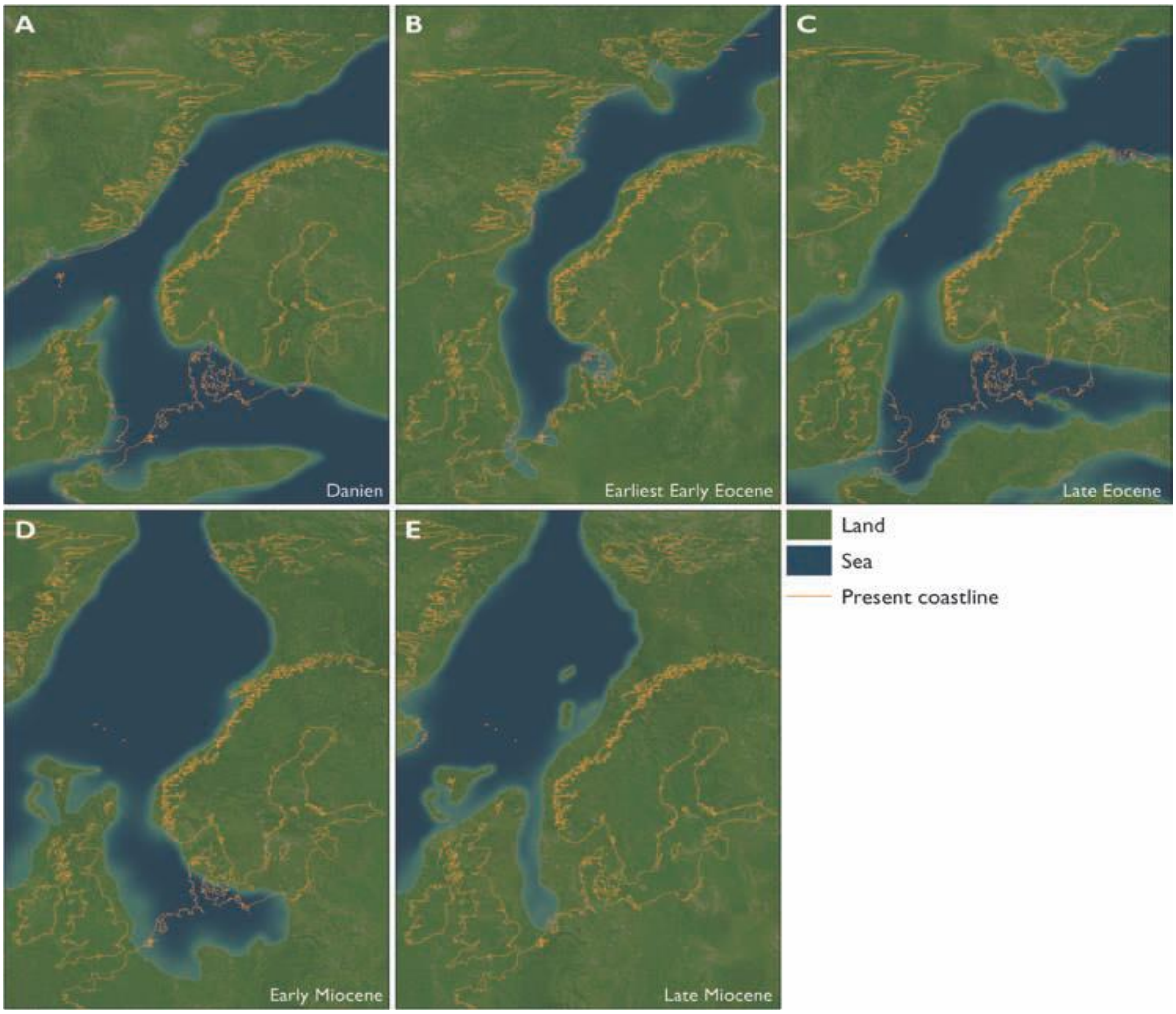


Figure 10: Paleogeographic reconstruction of the region during the A) Danian, B) Earliest Early Eocene, C) Late Eocene, D) Early Miocene, E) Late Miocene. (Modified after Rasmussen et al. (2008))

The spreading of seafloor continued during Eocene and the two continents drifted further apart as the newly formed seafloor cooled. This resulted in a regional subsidence and the area underwent transgression during the Ypresian (Tor Eidvin et al., 2007).

Another tectonic event affecting the Nordland Ridge was during the Oligocene, which resulted in compression and regional uplift (T Eidvin et al., 1998). The spreading and thermal cooling of newly formed seafloor caused the basin to subside further increasing the accommodation space (**Error! Reference source not found.**). However, due to this transgression transportation of sediments from the hinterland decreased. This was also a period of transition as from Eocene to Oligocene the climate changed from a predominantly warm to a less tropical and colder climate (Rasmussen et al., 2008).

The interval between Lower Eocene and Middle Miocene is defined as a lithostratigraphic hiatus known as the Mid-Miocene Unconformity. Interestingly this is a period of non-deposition and not of erosion (Tor Eidvin et al., 2007). The buildup of a polar ice cap in Antarctica led to a major fall in global sea levels. This also coincides with the middle to late Miocene compressional phase, which was recorded as the second compressional phase after the initiation of the seafloor spreading. The combined effect caused an uplift of the mainland resulting in a major regressive regime, causing the coastline to move 50-150 km westward of present day. Deltas prograded out into the basins, transporting sediments from the Fennoscandinavian mainland (Henriksen et al., 2005, Rasmussen et al., 2008).

The end of Miocene saw the onset of the Cenozic Ice Age. The region experienced climate cooling and an onset of glaciation. The first glaciations advanced in Late Pliocene, around 2.8 Ma. Until 1.5 Ma, the glaciers did not extend beyond the mainland., However, between 1.5 Ma and 0.5 Ma the glaciers advanced onto the shelf and eventually after 0.5 Ma they covered the shelf in three distinct glacial periods until the retreat in Holocene (Eidvin et al., 2007).

2.2 Facies and depositional environments

Complex tectonic evolution of the Nordland Ridge has provided for a variety of depositional environments and resulted in a highly heterogeneous tectonostratigraphic infill. Due to repetitive subaerial exposure events many formations that are found in nearby basins have

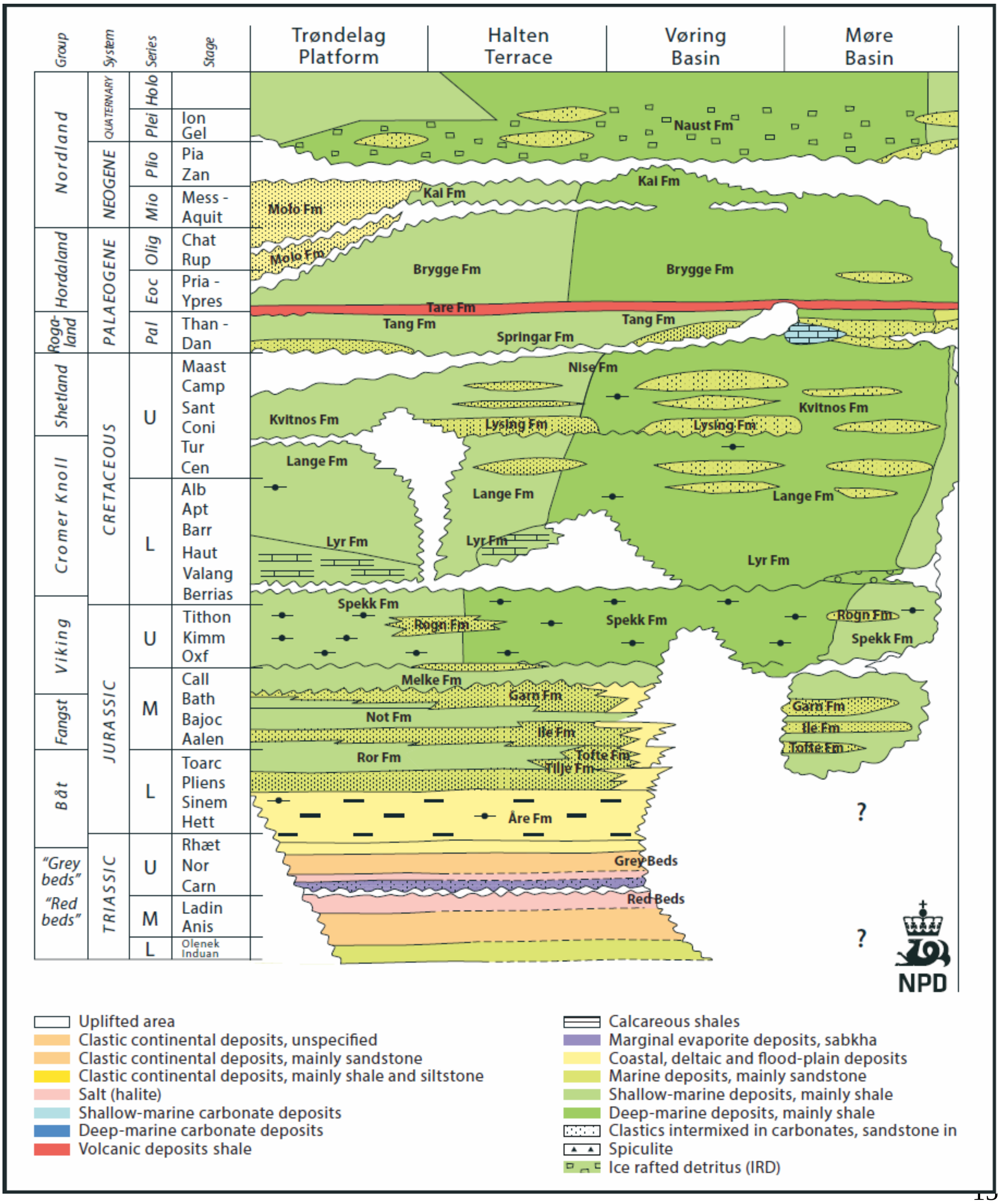


Figure 11: Sequence Stratigraphy of the Norwegian Sea. (NPD)

been eroded within the region. Hence, we shall only be discussing the deposits that are found within the area of study. Figure 11 shows a generalized lithostratigraphic chart of the Norwegian Sea structural elements, from east to west.

2.2.1 Permian deposits.

The Late Permian units are subdivided into three parts (Bugge et al., 2002). The shallow marine sandstone unit, the anhydrite unit and lower turbidite unit (Figure 12). The shallow marine sandstone unit, which is characterized by a series of massive bioturbated sandstone units, lies unconformably on top of the metamorphic basement. Above this unit are the conformable anhydrite beds which occur within laminated siltstone (Bugge et al., 2002). They have been interpreted as reworked sabkha deposits (Müller et al., 2005). The interbedded laminated siltstone indicate towards an offshore transitional environment which had inputs from the reworked sabkha deposits in the form of slumps (Bugge et al., 2002)

Succeeding the anhydrites are the lower turbidite units. They are the youngest deposits within the Late Permian and consist of multiple sequences of fining upwards sandstone beds. Two organic rich dark gray siltstones occur in the upper part of this unit (Bugge et al., 2002). However, well 6609/7-1 drilled on the Nordland Ridge, showed that the lower turbidite unit was composed of carbonates and shales which lie directly on top of the basement (Müller et al., 2005)

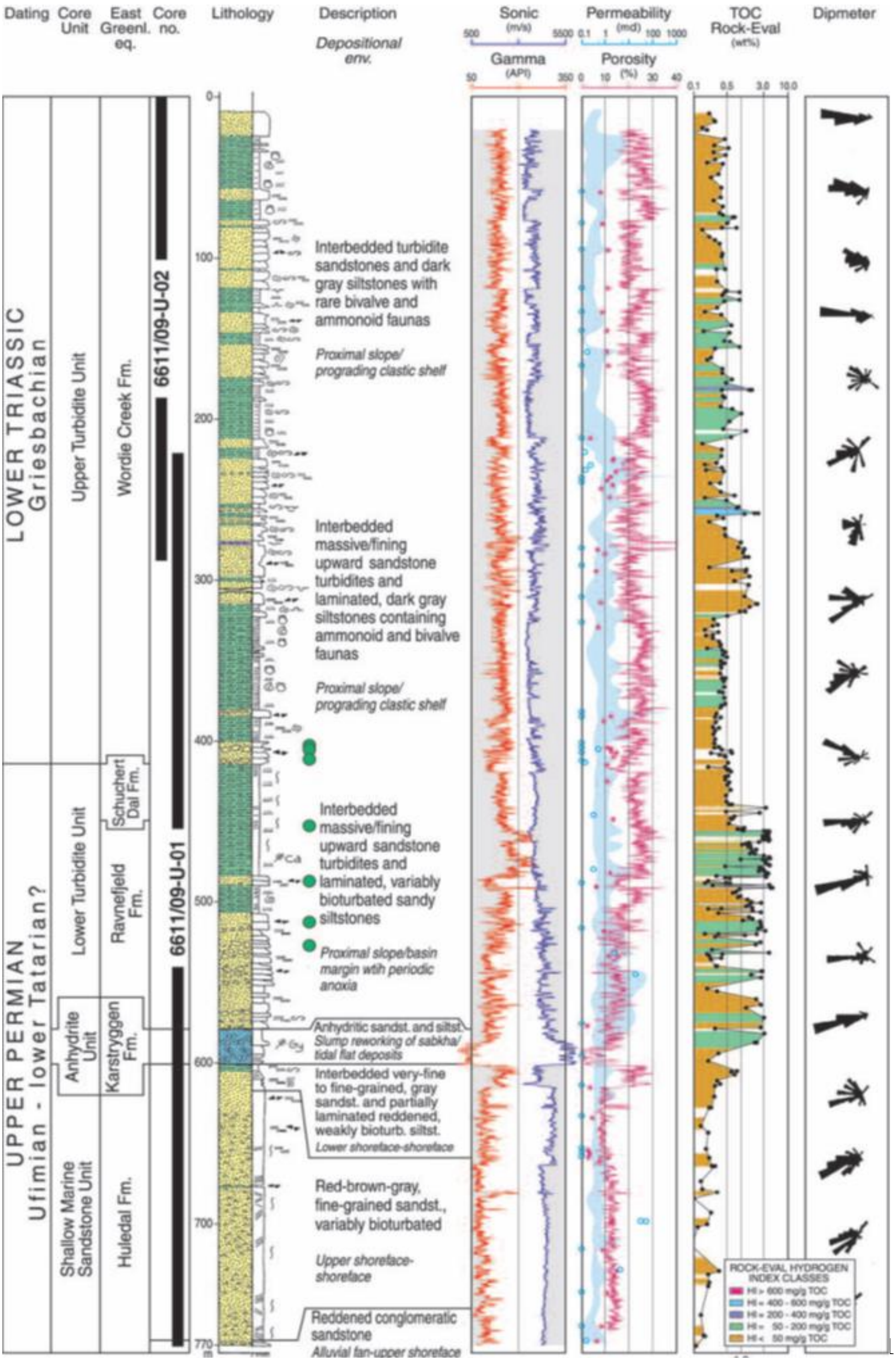


Figure 12 Lithostratigraphic correlation between the formations encountered in well 6611/09-U-01, close to Helgeland Basin with those found in East Greenland (Bugge.et al., 2002)

2.2.2 Triassic deposits.

Triassic deposits occur in similar climatic conditions as the Late Permian. The landmass was situated within the northern tropical zone and had a hot dry climate for most of the period (Ramberg, 2008). However, the Permian-Triassic boundary marks a shift in the depositional regime. The carbonate platforms of the Nordland Ridge were flooded with clastic deposits which represent a shallow marine setting. The lowest of the Triassic beds comprises of submarine fans and marginal marine deposits (**Error! Reference source not found.**A) deposited within a regressive regime (Müller et al., 2005). An increase in anhydrite content is recorded which verifies the shift from marginal marine to marine evaporitic facies.

The base of Red Beds (Figure 11) coincides with this shift and shows indications of the start of a period of renewed tectonic activity (Müller et al., 2005). The deposits exhibit variable thickness laterally and have a wedge shape which suggests the influence of fault block rotation within the basin (Müller et al., 2005). The faulting cannot be observed in the East Greenland deposits of the same age. This could be attributed to the location of the fault zones which were proximal to the Helgeland Basin (**Error! Reference source not found.**). The basin evaporite deposits represent structural isolation and restriction due to lower eustatic levels (Müller et al., 2005). Three evaporite successions have been observed within this unit. These thick evaporites thin out towards the present

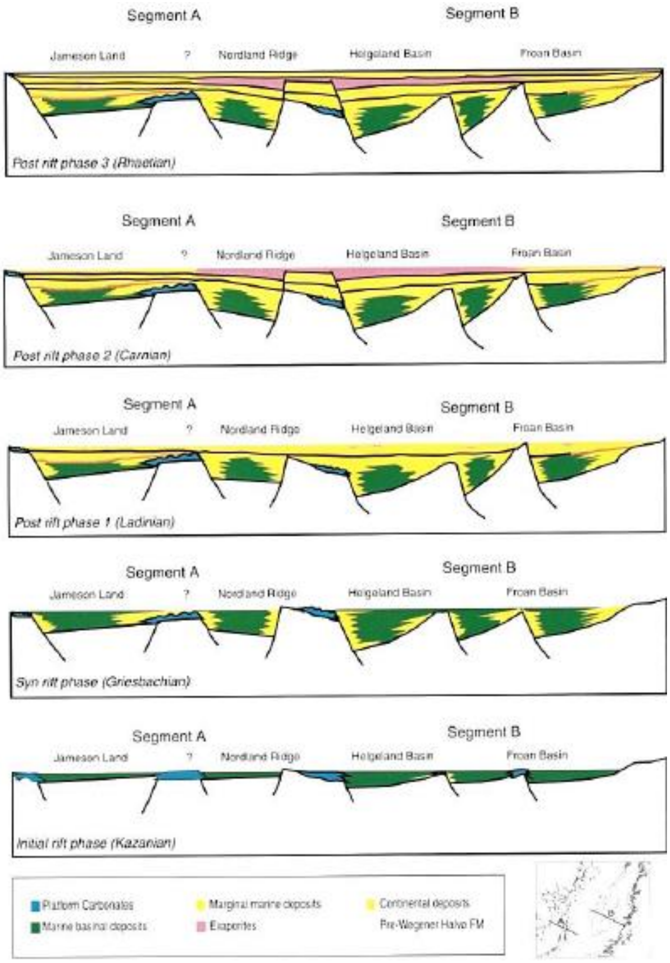


Figure 13: Generalized schematic showing the basin infill history of the Permo-Triassic Norway-Greenland basin.

Nordland Ridge (Müller et al., 2005). It has been theorized that these halite beds are of marine origin due to presence of marine algae (Müller et al., 2005).

The Grey Beds (Figure 11) are genetically related to the Red Beds. The lower part of these beds has a shallow mud dominated lacustrine origin with thicknesses exceeding 300 m (Müller et al., 2005). It covers most of the present day Norwegian shelf. The upper part of the unit contains thick sandstone beds with interbedded greenish gray mudstones and thin coal beds (Müller et al., 2005). These sediments seem to have been deposited within an extensive fluvial system with moderate to high sinuosity channels. The whole succession represents an overall coarsening upwards pattern from a mud dominated lacustrine flood basins to a sand rich fluvial setting (Müller et al., 2005).

2.2.3 Jurassic deposits

2.2.3.1 Båt Group.

The Båt Group (Figure 11) was deposited at the end of Triassic (Rhaetian) up to the end of Lower Jurassic (Toarcian) (Ramberg, 2008). During this period Norway was a part of the massive supercontinent Pangaea. It was closer to the Tropic of Cancer, gradually changing from an arid climate to a humid temperate zone. This resulted in an increase in vegetation and rainfall. The present day Norwegian Sea basins were full of swamplands and plains. The progression from Grey Beds to overlying Båt Group indicates the continuation of the transgressive

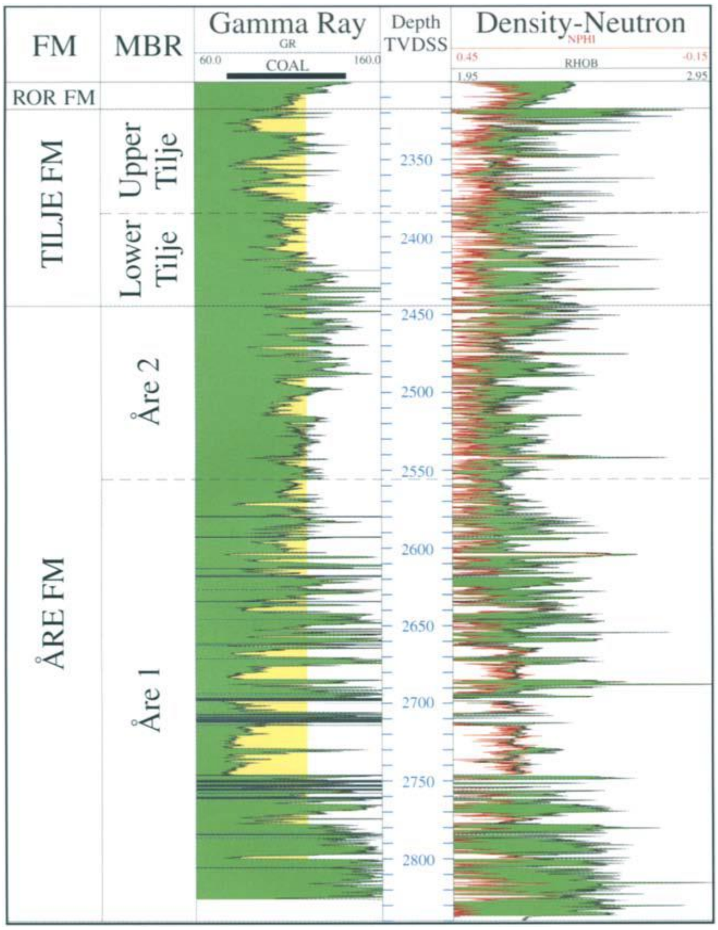


Figure 14: Åre and Tilje formation subdivisions showing the contact between them as a marine flooding surface. (Svela, 2001)

regime from a fluvial environment to a marshy ecosystem (Ramberg, 2008). The lower most member of the group is the Åre formation which comprises of a succession of sandstones, mudstones and coals from of Rhaetian to early Pliensbachian age (Dalland et al., 1988). From the well logs the top of Åre Formation is considered to be the first full marine flooding as seen by a gamma ray peak (**Error! Reference source not found.**). Informally it is s ubdivided into two members, the Åre 1 (base) and Åre 2 (top) (Svela, 2001). The coal bearing strata within the Åre 1 member signifying that the sequence was deposited in a terrestrial setting. The Åre 2 member shows a higher shale content towards the top and has been correlated as a stacked bay fill sequence. (Thrana et al., 2014)

The Åre Formation is overlain by the Tilje Formation (Figure 11) which was deposited during late Pliensbachian to early Toarcian in a shallow marine deltaic environment (Martinius et al., 2001). Large quantities of sand were transported and reshaped as sub parallel elongate ridges by the tidal currents (Martinius et al., 2001). The Tilje formation is characterized by its heterolytic nature which can be seen throughout the formations along with a rapid change in grains sizes between claystones or siltstone to fine and medium grained sandstones (Ichaso & Dalrymple, 2014). The formation is divided into 2 main sequences. The lower sequence is bounded by regional hiatus surfaces. The sequence represents delta front to pro delta deposits, which show intermittent transgressive influence. The upper sequence lies unconformably, but with no incision over these deposits and is followed by a flooding surface that marks the transition to shallow marine Ror formation (Figure 11). The formation is considered syn rift during the Jurassic faulting period (Ichaso & Dalrymple, 2014).

Presence of a transgressive regime led to a gradual submergence of the region resulting in deposits of clay and silt, which form the marine mudstones of the Ror formation (Ichaso & Dalrymple, 2014) This formation in not present within the area due to erosion.

2.2.3.2 Fangst Group

This Middle Jurassic group (Figure 11) is mostly absent in the region due to erosion. However, Not and Ile formations have been drilled in some wells. The Ile Formation was deposited in a shallow marine coastal environment during late Toarcian to Aalenian (Dalland et al., 1988). It is widespread in the Haltenbanken region but can be observed only on the fringes of the Nordland Ridge (McIlroy, 2004). The lithology is generally fine to medium-grained sandstones with thin interbedded siltstones. Micaceous intervals are also common. (Dalland et al., 1988).

The Not formation is topmost member of the Fangst Group that has been observed on the Nordland Ridge. It represents a semi regional transgression and is composed of claystones that coarsen upwards to fine-grained carbonate cemented sandstones containing mica rich intervals (Dalland et al., 1988).

2.2.3.3 Viking group

The Viking Group marks the end of the Jurassic Period. It was deposited in the late Jurassic (Bajocian to Berriasian). It is predominantly composed of fine grained Melke and Spekk formations along with potentially local Rogn sandstones found in the Draugen field.(Dalland et al., 1988).

The Melke Formation defines the base of this group (Figure 11) which occurs extensively on the highs of Nordland Ridge. It comprises of open marine claystones, siltstones and limestone stringers (Dalland et al., 1988).

The Spekk Formation overlies the Melke Formation, which is composed of dark brown to dark gray shales with high organic content. The depositional environment is anoxic marine bottom setting. (Dalland et al., 1988). This formation is absent over most of the Nordland Ridge. However it can be found on the western edge of the Nordland Ridge, Trøndelag Platform and localized grabens within the Nordland Ridge that are in proximity to the Trøndelag Platform.

2.2.4 Cretaceous deposits**.**

2.2.4.1 Cromer Knoll Group

Cromer Knoll deposits are predominantly found on the eastern part of the study area while being absent throughout the rest of the Nordland Ridge. They are however, present on the Trøndelag Platform. The stratigraphic members of this group are the Lyr, Lange and Lysing formations (Figure 11). The group consists mostly marls and calcareous claystones (Dalland et al., 1988) which validates the dominant transgressive regime during that epoch.

2.2.4.2 Shetland Group

The only member of the Shetland group that has been observed on some of the highs of the Nordland Ridge is the Springar Formation (Figure 11) which is composed of greyish green claystones (Dalland et al., 1988).

2.2.5 Cenozoic deposits

The Cenozoic sedimentary environment was a response to the Paleogene transition from the continental rift setting to a drift and passive continental margin setting due to the opening of Sea, and the subsequent climatic change (Brekke et al., 2001).

2.2.5.1 Rogaland Group

The Paleocene to Lower Eocene Rogaland Group (Figure 11) is composed of argillaceous marine sediments. In the Paleocene, uplift of the Norwegian mainland resulted in the transportation of clastic sediments into the Norwegian Sea. Most of the sediments came from the eastern coast, but some of might have originated from East Greenland before the commencement of seafloor spreading. In early Paleocene, the clay-dominated Tang and Tare formations (Figure 11) were deposited in an open marine setting. The Tare Formation has a high content of volcanic constituents mixed in with the clay-dominated lithology due to volcanism related to sea floor spreading towards the west.(Halland et al., 2013; Ramberg, 2008)

2.2.5.2 Hordaland Group

The Ypresian transgression of the Norwegian shelf and the mainland reduced the sediment influx and as a result a clay dominated Brygge Formation of the Hordaland Group was deposited in the basin (Figure 11) (Tor Eidvin et al., 2007). The Eocene sediments consist of extensive marine mud deposits. (Dalland et al., 1988)

2.2.5.3 Nordland Group

The Middle Miocene to recent Nordland Group (Figure 11). overlies the Mid-Miocene non-depositional unconformity. The Kai Formation is a growth strata deposited in depressions and synclines related to the compressional structures during the compressional regime (Tor Eidvin et al., 2007).. Due to the regression, the Kai Formation is the most basinward of the Cenozoic formations and consists of shallow to deep marine shale deposits (Dalland et al., 1988). The glaciations of the Pliocene and Pleistocene, caused erosion and deposition of thick sedimentary wedges onto the mid-Norwegian shelf (Halland et al., 2013; Ramberg, 2008). The Naust Formation was deposited in this glacio-marine environment, and is the youngest and shallowest formation in this study composed of shallow marine deposits and ice rafted detritus (Figure 11).

2.3 Petroleum geology.

On the western edge of the Nordland Ridge lie the Dønna and Halten terraces. They are some of the most prolific regions within the Norwegian Sea. The area of interest contains several working petroleum systems that are under various stages of development (Figure 15).

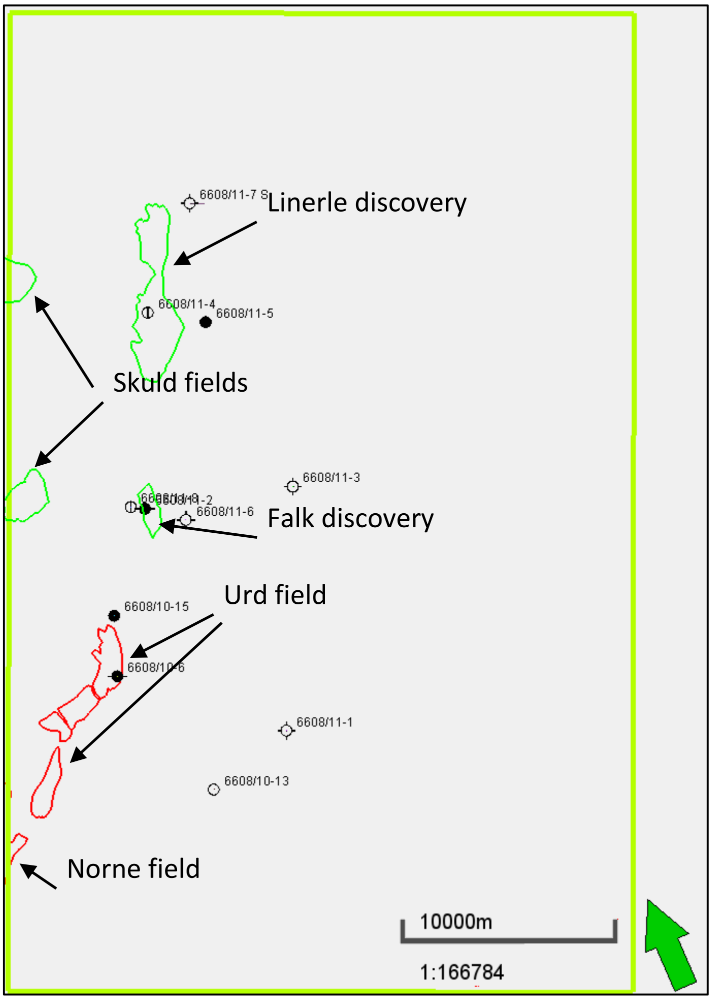


Figure 15: Discoveries and producing fields within the area of interest.

The first field to be discovered in this area was the Norne field in 1992, which started production in 1997. It is mostly located within the 6608/10 block. The production zones belong to the Lower to Middle Jurassic Tilje, Tofte, Garn and Ile formations within a horst structure. The porosities range from 25-30 percent while permeability varies from 20-2500 mD (Rwechungura et al., 2010). The source rocks for this field are the Early Jurassic Åre formation and Late Jurassic Spekk formations, buried deeper to the west of Donna Terrace. Both of these source rocks contain high organic content. The seal is the Late Jurassic Melke formation while the Not formation acts as an intra reservoir seal between the Garn and the Ile formations (Rwechungura et al., 2010).

The next field to be discovered was the Urd field in 2000, which started production in 2004. (NPD, 2002) This field shares similar petroleum system components with the Norne field, namely the source rock and trap, which is also a horst structure. The reservoir rocks consist of Early-Middle Jurassic Åre, Tilje and Ile formations (NPD, 2002)

The Falk discovery of well 6608/11-2 was also made the same year as Urd but it was abandoned due to presence of heavy biodegraded oil.

A similar discovery in well 6608/11-4 was made in 2004 called Linerle, which was also abandoned due to biodegraded oil.

Skuld was discovered in 2008 and began production in 2013. It has a similar reservoir zone of Lower to Middle Jurassic sandstones of the Åre, Tofte and Ile formations. The source rock is supposed to be the same as all the other fields in the region.

These accumulations are sometimes clubbed together and called the Greater Norne Area.

2.3.1 Reservoir Rocks.

The Lower to Middle Jurassic sandstones of the Båt and Fangst group are proven reservoir zones within the region. The Båt Group Åre and Tilje sandstones extend throughout the area while the Fangst group has mostly been eroded away.

The Upper Triassic Grey and Red beds have shown to have good reservoir characteristics in some of the wells drilled in the area. (NPD, 2006).

Wells have been drilled into other possible play zones such as the late Permian carbonate platforms (6507/6-4 and 6608/8-1) and they provide conflicting information on the reservoir qualities of the carbonate deposits. Well 6507/6-4 reported a tight formation with low porosity and permeability while well 6608/8-1 reports it as a good reservoir zone. (NPD, 2001, 2013)

2.3.2 Seal

Lower Triassic mudstones found within the Helgeland Basin and the Nordland Ridge may act as seals for Permian reservoir zones. Their observed thickness is considerably low but a basin ward thickening sequence could work as an effective seal (Bugge et al., 2002). The probability of this is considered low.

The anhydrite units within the Red Beds can act as seals for early to middle Triassic reservoir zones. The region underwent transgression at the end of Jurassic resulting in the deposition of Middle Jurassic Not shales and Late Jurassic Viking shales, which act as seals on the adjacent Dønna Terrace (Rwechungura et al., 2010).

The Cretaceous formations within the region are absent either due to non deposition or erosion by the base Paleocene unconformity. The formations that have been found within the area of study are the Lyr Formation from Cromer Knoll Group, which is made up of marls, and the Springar Formation from the Shetland Group, which is claystone (Dalland et al., 1988).

The Paleocene deposits consist of the Tang and Tare formations from the Rogaland Group, which consist of tuffaceous claystones deposited in a deep marine setting. (Dalland et al., 1988)

2.3.3 Source rock.

2.3.3.1 Jurassic.

Coal deposits of the Åre Formation and the shales of Spekk and Melke formations are proven source rocks within the region. The Spekk Formation is a high quality source rock with type II kerogen due to its marine dominated origin. Gas prone type III kerogen has also been observed probably due to minor terrestrial influences from the underlying Melke Formation, which is dominantly terrestrial in origin and is gas prone. The Åre Formation coals are also highly gas prone due to their terrestrial coal seams (Gowers & Lunde, 1984). They are considered thermally mature within Haltenbanken, Dønna Terrace and further westward regions, however the same formations are considered immature due to lack of proper burial conditions within the Helgeland Basin (Bugge et al., 2002). This has led to a development of migration shadow, as the charge from the western edge of the Nordland Ridge cannot reach the reservoirs and traps on the eastern margin bordering the Trøndelag Platform (**Error! Reference source not found.**).

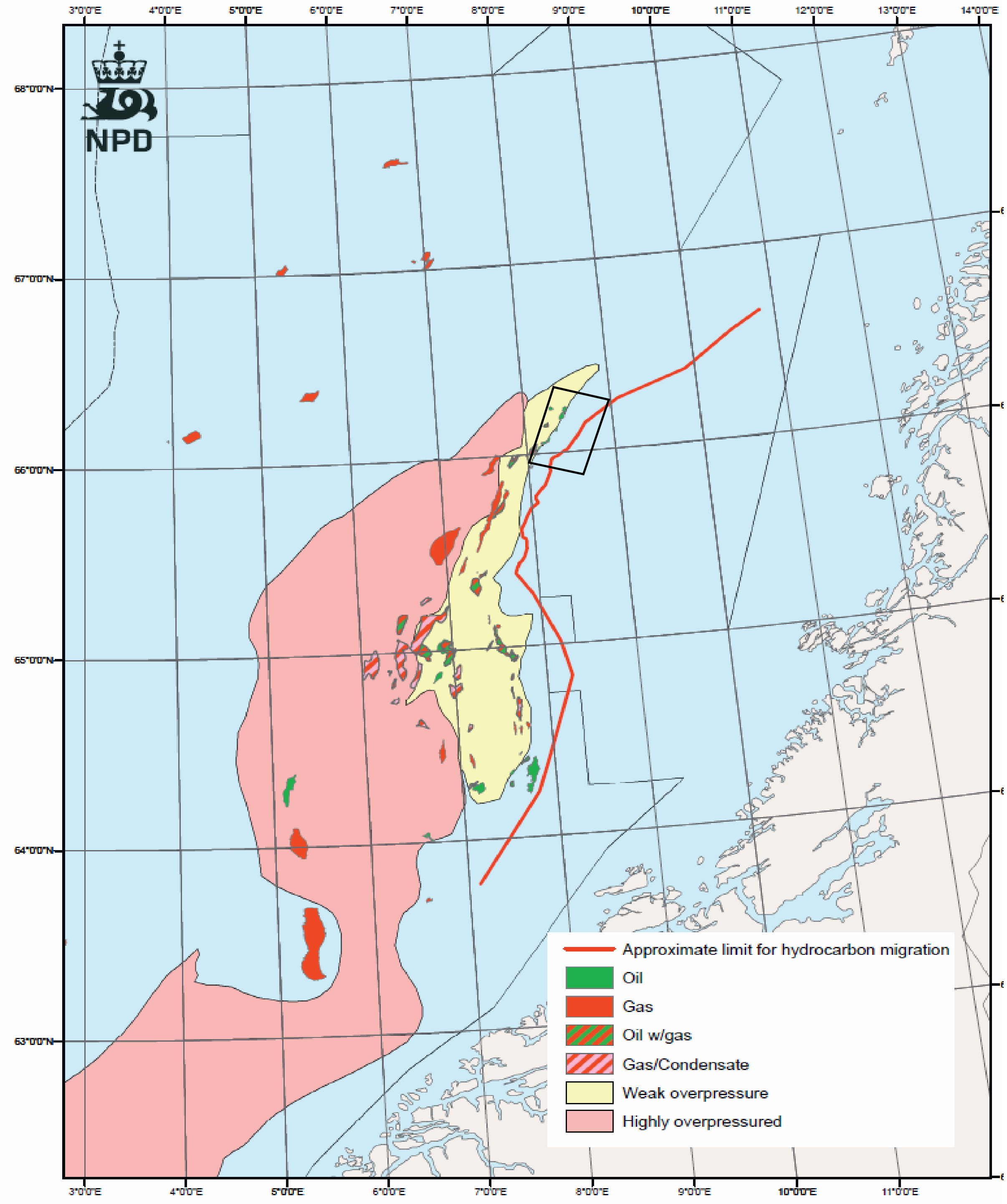


Figure 16: Maximum eastward extent of migration from the Jurassic source rock found on Donna and Halten terraces. Highlighted in black is the area of interest (source).

2.3.3.2 Lower Triassic.

The Lower Triassic upper turbidite succession has shown some source rock potential with layers of organic rich mudstones with a TOC of 2.8%. These layers have HI values within 200-450 mg/g TOC (Bugge et al., 2002). However, these layers are only .5-1.5 cm wide and hence their thicker lateral equivalents within the Helgeland Basin need to be proved and analysed (Bugge et al., 2002).

2.3.3.3 Upper Permian.

The Upper Permian lower turbidite unit contains two intervals of laminated organic rich mudstones: These intervals have been lithostratigraphically correlated with the Ravnefjeld Formation of East Greenland which is a kerogen type II (Karlsen et al., 1988) organic rich shale from the Foldvik Creek Group. Bugge et al. (2002) and Christiansen et al. (1993) have mentioned that these formations have an average thickness of 15-20 m with TOC of 4% and HI of 400. These Ravnefjeld Formation equivalent source rocks found in the Helgeland Basin have shown average TOC contents of 3-2-3.5% with HI ranging from an average of 114 mg/g TOC to 185 mg/g TOC (Bugge et al., 2002). The equivalent findings within the Helgeland Basin may have a lower HI as compared to those found on East Greenland but it has to be considered that the well 6611/09-U-01 has been drilled close to the coast where the formation is pinching out. Due to the Norway – Greenland common basin development during Upper Permian it is reasonable to assume that these Ravnefjeld equivalent shales within the Wegener Halvø formation are present throughout the Trøndelag Platform. Wells 6609/7-1, 6608/8-1 and 6507/6-4 which have drilled into Permian strata have found the carbonate platforms and thin layers of interbedded organic rich shales (Müller et al., 2005). The Foldvik Creek Group has a maximum thickness of 180 m (Stemmerik et al., 2001) whereas the equivalent succession recorded by IKU well 6611/09-U-01 is 350m approximately (Bugge et al., 2002). This encourages the notion that these shales will have thicker deposits within the basin, with higher HI values making them excellent source rocks. They could provide a possible alternate source to the locations of the ridge that are considered to be too far away for the charge from Jurassic Spekk and Åre formations from Haltenbanken and Donna Terrace to migrate to. However, due to lack of well data the maturity and expulsion from these units will have to be extrapolated from the studies by Christiansen et al. (1993), Stemmerik et al. (1997) and Stemmerik et al. (1998).on East Greenland.

3. DATA AND METHODOLOGY

All the subsurface interpretations, well correlations have been done on Petrel E&P 2014 at the University of Stavanger. Along with that ArcMap 10.3, CorelDraw and Adobe Illustrator were used to make figures

3.1 Data

The data for this study has been provided by the Statoil ASA in the form of two 3D seismic data sets and 11 well logs.

3.1.1 Seismic Data

A high quality 3D seismic cube was used for this study. The ST13M09 dataset is a fullstack merge of 21 surveys, covering a total of 17500 sq. km with normal polarity and 0.7 degree phase. Spacing between the inlines and crosslines is 25 m. The recorded length extends up to 6.125 seconds TWT which was cropped to 5 seconds for the purposes of this study. The geophysical vertical resolution was calculated to be 25 m approximately using the equation given below.

$$R_{vertical} = \frac{\lambda}{4} = \frac{1}{4} \times \frac{v}{f}$$

Along with this, the RS1002 3D seismic cube was also used for near, mid and far angle value analysis. It covers an area of 1402 sq. km with an inline and cross line spacing of 12.5 m. The polarity is normal with a 15 degree phase.

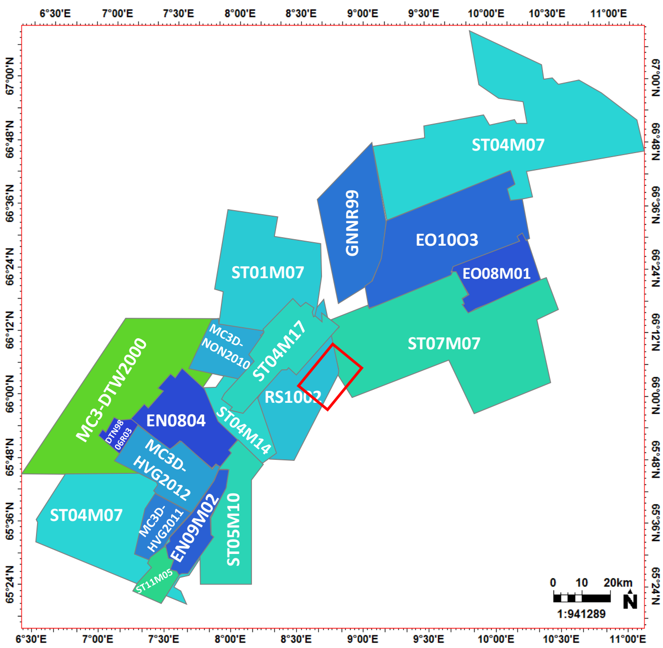


Figure 17: ST1309 seismic merge. Highlighted in red is the area of interest.

ST13M09 information table	
Geodetic datum	ED50
Projection	UTM 32N
Total area	17 500 km^2
Merged surveys	18
Sample interval	4
Number of inlines	10062
Number of X-lines	7399
Inline interval	25.000
X-line interval	25.000
Inline direction	-66.38°
Grid size	25x25
Polarity	Normal
Mean frequency	
Dominant frequency	
Bandwidth	
Wavelength	92
Wavelet phase	0,7 deg
Vertical resolution	23 meter

Table 1: ST13M09 survey information tableTable

3.1.2 Well Data

A total of 11 wells (Table 2) are used in this study to identify the ages and lithologies within the Ridge. The wells are mostly distributed along the western margin of the Ridge due to multiple discoveries in the region. Gamma ray, sonic, density logs are available along with other composite logs for almost all the wells.

Wells	Content
6608/10-6	Discovery
6608/10-13	Dry
6608/10-15	Discovery
6608/11-1	Dry
6608/11-2	Discovery
6608/11-3	Dry
6608/11-4	Discovery
6608/11-5	Shows
6608/11-6	Dry
6608/11-7S	Dry
6608/11-8	Dry

Table 2: List of wells used in the study.

3.2 Methodology

3.2.1 Seismic well tie

Well data provides high vertical resolution in depth domain while seismic lines, which are in time domain, provide a good regional overview. Seismic to well ties are done to achieve a reliable relationship between wells and seismic survey and increase the level of confidence in the interpretation.

For this study 2 wells, 6608/11-2 and 6608/11-3 have been tied to survey ST13M09 to provide more accuracy to the interpretation. Different methods have been used for both the wells in order to achieve the best fit. The wavelet for well 6608/11-2 has been extracted through the Statistical Method (Figure 18). The wavelet has a phase of 0.498 by default with a Hanning taper. The polarity is normal with a bulk of the frequency lying between 0-50 Hz.

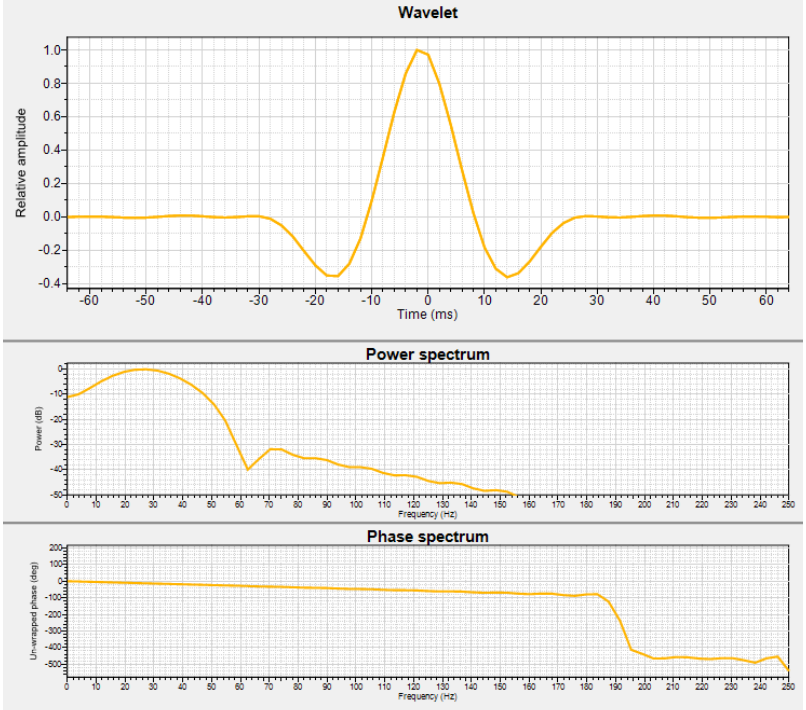


Figure 18: : Statistical wavelet with power and phase spectrum for well 6608/11-2

For 6608/11-3 the Deterministic Method was used in order to obtain the best fit. The wavelet has a normal polarity with a default phase of -2.704 degrees. The power spectrum shows that all of the high frequencies lie between 10-45 Hz (Figure 19).

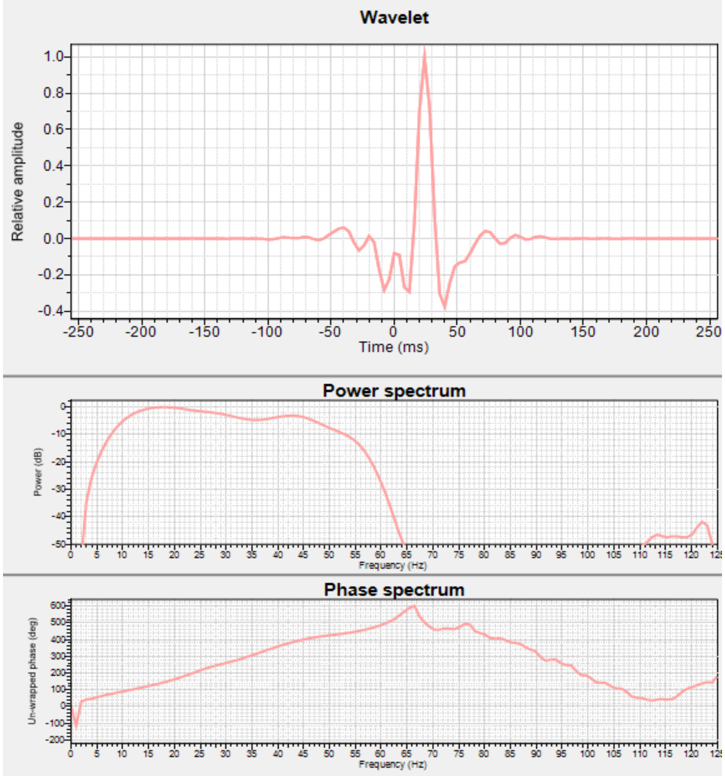


Figure 19:Deterministic wavelet with power and phase spectrum for well 6608/11-3

The acoustic impedance for the seismograms have been calculated by using the density and sonic logs along with the checkshot values provided by Statoil. The primary zones of interest are the Lower Jurassic and Upper Triassic formations, as they are proven reservoirs in the surrounding fields and discoveries. Efforts have been made to obtain a high degree of confidence in this region. The well 6608/11-2 well tie has the highest amount of correlation for base Cretaceous unconformity (BCU), which is a soft contact with a relatively shaly formation below (Figure 20). It can also be seen in the acoustic impedance (AI) log which shows an abrupt decrease in value. The Åre formation top also shows a similar behaviour even though the lithology change is from shale to sand. This is due to the presence of hydrocarbons within the formation, indicated by a small characteristic crossover in the density and sonic log (Figure 20A). The crossover effect is due to a drop in density value and a corresponding drop in sonic velocity as a result of a relatively less dense formation fluid. The 6608/11-3 well tie display a relative conformable top of Viking group, Tilje and Åre formation tops, base of Early Pliensbachian and top of Rhaetian (Figure 20B). The soft events above Rhaetian top are the coal beds within the Åre formation. They show a strong impedance contrast due to the large differences in densities of coal and surrounding rock, as can be seen by the drop in density values and sharp changes in AI log (Figure 20B).

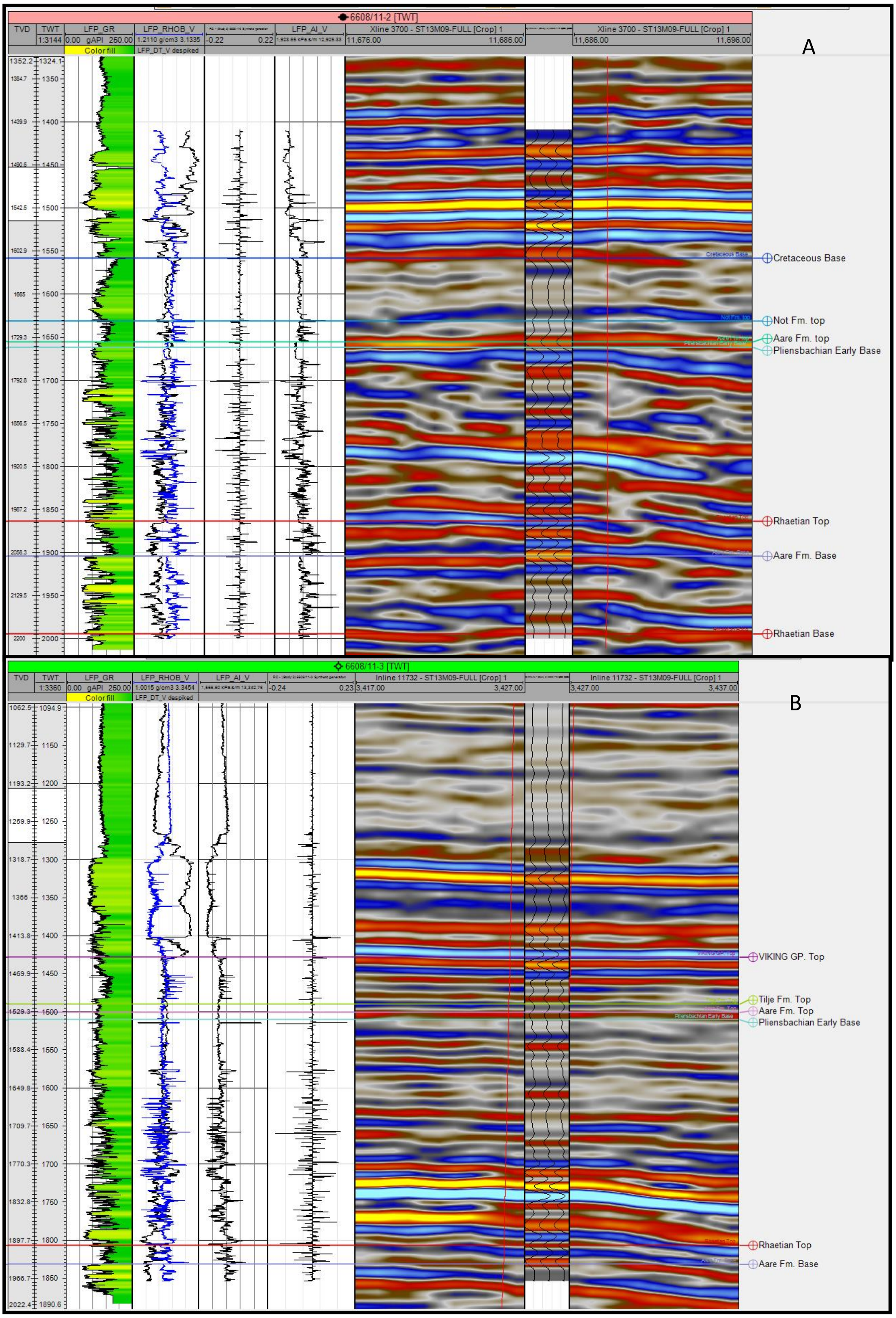


Figure 20: (top) Synthetic seismogram with gamma ray, density and sonic log, reflection coefficient and acoustic impedance log for well 6608/11-2. (bottom) Synthetic seismogram with gamma ray, density and sonic log, acoustic impedance and reflection coefficient

3.2.2 Well analysis

The wells that were provided contain individual as well as composite logs. These logs were analysed by examining the well reports in order to establish the accuracy of the log data. It was found that the data was reliable with no major inconsistencies. The limits of measurement, however, varied within the wells. The gamma ray logs were most affected by this variation which ranged from 0 to 150 in some wells and 0 to 300 in others. To minimize the effect of this variation a standard scale of 0-300 was chosen for all the wells.

Well correlation was also done in order to better understand the trends and thickness variations of various intervals of interest(Figure 21).

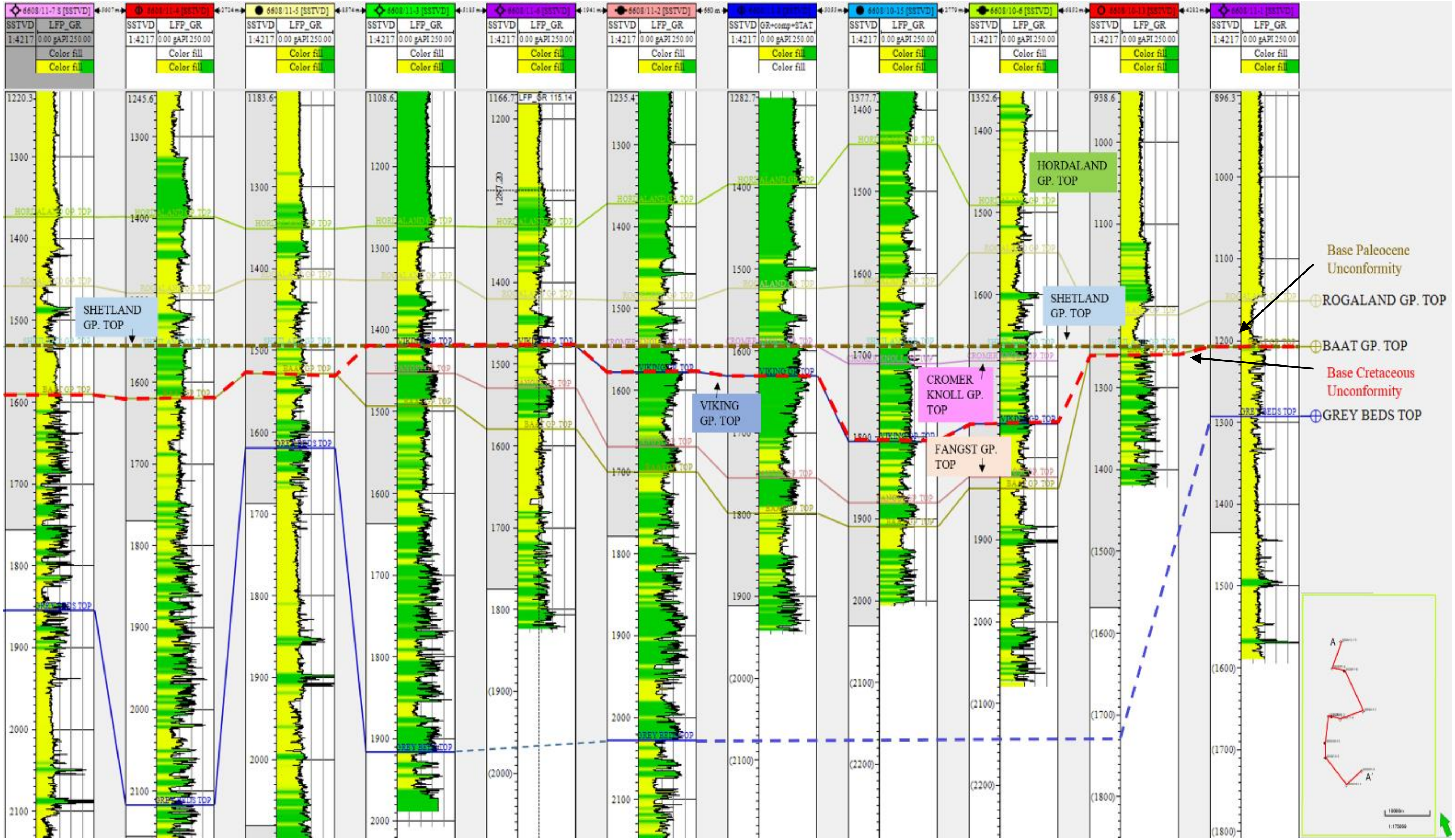


Figure 21: Well Correlation between all the wells in the area.

Apart from the preliminary well data quality check and well correlation, post well analysis was also performed. The primary reason for a post well analysis or a dry well analysis is that every year hundreds of wells are drilled for oil and gas exploration but only a handful are discoveries. Post well dry well analysis is done in order to assess the reasons why, in a particular region, some wells are dry while some strike hydrocarbons.

For an exploration well to be successful it has to satisfy the following four independent factors.

Probability of presence of source rock (P_{source})

Probability of a reservoir rock ($P_{reservoir)}$

Probability of trap ($P_{trap)}$

Probability of the entrapped hydrocarbon to be preserved or Play dynamics ($P_{dynamics).}$ It also includes the timing of trap formation in relation to the timing of migration.

The product of the abovementioned probabilities gives the probability of geological success (P_g)

$$P_g = P_{source} \times P_{reservoir} \times P_{trap} \times P_{dynamics}$$

Since all the probabilities are independent of each other, the combined probability becomes a product of all four, i.e. if any one of them is nonexistent or zero, the overall probability becomes zero, regardless of how favorable the remaining probabilities are (Demaison, 1984; Otis & Schneidermann, 1997).

Each element of an active petroleum system has an assigned value of risk. The viability of drilling an exploration well on a prospect depends upon the value of estimated risk of all the factors, independently. Wells are drilled with the objective of finding hydrocarbons and if they turn up dry then that is usually due to underestimation of the value of risk for any one of the elements.

3.2.3 Seismic interpretation.

The region is highly complex with multiple phases of deformation and erosion. Seismic attributes were applied to the 3D seismic volume in order to highlight various features.

a. Structural smoothening was done in order to reduce the noise and enhance the structural features, which particularly aid in fault interpretation in vertical seismic sections.

b. Variance (edge method) was used to supplement the fault interpretation process. This attribute represents the trace to trace variability in a sample space. It enhances the discontinuous trends within the seismic volume and helps in visualizing the horizontal extent of faults.

c. RMS amplitude is used to enhance amplitude anomalies within the volume. It calculates the root mean square amplitude divided by the number of samples.

The region is highly complex with multiple phases of deformation and erosion. Seismic attributes were applied to the 3D data in order to highlight these features.

Structural smoothening was done in order to reduce the noise and enhance the structural features which aid in fault interpretation in vertical sections.

Seismic interpretation was done on a volume cropped from the ST13M09 3D seismic survey. Chronostratigraphic and lithostratigraphic controls, provided by Statoil, were predominantly used for interpretation. In regions of high uncertainty additional controls were taken from

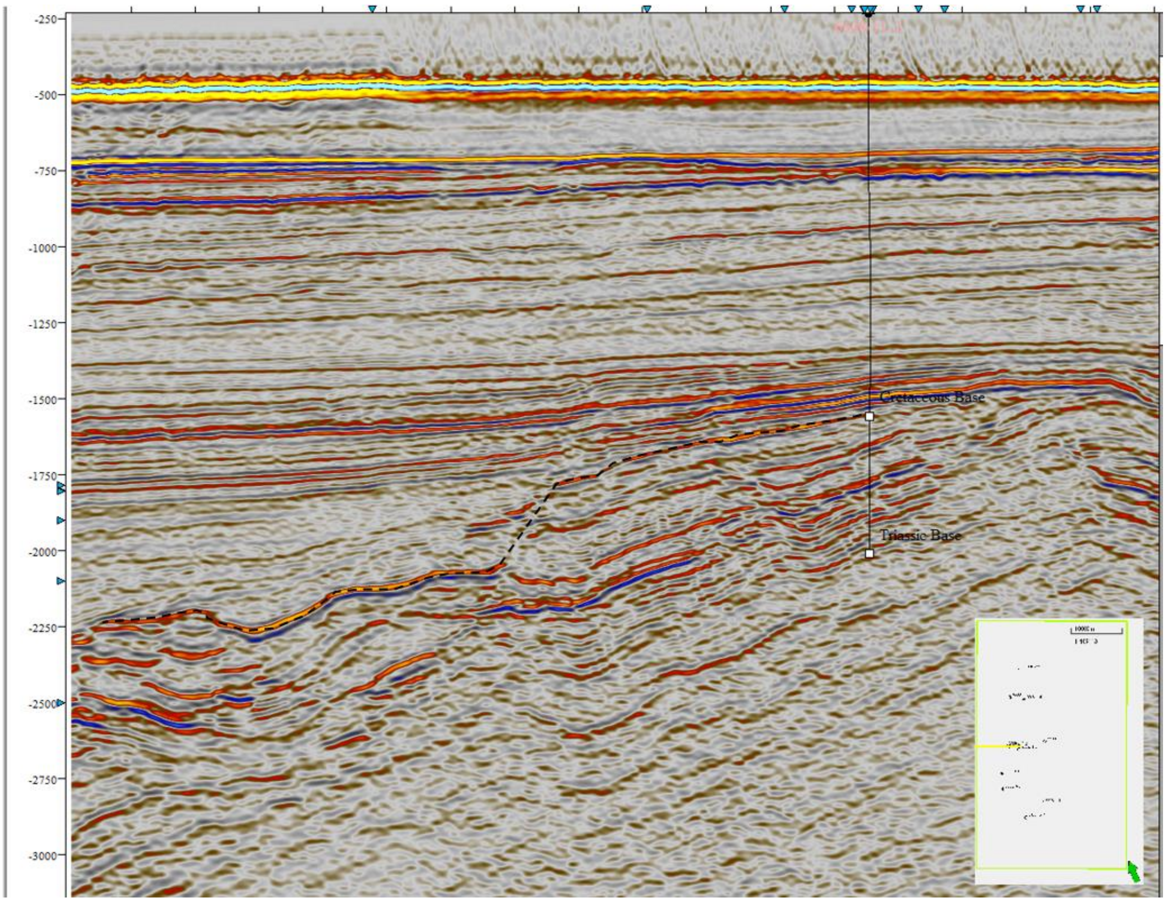


Figure 22: seismic line with BCU

NPD data. The Base Cretaceous Unconformity (referred to as the BCU) was the first to be interpreted using the well data (Figure 22), and it has been used as a major event in developing the stratigraphic framework of the region. The BCU marks a noticeable change in lithology on the well logs, especially the gamma ray and density logs. (Figure 23)

Another regional horizon that has been mapped extensively is the Base Paleocene Unconformity. The unconformities have been interpreted using an increment of 50 to understand a broader, regional extent of these events. It was decided to start the interpretation in a tree like structure instead of the usual grid pattern since emphasis needs to be given to the possible plays in the area which have been interpreted in greater detail.

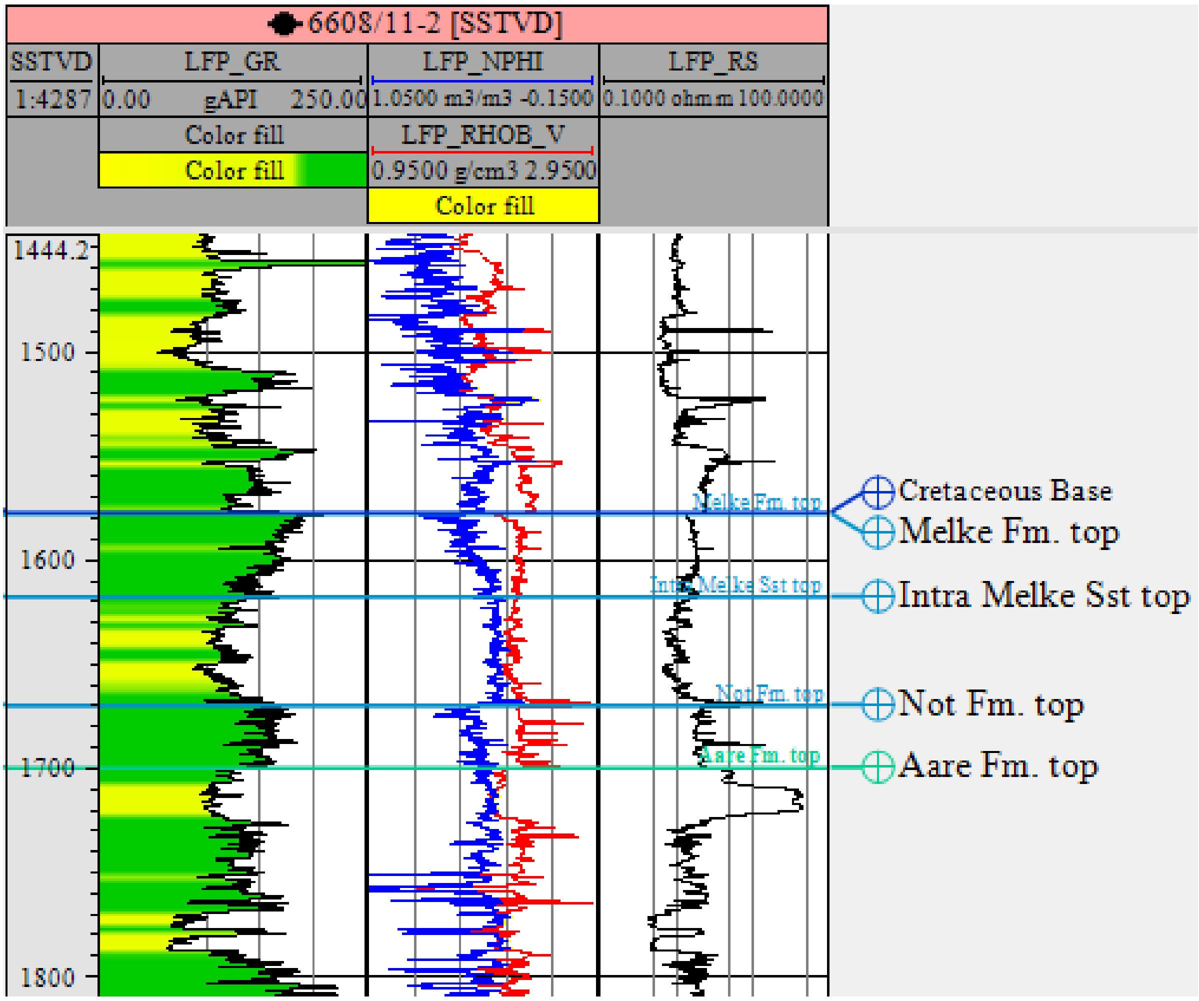


Figure 23 BCU on well 11-2

Following the interpretation of the unconformities, the faults and other important horizons were interpreted using the same methodology. The complex tectonic structure of the region made it practical to interpret the faults and horizons simultaneously. The importance assigned to the horizons was based on the ease of interpretation with thickness, lithostratigraphic correlation and areal extent being the deciding factors. Since most of the wells are drilled on rotated fault blocks the strata encountered below the BCU varies greatly on the tectonic uplift and subaerial exposure of that particular block. This has led to many formations being partially mapped as their lateral extent becomes uncertain due to lack of well control. The coals of the Åre formation have been interpreted as they are a part of a proven reservoir zone, have a very distinct seismic signature and can easily be discerned from the background lithology. These coal beds also help in locating the top of Åre formation, which is a challenging surface to define as the wells encounter it in various states of erosion. The top of Tilje formation, which is also a proven reservoir zone has been very hard to define in certain places at its thickness is less than that of the seismic resolution, which also leads to a loss in confidence while extending it within the downthrown blocks as there is a sudden increase in the thickness of the formation. However, it has been interpreted with reasonable degree of confidence outside the faulted zone, especially on the eastern side, using well controls from outside the area of interest. Other Jurassic groups such as the Fangst and Viking groups have been interpreted with a fair degree of confidence, as various formations within them are present and absent over different sections of the area due to multiple erosion events. Much of Cretaceous sediments are absent over the highs due to the erosive events which formed the Paleocene unconformity, but they have been marked within the faulted grabens and half grabens. Some of the formations however, are sub seismic in thickness and have therefore, not been interpreted.

The top of Grey beds is another important horizon that has been interpreted using the coals of the Åre formation as guiding lines, as it roughly correlates with the top of Triassic and has shown viable reservoir potential. (NPD, 2002)

Furthermore, the base of Norian has been marked to identify the Ladinian-Carnian evaporite sequences within the Red beds formation. The base of the Red beds, which corresponds to the top of Permian, cannot be discerned as no wells within the region have penetrated that zone and the seismic does not allow for any discernible markers. The basement has been interpreted by mapping the Upper Permian anhydrite units (Bugge et al., 2002; Müller et al., 2005). This is a strong reflector which overlies the basement rock and is easily seen throughout the region. It also marks the base of Late Permian carbonate platforms and shale sequences. These shale sequences are important as they provide a better understanding of the development of local Permian source rock zones within the ridge.

The region is extensively faulted due to high amount of activities during Permo Triassic, Jurassic and Late Cretaceous. Due to the time constraints only those faults have been interpreted that have cause large-scale movements in strata. Whenever a particular play has been identified then more focus in given to interpreting the smaller localized fautls as well.

3.2.4 Surface construction.

Following the interpretations of horizons and faults, surfaces were made to better understand the extent and thickness of the key formations. To make these surfaces, boundaries polygons had to be defined for each formation depending on its regional extent, zones of erosion and non-deposition. These formations used the area of interest as the outer limit but it was more important to have higher degree of accuracy for the internal boundaries.

Surfaces for unconformities and Cenozoic sediments did not require much effort as they are contigous, but the Mesozoic sediments, especially the key horizons posed some challenges due to their eroded nature and spatial constraints. It was important to get proper surfaces that adhered to the interpretations as they act as inputs for thickness maps.

4. OBSERVATIONS AND RESULTS

4.1 Well Correlation.

There have been four discoveries within the region and all of them lie on the western flank of the Nordland Ridge. (Figure 24). Wells 6608/10-15, 6608/10-6 and 6608/11-2 show that their primary reservoir targets were the Are Formation from Lower Jurassic and Intra Melke sandstone units from the Upper Jurassic Viking Group while well 6608/11-4 was drilled with Are and Tilje formation as its primary target Figure 24(Figure 25).. For wells 6608/10-15, 6608/10-6 and 6608/11-2, the presence of Not and Melke formations provides effective sealing capacity. Well 6608/11-4 completely lacks Middle and Upper Jurassic deposits along

Name	6608/11-4
Targets (primary and scondary)	Tilje and Åre sst (p)
Results	Discovery. 18 m oil column

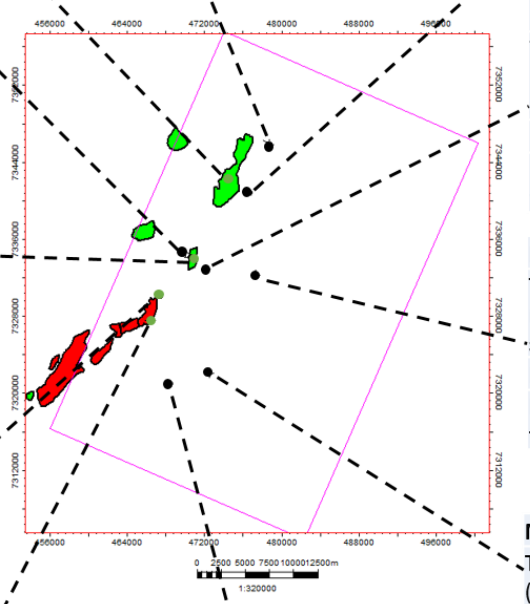
Name	6608/11-8
Targets (primary and scondary)	Appraisal. Upper Åre Fm (p), Intra Melke sst and lower Åre Fm (s)
Results	Dry
Reason for failure	Downward flank, possibly below OWC

Name	6608/11-2
Targets (primary and scondary)	Melke sst and Åre Fm (p)
Results	Discovery

Name	6608/10-15
Targets (primary and scondary)	Åre Fm (p), Intra Melke sst (s)
Results	Discovery. Intra Melke oil column 30-36 m, Not/Åre oil column 43-51 m

Name	6608/10-6
Targets (primary and scondary)	Intra Melke sst and Åre Fm (p)
Results	Discovery.

Name	6608/11-7S
Targets (primary and scondary)	Åre Fm (p), Grey and Red beds (s)
Results	Dry
Reason for failure	No Seal



Name	6608/10-13
Targets (primary and scondary)	Åre 2 Fm (p), Åre 1 Fm (s)
Results	Dry
Reason for failure	Erosion, lack of seal.

Name	6608/11-5
Targets (primary and scondary)	Åre Fm (p), Grey beds (s)
Results	Dry, weak shows in Åre.
Reason for failure	Lack of seal, trap risk.

Name	6608/11-6
Targets (primary and scondary)	Ile/Ror Fm and Tilje/Åre (p), Melke, Åre 1 Fm and Grey beds (s)
Results	Dry, minor shows in Åre.
Reason for failure	No seal, lack of charge.

Name	6608/11-3
Targets (primary and scondary)	Åre Fm (p), Intra Melk sst (s). Geological data from Grey beds (s)
Results	Dry
Reason for failure	Migration shadow/charge

Name	6608/11-1
Targets (primary and scondary)	Åre Fm (p)
Results	Dry
Reason for failure	Erosion of reservoir zone.

Producing fields 🟥
Discoveries 🟩
Dry wells/shows ●
Discoveries ●
Area of interest ☐

Figure 24:Dry well analysis of the area of interest.

with Lower Cretaceous Cromer Knoll Group. Nise and Springar formations directly overlying the Tilje Formation. High gamma ray readings from both these formations shows that they have high clay content, which is consistent with their depositional setting and thus provides a good seal for the hydrocarbon accumulations.

Based on the logs, Are and Tilje sandstone formations possess good reservoir qualities.

Well 6608/11-8 was drilled 660 m west from well 6608/11-2 of the Falk discovery and is documented as dry (NPD, 2015) (Figure 26 and Figure 27). A general thickening trend can be observed within most of the formations. A 10 m thick column of Ile Formation was encountered in well 6608/11-8, which seems to pinch out before reaching well 6608/11-2. Furthermore, the base Cretaceous Lyr Formation was also seen with a thickness of 36 m.

Wells 6608/11-5 and 6608/11-6 were drilled close to the Linerle and Falk discoveries, respectively (Figure 25). Well 6608/11-6 is only 1.95 km away from well 6608/11-2 but shows marked differences in lithology. (Figure 27). Lower Jurassic Tilje Formation has approximately 30 m thickness along with a 15 m thickness of Ile Formation and both of them are completely absent in 6608/11-2. However, there are no Cretaceous sediments on top of BCU with only Paleocene Tare Formation lying on top of the Viking Group.

Wells 6608/11-4 and 6608/11-5 which are 2.7 km apart exhibit similar differences (Figure 24, Figure 28. The Tilje Formation is absent in 6608/11-5 along with Nise Formation while the base Paleocene Tang Formation is present but with only 2 m of thickness. Both these wells have been documented as dry wells with weak shows in Are formation (NPD (NPD, 2002) factpages).

Well 6608/11-7S is a deviated borehole drilled close to the Linerle discovery (Figure 24) and is the northern most well in this study. Its lithology is similar to that of well 6608/11-5 except for the absence of the Tang Formation. The thickness of Grey Beds in both the wells is comparable with that from 6608/11-4 (Figure 28).

Wells 6608/11-1 and 6605/10-13 are drilled in separate uplifted fault blocks and hence have the shallowest depth for Jurassic deposits amongst all the wells.(Figure 29). Both wells lack substantial amount of Jurassic deposits including the Are Formation which is present but heavily eroded. They share similar lithologies except for a 9 m section of Upper Cretaceous Springar Formation that exists in well 6608/10-13.

Well 6608/11-3 is the eastern most well within the region, drilled in a graben structure(Figure 24 and Figure 27). It also contains a relatively well preserved Jurassic sequence including the Not and Melke formations but Cretaceous strata is lacking. It has also been documented as dry (NPD, 2002)

It can also be seen that only the central zone containing wells 6608/11-2, 6608/11-8, 6608/11-6 and 6608/11-3 along with 6608/10-6 and 6608/10-15 show presence of Viking and Fangst groups.

Following this correlation, a dry well analysis was done in order to gauge the extent of working plays within the region and to discard zones that have similar characteristics as those found in the dry wells. (Figure 24)

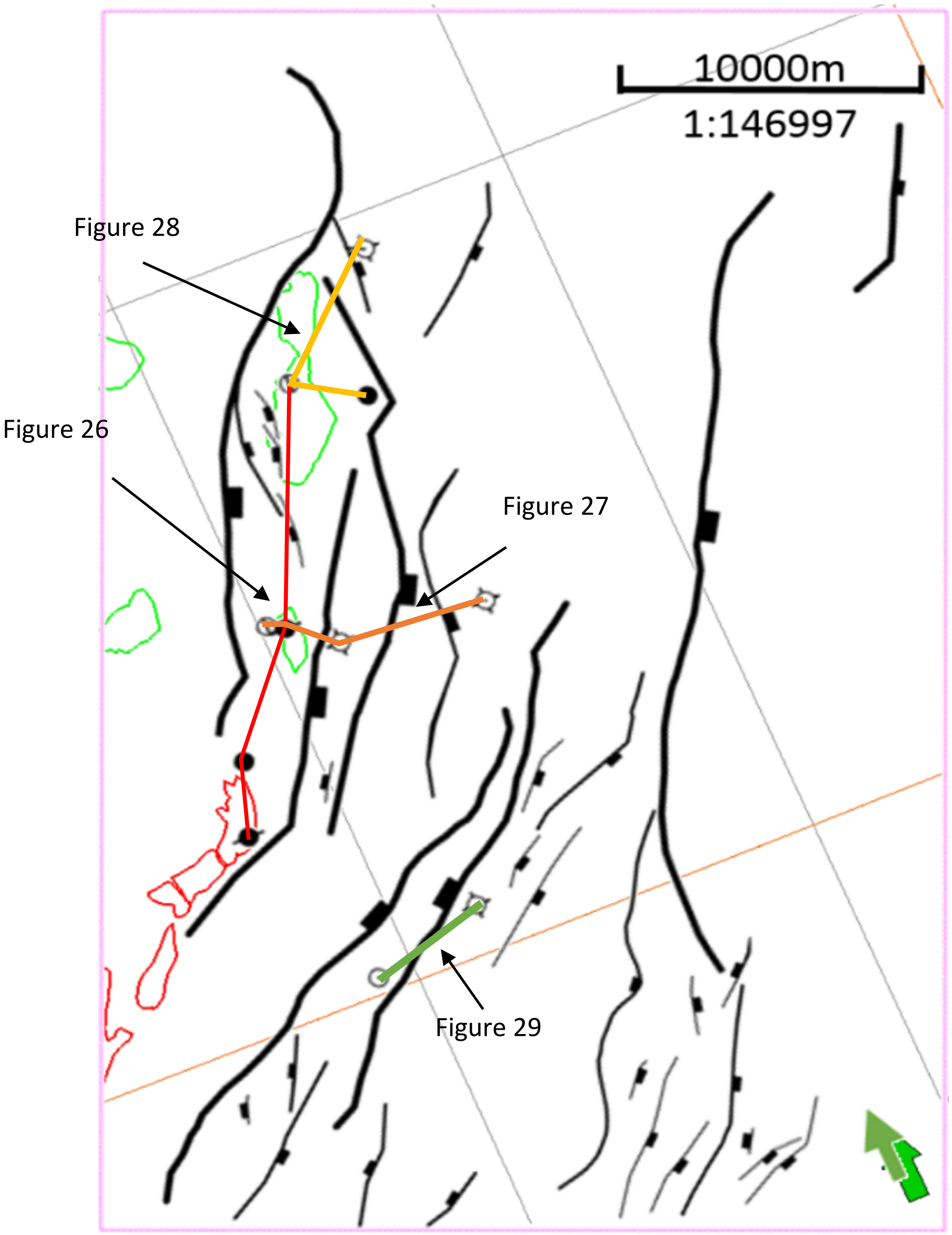


Figure 25: Map view showing the upcoming well and seismic cross sections.

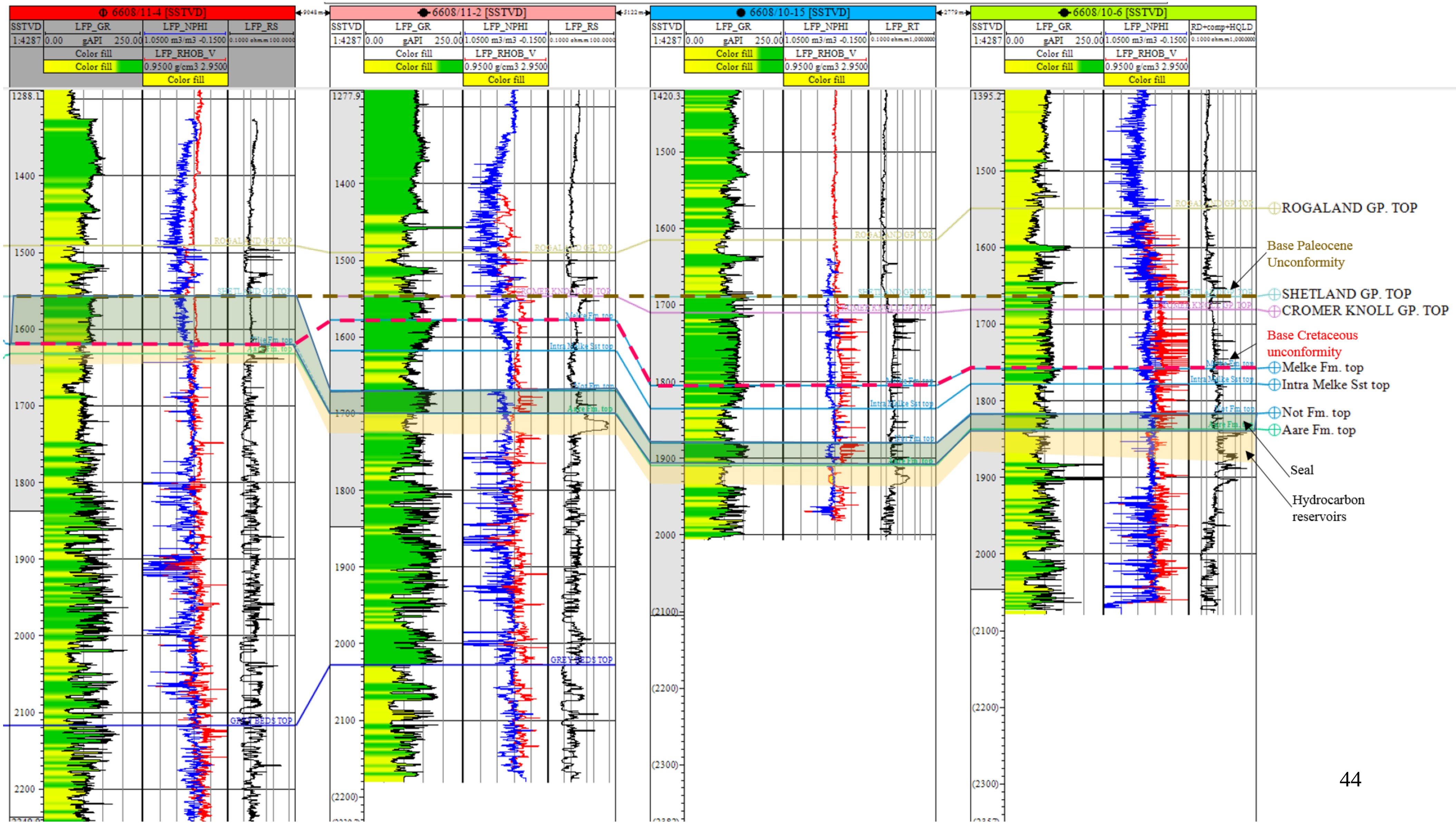


Figure 26: Wells with discoveries 6608/11-2 and 6608/11-4 along with production wells 6608/10-15 and 6608/10-6. Note that the Tilje Formation is absent in all the wells except 6608/11-4 while Not Formation is absent in this well. Refer to ***Error! Reference source not found.*** *for map view.*

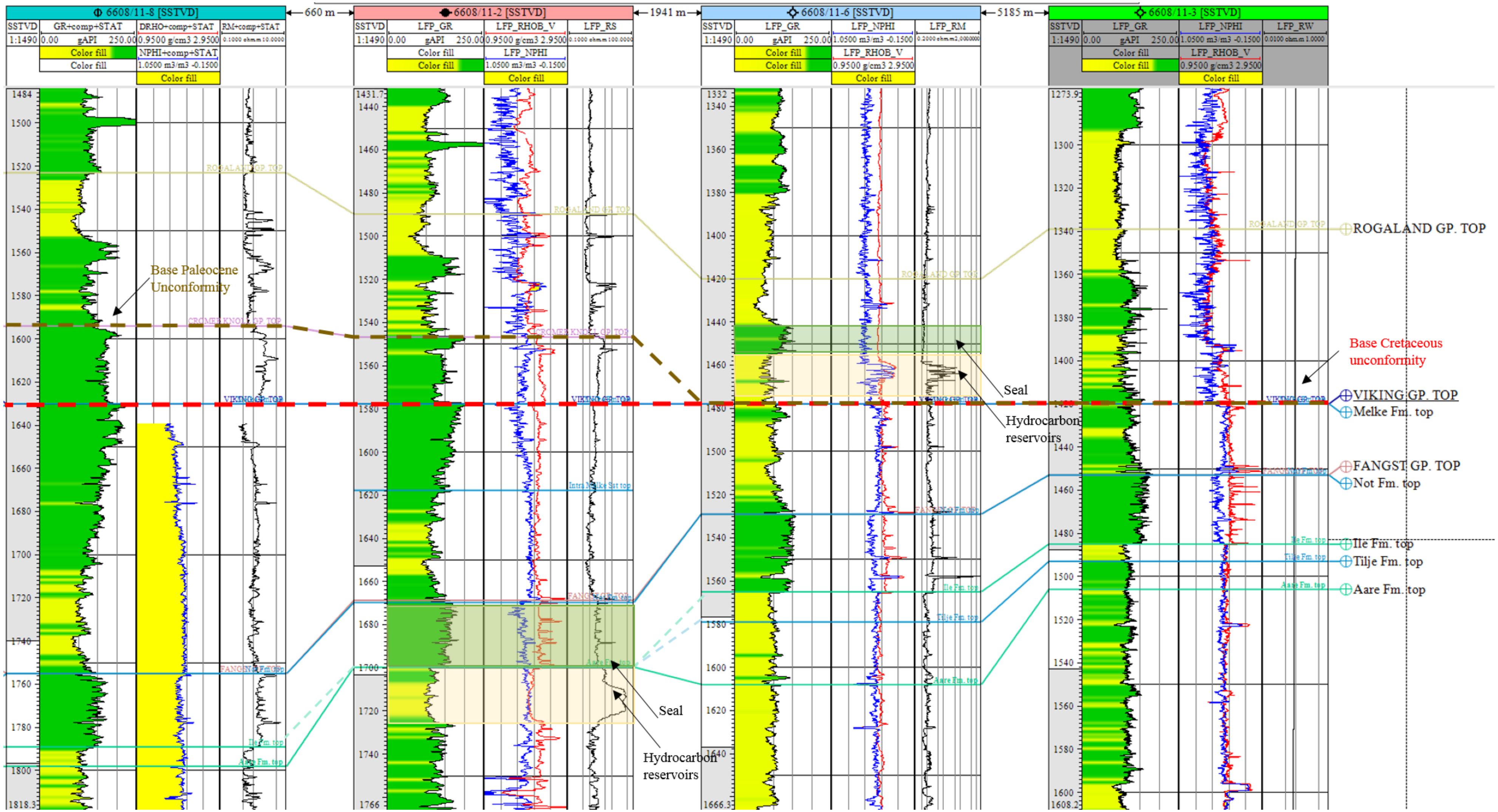


Figure 27: Central section. Well 6608/11-2 has both Tilje and Ile formations pinching outjust above the reservoir zone.. well 6608/11-6 has hydrocabons shows in the the Paleogene sediments but the reservoir quality is poor. These sandstones could not be mapped aerially.Refer to ***Error! Reference source not found.*** *for map view*

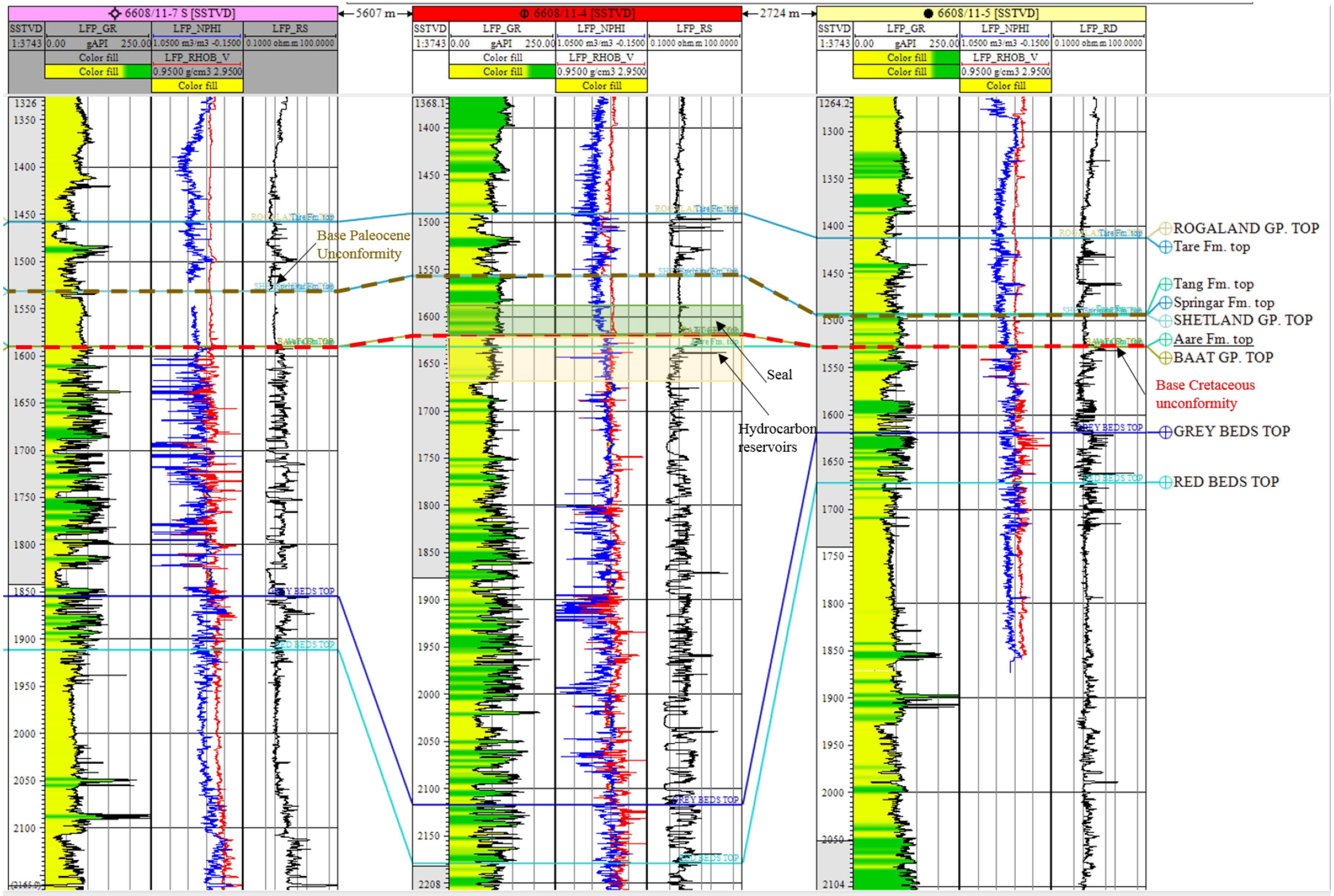


*Figure 28: Northern cross section. Notice the presence of complete Åre Formation while Tilje Formation pinches out on either side of well 6608/11-4. Refer to **Error! Reference source not found.** for map view*

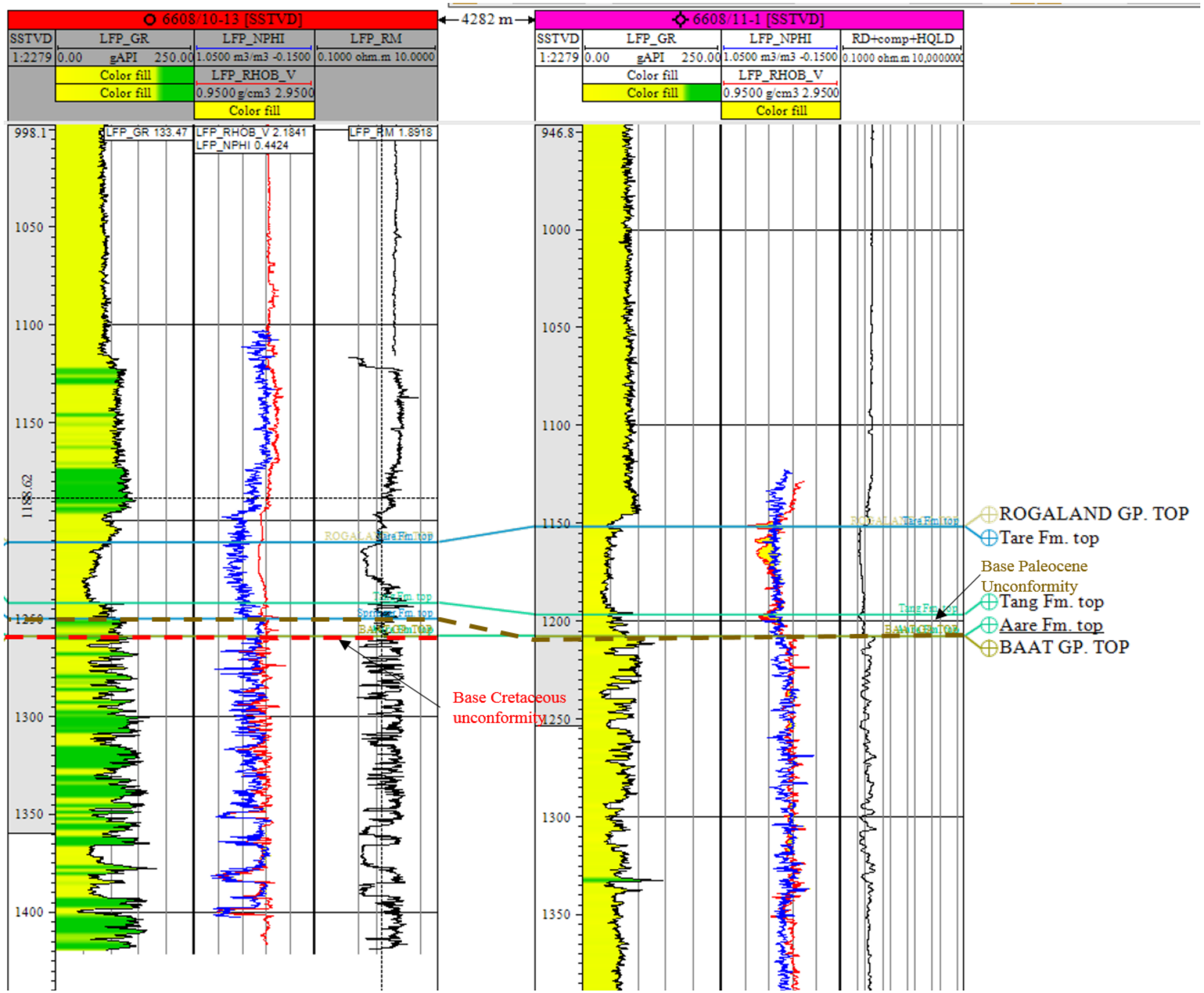


Figure 29: Southern cross section. Well 6608/11-1 shows heavy erosion of Jurassic and Cretaceous deposits. Refer to ***Error! Reference source not found.*** *for map view*

4.2 Seismic observations.

From the seismic it can be observed that the region is highly faulted.(Figure 30 and Figure 32) The quality of the seismic allows for a detailed interpretation in most part of the area. Unfortunately, due to multiple erosional events the lateral extent of the horizons becomes challenging to map in the eastern direction. Consequently, as we move away from the wells the level of confidence decreases for horizons that are less pronounced.

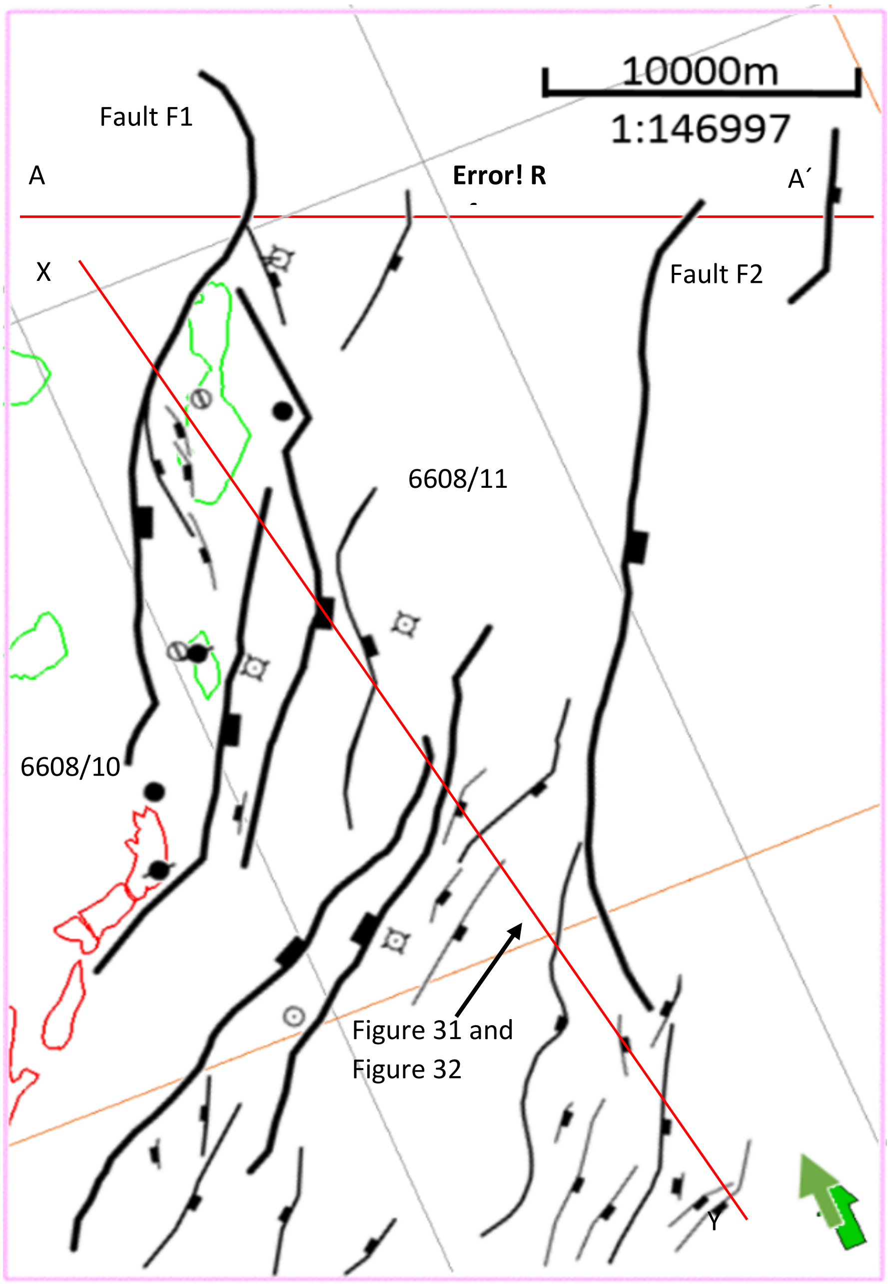


Figure 30: Major faults within the region of study. Red line represents cross section in fig 30.

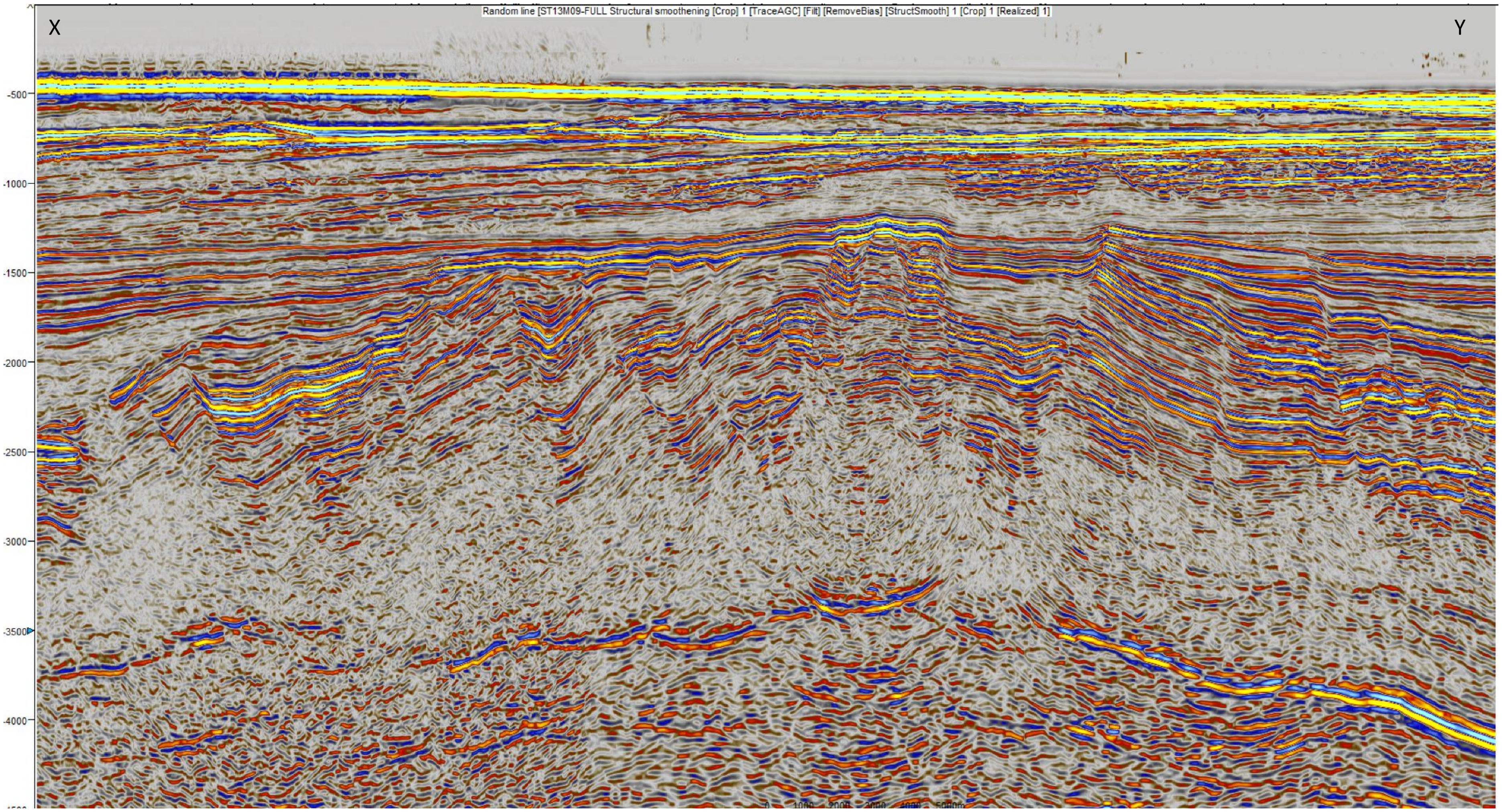


Figure 31: Seismic line across the main high of the Nordland Ridge. See Figure 30 for map view and Figure 32 for geological interpretation.

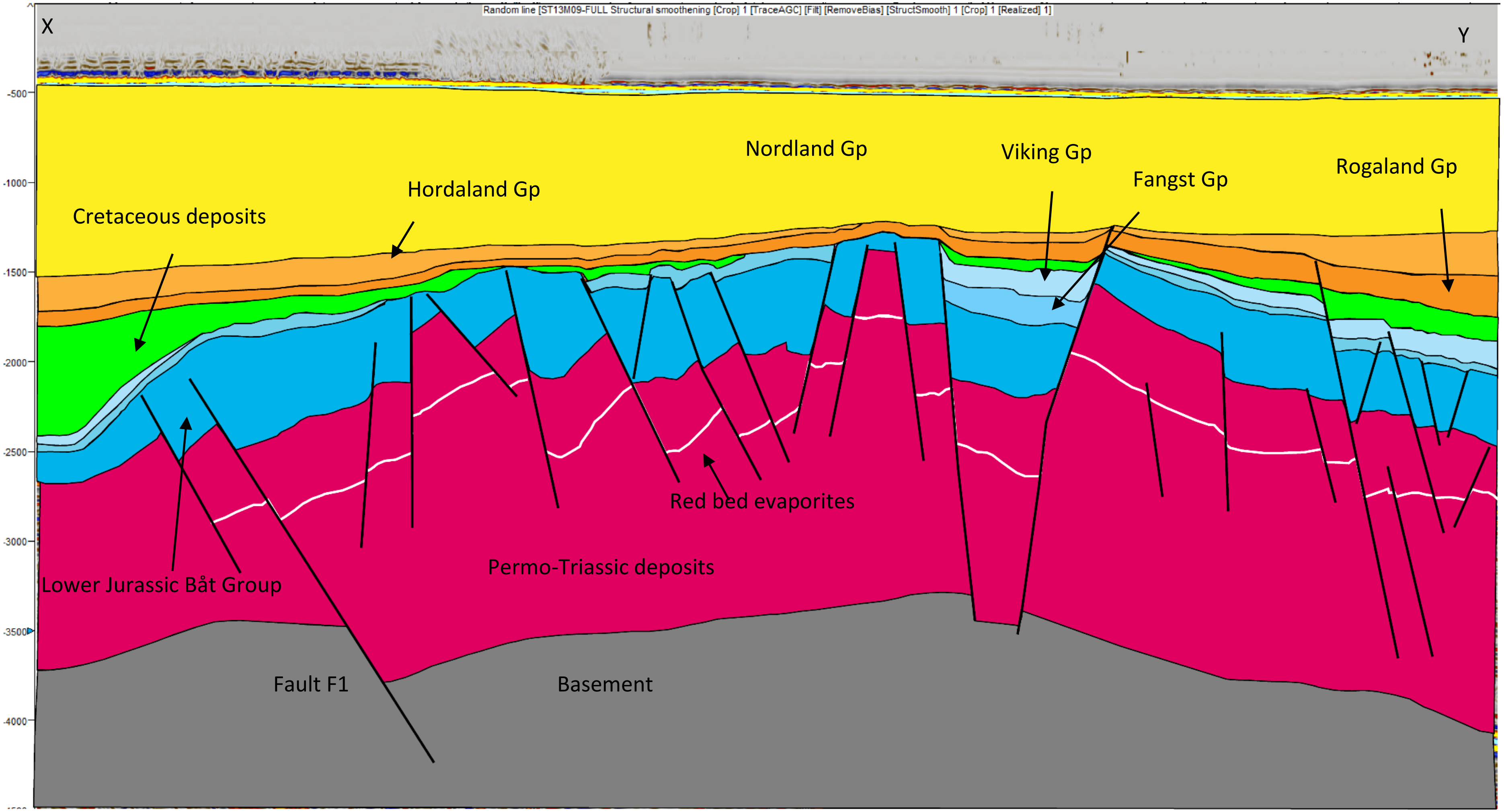


Figure 32: Geological cross section of the Nordland Ridge. See Figure 30 for map view.

Multiple faulting events (**Error! Reference source not found.**) with relatively similar trends were observed to interfere with each other Two major faults (Figure 30 F1 and F2) following a general trend of SW-NE and dipping in SE direction have been observed. Both these faults extend into the basement and form two major tilted fault blocks, within the area of interest which accommodate for subsequent rifting activities.

The interpreted Upper Permian Anhydrite unit (in yellow), which is overlying the basement, is comparatively shallow towards the northern edge of the area (Figure 33). This is the result of removal of the Jurassic and Upper Triassic strata with the Red Bed evaporite units truncating below the Paleocene units. These anhydrites have been interpreted as top of basement. The faulting pattern of the basement can be seen on Figure 34. The displacement of both faults F1 and F2 decreases towards the south.

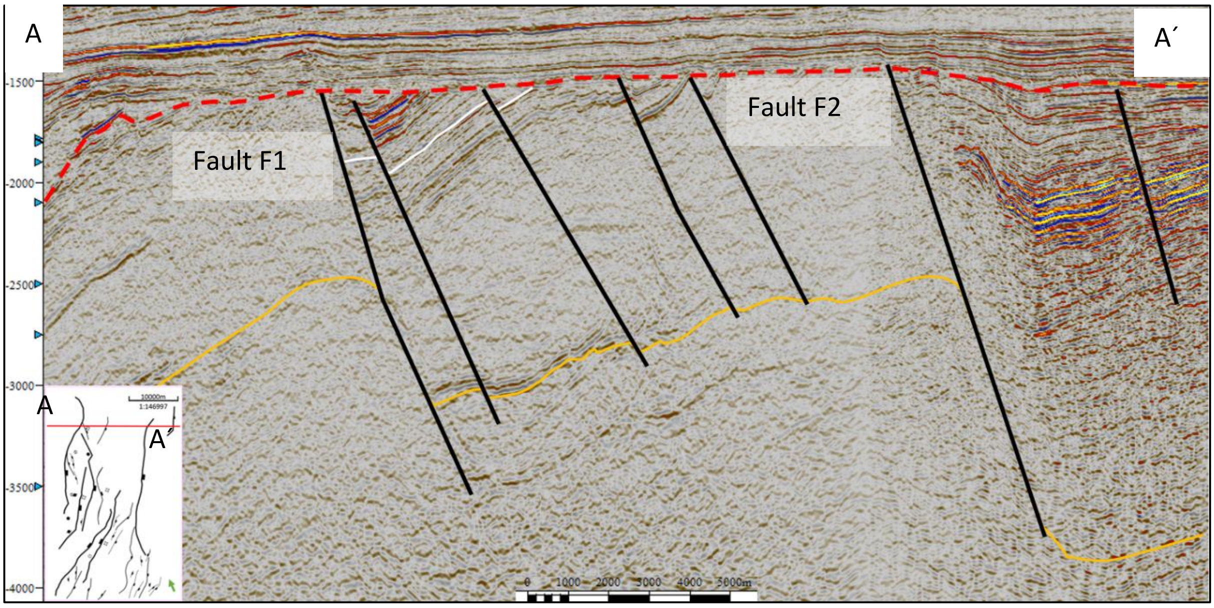


Figure 33: Inline 12294 showing Lower Triassic deposits in contact with Paleogene sediments. Top of Red Beds evaporite sequence (white), Permian anhydrites (yellow) and Base Cretaceous Unconformity (BCU).

The Ladinian-Carnian evaporite sequences (Figure 11) show three sets of strong hard reflectors, which are present throughout the region (Figure 35Figure 35). The topmost of these sequences is close to base Norian which was marked as top of the evaporitic succession (Figure 36 A). It also shows the lateral extent of the removal of Triassic strata which was observed in **Error! Reference source not found.**. The surface shows multiple smaller faults propagating within the Permo-Triassic tilted fault blocks. On comparing the basement map in **Error! Reference source not found.** with Figure 36 A, the structuring of Nordland Ridge c an be seen. These structural highs also coincide with the zones of large thickness on the time thickness map between the Permian anhydrite and Red Beds evaporite sequences (Figure 36 B). These regions represent the original thickness of the deposits, and show the effect of subsequent rifting episodes on Triassic deposits. They also indicate the locations where large accommodation spaces have been created by the Jurassic and Cretaceous extensional regimes.

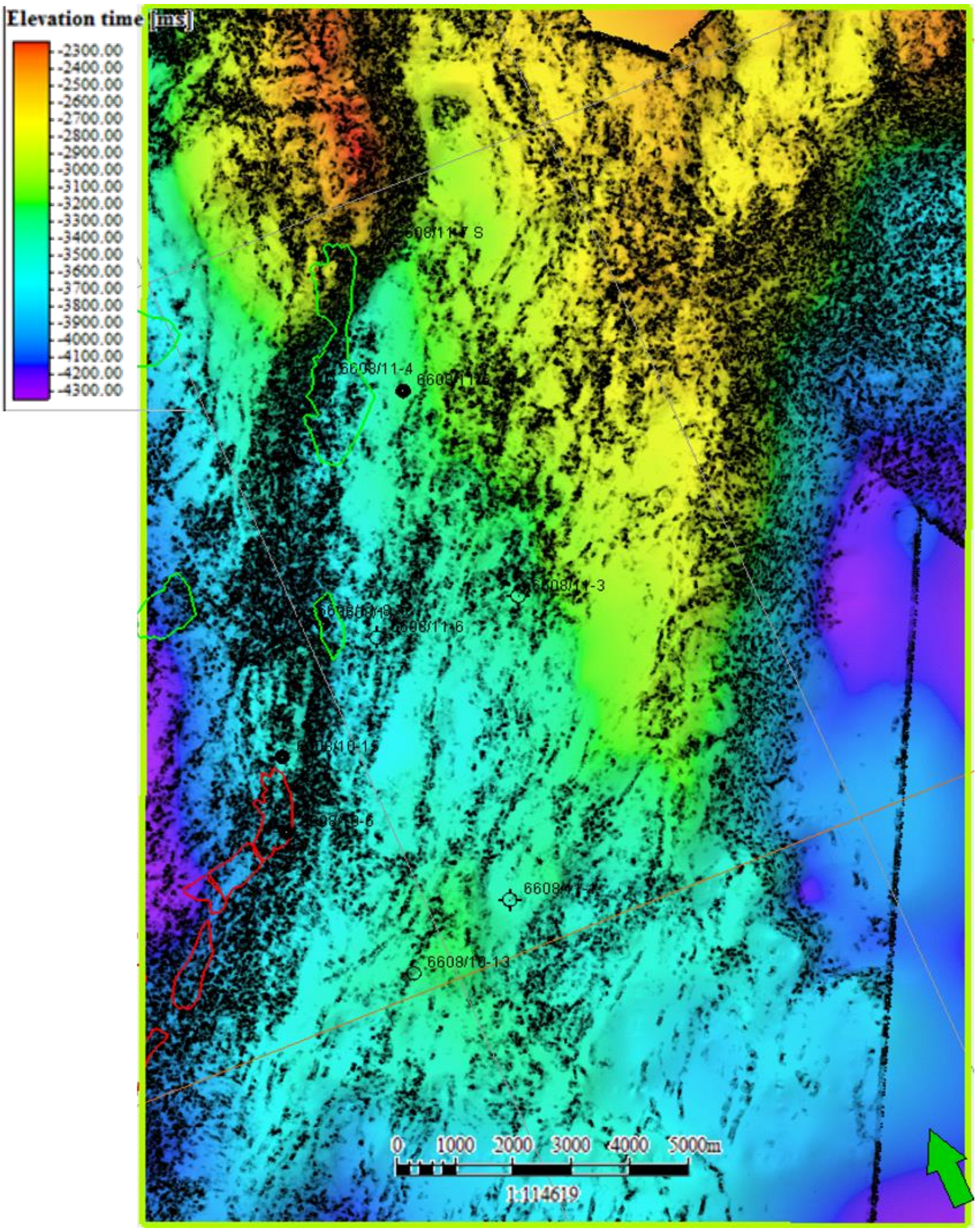


Figure 34: Surface map of Upper Permian anhydrite ovelain with variance of the same surface denoting fault trends.

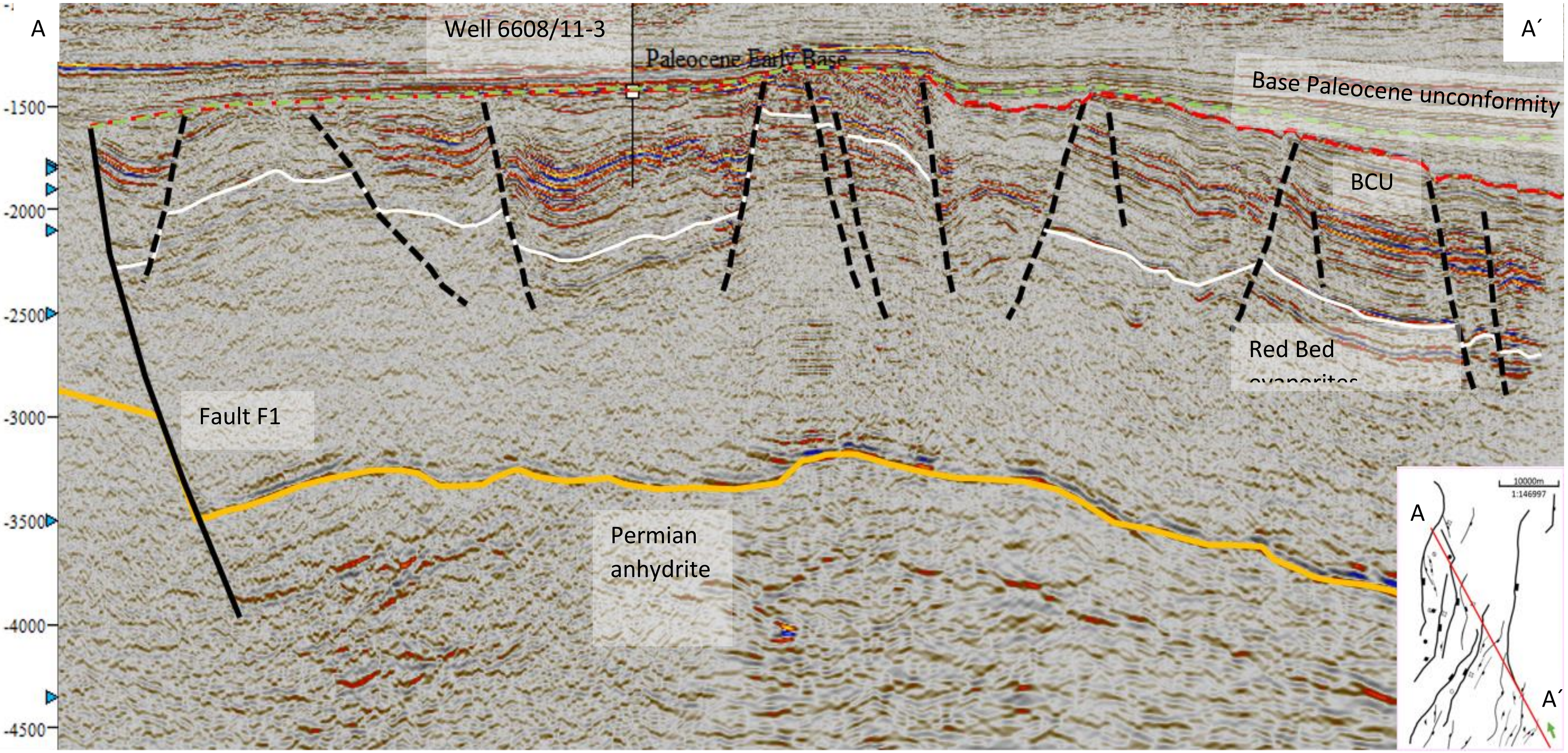


Figure 35: Seismic Line showing the Ladinian-Carnian evaporite sequence. Faults (dashed) represent younger rifting episodes. Base Paleocene Unconformity (green), BCU (red), Permian anhydrites (yellow) and Red Beds evaporite sequence (white).

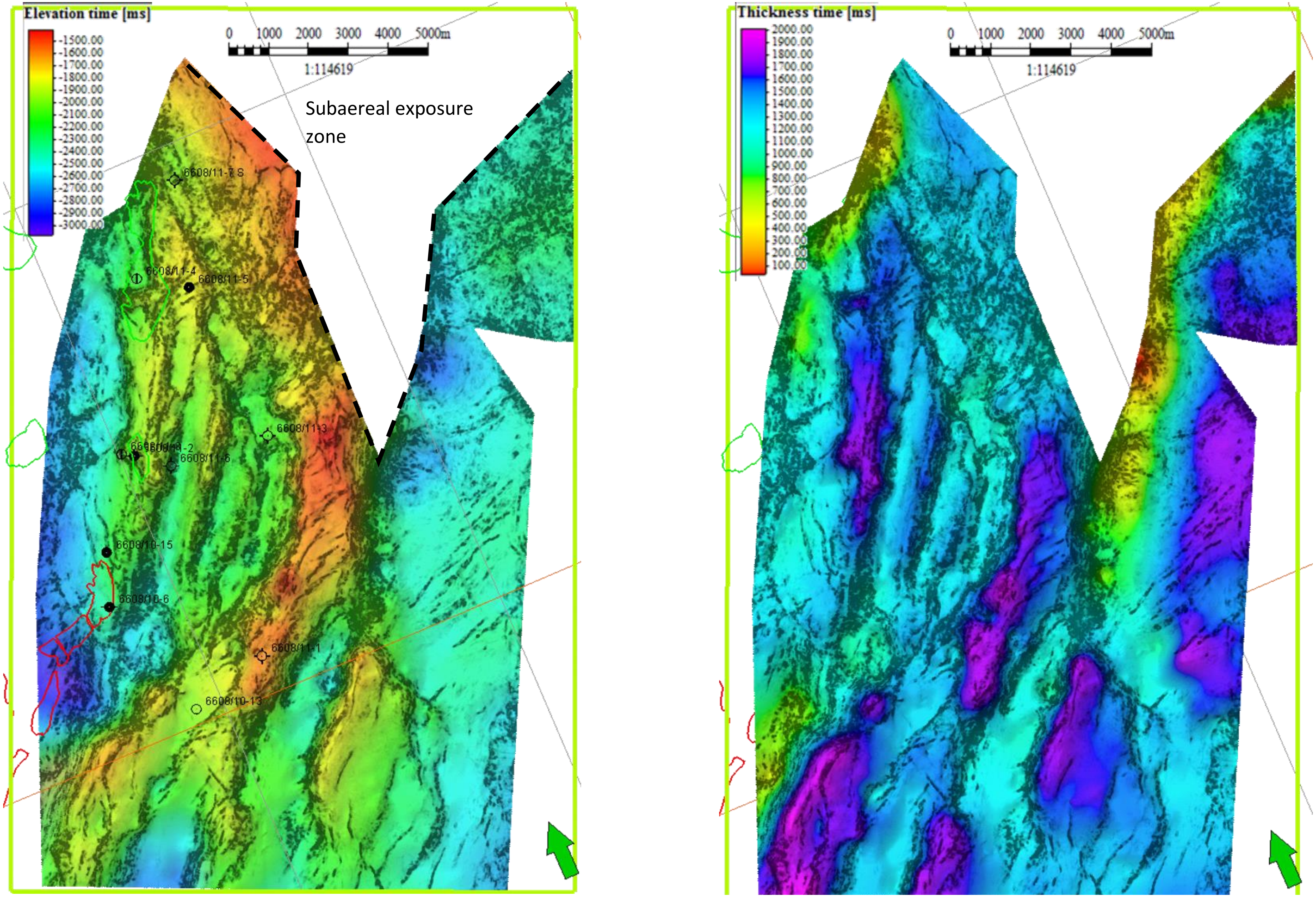


Figure 36: (A) Ladinian Carnian evaporites of Red beds

(B) thickness between permian and evaporites

4.2.1 Play Potential

4.2.1.1 Lower Jurassic

The base of Båt Group signifies the end of Triassic. It is also the top horizon for the Grey Beds. The Båt Group along with the Grey Beds are present in some quantities throughout the area, except for the northern part. On the Nordland Ridge, the top of Båt Group was interpreted as the top of Åre Formation as the resolution of the Tilje Formation is sub seismic. Furthermore, it has been encountered in only three wells thereby decreasing the confidence in interpretation. The Ror Formation, which is completely absent in on the Nordland Ridge does not provide any well control for it to be mapped with any degree of confidence. However, it has been encountered by a few wells drilled in the Helgeland Basin (NPD, 1985, 2005, 2011). The lithology variation between Ror claystones and Tilje sandstones would cause a decrease in sonic velocity and produce a soft contact. Due to this, a high amplitude soft horizon has been interpreted as the top of Tilje Formation on the Trøndelag Platform. The formation shows considerable thickness as compared to the well logs and has also been used to represent the top of Båt Group since the top of Ror Formation

Figure 37A shows the erosion pattern of the base of Åre Formation, which is similar to the rest of the Triassic deposits. A few notable depressions are seen in the southern part of the area (Figure 37 A, white highlights). The top of Åre Formation has been eroded by varying degree throughout the area, resulting in the actual contact between the Tilje and Åre formations not being present everywhere. The interpretation has managed to adhere to this contact as closely as possible however, due to structural variations there is a variable degree of confidence in it (Figure 37 B). As can be observed, the lack of strata coincides with the main structural high of the Nordland Ridge and the northern eroded zone. A time thickness map was made between the base of Åre Formation and the BCU highlighting the thickness variations in Jurassic deposits. In Figure 38 the north-eastern part of the area shows higher thickness values as compared to the south-eastern part. This fits with the tectonostratigraphic evolution of the Trøndelag Platform as the Permo- Triassic faults have larger displacement in the north. The localized depressions noted in Figure 37 A also contain thicker Jurassic deposits. The Tilje Formation that has been mapped on the Trøndelag Platform shows similar faulting trends as that of the top of Åre Formation. The top of Tilje These formations of the Båt Group are the primary reservoirs zones of the Lower Jurassic epoch.

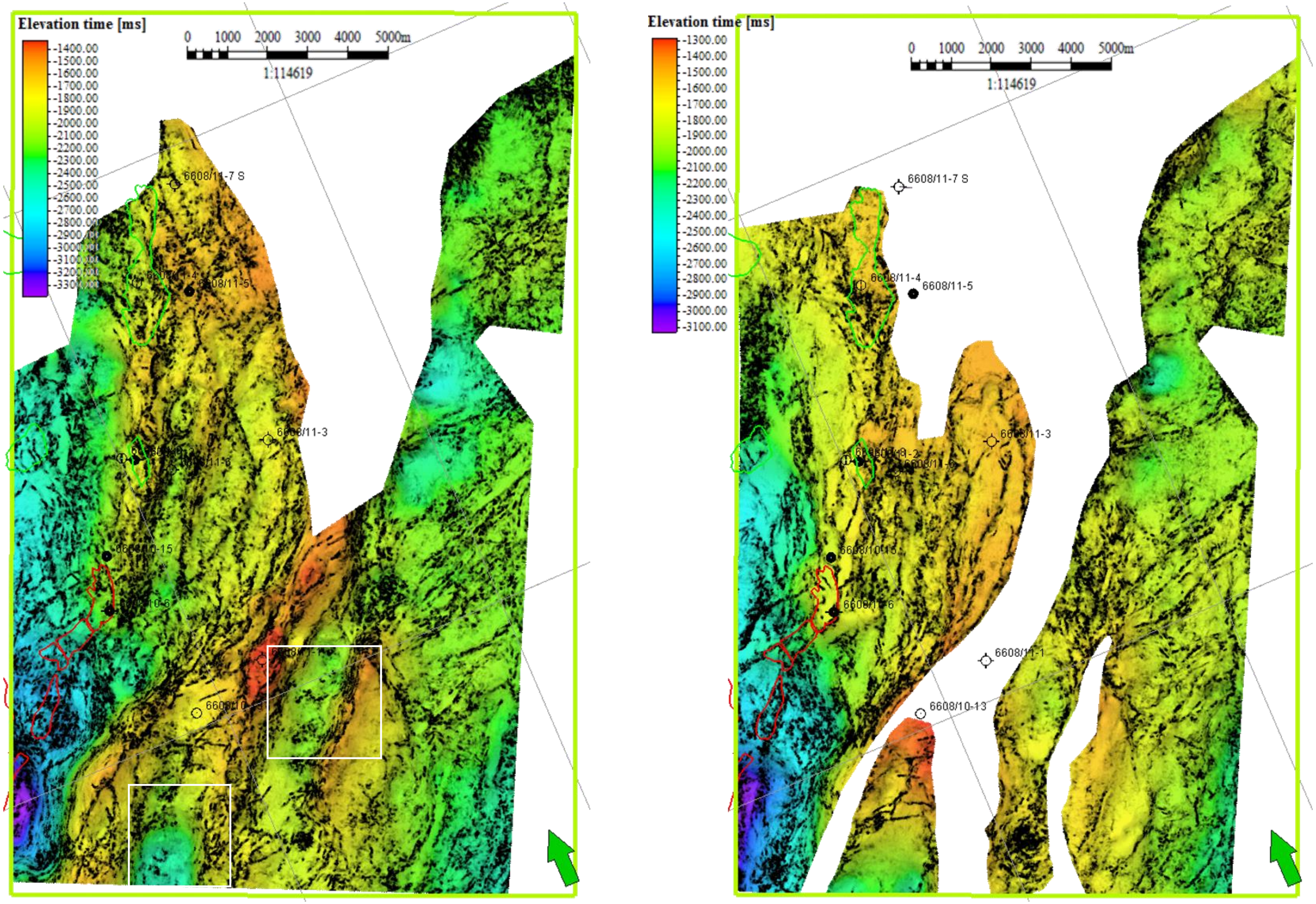


Figure 37 A Åre.White boxes highlight localised depressions.

B Top of Åre formation.

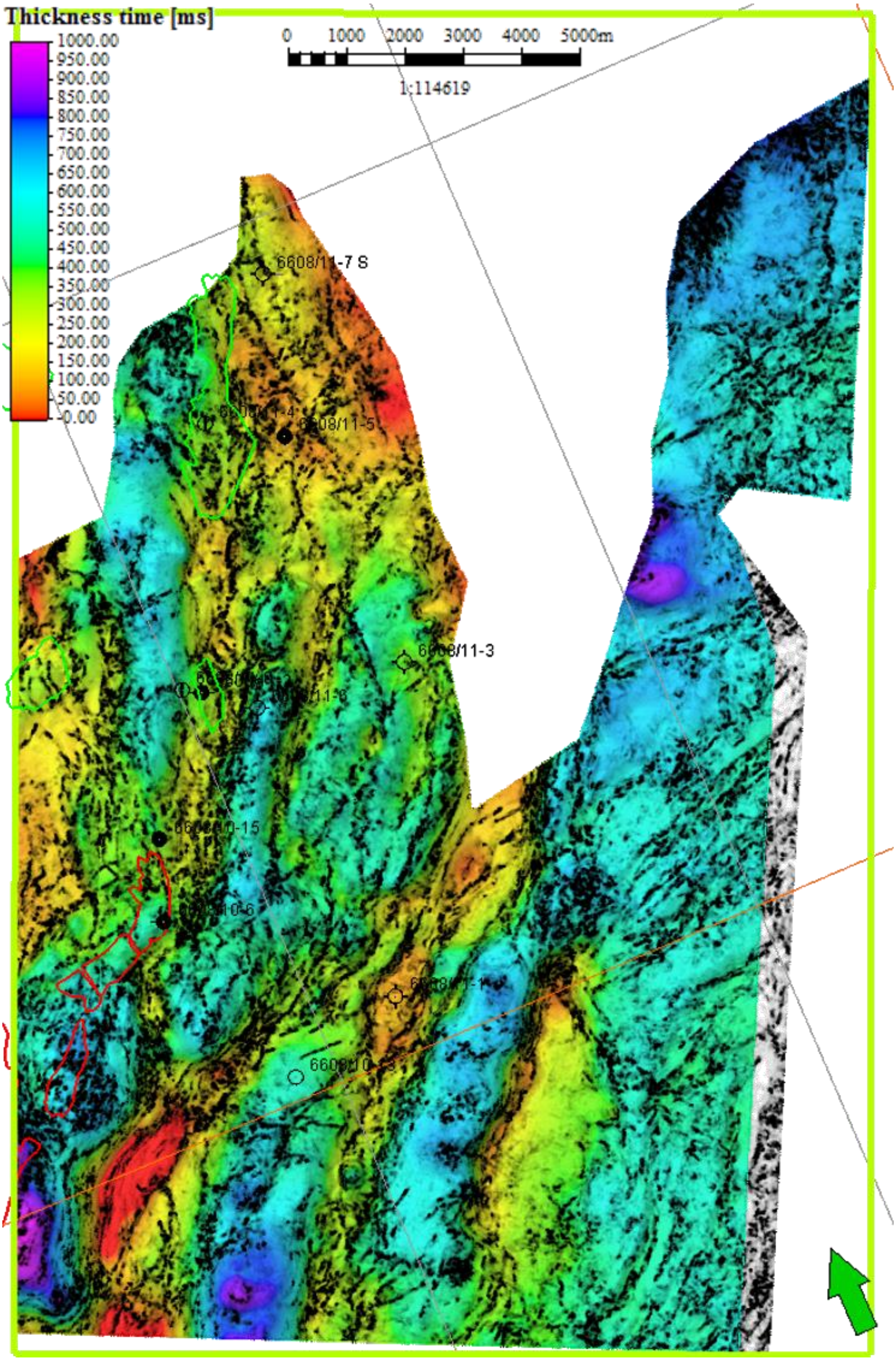


Figure 38: Time thickness map between base of Are Formation and BCU

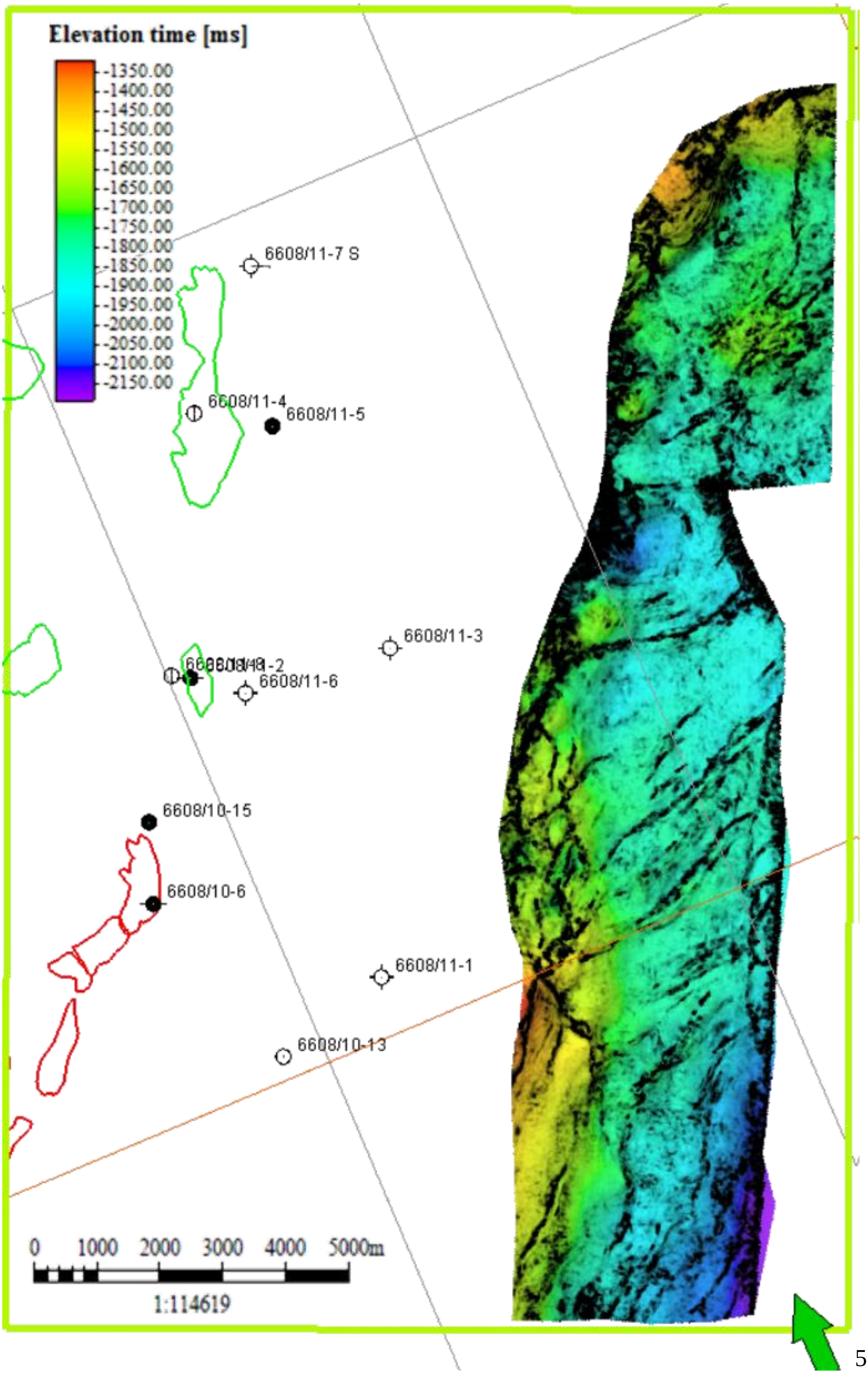


Figure 39: Top of Tilje formation present on the Trøndelag Platform

4.2.1.2 Middle Jurassic

The reservoir zones of the Fangst Group are absent on the main Ridge with only two wells having drilled through the Ile Formation (Figure 40). The Norne and Urd fields have it as a part of their main reservoir proving that they exist on the Donna Terrace which indicates that they may also be present on the Trøndelag Platform due to similar tectonic origins and can

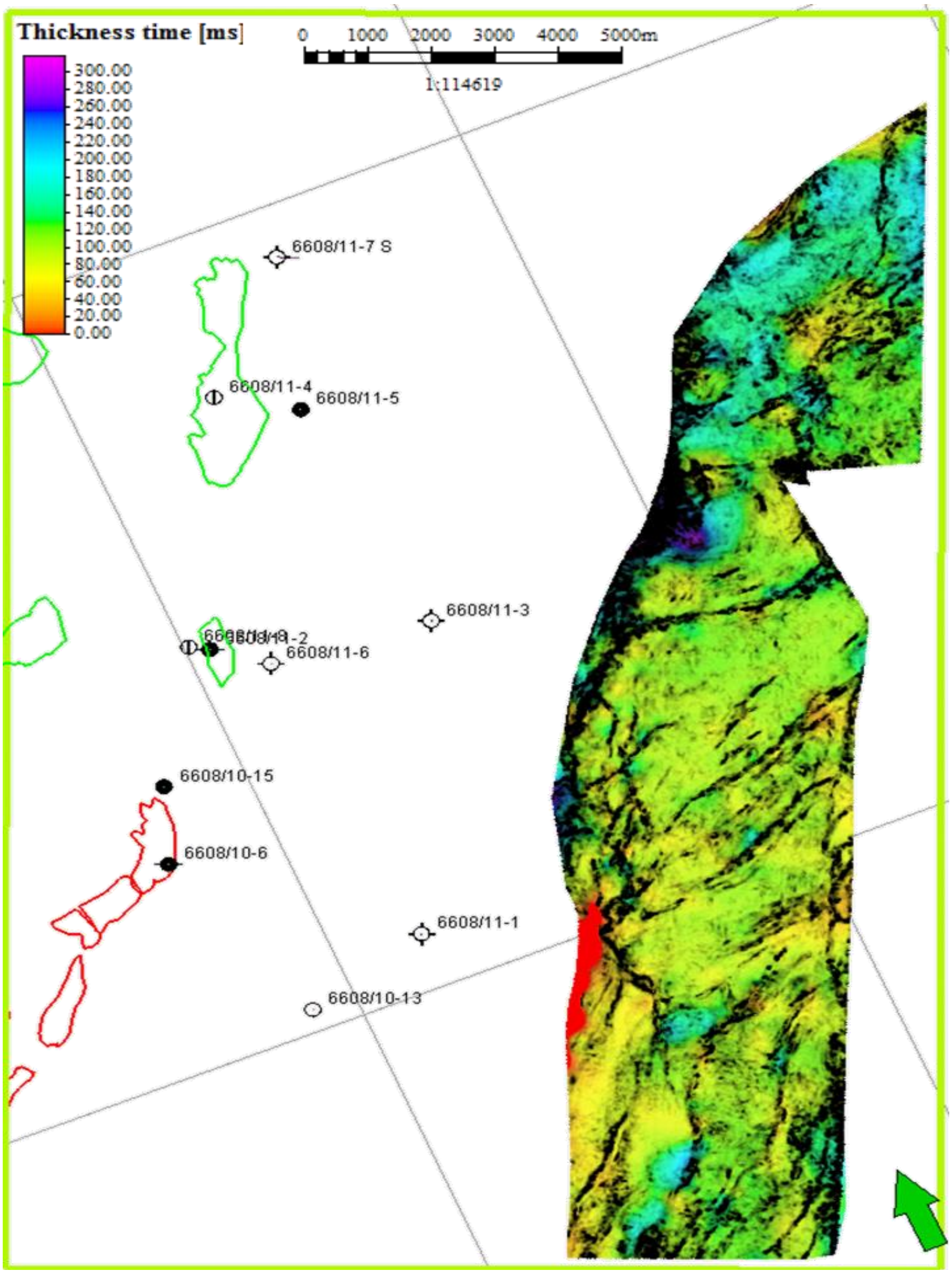


Figure 40: Time thickness map of the Fangst Group between the top of Tilje Formation and base of Viking Group on the Trøndelag Platform. The 'cooler' hues towards the northern part of the map indicate areas of thicker deposition.

act as viable reservoirs on the eastern side as well.

4.2.2 Potential Seals

Sealing element is one of the critical parts of a working petroleum system, which makes the Jurassic Viking Group an important lithostratigrahpic interval. Since they are thermally immature to act as source rocks, they can form excellent seals. The presence of Spekk Formation on the Trøndelag Platform (Figure 41) works as a sealing element for some leads

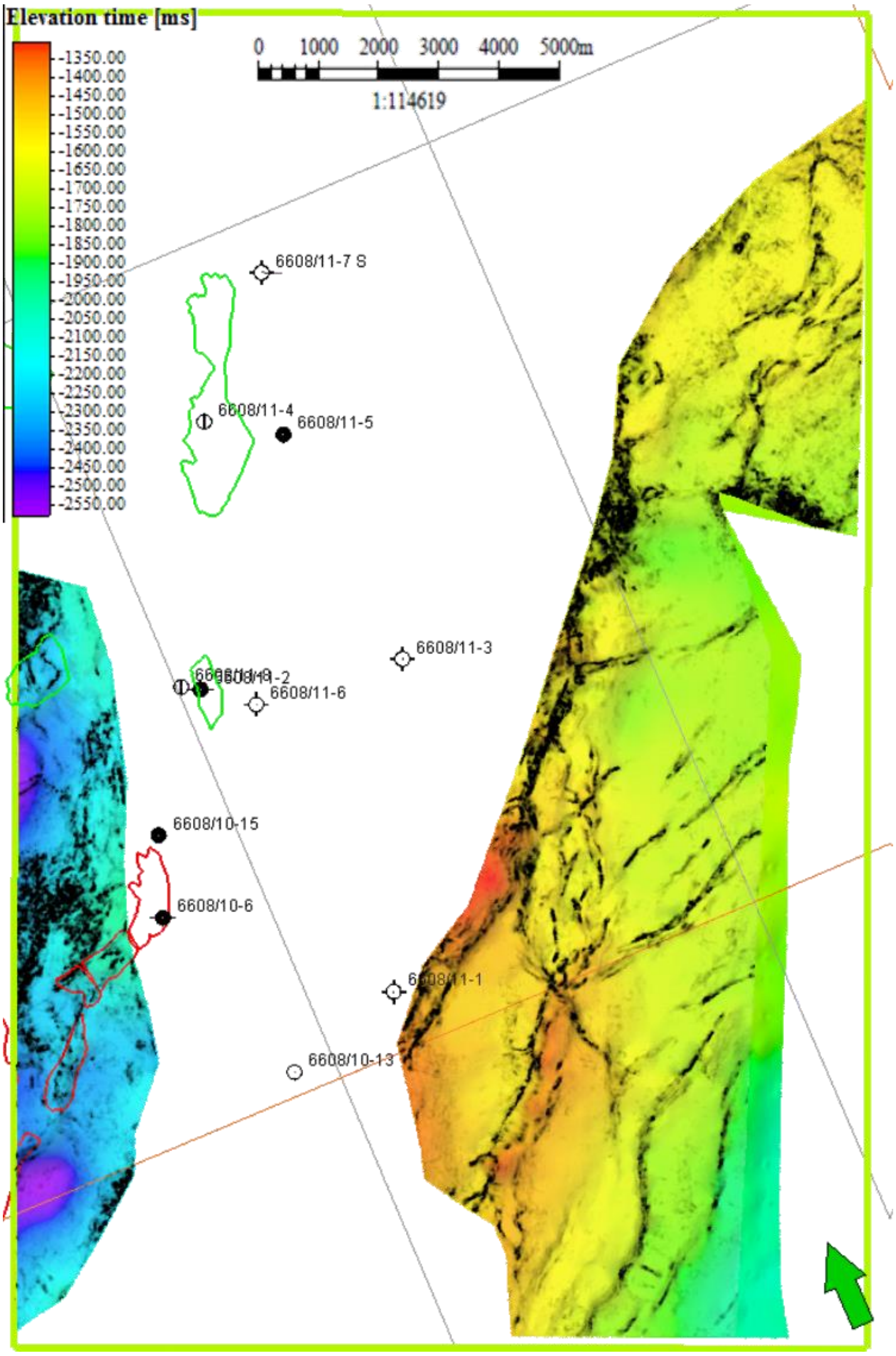


Figure 41: Surface map of the base of Spekk Formation. Notice that the western parts are deeper than the eastern deposits.

in the area. Figure 41 shows the areal extent of the Spekk formation on the Nordland Ridge and adjoining areas. It can be observed that the western part of the Nordland Ridge has under gone more subsidence as compared to the eastern side.

The Cretaceous deposits can be seen in all the wells but they differ in age and formations. The most extensive deposit is a thin sequence of claystones of the Springar Formation. Figure 42 shows the thickness of Cretaceous sediments by using a time thickness map between the BCU and the base Paleocene unconformity. It has been observed that the BCU is absent in some places and the Jurassic deposits subcrop to the base Paleocene unconformity. Most of the areas have a thickness close to zero as the BCU was interpreted as a strong soft reflector while the base Paleocene unconformity was marked on the overlying hard reflector.

The Paleocene claystone deposits of the Rogaland Group are ubiquitous and cover all parts of the region (Figure 43). The Tare Formation is the topmost member of the Rogaland Group and along with the underlying Tang Formation can be viable seals.

The Brygge Formation, which overlies the Rogaland Group, shows a lack of deposition over the main structural high of the Nordland Ridge. This interpretation ties in with the sediment starved depositional environment of the Eocene and Oligocene (Figure 44).

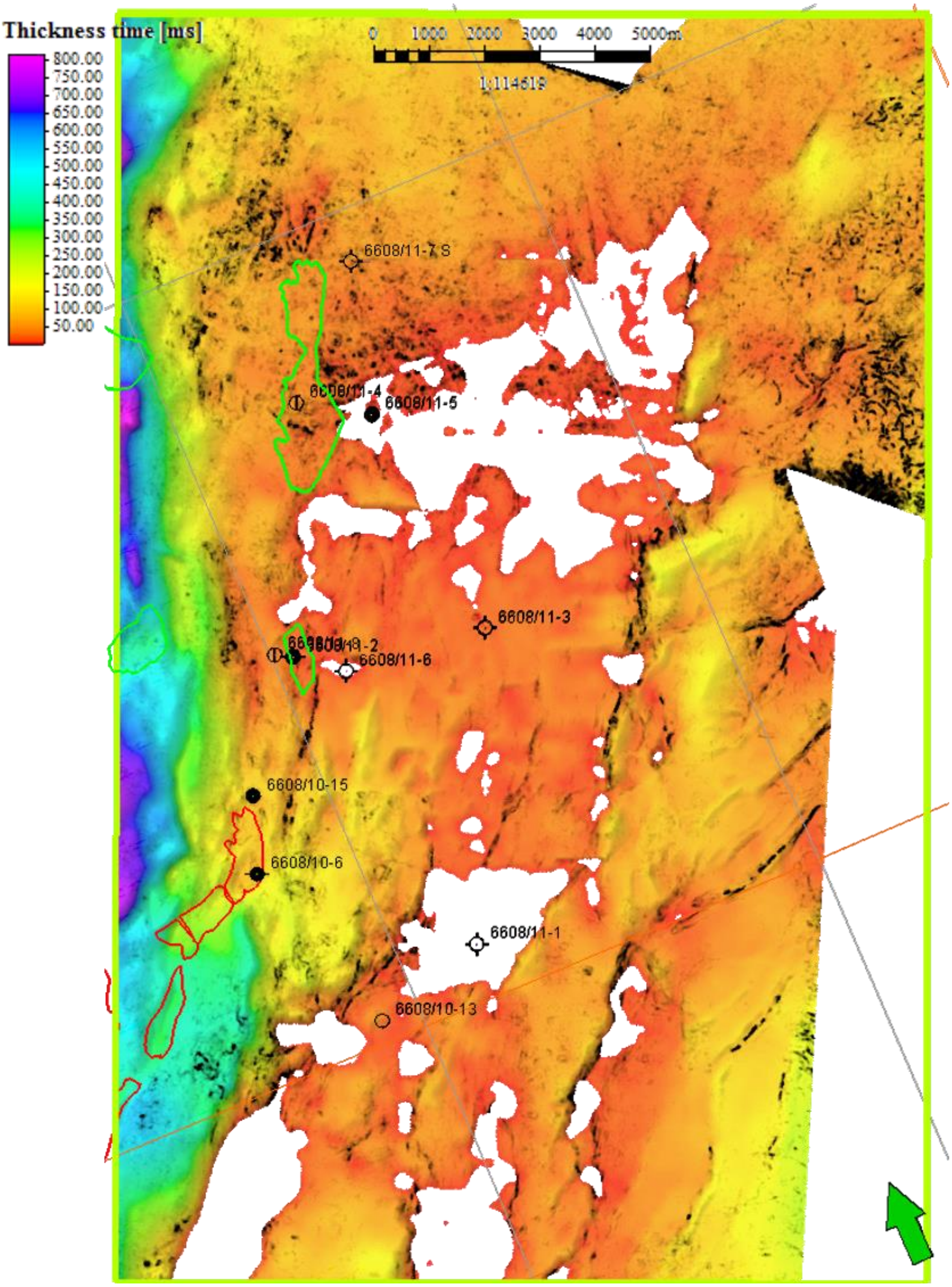


Figure 42: Time thickness map between the BCU and base Paleocene unconformity showing the extent of the Cretaceous sediments. In most places the thickness is close to zero as two different horizons were marked for each unconformity. The parts that lack any deposits are where the base paleocene uncoformtiy eroded into the BCU.

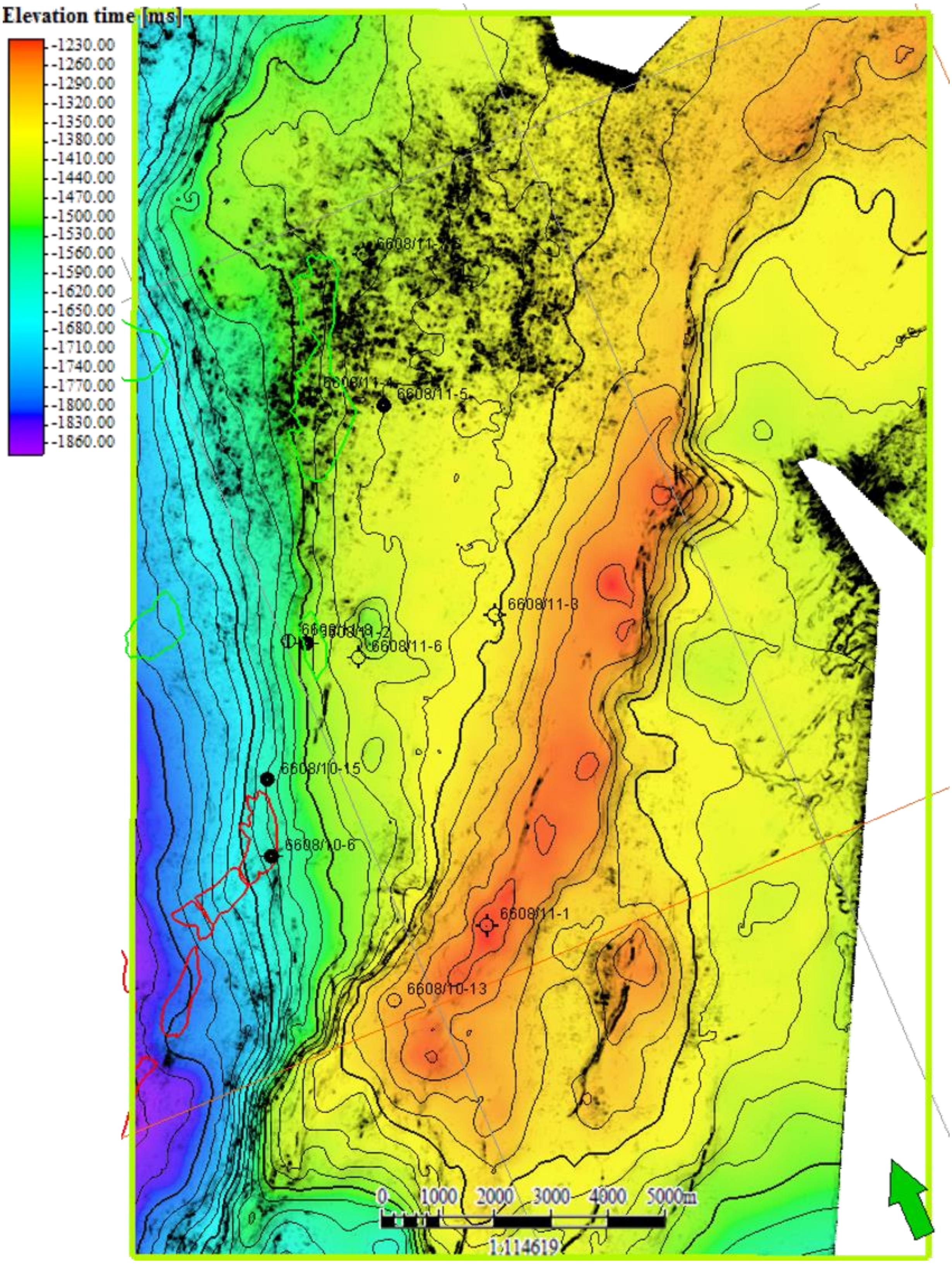


Figure 43: Surface map of the Tare Formation from the Rogaland Group. The formation is present throughout the region including the highs.

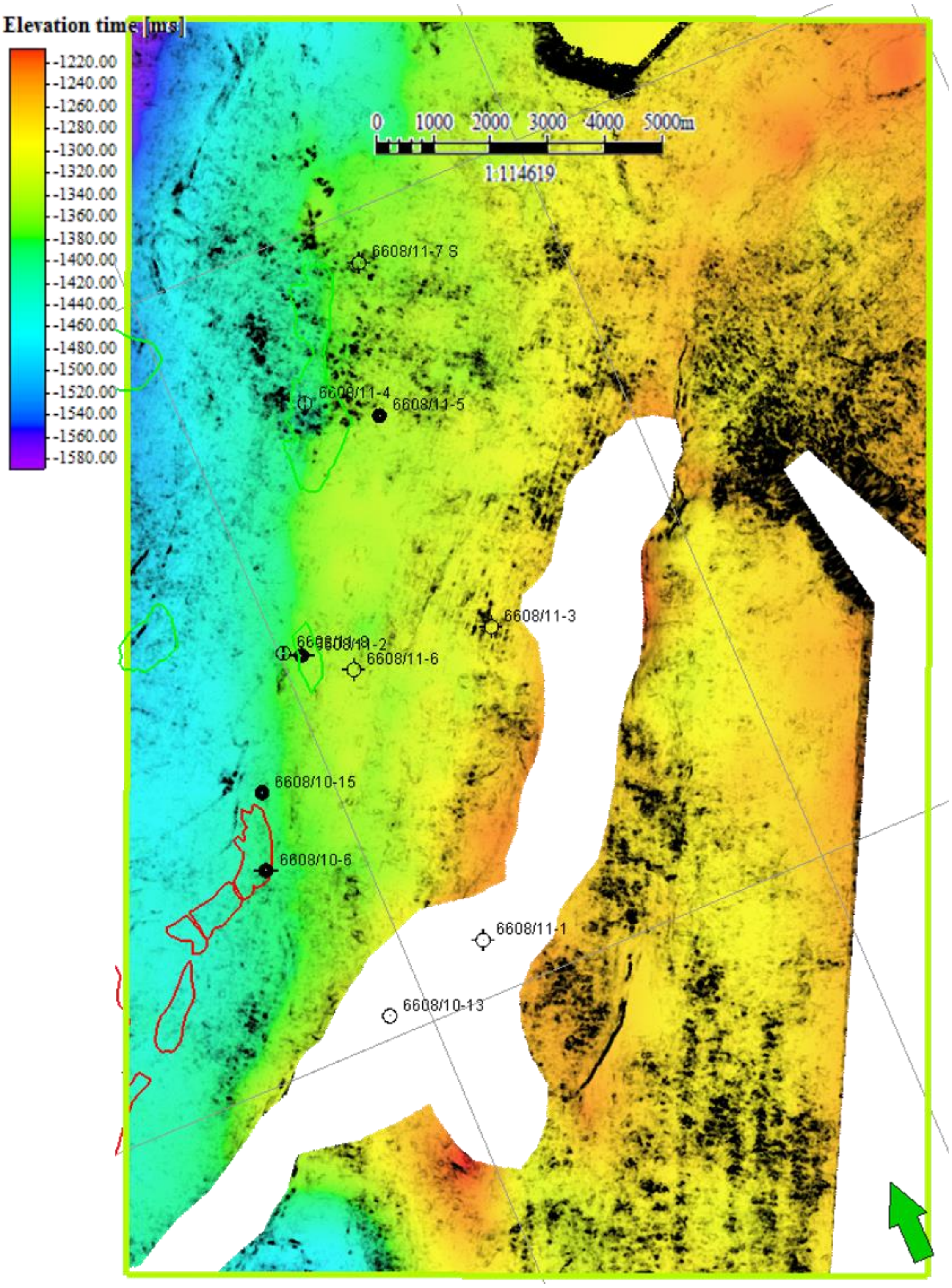


Figure 44 Brygge top

4.2.3 Trap formation

The timing of Jurassic extensional regime can be observed in the syn-rift wedges of late Lower to Middle Jurassic deposits. The beginning of faulting coincides with the deposition of the Fangst Group and later members of the Båt Group. Figure 45 shows each of the consecutive rotated fault blocks having a wedge which illustrates that the faults were active throughout the end of the Jurassic era. This can also be seen in Figure 46 where the sequence of various events can be better estimated. A Mid Jurassic wedge is seen in Figure 46 fault block X4, indicating that the fault is of Jurassic origin. Note that the mid-Jurassic deposits also form a wedge like structure in block X6 against the Permo-Trassic fault indicating a possible reactivation. The fault between blocks X2 and X3 provides a close estimate of the end of the Jurassic faulting and the Late Kimmeridgian compressional event. (Figure 46 A).where the base of Spekk Formation is seen to draping over the fault plane instead of forming a wedge as is normal with the case of syn-rift deposits indicating a hiatus in rifting activity. Furthermore, the parallel to subparallel Cretaceous and Paleogene deposits do not exhibit similar folding characteristics thereby indicating the compressional activity happened before the formation of the BCU.

Both, the late Jurassic and mid Cretaceous faulting events were a part of a larger regional rifting activity and were separated by a relatively short time span. The reactivation of Jurassic faults can be clearly observed in the fault between blocks X3 and X4 of Figure 46 B. A change in the angle of displacement along with the lack of wedge formation in the Upper Jurassic strata strongly indicate a post Jurassic extensional activity. This complements the observations from Figure 45 where a small sequence of Cretaceous deposits is seen in block I1 which is parallel to the BCU. This increases the confidence in ascribing the timing of fault reactivation to later in the Cretaceous era. The fault between I3 and I4, marked in red, is of Cretaceous origin as the displaced Middle Jurassic sequence seem to match in thickness on either side of the fault indicating that it is pre-fault deposit.

Other evidences of Cretaceous faulting are illustrated in Figure 47 where Cretaceous overprinting on Jurassic faults can be observed. The dashed line represents the older Jurassic fault which dips in an easterly direction while the younger Cretaceous fault dips towards the west. The younger fault can be seen to displace the strata across the fault plane of the older fault.

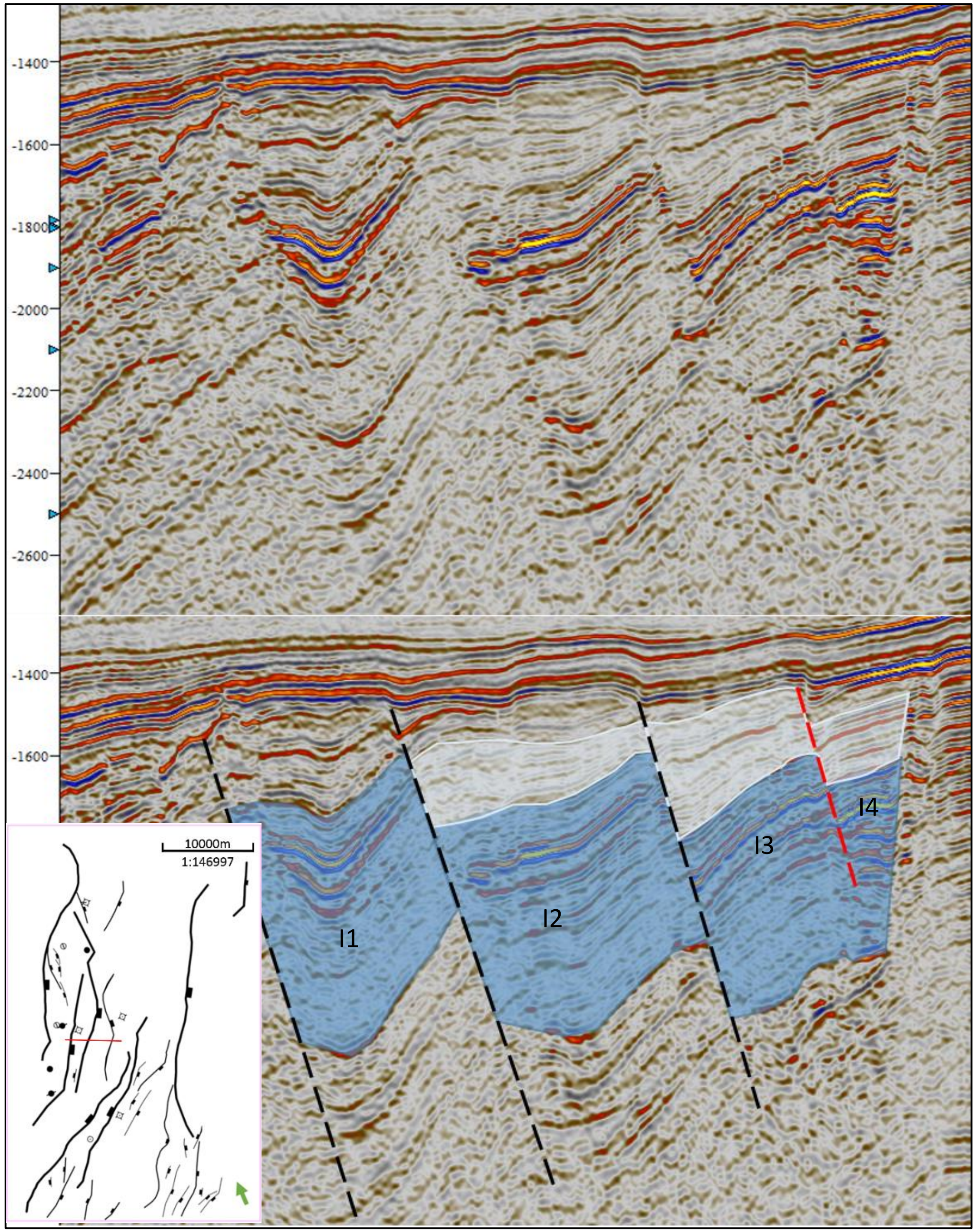


Figure 45: (A) Showing Inline 11613 zoomed in to the Jurassic sequence. (B) Shows interpretation with mid Triassic to Lower Jurassic sediments (dark blue) as pre rift deposits and Middle Jurassic sediments as syn rift sequences. Black dotted faults represent Jurassic faulting. Red fault represents possible Cretaceous origin fault.

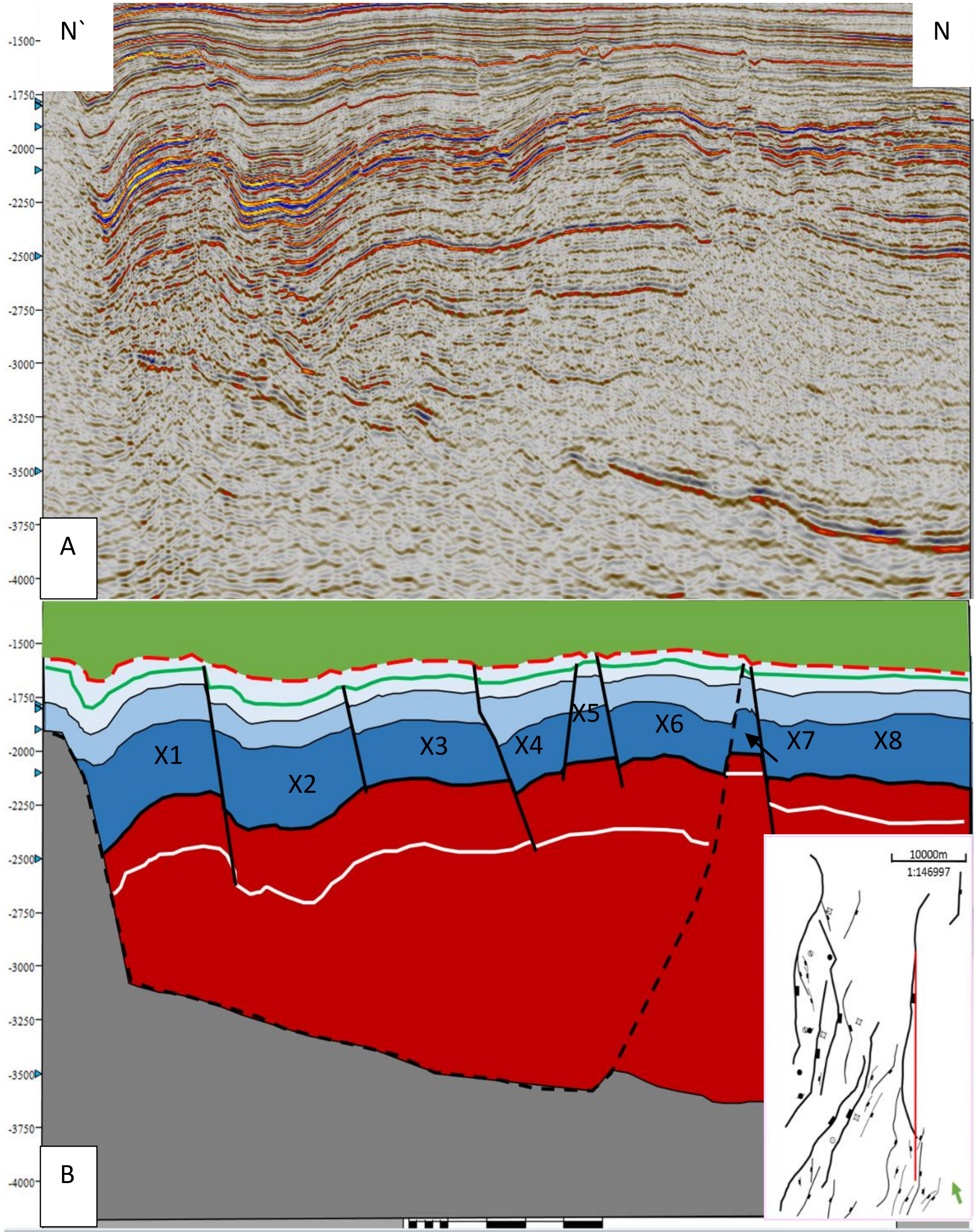


Figure 46: (A) X-line 3127. (B) interpretation shows plane of fault F2 (dashed black), Red Bed evaporites (white), Base of Båt Group (yellow), base of Spekk Formation (green) and BCU (dashed red), Cretaceous and Jurassic faults (solid black)

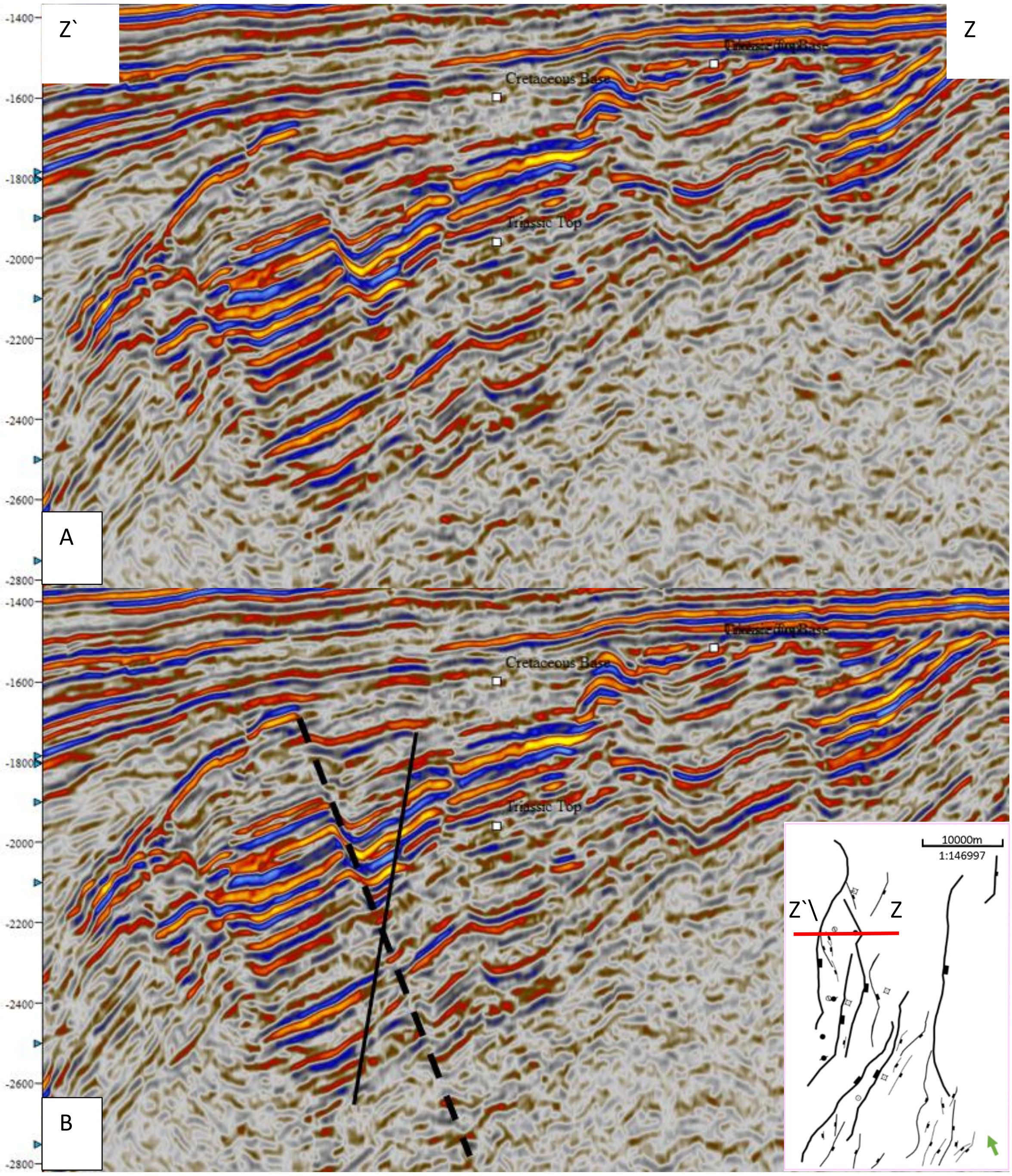


Figure 47: (A) Inline 12028. (B) Overlapping of faults indicating different faulting episodes. The stapled fault belongs to the Jurassic rifting episode while the solid fault is of the younger Cretaceous rifting period.

4.2.4 Source rock estimates

The proposed source rock of the Permian Ravnefjeld Formation equivalent shales need to be within the hydrocarbon maturity window to be able to have sufficient transformation of the organic content. A burial history analysis was outside the scope of this study due to time constraints, therefore rough estimates were made from the data available using seismic well ties (Figure 20), thermal gradient log and one way travel time (OWT). It was estimated that present day burial depth required for thermal transformation is an approximate 3300 m on the Norland Ridge, which roughly translates below 3000 ms of TWT. Using these values as guidelines a surface was generated to gauge the lateral extent of the maturity of these source rocks. Figure 48A shows the surface map of Upper Permian anhydrites marked with contours in two way time (TWT).This map was used to generate the extent of Upper Permian organic shales shown in Figure 48B. This map shows that most of the Permian source rocks are within the maturation window, especially on the Trøndelag Platform.

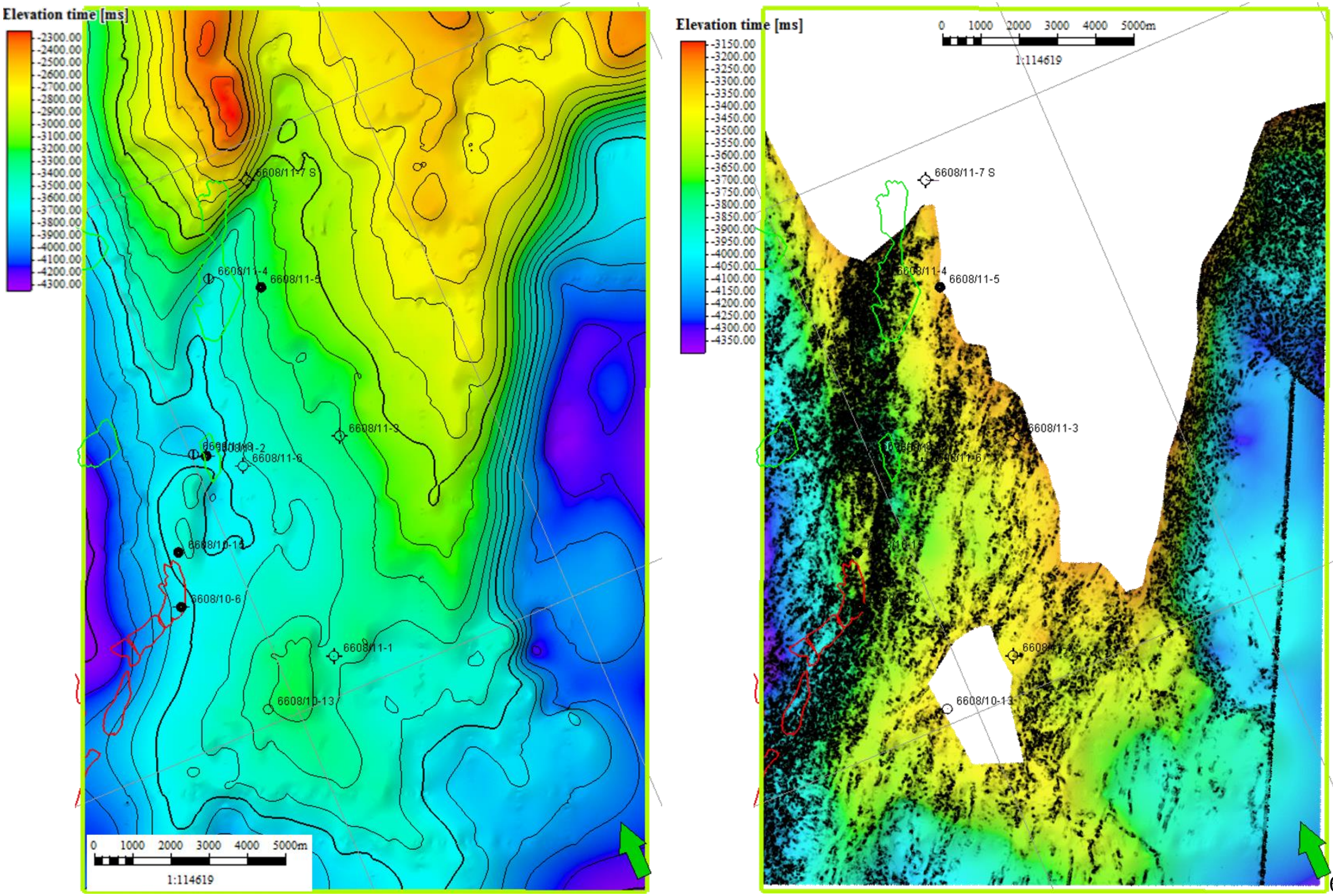


Figure 48: (A) Surface map of Upper Permian anhydrites marked with contours. (B) The depth of 3300 ms was chosen to mark the extent of Permian shale deposits within the thermal maturity window.

4.3 A Middle Jurassic lead.

4.3.1 Reservoir

The presence of Fangst Group units on Trøndelag Platform provide viable reservoir zones in this region. (Figure 49) A thicker sequence of deposits can be observed in the highlighted area on the time thickness map between Top Tilje and Base Spekk formations (Figure 40). The tectonostratigraphic evolution of the Trøndelag Platform indicate that the Permo-Triassic rifting created the initial accommodation space for the deposition of Lower Triassic strata Subsequent rifting episodes increased this accommodation space allowing most of the Jurassic deposits to be preserved and undergo comparatively less erosion than to the west, on the Rodoy High.

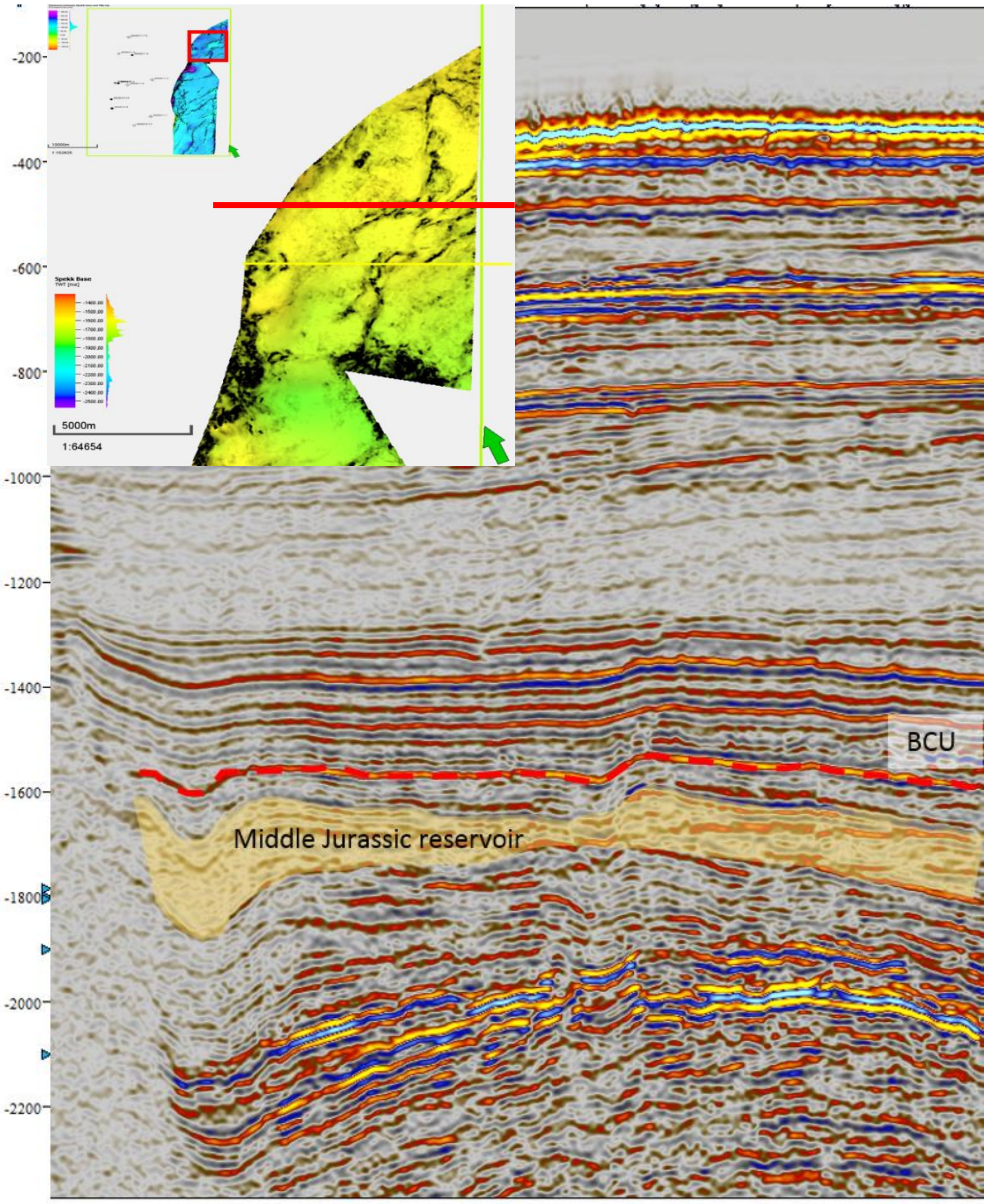


Figure 49: Reservoir zone for the lead are the Middle Jurassic sandstones

Seal

Seismic data indicates that marine shaly units of the Spekk Formation are present on the Dønna Terrace to the west and Trøndelag Platform to the east (Figure 41). None of the wells have encountered the Spekk Formation within the area of interest, but by comparing the seismic over Urd and the northeastern part of Norne fields, the base of Spekk Formation has been marked as a strong hard reflector between the BCU and top of Melke.

4.3.2 Trap

A fault block (Figure 51) has been observed with a juxtaposition of the Spekk Formation

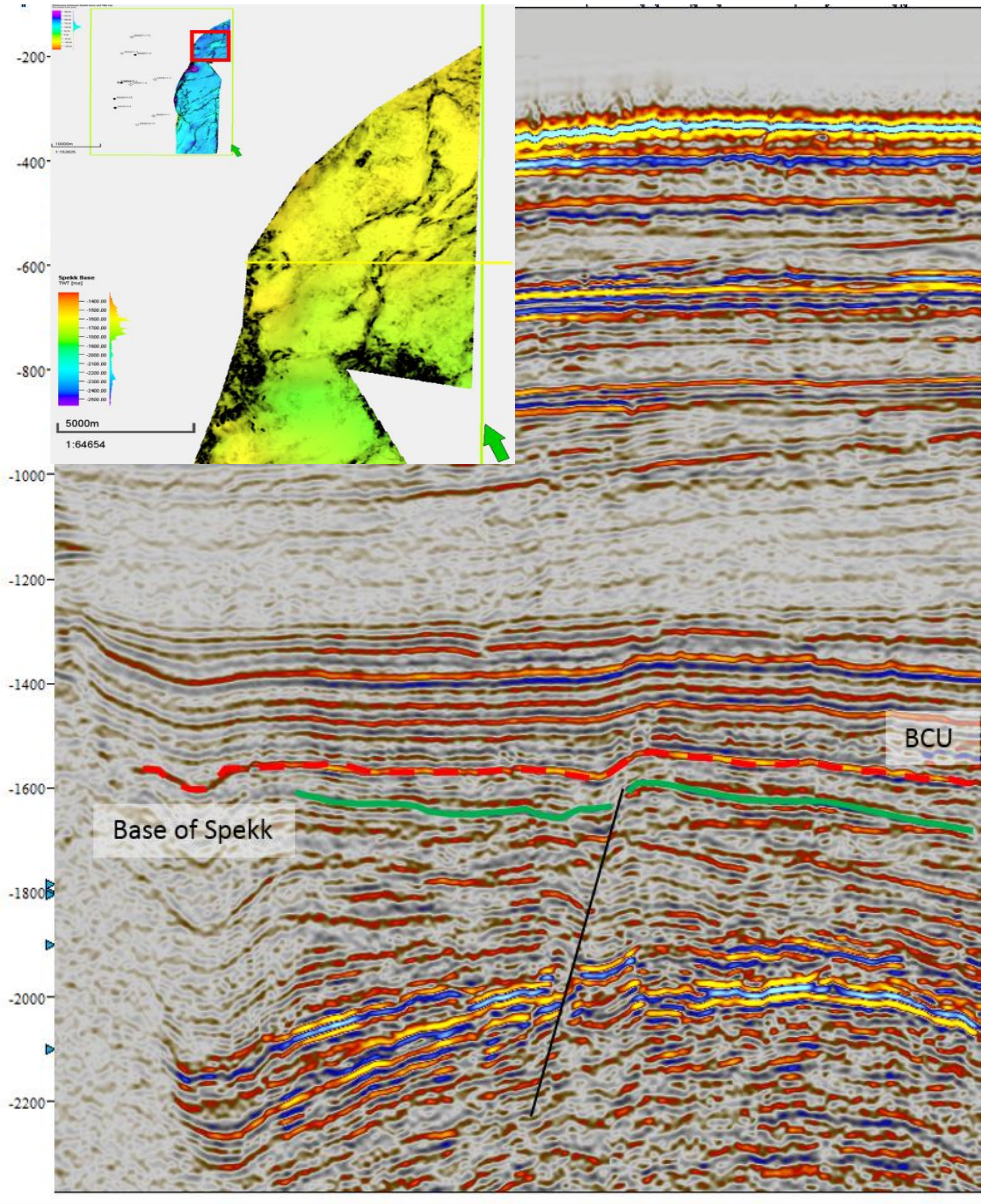


Figure 50: The Seal is provided by Late Jurassic Spekk Formation.

shales, which provide a 3-way fault closure. The fault can be dated to Late Jurassic-Early Cretaceous rifting episode as the Spekk Formation shows some syn-rift thickness while the Lower Jurassic strata seems to be of more even thickness and less affected by faulting.

4.3.3 Charge

The source needs to be the Permian shales deposited on the Trøndelag Platform as discussed before. The subsidence of the Trøndelag Platform allows the Permian shales to be buried deeper than the Nordland Ridge and may therefore be in the oil or gas generating zone.

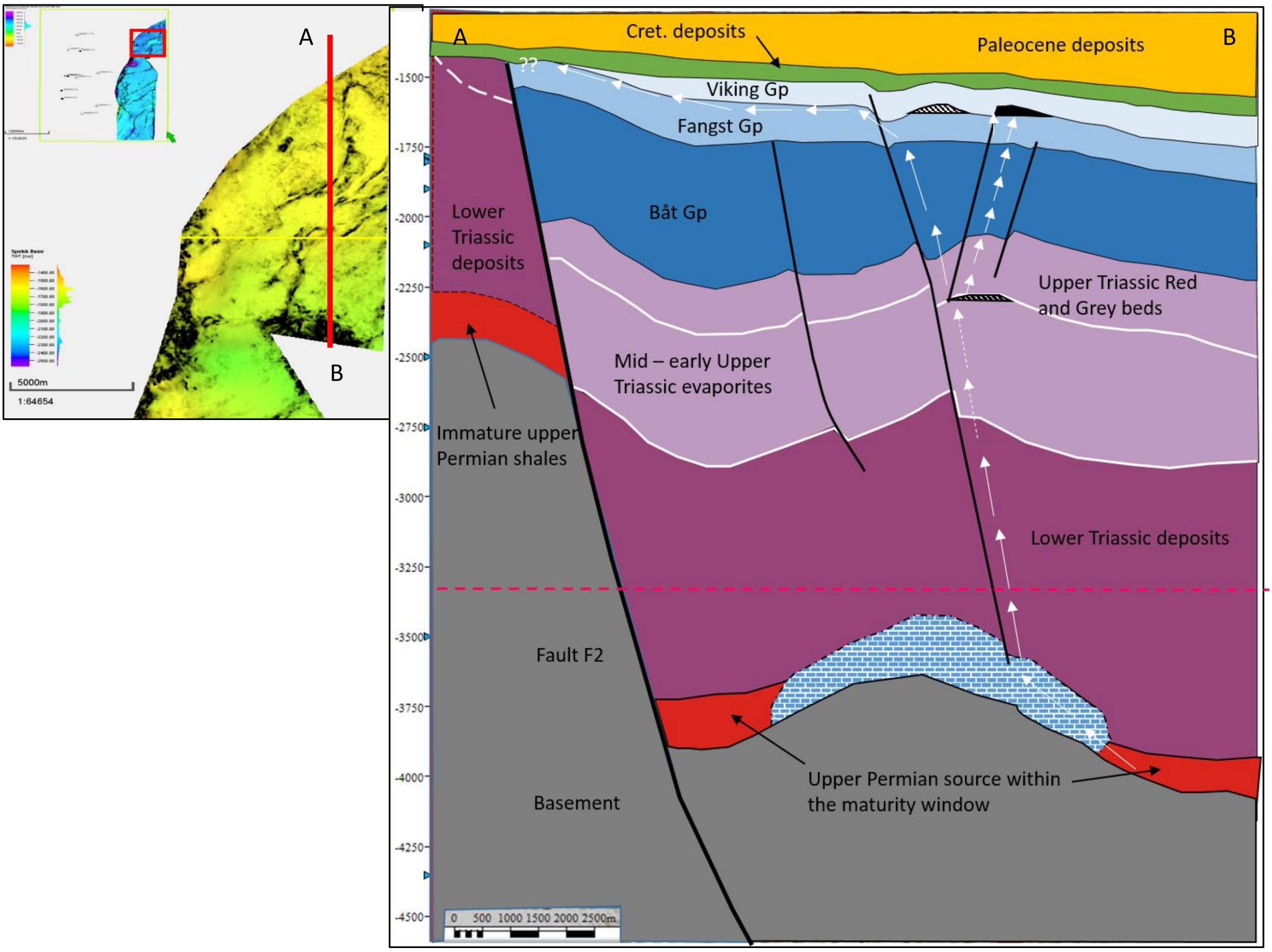


Figure 51: A schematic of the kitchen to trap migration for the lead. Dotted red line represents the depth for the onset of maturity

5. DISCUSSIONS

5.1 Petroleum System

From the observations it can be inferred that all the elements of a working petroleum system exist within the study area. A petroleum system events chart was made in order to summarize the various uncertainties within the region.

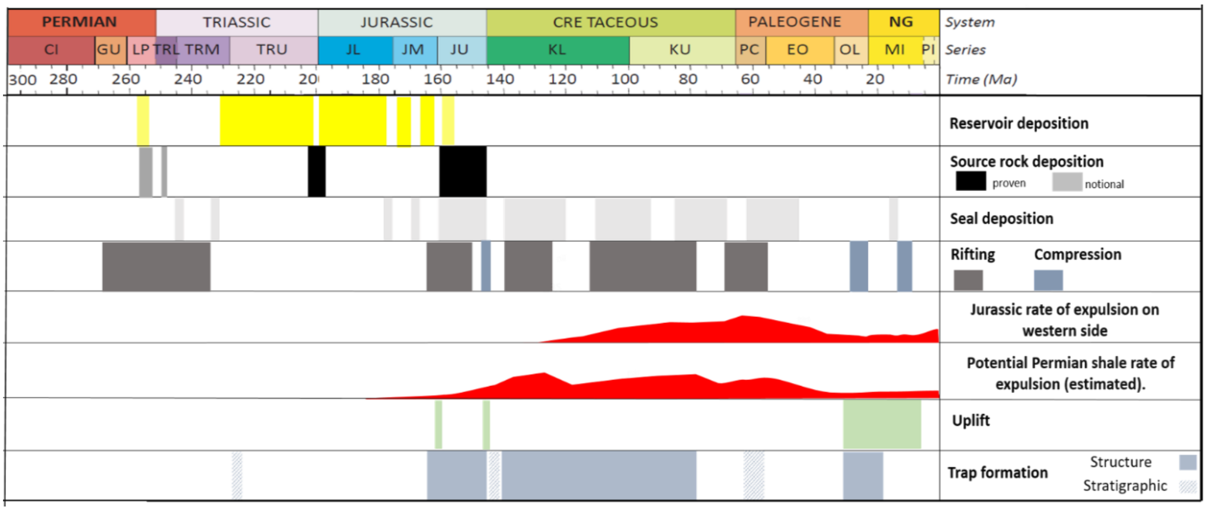


Figure 52: A Petroleum system events chart summarizing the various elements working within the study area.

5.1.1 Source rocks

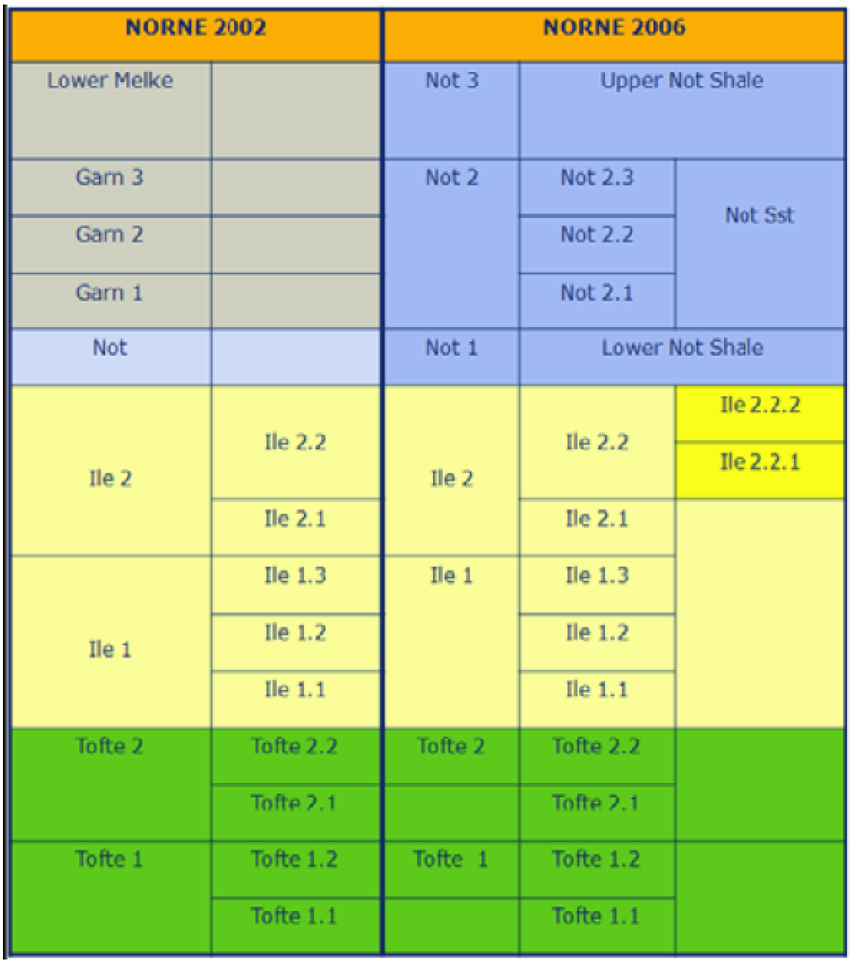
The Jurassic source rocks of Båt and Viking groups Halten and Dønna terraces are absent on the most of the Nordland Ridge and immature on the Trøndelag Platform as can be noted from the difference in depth in Figure 37 and Figure 41. They are however the prominent source rocks on the western margin. The Spekk Formation is a kerogen type II-type III source with TOC content ranging from 5-10 % while the coals in the Are Formation are kerogen type III with very high organic content (Gowers & Lunde, 1984).

The information regarding the potential of the Upper Permian source rock has been gathered from the works of Bugge et al. (2002) and Müller et al. (2005) in the Helgeland Basin along with the studies of Christiansen et al. (1993); Karlsen et al. (1988); Stemmerik et al. (2001); (Stemmerik et al., 1997); Stemmerik et al. (1998) on East Greenland equivalent Ravnefjeld Formation. (chapter 2.3). The Ravnefjeld equivalent organic rich Permian claystones (Bugge et al., 2002) (Figure 12) have been estimated to lie within the maturity window on the Nordland Ridge and Trøndelag Platform (Figure 48B). They offset the lack of charge from Jurassic source rocks on the Halten and Donna Terraces (**Error! Reference source not found.**). The presence of organic rich claystone sequences within the Lower Triassic Wordie Creek equivalent formation (Bugge et al., 2002) (Figure 12) can also act as viable source rocks if their thickness trends and areal extent are mapped. The difference in the burial depths is 250-300 m from **Error! Reference source not found.**. If proven, they are close enough to the Permian shales to be within the hydrocarbon generation window, albeit with lower transformation ratios. The maturity of Permian shales, however, also depends on the rate of burial and subsidence. A major uncertainty exists in the timing of bulk expulsion and migration due to lack of data. The thickness of Triassic strata observed on the Nordland Ridge; including the uplifted northern parts of the study area correspond to at least 1000 ms of depth (TWT) indicating the lower parts had a higher burial depth towards the end of Triassic. The rifting episodes of mid Jurassic and Cretaceous (sub chapters 2.1.5 and 2.1.6) provided a significant change in this depth of the underlying strata (Figure 36B). An inference drawn from this is that the beginning of expulsion happened during Middle to Upper Jurassic. Furthermore, as the organic content matured, the bulk of expulsion could have happened during the Cretaceous extensional regimes (**Error! Reference source not found.**).

5.1.2 Reservoirs

The reservoir zones in the region are at multiple stratigraphic levels (Figure 52). The primary targets are from the Mesozoic era. They have a proven potential in the fields and discoveries on Dønna Terrace and the western edge of Nordland Ridge. As discussed earlier, the Lower Jurassic Båt Group, especially the Åre Formation are found to be displaying reservoir potential throughout the region (Figure 37). The Åre 1 member has better reservoir qualities than the Åre 2 member. Åre 2 has instead a higher source rock potential due to interbedded coals (Svela, 2001). However, as observed from wells 6608/10-13 and 6608/11-1 the upper member has been truncated along the high of Nordland Ridge (Figure 37B) but is preserved on the Trøndelag Platform along with Tilje Formation which is absent almost throughout the Nordland Ridge except on the eastern side of the study area (**Error! Reference source not found.**). These two formations make the Båt Group a promising interval for reservoir.

The Fangst Group also contains proven reservoir formations (chapter 2.3). Its presence on the Trøndelag Platform increases the reservoir potential of the Middle Jurassic deposits. Furthermore, since the formations of this group have a better preservation than on the Nordland Ridge, the presence of Not Formation would provide an added internal seal element within the group, similar to the zonation of the Norne field (chapter 2.3) (Figure 53). Well 6609/10-2 (Figure 54) was drilled in the Helgeland Basin and encountered a 40 m sequence of Ile Formation(NPD, 2011).but the lateral extent of this could not be confirmed.



NORNE 2002		NORNE 2006		
Lower Melke		Not 3	Upper Not Shale	
Garn 3		Not 2	Not 2.3	Not Sst
Garn 2			Not 2.2	
Garn 1			Not 2.1	
Not		Not 1	Lower Not Shale	
Ile 2	Ile 2.2	Ile 2	Ile 2.2	Ile 2.2.2
				Ile 2.2.1
	Ile 2.1		Ile 2.1	
Ile 1	Ile 1.3	Ile 1	Ile 1.3	
	Ile 1.2		Ile 1.2	
	Ile 1.1		Ile 1.1	
Tofte 2	Tofte 2.2	Tofte 2	Tofte 2.2	
	Tofte 2.1		Tofte 2.1	
Tofte 1	Tofte 1.2	Tofte 1	Tofte 1.2	
	Tofte 1.1		Tofte 1.1	

Figure 53: Internal zonation of the Norne field producing zone (Rwechungura et al., 2010)

The absence of good Jurassic reservoirs in some areas brings the focus on older sequences. The Permian Wegener Halvø Formation equivalent carbonate platforms (**Error! Reference source not found.**) were partially mapped by extending the interpretation from well 6608/8-1 that lies on the northern edge of the study area but is not a part of the data set. The other wells in the area have not drilled through this formation (chapter 4.1) (Figure 21). This made interpretation a challenge. Furthermore, due to conflicting information from wells that have encountered the formation (chapter 2.3) and time constraints the interpretation of this horizon was abandoned. The differing observations from wells 6507/6-4 and 6608/8-1 could be attributed to the burial depth of these carbonates. Well 6608/8-1 has been drilled close to the crest of fault F1 (Figure 30) where the basement is relatively shallow as compared to well 6507/6-4 where the formation was encountered at a depth interval of 4147-4224 m TVD (NPD, 2013).Nevertheless, the Permian carbonates remain a zone of interest and can be classified as reservoir rocks.

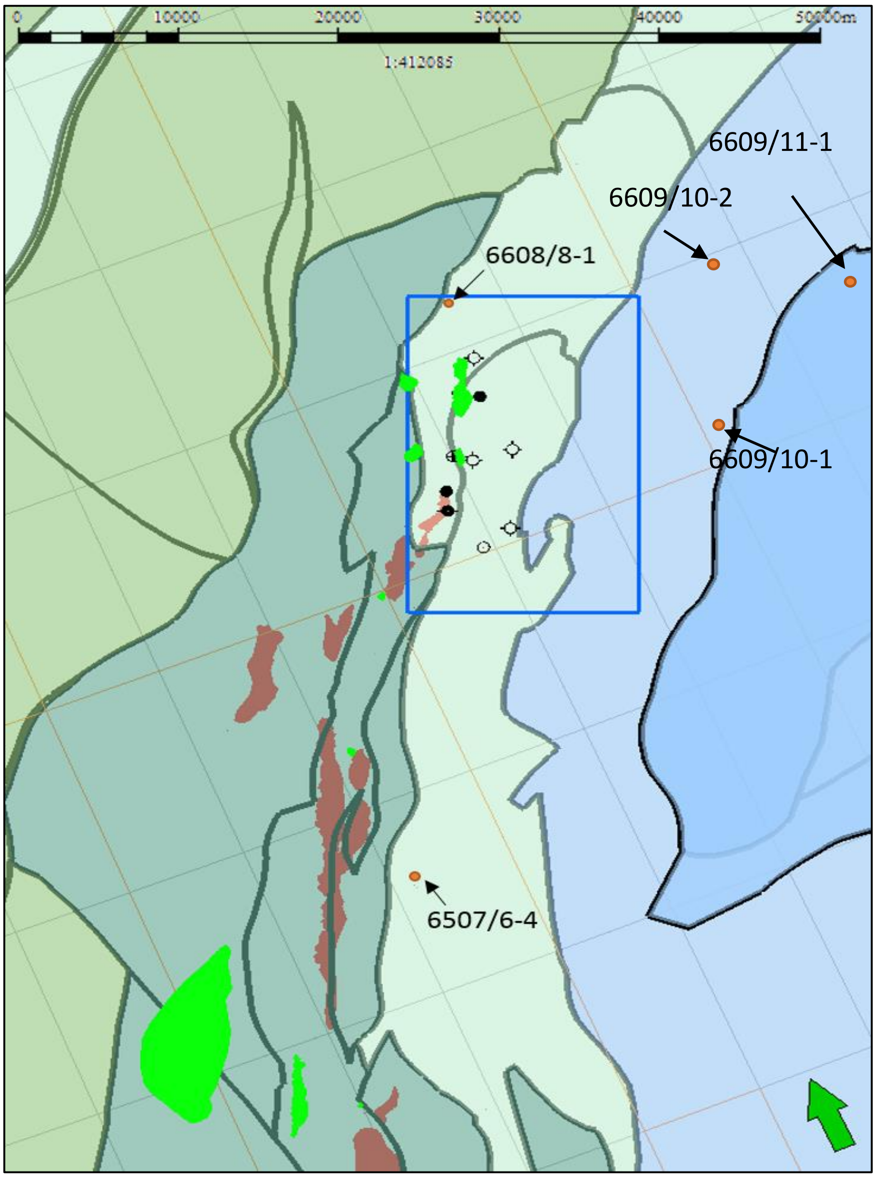


Figure 54: Map showing the locations of wells 6608/8-1,6507/6-4, 6609/10-2, 6609/10-1 and 6609/11-1 (marked as orange circles) relative to the study area (marked in blue rectangle. The wells that are a part of the data set are shown in black on a structural map of the Norwegian Sea. The producing fields shown in red and discoveries are shown in green.

The Upper Triassic sandstones of the Grey Beds have been penetrated by multiple wells and have shown good reservoir characteristics (Figure 52). Lower Triassic deposits on the Nordland Ridge and Trøndelag Platform correspond to the Wordie Creek and Pingo Dal formations from East Greenland (Müller et al., 2005). These formations have not been penetrated by any of the wells and were therefore, not marked on the petroleum system chart under any category. Their understanding is based purely on the studies done by Bugge et al. (2002); Müller et al. (2005). These formations are overlain by the Red Bed evaporite sequence deposited from Anisian to Norian. Müller et al. (2005) have subdivided these sequences on the basis of anhydrite content. The Anisian-Ladinian, Middle Triassic deposits show an increasing concentration of anhydrite content and were deposited as growth strata during the Permo-Triassic rifting phase. The Upper Triassic Carnian deposits are from a dominant marine evaporitic enviroment.and are post rift sequences that were faulted during the subsequent Jurassic extensional regime. This implies that the Lower Triassic growth strata could have potential as a play zone and might have a working petroleum system due to the close proximity to the Permian source and an evaporitic seal on the top. The reservoir quality however might be a challenge with these formations. As discussed earlier, the Permian carbonate platforms do not prove to be good reservoirs at greater depths. Wordie Creek Formation is also a carbonate dominated deposit (Stemmerik et al., 2001) and with similar burial depths, it could also exhibit loss of porosity and permeability.

5.1.3 Seals- an uncertainty.

Even though the Middle Triassic evaporites units would form an excellent seal, this element of the petroleum system has a high degree of uncertainty within the area. Some parts of the Nordland Ridge were not submerged until the late Cretaceous. Thereafter the uplift during the Paleocene may have removed some of the deposits. The Rogaland Group and late Cretaceous Springar Formation which were deposited during a period of high sediment inflow may not have been adequately buried due to the subsequent starvation during the Ypresian transgression followed by a period of non-deposition from mid Eocene to mid Miocene (chapters 2.1.7 and 2.1.5). At this point it is safe to assume that until the beginning of deposition of the Nordland Group, adequate seals might not have been present over the Nordland Ridge. The hydrocarbon generation window for Lower Jurassic source rocks began in early Cretaceous while the Upper Jurassic shales began producing by mid Cretaceous

(Larsen & Skarpnes, 1984) which precedes the formation of the top seal (**Error! Reference source not found.**). Subsequent Lower Cretaceous rifting activity could have allowed appreciable amounts of hydrocarbons to escape entrapment.

On the eastern margin, The Viking Group shales of Melke and Spekk formations were found in wells 6609/10-1 and 6609/11-1 (Figure 54) with thicknesses upwards of 100 m which can act as viable seals. Both these wells along with well 6609/10-2 (Figure 54), also drilled in the Helgeland Basin, have encountered thick sequences of the Lower Jurassic Ror Formation (NPD, 1985, 2005, 2011) (chapter 4.2). This would form a good seal between the reservoirs of the Båt and Fangst groups. The Not Formation is present over some parts of the study area, however three of the wells that encountered this formation were dry wells. The wells from Helgeland Basin also did not show the presence of the Not Formation, which reduces the confidence on the coverage of the Not Formation as a viable sealing unit.

The Red Bed evaporite units. (Figure 36) are also widespread in the area. Their thickness (chapter2.2.2) and lateral extent in the Trøndelag Platform and Nordland Ridge also make them excellent seals.

both Spekk and Melke formations, which act as seals on the Dønna. The evaporite units within the Red Beds are present all over the region and can act as potential sealing elements for Lower Triassic formations.

5.1.4 Traps

The Nordland Ridge has a complex tectonic evolution which has resulted in the development of various types of traps within the region. (Figure 46, Figure 45, Figure 56)

- Structrural traps.: These are formed on fault block footwalls due to juxtaposition against a seal. These were formed during the Middle to Late Jurassic and Cretaceous rifting phase. The mid Jurassic lead proposed in the observations is a structural trap juxtaposed against shales of the Spekk Formation (Figure 52).

  Structrual traps are also formed in folded anticlines that are sealed by overlying strata or by truncation against the BCU and base Paleocene unconformity. Linerle is an example of a structural trap within a fold that has the Cretaceous deposits acting as seal after erosion. The Late Kimmeridgian compressional regime formed multiple folded structures in the Trøndelag Platform and Nordland Ridge (Figure 46). The compressional events of Oligocene and Miocene, however, do not show any significant impact on the Mesozoic and early Cenozoic strata. Another sub type of structural traps are the syn rift wedges, but those that were observed within the area do not have sufficient throws to be completely juxtaposed against a seal (Figure 46 block X4 and Figure 45).

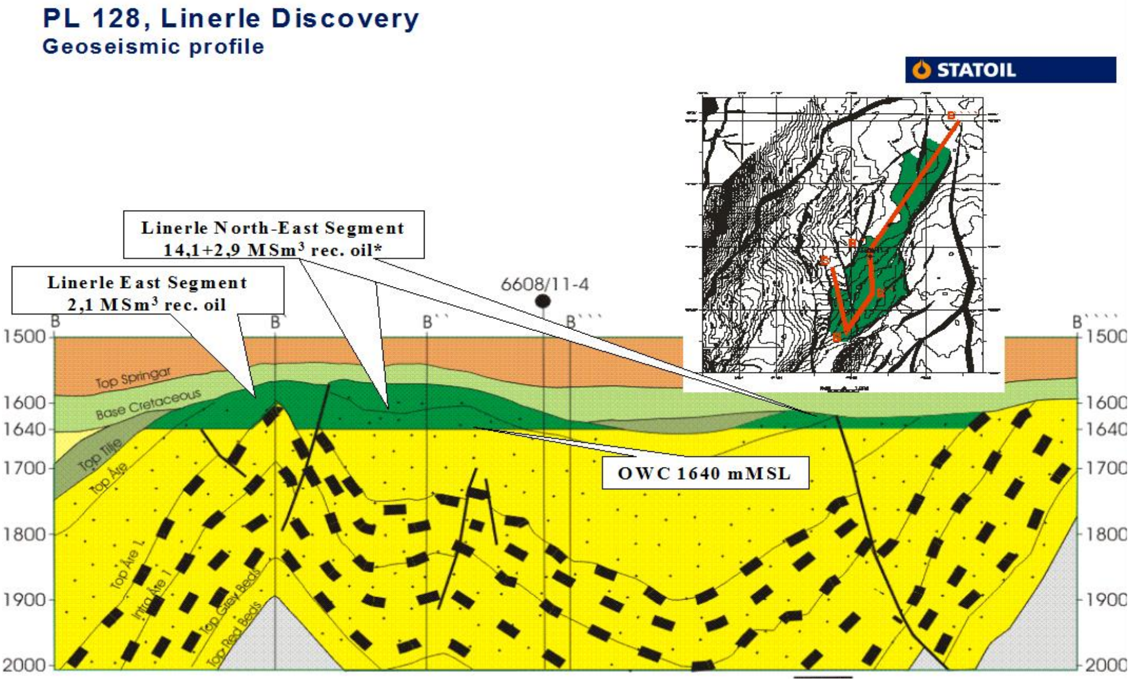


Figure 55: The cross section of the Linerle discovery. Courtesy Statoil.

- Stratigraphic traps that have been observed in the region are due to truncation against against the unconformities (**Error! Reference source not found.**).

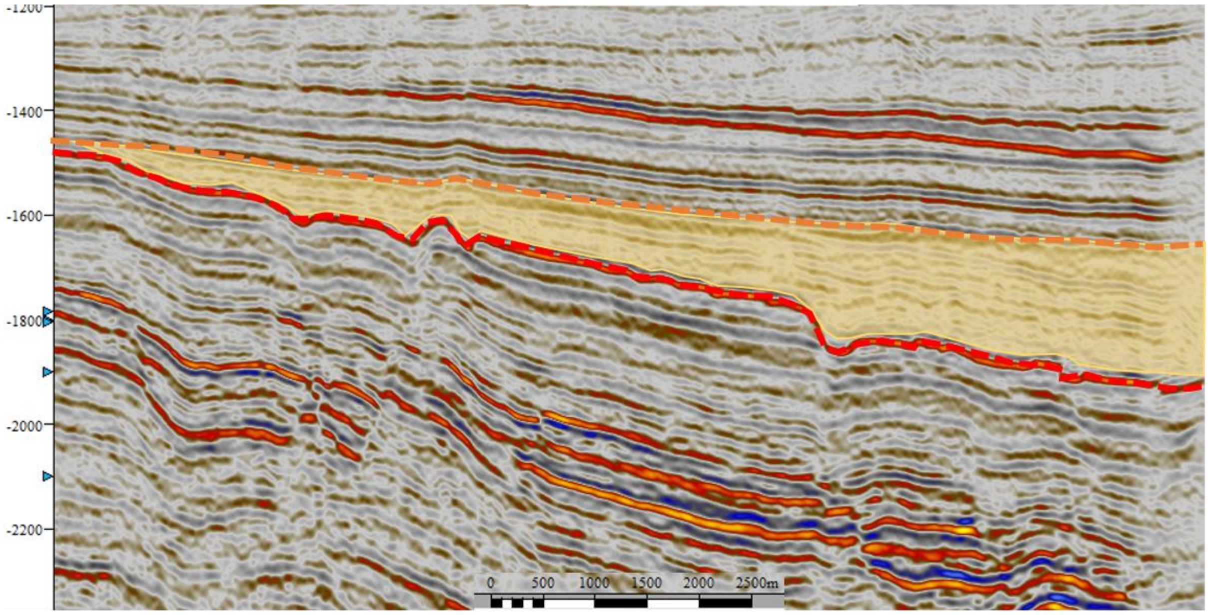


Figure 56: A conceptual example of how a stratigraphic trap would look in this area. A pitchout of Cretaceous sediments between the BCU (red) and the base Paleocene unconformity (orange). The deposits between them are clay dominated.

5.1.5 Migration – another uncertainty

The Haltenbanken and Dønna Terrace source rocks have charged all of the hydrocarbon accumulations of the greater Norne area, which indicates large migration distances and increases the inherent uncertainty of the system. This also explains the progressive degradation in the quality of charge implying that if any traps with these accumulations were found towards the eastern side they would be of very low quality.

The hydrocarbon generation from Permian source rocks in the deeper parts of Nordland Ridge and Trøndelag Platform is a notional concept for now. The potential of this area also depends on the migration of charge making it another one of the major uncertainties of the system. Most of the faults that border the Trøndelag Platform dip in an easterly direction (Figure 30, Figure 45, Figure 32), which is a positive factor as it provides a natural path to the migrating hydrocarbons to accumulate within the traps. However, the overlying stratigraphic column of the Triassic deposits inhibits the vertical migration of hydrocarbons through percolation. Primary migration pathways through conducting faults provide a plausible alternative to the problem Most of the faults in the region have permeable zones juxtaposed against each other allowing for migration pathways but the presence of thick sequences like the Red Bed evaporites poses a significant barrier. Secondary migration is dependent on minor fault complexes and unconformity surfaces within Trøndelag Platform towards Nordland Ridge The deeper structures within the Trøndelag Platform are better positioned to trap these hydrocarbons and any spillovers might migrate towards the shallower structures in the Nordland Ridge. Migration from source rocks within the Nordland Ridge would be a preferred method to charge the traps in the northern parts of the area as the Lower Triassic units are underlying Paleocene marine shales but most of the wells in the central part of the Ridge are dry thus negating this concept. Migration from further down south would probably be trapped closer depending on the sealing capacity pinchouts and faults.

6. CONCLUSIONS

This thesis has provided a play based evaluation of the eastern margin of the Nordland Ridge by identifying and evaluating petroleum system elements such as trap, reservoir, seal, charge and retention. To provide a coherent and thorough assessment of the play potential, some key concepts had to be answered:

1) **Investigate basin framework to improve the understanding of the development of trap mechanisms.** The Nordland Ridge has been molded and influenced by a complex tectonic history, and the major events has been well defined trough previous studies. By studying the timing of the different tectonic events, it has been possible to determine a range of structural trap mechanisms in the area often linked to the Middle – Late Jurassic rifting. This created a series of westerly rotated fault blocks on the eastern flank of the Nordland Ridge and consequently a number of 3-way structural closures with syn-rift stratigraphic Jurassic infill linked with reservoir potential. While of varying size, some of the larger structural entrapments could potentially support significant volumes of hydrocarbon and do therefore represent attractive exploration targets for further studies.
2) **Examine regional source rock maturation to determine the extent of the hydrocarbon charge.** On the western part of Nordland Ridge, there has been proven significant hydrocarbon source potential in the Jurassic Spekk Formation. The success of the fields in this area can be largely attributed to a constant petroleum charge since Cretaceous times, from the oil- and gas-mature marine shales of the Spekk Formation and the coal seams od the Are Formation deposited at Haltenbanken to the west. This is an issue in the eastern area of the Nordland Ridge, as the marine shales of the Spekk Formation, have not reached deep enough burial depths to initiate hydrocarbon generation in regions proximal to the study area. The lack of maturation in the Spekk Formation and the location of the Nordland Ridge between the study area and the source to the west, make it unlikely that the eastern flank of the Nordland Ridge receives any significant hydrocarbon charge from the Spekk Formation. Alternatively, there has been proven source rock potential in the Permian Ravnefjeld Formation equivalent in the study area, which has seen the main expulsion since the rifting in Jurassic Times. Due to the imposed vertical migration pathway, there is however a significant uncertainty tied to a proposed charge to any Jurassic reservoirs.

3) **Analyze possible migration risks due to complex tectonic history of the region.** Migration poses a relatively high risk on the eastern part of the region. The accumulation of charge in Nordland Ridge shallow traps through migration pathways in the Trondelag Platform is complicated and some hydrocarbons may have escaped entrapment. Lack of significant research on the Lower and Middle Triassic deposits on Trondelag Platform inhibits a better understanding of the minor fault pathways within the Early Triassic rifting phase. Furthermore, with expulsion since Middle Jurassic, a lack of observed hydrocarbon accumulations on Trondelag Platform or Helgeland Basin poses an important question towards the migration patterns of the charge and possible accumulation within Triassic evaporite traps.

7 RECOMMENDATIONS AND FUTURE WORK

This play-evaluation study has highlighted some strengths and weaknesses of the different petroleum system elements and by these findings, it is possible to acknowledge the potential in conducting further studies of the area. This thesis has highlighted the uncertainty of hydrocarbon charge in the eastern flank of the Nordland Ridge. The Spekk Formation is well defined in the area, but fewer studies have been done on the Permian source rock. If a detailed evaluation of migration pathways could be conducted, this could prove beneficial in further assessing the potential of Permian charge to Jurassic reservoirs.

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