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The Integrated Study of Sequence Stratigraphy in The Upper Jurassic of The Horda Platform, The Northern North Sea

by

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Thesis

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The Integrated Study of Sequence Stratigraphy in The Upper Jurassic of the Horda Platform, The Northern North Sea

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Abstract

The Northern North Sea area is one of the most prolific hydrocarbon provinces in the world. The great successful development of the Troll field leads to a search for hidden potential in the Horda Platform and surrounding areas. This resulted in the launching of this study with the aim of building an extensive study of sequence stratigraphy framework and depositional evolution in the upper Jurassic.

This study aimed to use the state-of-the-art 3D broadband cube, which acquired by CGG 2014-2016 combined with 18 key well data to build a new sequence stratigraphic framework for the upper Jurassic. The study result was linked to the petroleum significance to provide an opportunity and a new concept for further exploration and development work.

Seven key stratigraphic surfaces were interpreted in well data and mapped in 3D seismic data. Stratigraphic surfaces comprised the Top Brent, U60, FS50, U40, FS30, U20 and the BCU. The stratigraphic surfaces were divided into six stratigraphic units which were Unit 1 to Unit 6. The Units were classified into two tectonic periods during the upper Jurassic as Inter-rifting period; Unit 1 to Unit 3 and Syn-rifting period; Unit 3 to Unit 6

The stratigraphic interpretation indicated the overview sea level rise in the first order and interrupted with one sea level fall in the second order. The sea level played an essential role together with the tectonic event to control the depositional regime in the Horda platform, especially during the syn-tectonic rifting of the upper Jurassic. Four stratigraphic sequences were generated in the third order including three highstand system tracts, three lowstand system tracts, three transgressive system tracts and five sequence boundaries.

The seismic facies analysis were introduced to explain more high resolution detail of the depositional environment between key wells. The facies and paleogeographic maps suggested the marginal marine/delta environment to offshore marine in the Horda Platform. The high temporal and lateral variation of the study result referred to a completed system of petroleum elements. The depositional setting in the Horda Platform led to good source and seal deposits in Unit 6 which was correlated to the Draupne Formation. High potential reservoirs which were Unit 2, Unit 3 and Unit 4 can be correlated to the Krossfjord, the Fenfjord and the Sognefjord Formations which were the main potential for the Troll field. The tectonic and structural regime created excellent traps from rotated tilting fault blocks. Finally, the hydrocarbon was generated and charged from the Viking Graben during the post rifting period.

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1. Introduction

The Northern North Sea is one of the most prolific hydrocarbon areas in the world. The petroleum production in this area has served the energy demand of Norway and Europe for more than 30 years. The production area comprises many giant petroleum fields such as the Tampen area which includes the Statfjord, the Gullfaks and the Snorre field, the Oseberg and the Troll fields.

The Horda Platform is located in the northern North Sea. The platform orientates in the north of 60°N to the south of 62°N. It is surrounded by two N-S trending fault zones; the Øygarden fault complex to the east and the Mokkurkalve fault complex to the west (Halland et al., 2011) (Figure 1). After the successful discovery of the Giant Troll field in 1995, the Horda Platform becomes an attractive area in the North Sea. Numerous extensive studies have been published in order to understand more of the structural and stratigraphic development of the main reservoir intervals, which are in the middle to upper Jurassic. Even if many contributions have been concentrated in the Horda Platform (Ryseth & Ramm, 1996; Christiansson, 2000; Fossen, 2003), in-depth details of sequence stratigraphy framework are still unclear. The formation of the Base Cretaceous unconformities (BCU) and the depositional environment of the Krossfjord and the Fensfjord formations are still in controversial (Osborne and Evans, 1987; Whitaker, 1984; Gabrielsen et al., 2001; Kyrkjebø, 2004; Holgate, 2015; Patruno et al., 2015). Therefore, an extensive study at the Horda Platform is still needed. New ideas from new studies will lead to new concepts for further explorations in this area.

The Northern North Sea area is a part of the North Sea rift system. Two main tectonic events divided the rift basin into two stages (Fossen et al., 2003). The first extensive rifting period was during the Permo-Triassic time, which formed normal faulting in the Horda Platform. The second active rifting was during the late Jurassic to the early Cretaceous, which resulted in the formation of the Viking Graben in the western part. The compressional forces from the Alpine continental collision affected the north-western part of Europe, which responded to fault reactivations in the Tertiary (Riddle, 1988). 3D seismic profile shows normal faults that increased accommodation space at downthrown blocks along the fault planes (Ravnas et al., 2000) (*Figure 4*). Faults primarily controlled the depositional patterns during the syn-rift period.

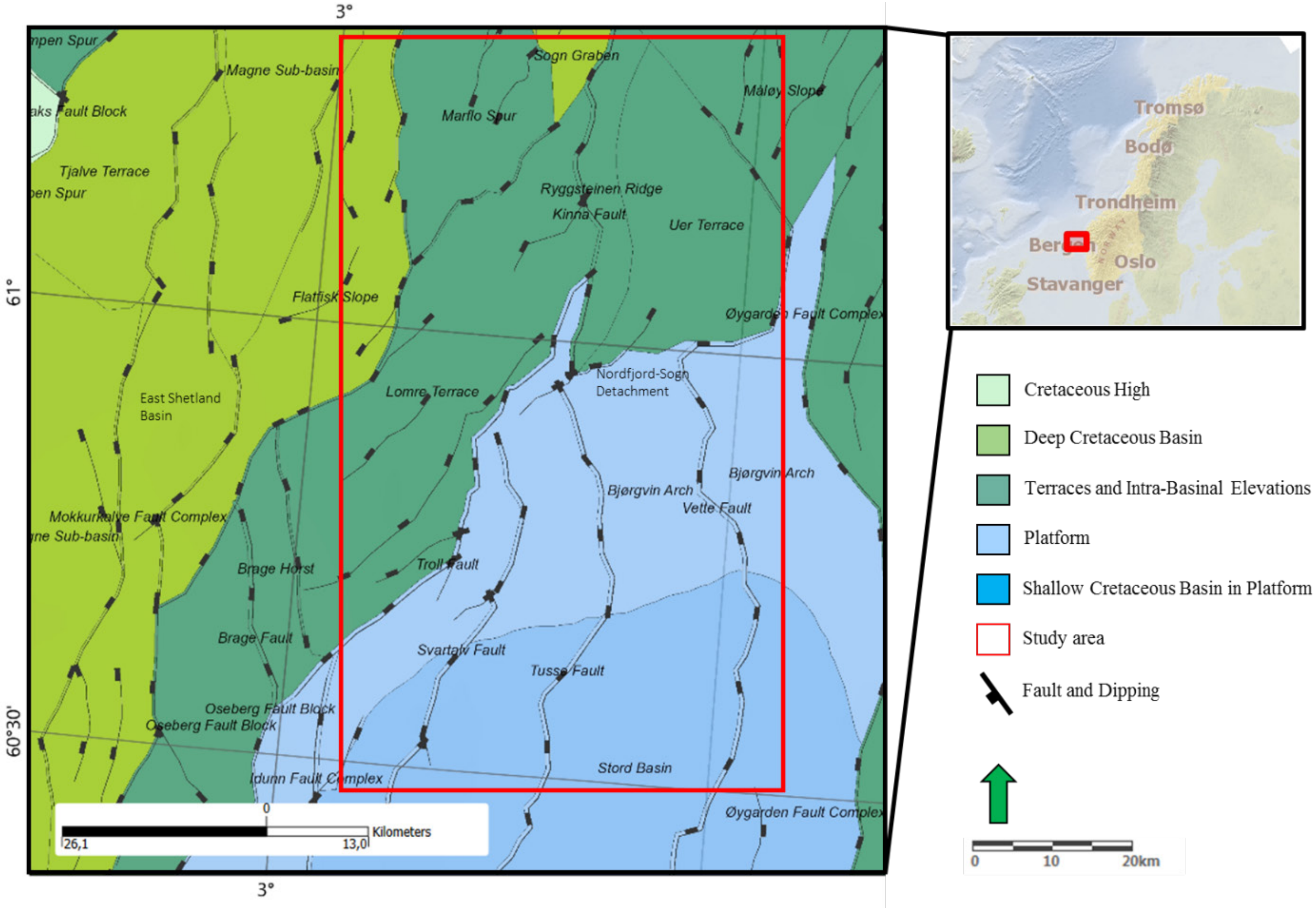


Figure 1. The location of the study area is in the Northern North Sea. It is located between 60°E to 62°E and 3°N to 4°N. The study covers main interesting areas such as the Troll area, the Bjorgvin Arch, the Uer Terrace, the Flatfisk Slope and the Lomre Terrace (modified after NPD, 2018).

Stratigraphy of the Horda Platform shows substantial hydrocarbon potential zones. Most wells were drilled to the main target reservoirs in the Jurassic interval. The middle to late Jurassic reservoirs consist mainly of deltaic and shallow marine depositional environment. Most successful petroleum plays in the Horda Platform were in the middle to late Jurassic (Brown, et al., 1987; Ryseth, 1989). The late Jurassic rifting caused significant mean sea level changes that deposited a thick sequence in restricted marine shale that formed a world-class source rock during the late Jurassic. The deposition of marine sediments was affected by the basin subsidence, which controlled by rotating and tilting fault blocks in the area. The deposition continued into the Tertiary. Then, uplift started in the Paleogene time which associated with the opening North Atlantic Ocean.

This study focuses on sequence stratigraphy analysis with the use of wells and 3D seismic data to suggest the geological model of the middle to late Jurassic interval of the Horda Platform. The study covers an area of 11,691 km^2. The study uses the new state of art 3D seismic data cube, which was acquired with the full-bandwidth BroadSeis™-BroadSource™ technology by CGG during 2014-2016. Well data in the quadrants 31 and 35 are used in this study. Key wells selections are picked to be used this study to control the seismic and stratigraphic interpretation. The integration of very high-resolution interpretations from wells and seismic data enhanced the stratigraphic model for the study area. The main software in this study is Petrel 2016 version from Schlumberger Plc. and Paleoscan 2017 version from Ellis. Deliverables from this study include

1) Key wells interpretation and correlation panels
2) Seismic interpretations of the study area
3) Time structural and isochrone maps
4) Stratigraphic interpretation with stratigraphic units, terminations and system tracts
6) Facies maps, paleogeographic maps and chronostratigraphic diagram
7) The conclusion of petroleum system significances in the study area.

1.1 Objectives

In general, modern sequence stratigraphy is an integrated study which uses well and seismic data. The aim is to create a stratigraphic framework from the geological model and depositional environment. The stratigraphic sequence field usually focuses in a regional area. High-quality control points are needed to generate a consistent result.

This study focuses on enhancing the quality of the stratigraphic models by integrating 3D seismic and well data. The study aims to use applications of both geophysical and geological fields in processes. Main objectives of this study are in twofold:

1) To produce a sequence stratigraphic model of the middle to upper Jurassic on the Horda Platform using the sequence stratigraphic methodology
2) To apply the sequence stratigraphic framework to build and improve paleogeographic understanding.

1.2 Previous Works

The Northern North Sea area is a mature oil province, which has supplied petroleum demands throughout Europe for decades. This area includes many large fields of both Norwagian and the UK concessions. High production rate within the area led to a significant amount of publications. Most studies were published in order to expose subsurface understanding in the giant fields. Many extensive studies were attracted in the nearby area in order to explore undiscovered places.

The study of the structural evolution is the most fundamental part for petroleum province to explain the overview picture. Fjerseth et al., (1997); Kwanjai, (2012); Whipp et al., (2014); Duffy et al., (2015); Jonassen, (2015) had publications related to the structural geology of the Horda Platform.

Fjerseth et al., (1997) provided the overview of the structural development during the Jurassic period. The study explained fault obliquity that changed the orientation during the Permo-Triassic to the Jurassic. The tectonic development through times resulted in differences in fault system characteristics (Figure 2). The largest extensional area of the North Sea is in the Viking and the Sogn Graben during the Jurassic.

Duffy et al., (2015) explained fault interactions and evolutions in the Horda Platform. The application of 3D seismic and borehole dataset was used to determine the interaction of fault intersections. The integrated data of well and seismic revealed interaction of non-colinear fault networks with multiple phases of extensions. The study explained fault evolutions in stages. The range of interactions was documented with the factors of both mechanical and kinematic regimes.

Whipp et al., (2014) highlighted the normal fault array evolutions during the phase of basin extensions using 3D seismic and borehole data. Observations and interpretations resulted in a conceptual model that indicated the influence of pre-existing rift on the fault array in the syn-rifting. Kwanjai, (2012) and Jonassen, (2015) published seismic, and fault interpretation works to improve more understanding of structures, fault geometries, growths and displacements in the Horda Platform area.

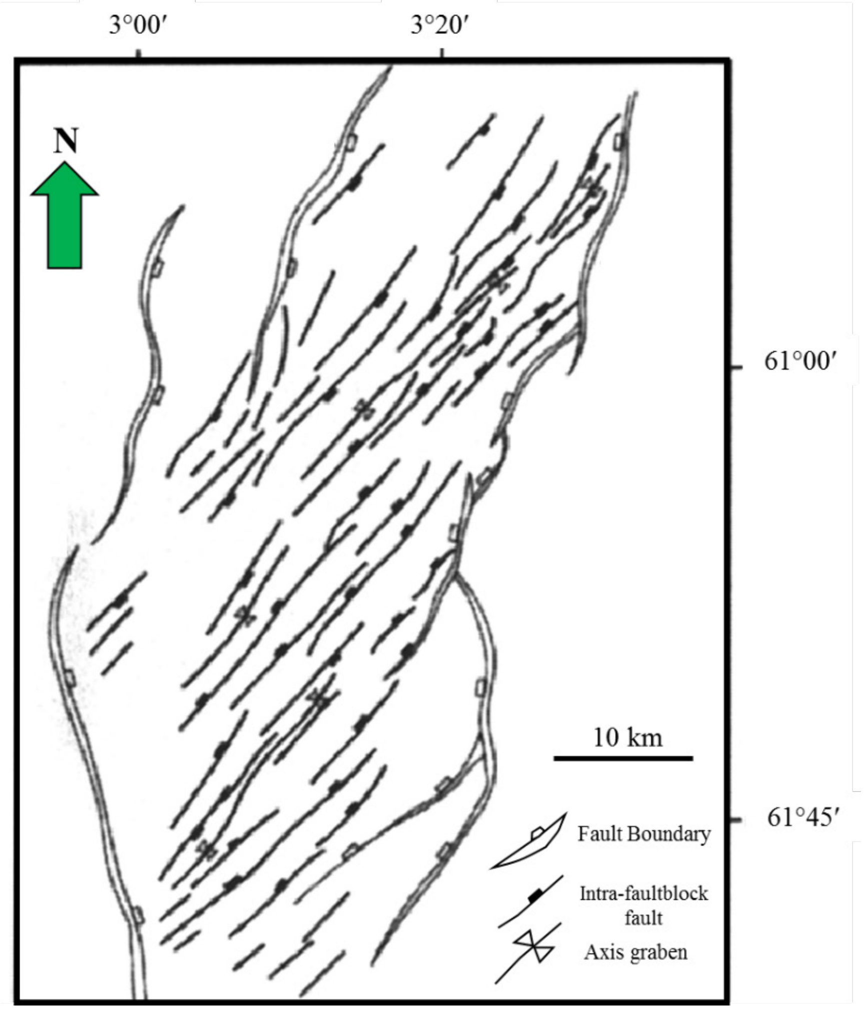


Figure 2. Base map shows oblique fault characteristics in the Jurassic rifting. N-S and NE-SW orientated faults were initiated during the Bathonian. The NE-SW extension was formed with 90-degree obliquity in association with the regional extension direction (modified after Fjerseth et al., 1997).

Stewart et al., (1995) performed a classical study of depositional systems and sequence stratigraphic models of the Jurassic. The use of core and biostratigraphic data provided consistent calibrated data for a sequence stratigraphy study. The study gave a summary in stacking pattern, stratigraphic geometries, and tectonic association during the Jurassic.

Ravnas et al., (2000) published a sedimentary architectures study in the Northern North Sea area, including the Horda Platform. The paper illustrated depositional environments of the area from the Permian to the Jurassic. The study suggested a tectonostratigraphic evolution of the

Horda Platform that observed at several scales. The rift basin evolved through multiple rifting phases on a regional scale. The short inter-rifting periods separated the rift episodes into several periods. The smaller scale was explained by a rotational tiling fault events which correlated to the third order sequence hierarchy (Figure 3).

A good understanding of Tectono-stratigraphic led to several details of local sequence stratigraphic models in the Horda area. The publication of Holgate et al., (2013); Holgate et al., (2014); Holgate et al., (2015) mainly focused on the Troll field during the middle to upper Jurassic stratigraphy. The Krossfjord and the Fensfjord formations are the main target study. The studies explained the source of sediment that came from the east. Facies classification using core descriptions in combination with clinoforms observations were used to summarise depositional systems and base level changes.

The Base Cretaceous Unconformities (BCU) was the main event that divided the chronostratigraphic change between the late Jurassic and the early Cretaceous strata. Kyrkjebø et al., (2004) explained the great unconformities in several scales of wavelength variations. The short wavelength variation indicated the local structural, e.g. the rotational tilting fault blocks. The long wavelength variation suggested the thermal and isostatic processes on a large scale. The use of seismic data and wireline log were used in the study to define complex configuration characters of the BCU.

Krivenko, (2014) performed the seismic interpretation in the Horda Platform. The study did a detailed study in three main reservoirs in the Jurassic period. The outcome showed a geological model of the Sognefjord Formation. This study provided a good example of detailed seismic interpretation and reservoir characterisation workflow, which is an essential step for sequence stratigraphic study.

Vindenes, (2013) and Amrizal, (2017), performed sequence stratigraphic analysis in the Northern North Sea area. They used the combination of 2D, 3D seismic data and well log data to interpret sequence stratigraphic distributions. Key seismic surfaces and units were interpreted on the state of art 3D seismic data. The studies described system tracts and facies classifications in the study interval. Chronostratigraphic diagrams were also generated to explain the spatial and temporal depositional trend. The studies linked petroleum significances into sequence stratigraphic model in order to reveal the potential of hydrocarbons in the study areas.

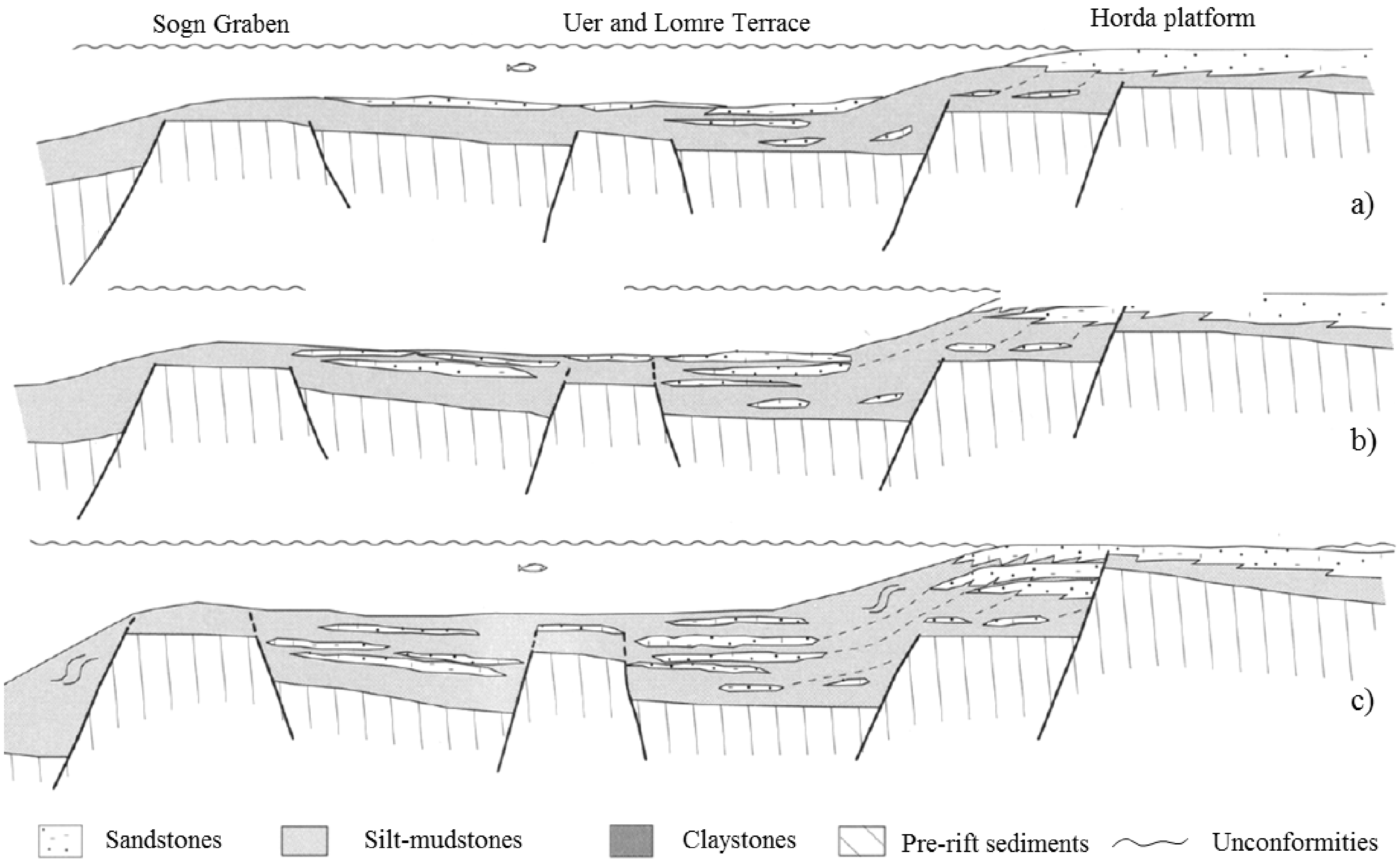


Figure 3. Schematics of sediments filled in the basin during the late Oxfordian-Volgian. The basin inclined toward NW of the Horda Platform. a) the tectonic quiescence stage – the late stage progradation. b) early syn-rotational – fault-scarp slope, depositional from gravity flow transport c) Rotation climax – isolated sand layers from gravity flow into the basin center. Higher mass flows along fault scarps (modified after, Ravnas et al., 2000).

2. Geology and Theoretical background

2.1 Geology of the study area

2.1.1 Tectonostratigraphic evolution

The Northern North Sea is a part of the North Sea rift system. The area of the Northern North Sea is surrounded by the Shetland Platform to the west, the Norwegian Sea to the North, Norwegian mainland to the east and the Stord basin to the South (Figure 1). The geological evolution of the Northern North Sea area can be explained in association with the background of the northwest Europe tectonic evolution. Two large grabens, the Viking and the Sogn Grabens, mainly controlled structural evolution in term of geometries and depositional trends (Figure 3 and Figure 4) (Yielding et al., 1992). Thick strata packages were accumulated from the pre-Triassic to the Tertiary (Nøttvedt et al., 1995). Tectonic evolution was mainly active between the Permo-Triassic to the early Cretaceous time. The Northern North Sea experienced two main rifting episodes and one inter-rifting period during the late Permo-Triassic to the early Cretaceous ages (Ziegler, 1975; Ziegler, 1990 ; Yielding et al., 1992). The tectonic episodes can be summarized as follows:

1. The late Permian to the early Triassic rifting
2. The middle Triassic to the middle Jurassic inter-rifting
3. The middle Jurassic to the early Cretaceous rifting

The Permian to early Triassic and the middle Jurassic to early Cretaceous rifting phases were dominated by tectonic extensional forces both spatially and temporarily. Multiple small extension phases controlled the area during active time. Two rifting periods specified structural configurations, e.g. the fault obliquity between the Permo-Triassic and the Jurassic (Lervik et al., 1989; Faerseth, 1997). In addition, paleotopographic geometries were different. Isostatic rebound during the inter-rifting phases made the changes of the topography that resulted in the different shape of local basins and high variability of the sediment fillings. (Nottvedt et al., 1995; Roberts et al., 1995). The rift basin during the Permian to early Triassic was stretched extensively in the Northern North Sea. The basin extended from the Norwegian mainland to the East Shetland Platform (Johns & Andrews, 1985; Lervik et al., 1989; Roberts et at., 1995). Half-graben and wedge-shaped infill geometries were main evidence of the Permo-Triassic rifting. The Horda Platform showed fault-bounded, wedge-shaped units formed during the

Permian to early Triassic times (Steel and Ryseth, 1990). Rotating faults associated with growth internal strata patterns, and represented growth faults during the syn-deposition. After the Permian to early Triassic stretching, the overlying middle Triassic to middle Jurassic sediments were generally assigned to the post-rift or inter-rift stages. During this time, faults still rotated but the strata showed the less divergent characteristic in the late stage and post-rift stages (Figure 4) (Olaussen et al., 1994).

It seemed reasonable to assume that the lower part of the first rifting was dated back to the late or probably early Permian (Johns & Andrews, 1985; Lervik et al. 1989; Steel, 1993; Faerseth et al., 1995a). The evidence of Permian dykes and ancient faults reactivation along the Nordfjord-Sogn detachment, an onshore western of Norway and the Northern Troll area, supported the syn-rifting origin (Faerseth, 1978; Furnes et al., 1982; Torsvik et al., 1992). The Permian to early Triassic syn-rift strata were underlain by another sedimentary package of the early Permian or Carboniferous (Christiansson et al., 2000). The sediment package was similar to ancient sediments below the East Shetland Platform (Piatt, 1995), and in the Oslo graben (Olaussen et al., 1994). On the Horda Platform, the notion of syn-rifting was found underneath the Viking Graben and in the East Shetland Basin, which based on wedge-shaped patterns and stratal geometries change (Lervik et al., 1989; Faerseth, 1997). Some areas on the Horda Platform showed very thick sediment succession of more than 2 km, and these were believed to be deposited by the alluvial depositional environment. The well 31/2-4 targeted at the top of the syn-rift succession (Steel & Ryseth, 1990).

The Permo-Triassic rift axis was believed to lie beneath the present Horda Platform, while the Late Jurassic rift axis was located underneath the present day Viking Graben (Figure 4). Thermal cooling stage and regional subsidence in the basin area commonly followed rift stages (Gabrielsen et al., 1990). The first inter-rifting event occurred after the Permo-Triassic extension (Faerseth et al., 1997). Little evidence of syn-rift was found during this time. In this period, the basin accumulated more uniform sediment thickness. This related to the thermal cooling and subsidence of the basin, which continued throughout the Middle Jurassic.

Reactivation of rifting occurred again during the Early Bathonian. The Viking Graben and the Sogn Graben represented main evidence again for the Jurassic triple rift system similar to the Permo-Triassic system (Dore et al., 1997). The NNE-SSW new fault system cut across the former N-S Permo-Triassic fault. This was postulated to be the main reason for the change of the system from symmetrical to asymmetrical grabens (Figure 2) (Marsden et al., 1990; Faerseth, 1997). Diachronous surfaces existed on high structural areas providing evidence of rifting since the middle Jurassic into the early Cretaceous (Graue et al., 1987). Also, sediment successions along rotated fault blocks inferred the second syn-rift period (Partington et al., 1993; Rattey and Hayward, 1993).

The climax rifting was in the late Jurassic where large sedimentary supplies and high fault active were observed in most faults throughout the basin (Badley et al., 1988; Gabrielsen et al., 1990). After this, the rift system became mature with stable base topographies, platforms and marginal highs along the axis (Gabrielsen et al., 1990; Nottvedt et al., 1995). The timing of the transition from syn-rift to post-rift periods is still unclear. Gabrielsen et al., (2001) commented that the termination of the rifting did not occur at the same time over the area due to differences in local thermal gradient distributions and fault configurations. However, conclusions from many publications suggested that the final stage of the Jurassic rifting system almost ended in the late Volgian when the basin was in quiescence period and sediment deposited up to 2 km (Rattey and Hayward, 1993). Some wedge shapes deposited during the post-Volgian was explained by the gravity mass flow depositional pattern succeeding the rifting phase (Harker and Rieuf, 1996).

2.1.2 Lithostratigraphy of the Viking Group

The Viking group strata were widespread on the Horda Platform. The BCU eroded the top Viking strata in most areas. The complete sections were mainly found in the east of Shetland Platform where was a basin centre (Figure 1). The stratigraphy of this group covered ages from Bathonian to Volgian (Vollset et al., 1984). The use of biostratigraphic data helped to date the stratigraphy. Palynofacies data used to correlate with sea level change and indicated ages for the biostratigraphic framework (Haq et al., 1987; Nio et al., 1991). In addition, trace fossils, dipmeter data were used in association with sedimentology to explain a depositional model of the formations of the Viking group (Bockelie, 1991). However, there were still uncertainties in the boundary between the late Jurassic and early Cretaceous due to the large unconformities and diachronous nature of this boundary. Many publications focused on the reservoir modelling and stratigraphy in the Horda Platform (Ravnas et al., 2000; Holgate et al., 2013; Holgate et al., 2014; Patruno et al., 2015).

The Viking Group was subdivided into five formations such as the Draupne, the Sognefjord, the Fensfjord, the Krossfjrod, and the Heather formations. The log type section of the Viking group is the well 31/2-1 in the Troll field which penetrated the Draupne, the Heather, the Sognefjord, the Fensfjord and the Krossfjord formations (Figure 5). The Heather and the

Draupne formations were the most widely distributed, while the Krossfjord, the Fensfjord and the Sognefjord formations represented more restricted the marginal marine area in the east (Vollset et al., 1984). The Brent group formed at the lower boundary and the BCU formed the upper boundary of the Viking group. The base of the Viking group identified by an unconformity boundary which separated sandstone of the upper Brent group and blocky log shape sandstone of the Krossfjord formation. The upper part of the Viking group was eroded due to the BCU, especially at most of the Northern Horda (Johnsen et al., 1995). Deposition overlain the unconformity was low radioactive Cretaceous to Paleocene sediments. The Viking group was deposited during the syn-rift led to varying thicknesses of sediment against the fault plane. The thickness measured from wells vary from few meters up to 1,000 meters (Vollset et al., 1984).

The depositional trend of the Viking group was anticipated to vary from the mixed shallow marine environment in the Horda Platform to the deep marine environment in the Lomre Terrace and the Flatfisk Slope. Successions toward west supported higher subsidence rates at the basin axis, the Viking Graben (Figure 4 and
Figure *6*). The rifting during the Jurassic period was a syn-rotational infill by tilting faults. The rifting type was a half graben which the active margin was in the Øygarden fault complex zone. The Viking intervals were dominated by three main sequences of interbedded sandstones-mudstones (
Figure *6*).

The summary of the Viking group stratigraphy was the strata in the middle to upper Jurassic with the main stacking pattern represented in progradation-aggradation-backstepping of deltaic and shallow-marine depositional systems across the Horda Platform. Depositional sequences were dominated by regressive and transgressive cycles. The presence of the interfingering sand layers suggested that sediments were supplied from the uplifted Norwegian hinterland and accommodation space increased due to higher rifting rate toward the west of the Horda Platform (Fraser et al., 2002; Ravnås and Bondevik, 1997; Sømme et al.,2013; Whipp et al., 2013).

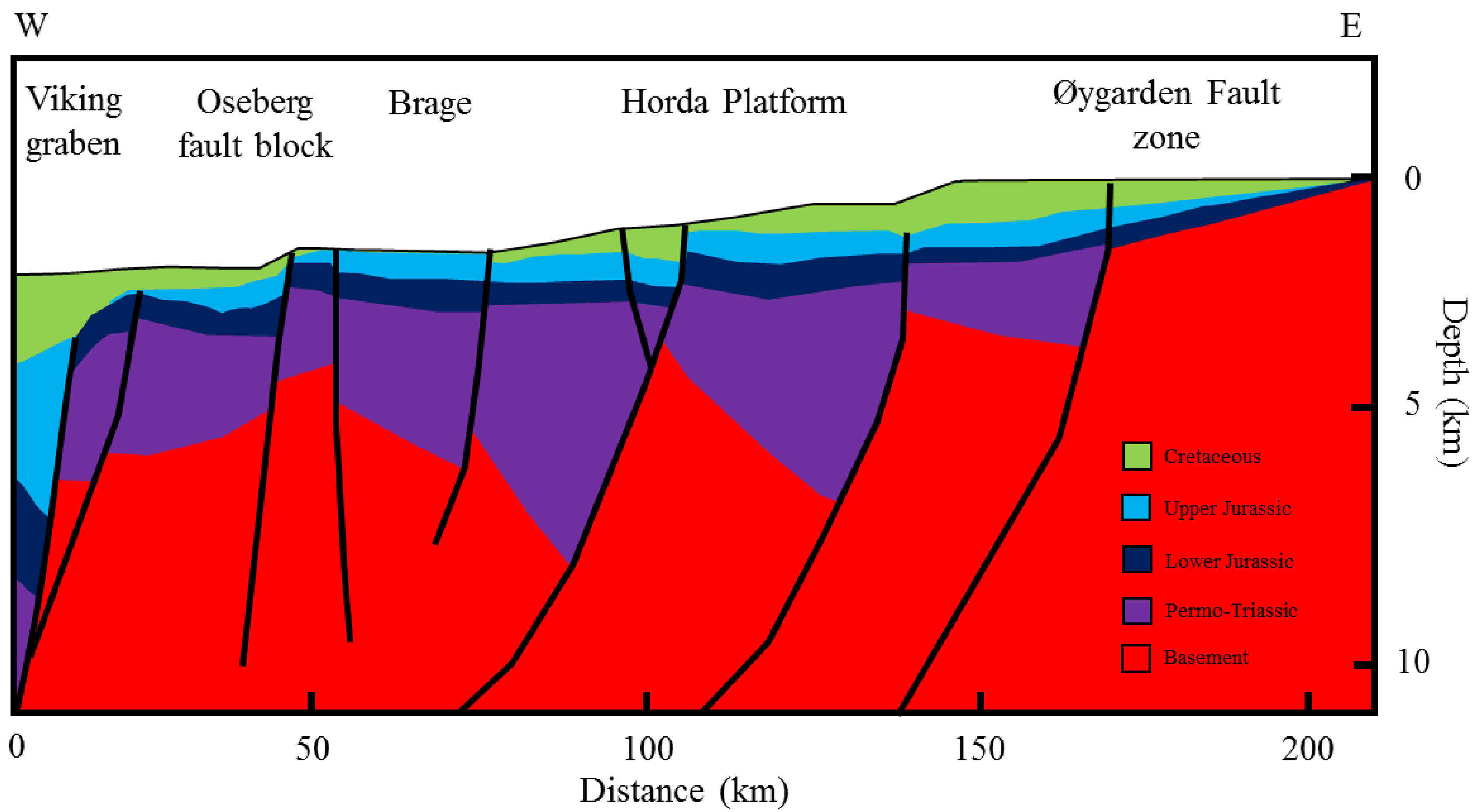


Figure 4. Structural schematic of the study area from the interpretation of seismic line. The line shows the structure and stratigraphic deposit from the Øygarden fault complex to the Viking Graben. The geometry of sediment deposits shows sediment thickness increases in the downthrown blocks against the fault plane (modified after Ravnas et al., 2000).

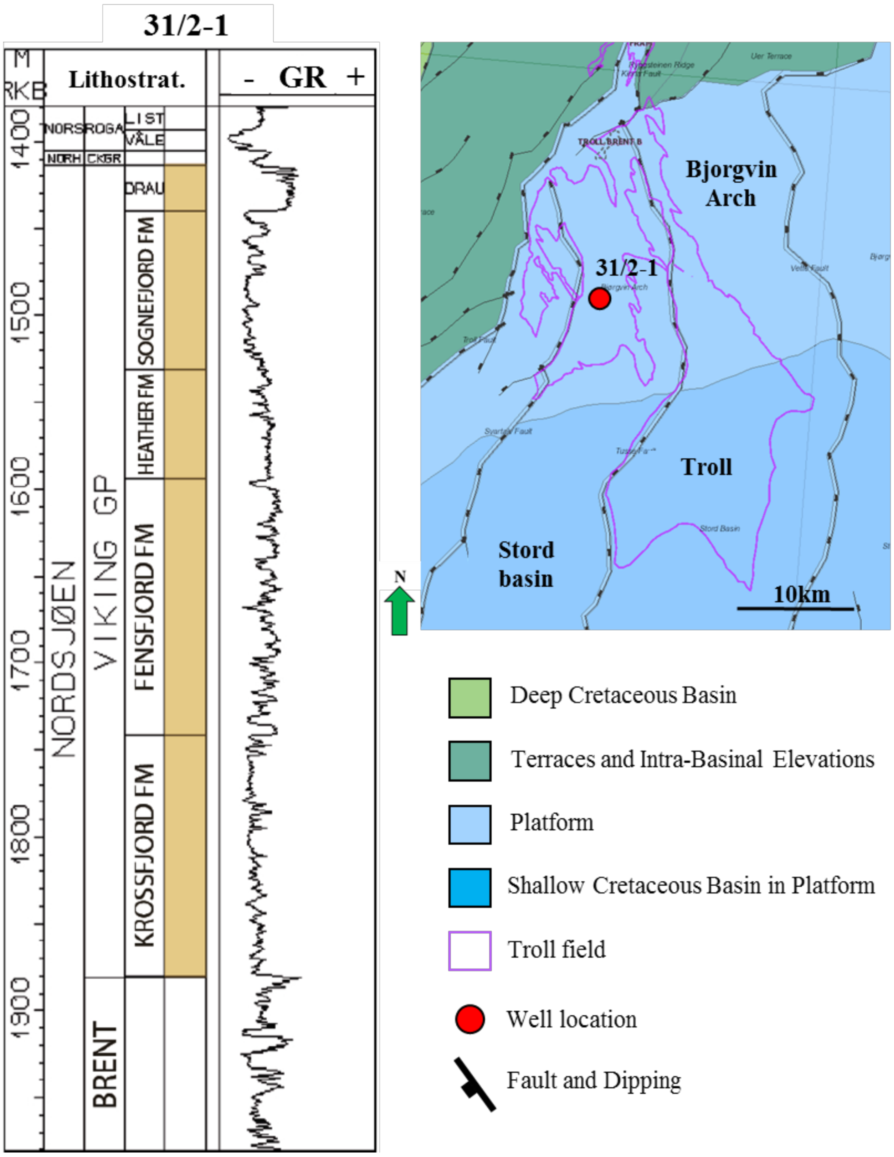


Figure 5. The log type section of the Viking group from the well 31/2-1. The well was drilled in the Troll field, penetrating the Draupne, the Heather, the Sognefjord, the Fensfjord and the Krossfjord formations. The GR log shows aggradational stacking pattern of sandstones in the lower part and fining upward stacking pattern at the upper part (modified after NPD, 2018).

2.1.2.1 The Heather formation (Bathonian to Kimmeridgian)

The Heather Formation is unofficially split into three parts on the Horda Platform. Three major sandstones of the Krossfjord, the Fensfjord and the Sognefjord formations are stratigraphic interferences the Heather formation (
Figure *6*).

The Heather A unit was the lowermost unit that separates the underlying Brent group and the overlying Krossfjord Formation. The overlying Heather B unit lay between the Fensfjord Formation and the Sognefjord Formation. Finally, the Heather C unit overlaid the Sognefjord Formation which was time equivalent to the Draupne formation (Stewart *et al.* 1995). The Heather and the Draupne Formations were regionally defined mainly silty claystone deposits with thin streaks of limestones and mudstones. However, the Draupne formation contained more blackish mudstones, which particularly had very high radioactivity due to high organic carbon content (Vollset et al., 1984). The formation was distributed over the Northern North Sea area (Deegan and Scull 1977). The Heather formation was deposited in an open marine environment which consisted of mainly grey silty claystone deposits.

2.1.2.2 The Krossfjord formation (Bathonian)

The Krossfjord formation was well developed in the Troll field area. It was bounded by the Heather C formation below and the Fensfjord formation above (
Figure 6). The main lithology of this formation was medium to coarse-grained sandstones with light greyish-brownish in colour. The lower part of the Krossfjord Formation was argillaceous and carbonaceous with minor shale intercalations (Vollset et al., 1984). Series of faulted terraces and rotating fault blocks were developed between the Viking Graben and the Horda Platform which caused shallow marine environment characteristics (Figure 4) (Vollset & Doré 1984; Steel, 1993). Previous works suggested that the formation was deposited in an offshore bar environment which resulted in poorly distributed sandstones throughout the Horda Platform (Hellem et al., 1986; Osborne and Evans, 1987; Whitaker, 1984). However, relatively low rates of fault movement and fault-block rotation at the southern Horda Platform caused thick sand-rich delta progradation for the Krossfjord reservoirs (Ravnas et al., 2000).
Stewart et al., (1995) and Holgate et al., (2013) indicated that the Krossfjord formation still contained a complex schematic of depositional environments. The western part of the Horda Platform mainly consisted of an N-S trending belt of wave-dominated shoreface. The eastern part contained irregular tide-dominated shoreline.

2.1.2.3 The Fensfjord formation (Callovian)

The Fensfjord formation was deposited in a similar depositional environment as the Krossfjord formation. The age of deposition was during the Callovian. It was bounded by the underlying Krossfjord and the overlying Heather B formations. The main lithology consisted of thick, coarse siltstones to coarse sandstones with a clear coarsening upwards sequence. The depositional environment has been interpreted to be a shallow or marginal marine environment under tidal influence Holgate et al., (2013). Recognition of the Fensfjord formation was based on the Gamma ray (GR) log trend which lower values than the Krossfjord formation (Vollset et al., 1984). The depositional trend of the Fensfjord formation was the progradation of the shallow shelf toward a deeper shelf at the west. Following by active fault period and fault block rotation in the Bathonian, the shoreline shifted toward the Brage area (Steel 1993; Stewart et al., 1995; Ravnas & Bondevik, 1997). The formation dominated by base level fall during the middle Callovian. A small period of tectonic quiescence during the middle Callovian caused a low basin subsidence rate and this period coincided with a higher sedimentary supply from the east. During the late Callovian, the Fensfjord delta reached the maximum regression and covered the entire Horda Platform including some part of Brage and Oseberg fields (Husmo et al., 2002). The maximum regression period in association with high sedimentary supply led to the gravity flow along the fault plane to the downdip direction. Deep marine sandstone deposits presented in the Lomre Terrace and the Flatfisk Slope where Fram area located. Reactivated extension and increasing rates of basinal subsidence resulted in the eastward retreat of the marginal shoreline, across the Horda Platform in the late Callovian (Steel, 1993).

2.1.2.4 The Sognefjord formation (Oxfordian to Kimmeridgian)

The Sognefjord formation is the primary reservoir for the Horda Platform, especially for the Troll field. The overlying formation is the Draupne, and the underlying formation is the Heather C.

Coastal shallow marine was the main depositional environment of this formation. Typical successions found in this area were coarsening upwards sequences consisting of coarse siltstones to very coarse sandstones (Figure 5). Pebbly and massive sandstone layers were found in the log data of the Horda Platform with high prograding stacking patterns. This reflected the proximal area of the sediment source on the Horda Platform (Vollset et al., 1984). The Sognefjord formation was deposited during the Oxfordian to the Kimmeridgian times when the climax rifting took place. The movement of major structures separated the Viking

Graben from the Horda Platform (Figure 4) (Stewart *et al.,* 1995). Higher tectonic activity resulted in more rotating and emerged fault blocks above sea level. This caused erosion and redeposition of eroded sediments in some areas (Fraser *et al.,* 2002). The progradations of the Sognefjord Formation evolved from the east across the shelfal area. Base level fluctuation also resulted in distribution and deposition of the Sognefjord formation sediments in small sub-basins throughout the Horda Platform (Gibbons, 1991).

2.1.2.5 The Draupne Formation (Oxfordian to Ryazanian)

The Draupne formation formed at the upper Viking group. The name was replaced with the former Kimmeridge Clay Formation in 1984 (Vollset et al., 1984). The Draupne Formation was deposited in a deep marine environment with restricted bottom circulation. This caused the Draupne formation to deposit high organic matter sediment in mudstone beds. The Draupne formation is the most prolific hydrocarbon source rock in the Northern North Sea (De' Ath and Schuyleman, 1981; Harms et al., 1981). The Draupne formation overlaid diachronously the Sognefjord formation, and in some areas on the Heather C formation (Fraser *et al.,* 2002). The age of the Draupne formation is from the Oxfordian to Ryazanian times. However, the age of the top Draupne formation is still in arguments. The final rifting period coincided with the Draupne formation, which created a substantial extension in the Viking graben with less throw on the Horda Platform area. Moreover, the uplifting during the early post-rift caused the strata truncated beneath the lower Cretaceous strata (Fossen *et al.,* 2003). This resulted in large erosions in several locations of the Horda Platform and lack of clear evidence for the age summary (Rawson and Riley, 1982; Husmo et al., 2002).

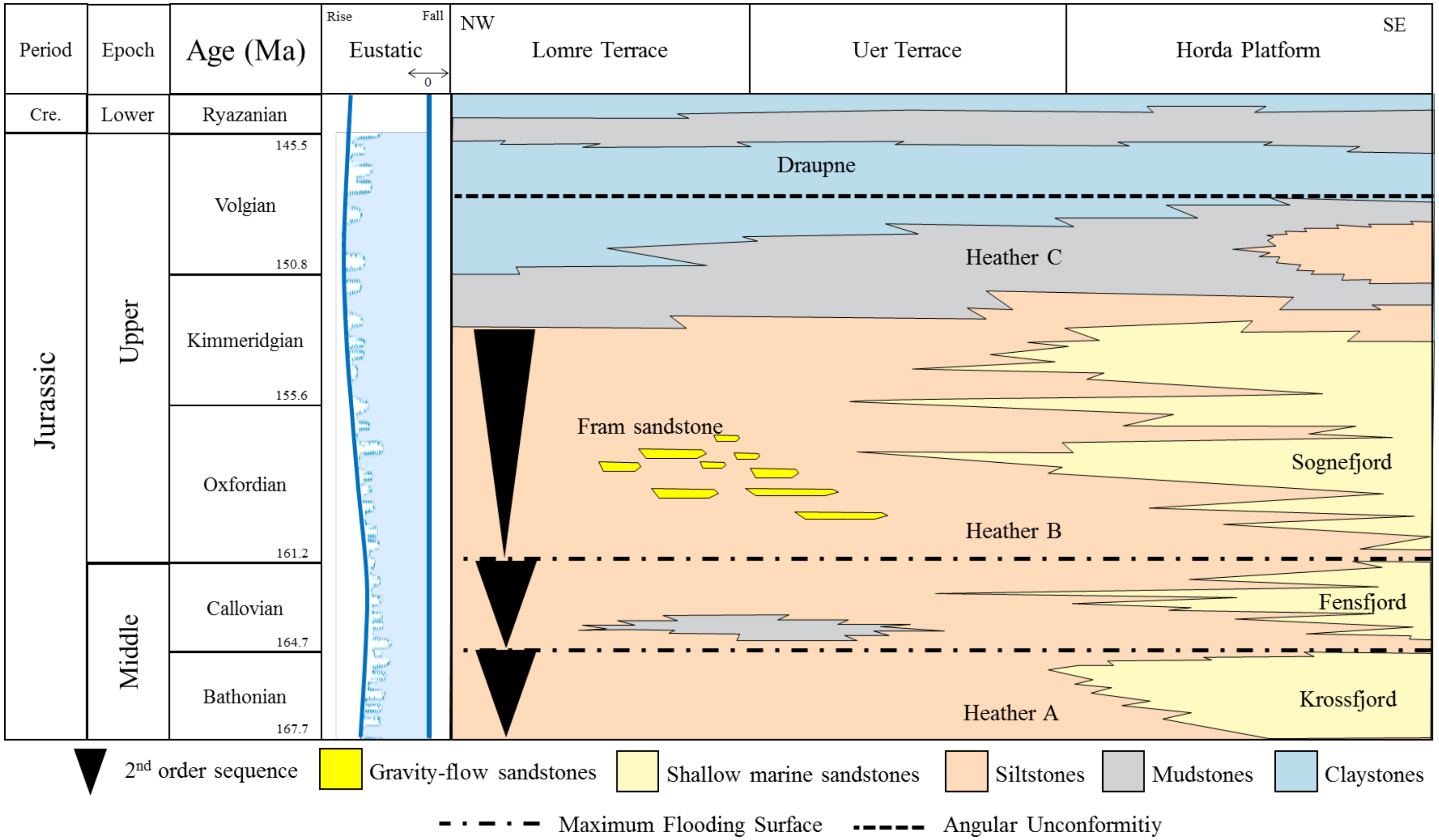


Figure 6. Chronostratigraphic chart, lithostratigraphic chart and eustatic level change (Snedden and Liu, 2010) show depositional schematic in the study interval. The schematic profile represents the area from the SE to NW direction covering the Horda Platform, the Uer terrace and the Lomre Terrace. Fram sandstone units are observed in the basinward during the Sognefjord formation deposited when the Horda platform highly prograded. The sea level rapidly rose following the Snedden and Liu, (2010) and resulted in deeper marine sediments deposited after the Kimmeridgian (modified after Fraser et al., 2002; Steward et al., 1995 and Snedden and Liu, 2010).

2.2 Sequence Stratigraphy

Sequence stratigraphy was in the old days a well-based data application that was used to investigate rock strata and succession (Hansen and Hampson, 2009). Sequence stratigraphy was integrated with seismic interpretation to be a modern application for sedimentology and depositional environment study (Miall, 1995). The objective of sequence stratigraphy analysis was the study of rock strata in order to find relationships between depositional environments and chronostratigraphic frameworks (Van Wagoner et al., 1988). There were many sequence stratigraphic tools in stratigraphic frameworks, including lithostratigraphy, chronostratigraphy, biostratigraphy and chemostratigraphy (Embry, 2009). The explanation of depositional sequences was beneficial for the exploration work to track back the source rock or pinched out reservoir in the stratigraphic trap (Ramsayer, 1979).

Catuneanu et al., (2011) suggested that stratigraphic study needed three main elements, which were sequences, system tracts, and parasequences. The fundamental tools of sequence analysis were surface boundaries that bound the stratigraphic unit. The presence of the surface boundary could be either unconformities or correlative unconformities. Sequence stratigraphic units comprised parasequences or parasequence sets. The parasequence was genetically related and bed bounded by marine flooding surfaces, correlative surfaces and unconformities. The evolution within the unit succession was explained by stacking patterns that finally linked to the system tracts (Van Wagoner et al., 1988). Genetic sequence was related to strata and succession, and this sequence was used to explain depositional sequences that formed the stratigraphic unit. Sequence stratigraphic hugely relied on the depositional regime including eustatic change, subsidence rate and sedimentary supply (Mitchum et al., 1977).

The modern sequence stratigraphy began when seismic reflection was integrated with sequence stratigraphy analysis. Vail et al., (1977) suggested that seismic sequence stratigraphy used the primary reflector to explain parallel-bedding planes and unconformities. Sedimentary surfaces could not cut across the time-transgressive lithostratigraphic boundary, so it behaved similarly to the seismic reflectors.

Seismic reflectors represented sequence stratigraphy in a regional trend, so the application provided a higher resolution of depositional environment. Modern stratigraphic interpretation allowed the geologist to recognise a significant variation of depositional environment controlled by seismic data. The seismic unit was subdivided into the package of concordant

reflections. Discontinuity surfaces separated stratigraphic units into packets, then used systematic reflection terminations to explain the unit (Ramsayer, 1979).
Many publications were conducted with applications for sequence stratigraphic analysis (Figure 7). Catuneanu et al., (2009) reviewed applications to standardise sequence stratigraphy applications (Figure 7). The conclusion showed four main criteria that were addressed in most publications:

1) Cyclicity (i.e. the sequence of rock record)
2) Temporal framework (i.e. the facies mapping or depositional sequence)
3) Genetic strata (i.e. correlative sequence within the strata)
4) The relationship between accommodation and sedimentation.

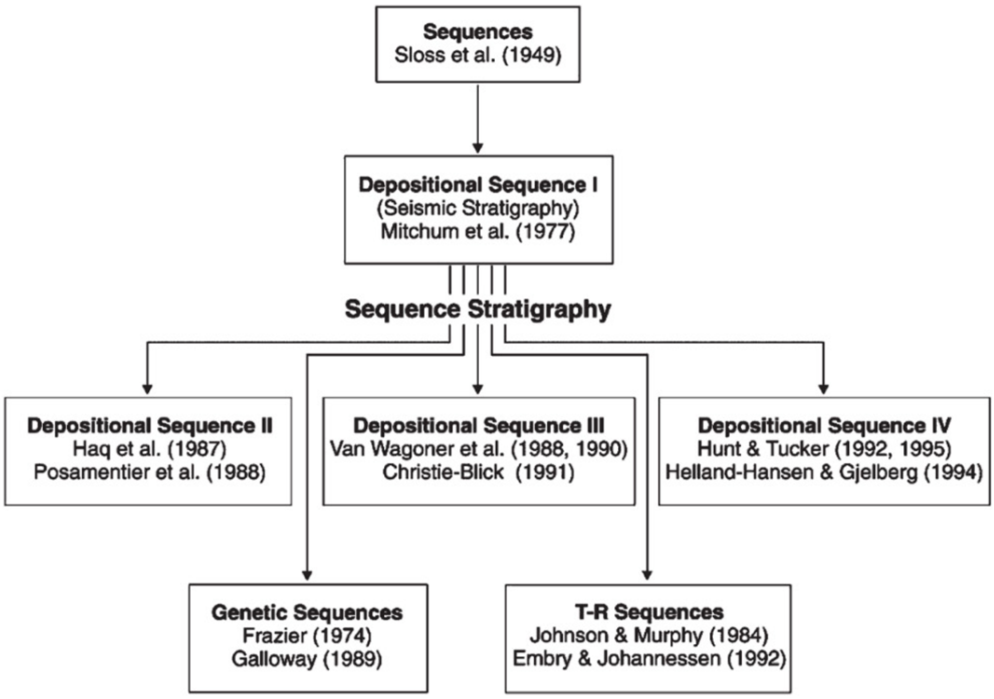


Figure 7. The model of sequence stratigraphy from Catuneanu, 2006 (modified after Donovan, 2001).

2.2.1 Stratigraphic Surfaces

The fundamental idea for stratigraphic surface marking was the depositional regime that included the relationship of accommodation space and sedimentary supply (Pitman, 1978). The stratigraphic surface was an essential tool, connecting the concept of sequence stratigraphy and geology scientifically. The definition of stratigraphic surface was associated with a conceptual horizon or a physical deposition where the surface showed an impedance contrast or a clear unconformable surface (Carter et al., 1998). There were six stratigraphic surfaces broadly used in sequence stratigraphy, which were subaerial unconformity, correlative conformity, maximum flooding surface, maximum regressive surface, transgressive ravinement surfaces and regressive surface of marine erosion.

2.2.1.1 Subaerial unconformity

Sloss et al., (1949) suggested that the subaerial unconformity was formed in the low sea level with high sedimentary supply condition, commonly presented in the non-marine environment. Subaerial unconformity was the most significant sedimentary hiatus in the stratigraphic sequence. It may have existed during the lowstand, the regressive surface of fluvial erosion and forced regression, within the downstream-controlled portion of fluvial systems (Posamentier et al., 1988; Schlager, 1992; Plint and Nummedal, 2000).

2.2.1.2 Correlative conformity

There were many terminations in correlative unconformities (Catuneanu et al., 2011). Posamentier et al., (1988) suggested a surface bounded by the highstand normal regression and the lowstand forced regression. Hunt and Tucker, (1992) proposed that the correlative conformity was between the lowstand forced regression and the lowstand normal regression. These methods were shown differently in the timeline. Therefore it was important for the user to rely on only one approach when interpret the sequence boundary.

2.2.1.3 Maximum flooding surface

The maximum flooding surface was a stratigraphic surface that represented the highest transgressive sequence (Frazier 1974). It was a type of marine flooding surface. The maximum flooding surface was the surface marks between transgressive and highstand system tracts, or the change from retrogradational to aggradational parasequence set (Figure 8) (Van Wagoner et al., 1988). Sometimes, the term ‘final transgressive surface’ was used alternatively (Nummedal et al., 1993). The maximum flooding surface was often used as a downlap surface in sequence interpretation. It typically showed the overlying and downlapping surface by the prograded clinoform of highstand system (Catuneanu et al., 2011).

2.2.1.4 Maximum regressive surface

The maximum regressive surface had the opposite meaning to the maximum flooding surface. It was the marked surface during the maximum shoreline regression. The thick sequence of massive sandstones with generally blocky shape on logs created an uncertainty to mark the surface in an interpretation (Catuneanu et al., 2009). The stratigraphic surface represented the end of lowstand system tract and the start of transgressive surface, the surface is correlative with the non-marine environment (Helland-Hansen and Martinsen 1996).

2.2.1.5 Transgressive ravinement surfaces

The transgressive ravinement surface was first expressed by (Nummedal and Swift 1987). It was the erosional surfaces from wave or tidal currents during the marine transgression (Allen and Posamentier 1993). The ravinement surfaces were diachronous and could be observed close to the shoreline. The surface merged with the maximum regressive surface in the basinward.

2.2.1.6 Regressive surface of marine erosion

The regressive surface of marine erosion was first expressed by Plint, (1988). It was an erosional surface generated by a wave current during the regression. The shoreline attempted to make an equilibrium state and resulted in the erosional surface which migrated seawards following the low base level. The regressive surface of marine erosion was diachronous (Embry, 1995). This could be caused from both forced and high energy normal regression environments (Helland-Hansen and Martinsen 1996).

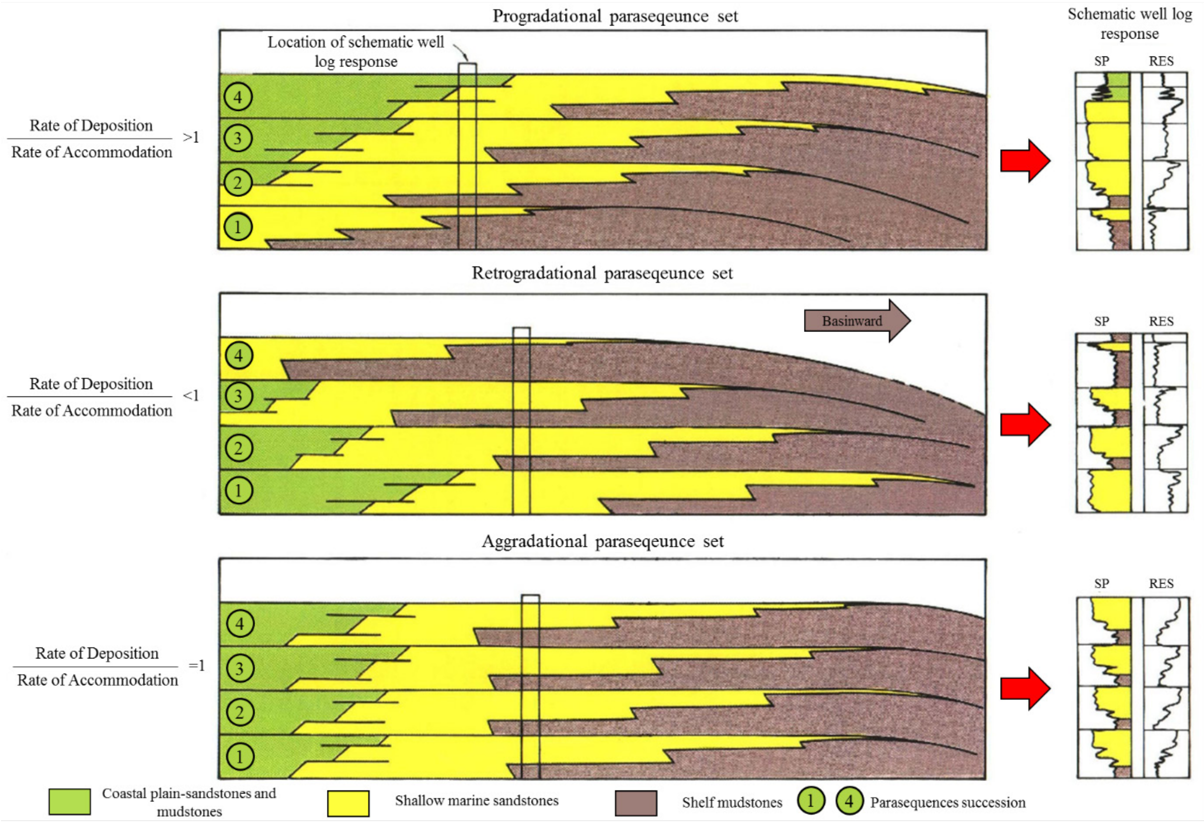


Figure 8. Vertical stacking pattern of parasequence sets. The stracking pattern reflects stratigraphic surfaces, stratigraphic system tracts and log responses. The stacking pattern is the interaction between base level change and sedimentary supply (modified from Van Wagoner et al., 1988).

2.2.2 Stratigraphic System tracts

Van Wagoner et al., (1988) suggested the fundamental unit of sequence stratigraphic which was the sequence. The sequence unit is bounded either by an unconformity or correlative conformity. Elements inside the sequence are system tracts which are defined by their stacking patterns. The definition of the system tract depends on the scale of observation and facies succession. However, a common agreement of system tract is the succession of the stratigraphic unit, which composes of genetically related strata and bounded by either unconformities or correlative conformities (Mitchum et al., 1977). System tract is the expression of units that linked units and sequences (Brown and Fisher, 1977). The system tracts are interpreted based on bounding surfaces of conformable or unconformable surfaces and stacking pattern. System tracts can be missing due to the large erosion from a rapid base level change (Posamentier and Allen, 1999). Since the presence of the surface boundary can be either unconformities or correlative unconformities, and there are different concepts to mark the surface boundary.

Catuneanu et al., (2009) reviewed applications to summarise the concept for sequence boundary marks and system tracts (*Figure 10*). This study used the depositional sequence type III for sequence boundary identifications (Figure 9 and *Figure 10*), sensu Van Wagoner et al., (1988).

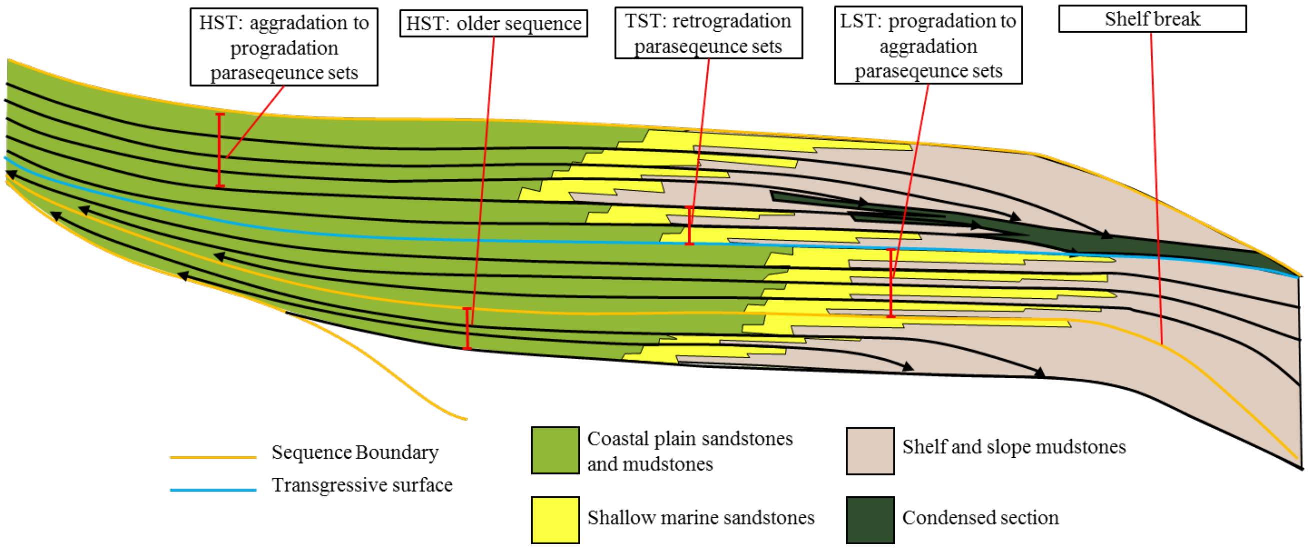


Figure 9. Strata patterns of system tracts and parasequence sets of the depositional sequence III in the shelf area. It comprises of LST, TST, HST and SB (modified, Van Wagoner et al., 1988)

2.2.2.1 Falling-Stage Systems Tract (FSST)

The FSST is deposited during a rapid marine regression after the fall of the relative sea level. The erosional surface is the evidence of sea level fall and subaerial exposure. Lowstand or transgressive system tract shows onlap surfaces on the top of FSST. The mark of FSST is described independently based on its applications. Posamentier and Allen, (1999) marked the FSST above the sequence boundary, while Hunt and Tucker, (1992) proposed to mark it under the sequence boundary. FSST is a good evidence for the diachronous line since it suggests the subaerial expose of the bed during the base level fall. The FSST generated an unconformity overlying on the high stand system tract (HST). However, the unconformity can also be onlapped by either the lowstand or transgressive system tract. They depend on the change in the rate of accommodation space and sedimentary supply (Catuneanu et al., 2011).

2.2.2.2 Lowstand Systems Tract (LST)

The LST is a depositional event during a normal regression. It overlays either on the FSST or the subaerial unconformity (Catuneanu et al., 2011). Shoreline progradations are generated by the FSST and LST deposits during the base level fall (Figure 8) (Posamentier et al., 1990). The

LST can erode and deposit in the HST or other former sequences by the rapid sea level drop. Posamentier et al., (1988) and Posamentier and Allen, (1999) used the term of the late lowstand system tract instead. In a condensed area, the LST may not exist due to lack of accommodation space from the fast base level fall (Posamentier et al., 2003).

2.2.2.3 Transgressive System Tract (TST)

The TST deposits during the stage of marine transgression until the reach of the maximum transgression of the shoreline. The TST lies on the LST and caps by the MFS. Onlap surface on the LST in the landward direction is the main characteristic of TST. The top of TST is the downlap surface which is a prograding clinoform from the HST. The TST terminates when sea level reaches the MFS. Parasequence sets change from the retrogradation to aggradation (Figure 8) (Van Wagoner et al., 1988).

2.2.2.4 Highstand Systems Tract (HST)

The HST is generally an upper system of the sequence stratigraphic unit. The main characteristic of HST is aggradational parasequences with prograding clinoform geometries (Figure 8) (Van Wagoner et al., 1988). The HST appears during the late sea level rise. Low mean sea level causes a smaller accommodation space. The prograding clinoforms form when sedimentary supply is higher than the accommodation space. The mark of HST is directly on the TST and underlying the subaerial unconformity (Posamentier and Allen, 1999).

2.2.3 Seismic Sequences Termination

In a modern sequence stratigraphy study, a seismic reflector is used to explain the system tract. Four basic terminations that connect lithology and seismic reflector are onlap, downlap, toplap and erosional truncation (Figure 11) (Ramsayer et al., 1979). Onlap is some horizontal or inclined strata that terminates updip against a greater inclined surface. Downlap is some inclined strata that terminate downdip against an inclined or horizontal surface. Toplap and erosional truncation are included in upper boundary relations. Toplap indicates nondeposition surface or minor erosion at the top. It is generally found in a local or subbasin area. Erosional truncation indicates the unconformity or erosional surface. The reflector shows a clearer image for high angular unconformity event due to high AI contrast (Mitchum et al., 1977).

The limitation of termination is the seismic resolution. Thin sediment deposition, homogeneity and fault area decrease reflector resolution and result in an uncertainty for termination detection.

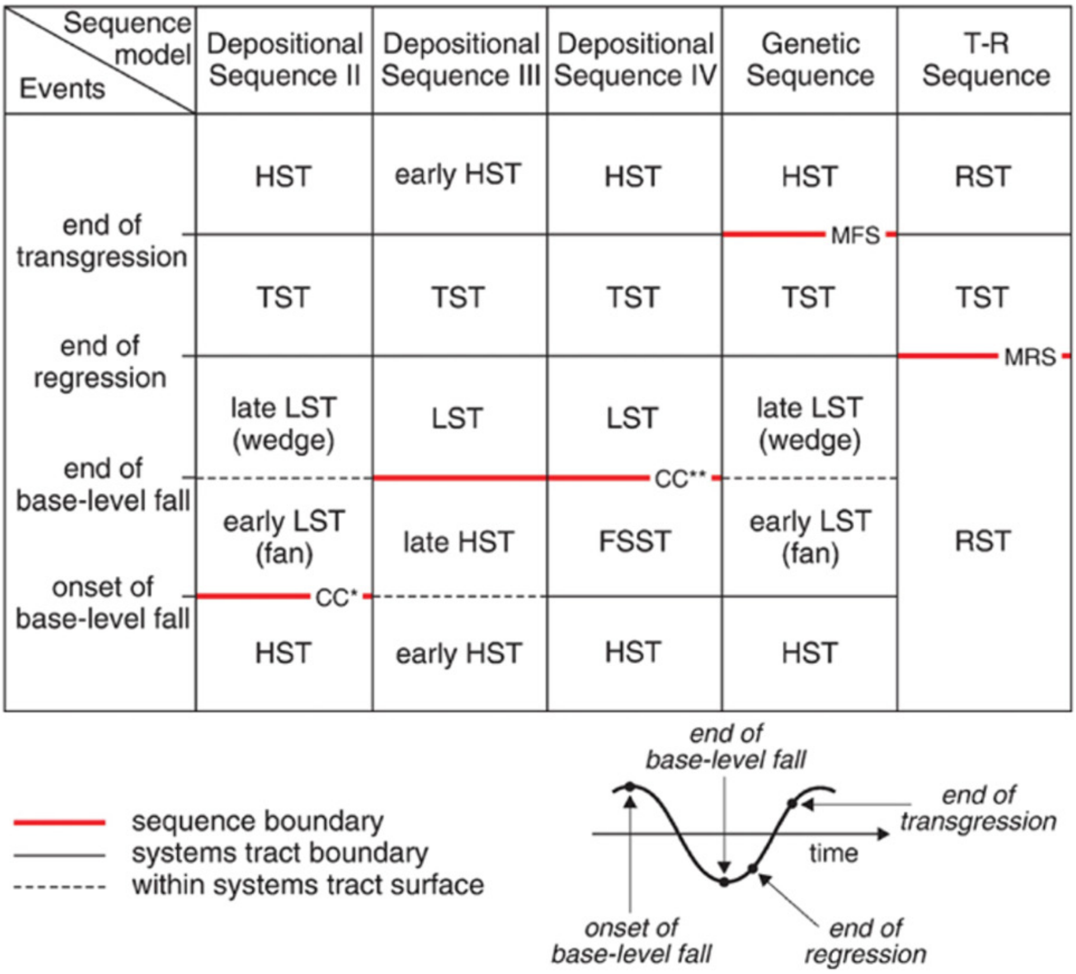


Figure 10. The standardised sequence stratigraphy applications from Catuneanu et al., (2009) shows different approaches for sequence boundary marking. This study used the type three sequence boundary for system trace interpretation. Abbreviations: FSST - falling-stage systems tract; LST stands for lowstand systems tract; TST - transgressive systems tract; HST - highstand systems tract; RST - regressive systems tract; T–R - transgressive–regressive; CC - correlative conformity sensu Posamentier and Allen, (1999); CC** - correlative conformity sensu Hunt and Tucker, (1992); MFS - maximum flooding surface; MRS - maximum regressive surface.*

2.2.4 Chronostratigraphic Diagram

The construction of chronostratigraphic diagram or alternatively known as ‘Wheeler diagram’, reduces the complexity between times and depositional systems in the time-space diagram. A fundamental of chronostratigraphic chart consists of system tract boundaries, sequence boundaries and stratigraphic terminations. Stratigraphic interpretation in both well and seismic data illustrates the relationship of deposition environments in both timelines and beddings. Unconformity influences much higher at the marginal area, while the marine condensation influences much higher at the basinward (Emery and Myers, 2009). The chronostratigraphic diagram is usually used with the mean sea level history curve in order to explain the change of depositional setting along the base level.

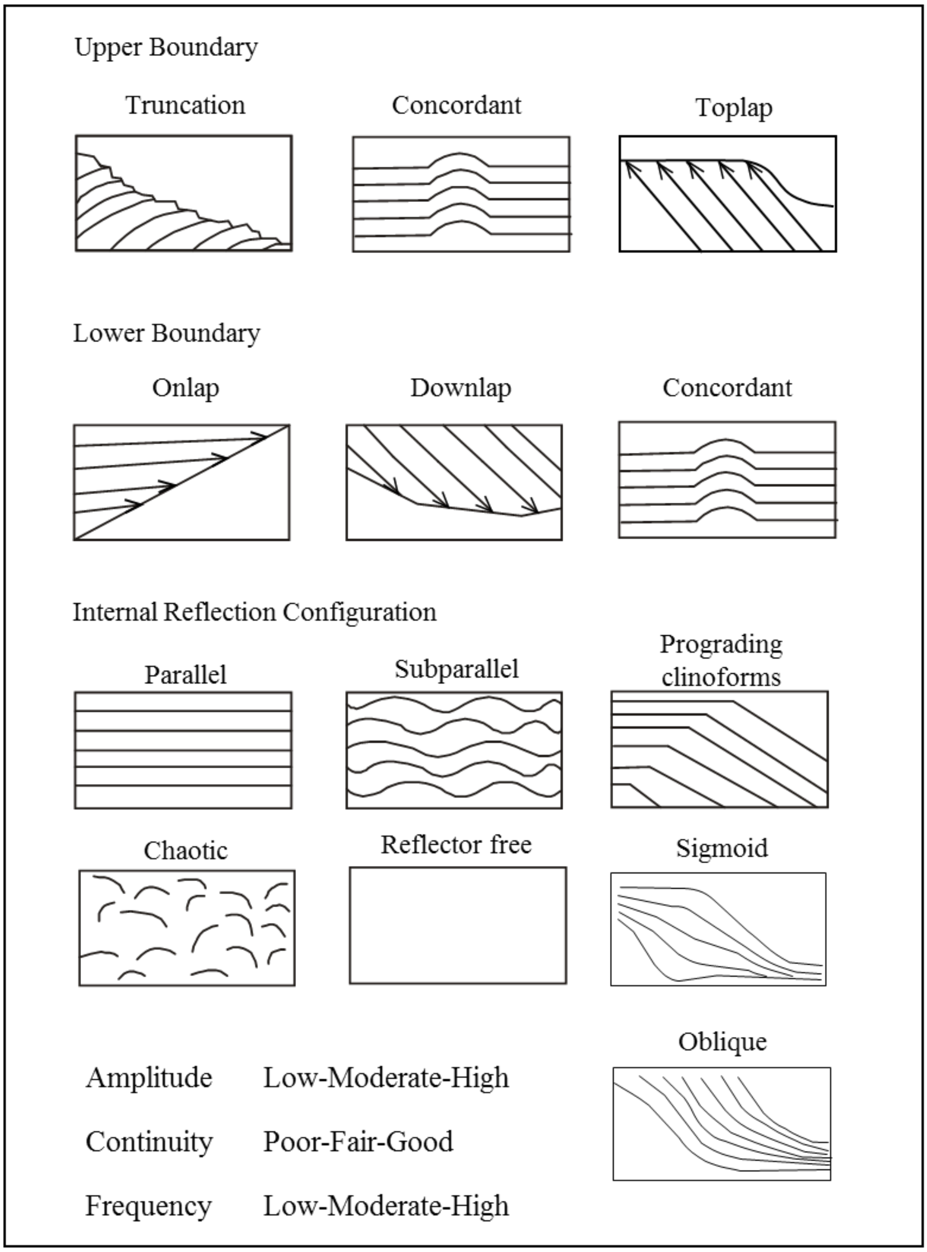


Figure 11. Seismic termination and internal reflection configurations for seismic sequence stratigraphic interpretation (modified from Mitchum et al., 1977; Roksandic, 1978 and Ramsayer, 1979).

2.2.5 Seismic Facies Analysis

Roksandic et al., (1978) suggested that the seismic reflector can be used in sequence stratigraphic approaches. The high resolution stratigraphic framework leads to the high accuracy of stratigraphic trap location in exploration work. Seismic facies explain sedimentary units from differentiation of seismic data and adjacent areas. The outcomes of seismic facies analysis show on both seismic sections and seismic facies maps. Seismic facies map can be used to construct a paleogeographic map that displays a depositional environment of the study area. It is an important data for paleoreconstruction and stratigraphic reservoir prediction in the further step (Ramsayer et al., 1979). Facies map is also used to locate pinched out stratigraphy of the reservoir. Seismic facies interpretation needs parameters such as seismic reflection configurations, frequency, geometries, and continuity as shown in Figure 11 (Mitchum et al., 1977; Roksandic et al., 1978; Ryan et al., 2009).

2.2.6 Seismic Attributes

The seismic attribute is an important process that is used in seismic interpretation. It was introduced in the seismic interpretation workflow in the early of 1970's (Subrahmanyan et al., 2008). The concept of mathematics and waveform analysis are used for measurement and computation in seismic data. The operation of seismic attributes converts a seismic value from the amplitude domain into other domains which may enhance geological features. Seismic attributes mainly use the post-stack seismic volume. The primary objective of seismic attribute generation is to identify a change in the seismic signal that gives clues for geological interpretation. This study uses several types of post-stack 3D seismic attribute to help characterise the sequence stratigraphy and facies analysis.

2.2.6.1 RMS amplitude

The seismic reflection root means square (RMS) is one of the most common attribute types for seismic interpretation. The RMS amplitude is usually used for channel identification. The RMS amplitude reflects the relative variation of the amplitude between traces over a selected sample interval (Brown, 2003). The use of RMS amplitude highlights the background features and hydrocarbon indicators by the amplitude response, which is reflected by the AI contrast. The attribute is also used to identify either high frequency stacking layers or channel –cut the finesediment depositional plain. The limitation of feature enhancement is dependent on the seismic resolution.

The RMS amplitude is calculated by the following formula (Schlumberger, 2016):

$$RMSamp = \sqrt{\frac{\sum_i^n amp^2}{k}}$$

; where k is the number of live samples

2.2.6.2 Variance amplitude

Variance amplitude is an edge method calculation, which measures the difference of mean amplitude value. The calculation finds the event continuity value in three dimensions. It is subsequently in the variability correlation by a trace to trace. (Schlumberger, 2016). High variance values indicate discontinuity anomaly zones which referred to major faults. Variance can also be applied for the stratigraphic purpose to find a channel-cut feature, the continuity of deltaic clinoforms or igneous body features (Pigott et al., 2013)

2.2.6.3 Spectral decomposition

The main concept of spectral decomposition is the colour blending of iso-frequency cubes. The principle of iso-frequency assumes that a geological layer has its individual frequency. Seismic amplitude value is transformed into a frequency domain by using the Fourier transform or the continuous wavelet transform method. Transformations are done by internal calculation in the software (Schlumberger, 2017; Li and Zheng, 2008). Several frequency cubes display in RGB colour blending. Proper use of RGB blending enhances geological features that might exist in the specific frequency band (Nanda, 2016). This application approaches the extension of tuning thickness in seismic reflector and reveals the geological features behind.

3. Data and Methodology

The study integrates both geological and geophysical data into sequence stratigraphic analysis. Key exploration wells data such as well tops, formation age, biostratigraphic data and wireline logging data are provided from NPD (NPD, 2018) and Statoil Norge. Well data are available in the groups of wells 31 and 35. The study used state of the art 3D seismic data acquired by CGG Service (Norway) during 2014-2016. The Petrel 2016 and the Paleoscan 2017 were main software used for this study. The Petrel software was developed by the Schlumberger Plc. And the Paleoscan was from Ellis.

3.1 Data

3.1.1 Well data

Well data are provided by NPD and Statoil Norge. The data comprises the group of wells 31 and 35. In this study, 18 key wells are selected for interpretations (Table 1). The selection criteria were log availability, check shot data and target depth. The study interval was between the middle to late Jurassic which covered the entire Viking group. Check shot data was important for well tie process. Wells were chosen to cover the entire study area. The log availability data was chosen as this study requires GR, DT, density, lithological and biostratigraphic log data, well correlation and stratigraphic interpretation. The list of selected wells is shown in Table 1, and the list of well data availability is shown in the methodology part (Table 3).

List Number	Well Name	X location	Y location	KB depth (m)	Total TVD depth (m)	Purpose	Oldest penetrated formation	Oldest penetrated Age
1	31/2-19S	520149.18	6753026.19	22.0	3669.0	WILDCAT	STATFJORD GP	EARLY JURASSIC
2	31/2-21S	525290.05	6759849.93	31.0	3009.0	WILDCAT	COOK FM	EARLY JURASSIC
3	31/2-2R	533940.27	6738597.32	32.0	2599.0	APPRAISAL	HEGRE GP	TRIASSIC
4	31/2-3	531872.26	6745386.82	25.0	2600.0	APPRAISAL	HEGRE GP	LATE TRIASSIC
6	31/2-8	526925.96	6758502.04	25.0	3373.0	WILDCAT	HEGRE GP	TRIASSIC
5	31/3-3	545884.32	6744748.95	26.0	2571.0	WILDCAT	STATFJORD GP	EARLY JURASSIC
7	31/3-4	537255.02	6759161.09	40.0	2122.0	WILDCAT	ETIVE FM	MIDDLE JURASSIC
8	35/11-1	535626.01	6783527.21	25.0	3360.0	WILDCAT	HEGRE GP	TRIASSIC
9	35/11-11	530381.59	6775189.73	23.5	3224.0	APPRAISAL	DRAKE FM	EARLY JURASSIC
10	35/11-3S	518257.03	6772656.11	25.0	4025.0	WILDCAT	STATFJORD GP	EARLY JURASSIC
11	35/11-5	521483.79	6771849.34	27.0	3768.0	WILDCAT	STATFJORD GP	EARLY JURASSIC
12	35/11-8S	528987.44	6773139.14	26.0	3355.0	WILDCAT	DRAKE FM	EARLY JURASSIC
13	35/12-1	551762.89	6783875.97	26.0	3018.0	WILDCAT	AMUNDSEN FM	EARLY JURASSIC
14	35/12-2	536069.13	6781688.99	29.0	2541.0	WILDCAT	ETIVE FM	MIDDLE JURASSIC
15	35/12-3S	540398.01	6773079.85	29.0	2758.0	WILDCAT	ETIVE FM	MIDDLE JURASSIC
16	35/8-5S	534934.95	6805219.70	29.0	3831.8	WILDCAT	RANNOCH FM	MIDDLE JURASSIC
17	35/9-2	550196.62	6800705.66	25.0	2877.0	WILDCAT	BASEMENT	PRE-DEVONIAN
18	35/9-6S	537025.98	6804492.08	25.0	3689.0	WILDCAT	LUNDE FM	LATE TRIASSIC

Table 1. General information of selected wells in this study (modified from NPD, 2018).

3.1.2 Seismic Data

The 3D seismic of the Northern Viking Graben cube from the CGG Services (Norway) AS is used. The seismic was acquired during the 2014-2016 with the bin size of 18.75 m *12.5 m (Figure 13). The coordinate system and projection in this survey were the European Datum 1950 with UTM 31N. The seismic survey was applied with the full-bandwidth BroadSeis™-BroadSource™ technology that enhanced the resolution of seismic data, especially with the reduced ghosting effect (CGG, 2018). The seismic cube covered the total area of 35,410 km^2 which covered most of the Northern North Sea. The seismic cube was cropped into a smaller area to cover the Horda Platform and surrounding areas (Figure 12).

The final seismic cube of this study covered the total area of 11,691 km^2. The IL number started from 5700 to 10264, and the XL number started from 20325 to 31251. Seismic data was processed into the zero-phase with normal polarity (increase in impedance with peak) (Figure 13).

Seismic data were analysed in order to find the seismic resolution in both vertical and lateral dimensions. The dominant frequency of seismic data at the target interval was determined by the spectral analysis feature in Petrel. The result showed the range of dominant frequency between 18-25 Hz (Figure 14). Average velocity was calculated form key well sonic logs. The average velocity is 2,811 m/s. The vertical resolution of the study interval is 28.11 – 39 m

Parameters	Value	
Average velocity	2,811m/s	
Dominant Frequency	18 Hz	25Hz
Wavelength	156.2	112.4
Vertical Resolution	39.04	28.11

Table 2. The table shows vertical seismic resolution of the cube. Dominant frequency is picked in the range of 18-25 Hz. The velocity value is based on the constant velocity from sonic log of key wells.

3.1.3 Software tools

Petrel in the 2016 version was the main software for well and seismic interpretations. The software was used for the main process of well correlation, seismic to well tied, horizon interpretation and attribute map generation. Paleoscan in the 2017 version from Ellis was used for the auto-interpretations in two horizons those are the BCU and the top Brent.

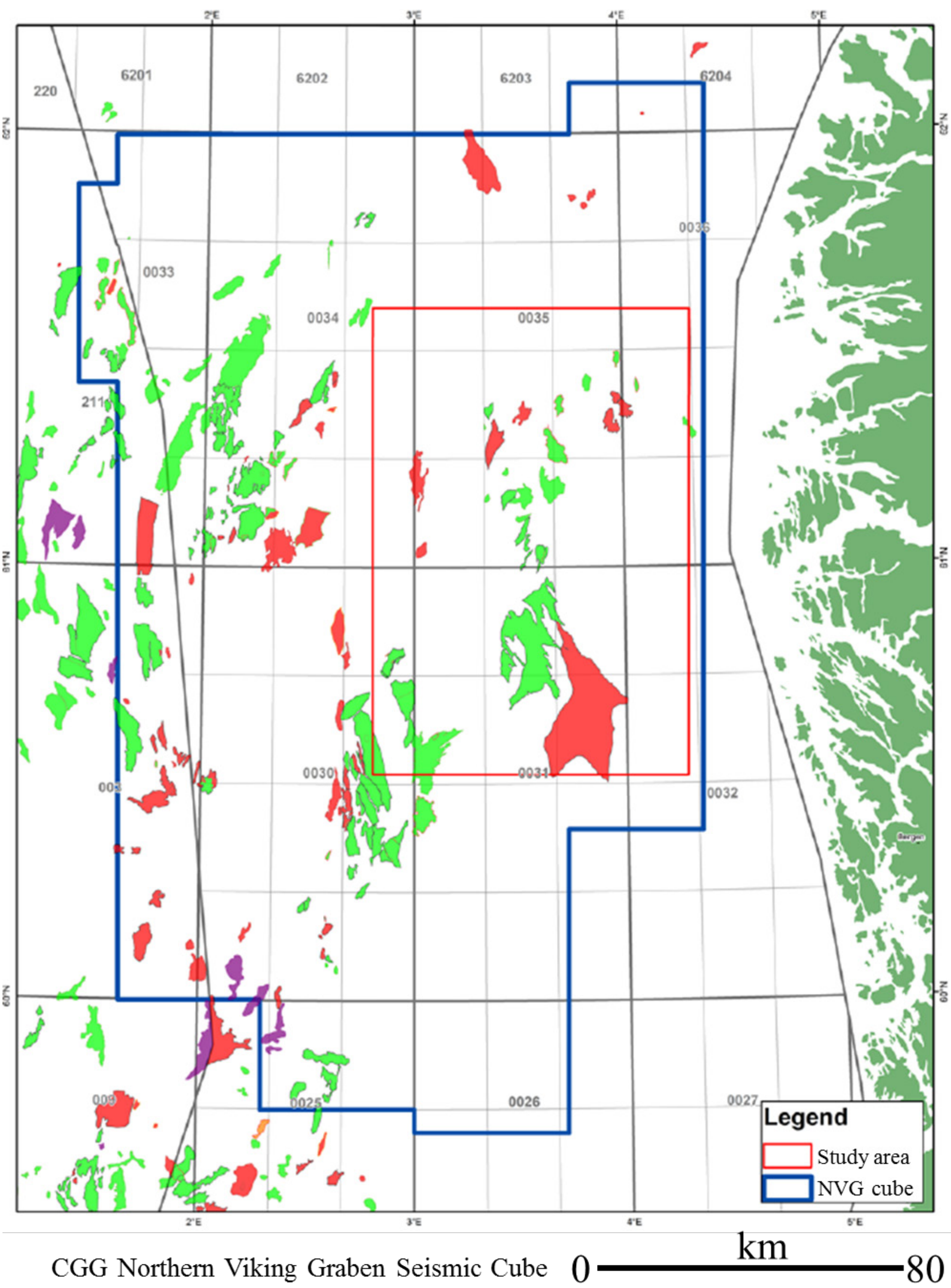


Figure 12. The location map shows the area of CGG NVG 3D seismic cube with the total area of 35,410 km^2. The study is marked in the red polygon. The cropped 3D seismic cube (blue polygon) covers the total area of 11,691 km^2.

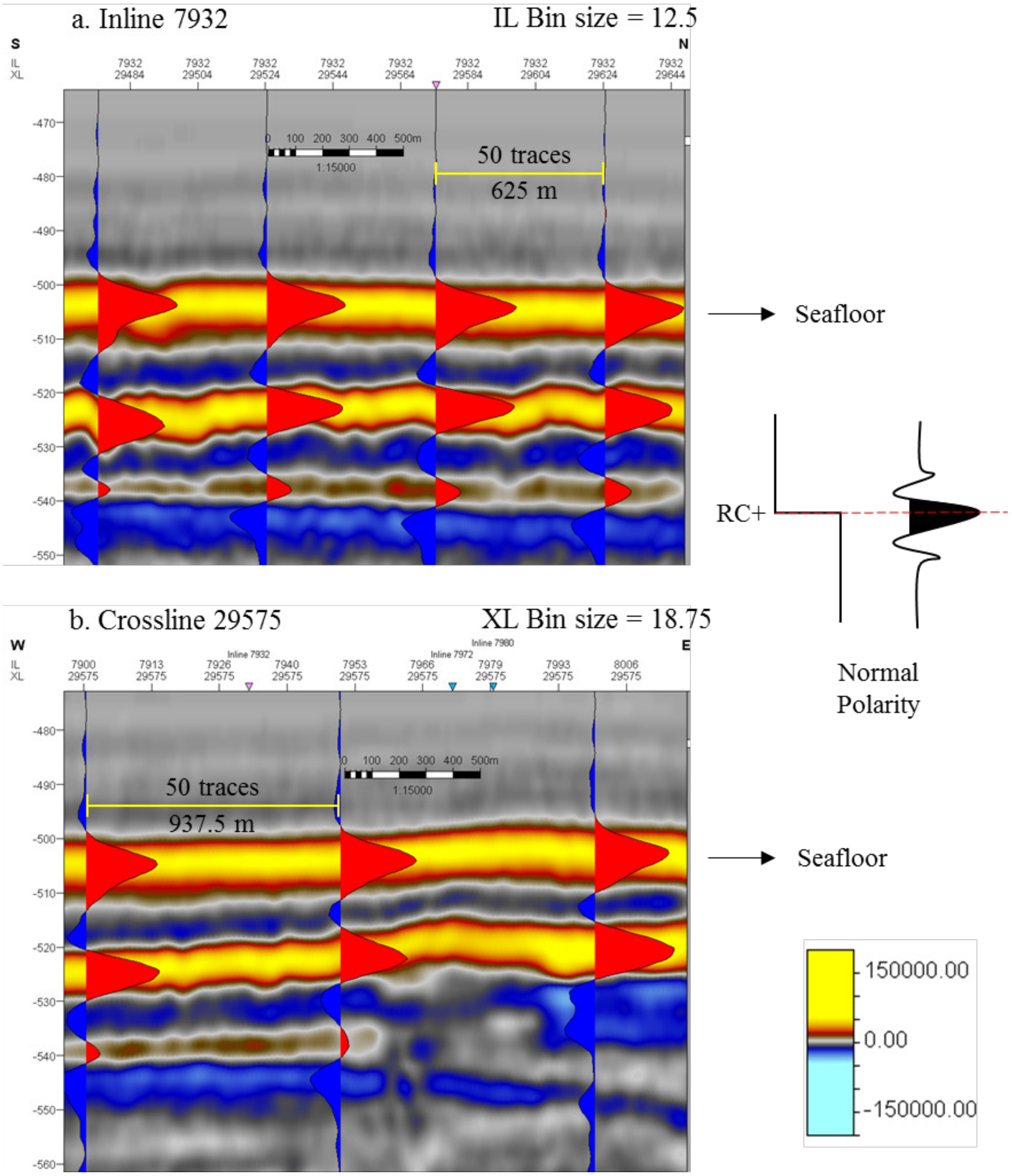


*Figure 13. The seismic inlines and crosslines show the seismic polarity of the data including bin sizes information. The seismic cube was processed in zero phase with a normal polarity. The red colour is the positive values while the blue colour is in negative values. The seismic sections show seismic traces in every 50 traces in both IL and XL. The bin size of seismic cube is 12.75*18.75. The polarity convention is introduced from Sheriff, (1995).*

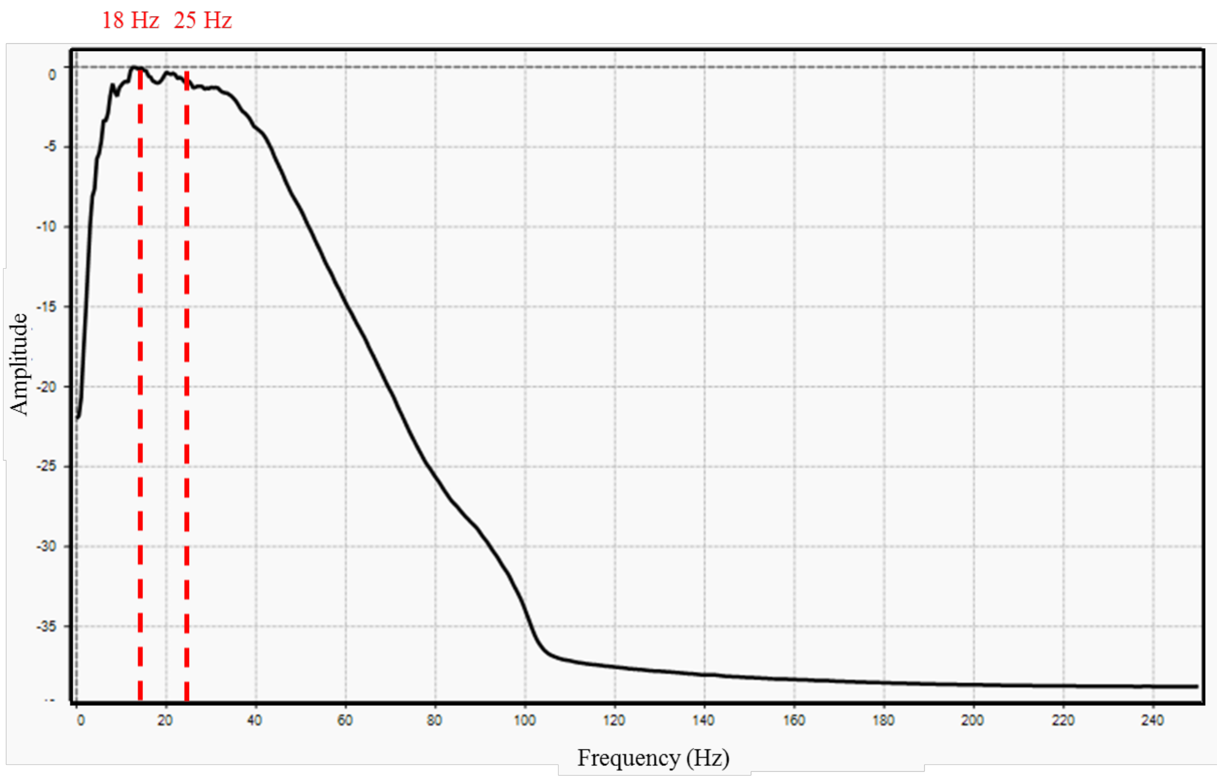


Figure 14. The frequency analysis of the CGG NVG seismic cube using the spectral analysis in Petrel. The dominant frequency of seismic cube in the middle to upper Jurassic interval is between 18Hz-25Hz.

3.2 Methodology

The study started with well data review. 18 key wells data were checked and listed before the well correlation (Table 3). After the data review, well correlations were completed in Petrel 2016. The completed available log data set supported the high-resolution well interpretation for a higher sequence stratigraphy hierarchy. The seismic to well tie process was conducted before seismic horizon interpretation. Seven main horizons were interpreted and generated into two-way-time (TWT) structural map. Well and seismic interpretation required many revision to get a robust model. Geological map and seismic attributes generation were constructed and analysed for every stratigraphic unit after the horizon interpretation process. Seismic attribute types used in this study were variance, RMS amplitude and spectral decomposition attributes. The result from stratigraphic analysis were generated in chronostratigraphic diagrams. Facies analysis was conducted to link the stratigraphic framework and depositional environment. The last step was the discussion of the depositional environment, which was then linked to petroleum significances. The workflow overview is summarized in the (Figure 15).

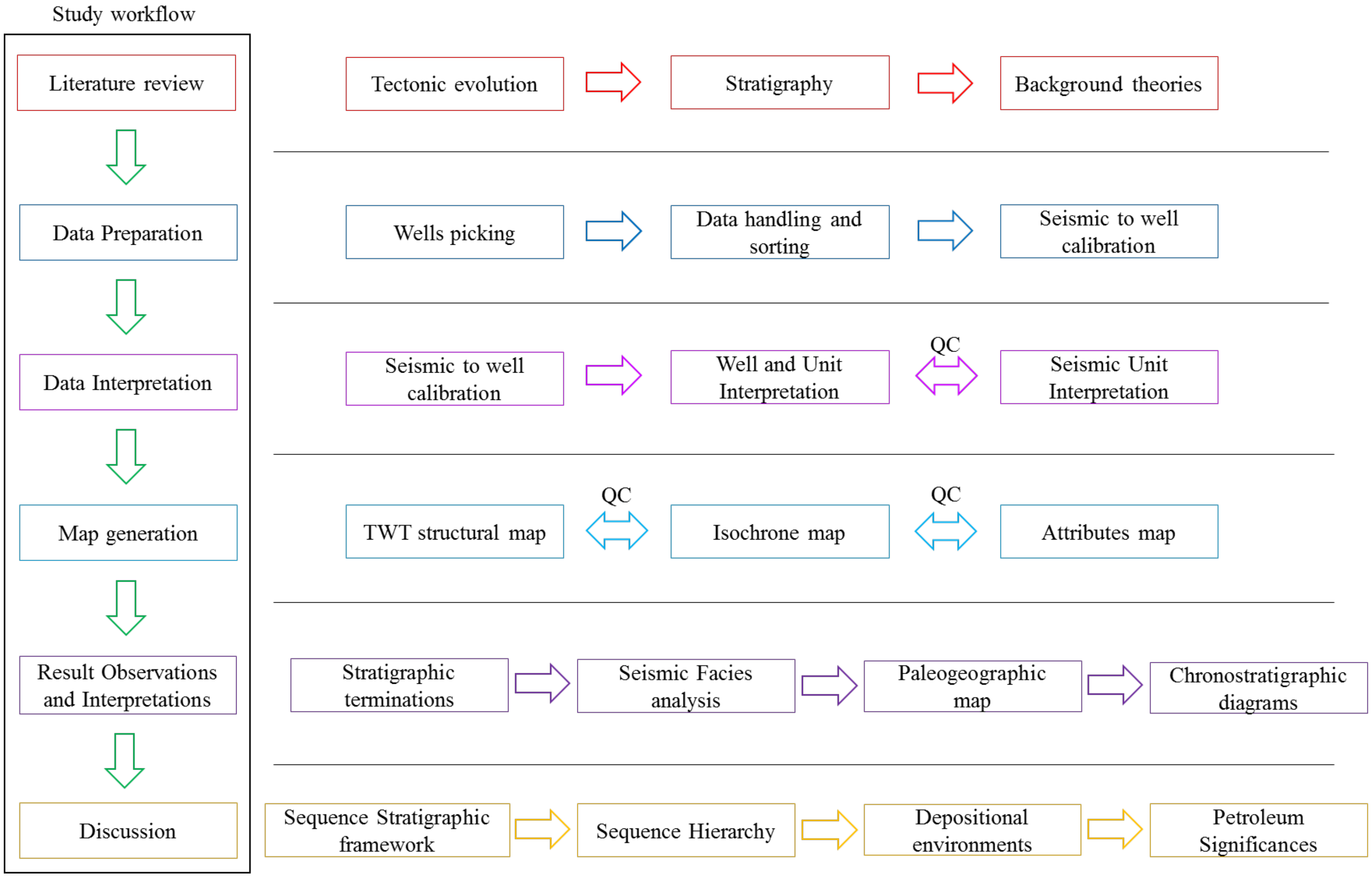


Figure 15. The diagram shows the overall workflow of the study. Main processes are shown in the left box. Due to sequence stratigraphic study is an intuitive process. The interpretation needs many revisions and QC to get a robust model.

3.2.1 Well data review

18 key wells were selected in the study. The study required GR, sonic (DT), density (RHOB), lithologic and biostratigraphic logs (Table 1 and Table 3). Lithologic and biostratigraphic log data were introduced to provide information with petrophysical analysis and depositional ages. In addition, check shot (CS) data and density log were also necessary for the seismic to well calibration process. The first step of the study was data handling and sorting out process (Figure 15).

List Number	Well Name	GR	DT	RHOB	LITHO LOG	BIO LOG	CS
1	31/2-19S	✓	✓	✓	✓	✓	✓
2	31/2-21S	✓	✓	✓	×	✓	×
3	31/2-2R	✓	✓	✓	✓	✓	✓
4	31/2-3	✓	✓	✓	✓	✓	✓
6	31/2-8	✓	✓	✓	✓	✓	✓
5	31/3-3	✓	✓	✓	✓	✓	✓
7	31/3-4	✓	✓	✓	✓	✓	✓
8	35/11-1	✓	✓	✓	✓	✓	✓
9	35/11-11	✓	✓	✓	✓	✓	✓
10	35/11-3S	✓	✓	✓	✓	✓	✓
11	35/11-5	✓	✓	✓	✓	✓	✓
12	35/11-8S	✓	✓	✓	✓	✓	✓
13	35/12-1	✓	✓	✓	✓	✓	✓
14	35/12-2	✓	✓	✓	✓	✓	✓
15	35/12-3S	✓	✓	✓	✓	✓	✓
16	35/8-5S	✓	✓	✓	✓	✓	✓
17	35/9-2	✓	✓	✓	✓	✓	✓
18	35/9-6S	✓	✓	✓	✓	✓	✓

Table 3. Available well log data is shown in the table. GR, DT, Litho logs and Bio logs are used for well interpretation and correlation process. RHOB, DT logs and CS are used in the seismic to well calibration process..

3.2.2 Well correlation

The correlation was derived from the well interpretation with the aim to construct the sequence stratigraphic framework at a high resolution scale. GR and DT were the most essential logs for the well interpretation. Lithology log and Biostratigraphic log were also introduced in the well correlation process. The eustatic change was interpreted in the lower stratigraphic hierarchy order using the lithological vertical variation. Then, the depositional sequence III method was used to indicate stratigraphic surfaces such as downlap surface, transgressive surface, flooding surface, regressive surface and subaerial unconformity (Van Wagoner, 1988).

3.2.3 Seismic to well tie

The seismic to well tie was an important process that links the time domain of seismic data and the depth domain of well data. The accurate well to seismic calibration resulted in a robust model for main horizon identifications. Seismic to well tie processes were calibrated in the Petrel software in all CS available wells. The well 31/2-21S used the CS from the well 31/2-8 due to missing data (Table 3).

The synthetic seismogram process required sonic and density logs. CS data were calibrated with sonic logs in order to create the velocity trend of the study interval. The revised sonic and density logs were then used to produce reflection coefficient logs of each well. Wavelets were extracted along the well using a deterministic method within the time window of study interval. Then, wavelets and impedances were convolved to construct the synthetic seismogram. Figure 16 shows an example of synthetic seismogram of the key well 35/9-2 in the Troll field, and the result of seismic to well calibration process. 3-5 ms time shift was applied in calibration processes.

3.2.4 Seismic interpretation

There were seven main horizons in the study. The horizon interpretation started from the most explicit horizon, which are the BCU and the top Brent group. The interpretation of the BCU and the top Brent was conducted in Paleoscan. Three main unconformities were interpreted at the later step, started from U20, U60 and U40 respectively. Then, two seismic horizons of FS30 and FS50 which showed a weaker contrast were interpreted in the last step. The study did a simultaneous work between well correlation, seismic interpretation and QC data in order to get the most accurate result in both domains.

Due to the complex structure during the syn-rift with the regional erosion and non-deposition zone, most top stratigraphic units were picked mainly by manual picking. There were only the

BCU and the top Brent horizons that used a model grid feature in Paleoscan 2017 for interpretation.

3.2.5 Geologic maps and seismic attributes

The time structural maps generated from each time point interpretation of top horizons. Then, isochrones maps were generated by time difference values calculation between each horizon. Seven time structural maps were generated with six isochrones maps in the study interval.

The seismic attributes map was used to explain geological features. There were three types of attributes generated in this study such as RMS, variance and spectral decomposition. The RMS and variance map were calculated by mathematical algorithms from the software to transform amplitude values to other attributes. The RMS amplitudes maps were used to classify the geological feature that might reflect the velocity and density contrast in seismic. The Variance attribute used a statistical method to measure discontinuity of seismic data from surrounding area (Schlumberger, 2018). It was used efficiently for fault and lineament detection. Spectral composition transformed the amplitude value in seismic into three frequency domains of 9-27-45 Hz with the assumption that frequency domain approaches the extension of tuning thickness in amplitudes domain (Nanda, 2016). The attributes observations requires the proper colour adjustments in every attribute maps.

3.2.6 Chronostratigraphic diagrams

The chronostratigraphic diagram was generated after the observations and interpretation process. It integrated information of system tract boundaries, sequence boundaries and stratigraphic terminations. This study selected well data from reference lines to generate the chronostratigraphic diagram. The chronostratigraphic diagram is calibrated with seismic data to confirm the result between inter-well areas. Stratigraphy, depositional system and time were displayed on the vertical scale. The distance across the area was displayed in the horizontal scale (Mitchum et al., 1977).

3.2.7 Seismic facies analysis and Paleogeographic maps

Seismic facies analysis and paleogeographic maps constructions were the last stages of the interpretation. Seismic facies analysis linked internal seismic reflectors to depositional environments. Paleogeographic maps displayed depositional environments of each stratigraphic units. The summary of depositional environments from paleogeographic maps led to petroleum system definition of the study area. The facies analysis was completed through several parameters such as reflection continuities, reflection amplitudes and reflection frequencies from Mitchum et al., (1977), Roksandic, (1978) and Ramsayer, (1979).

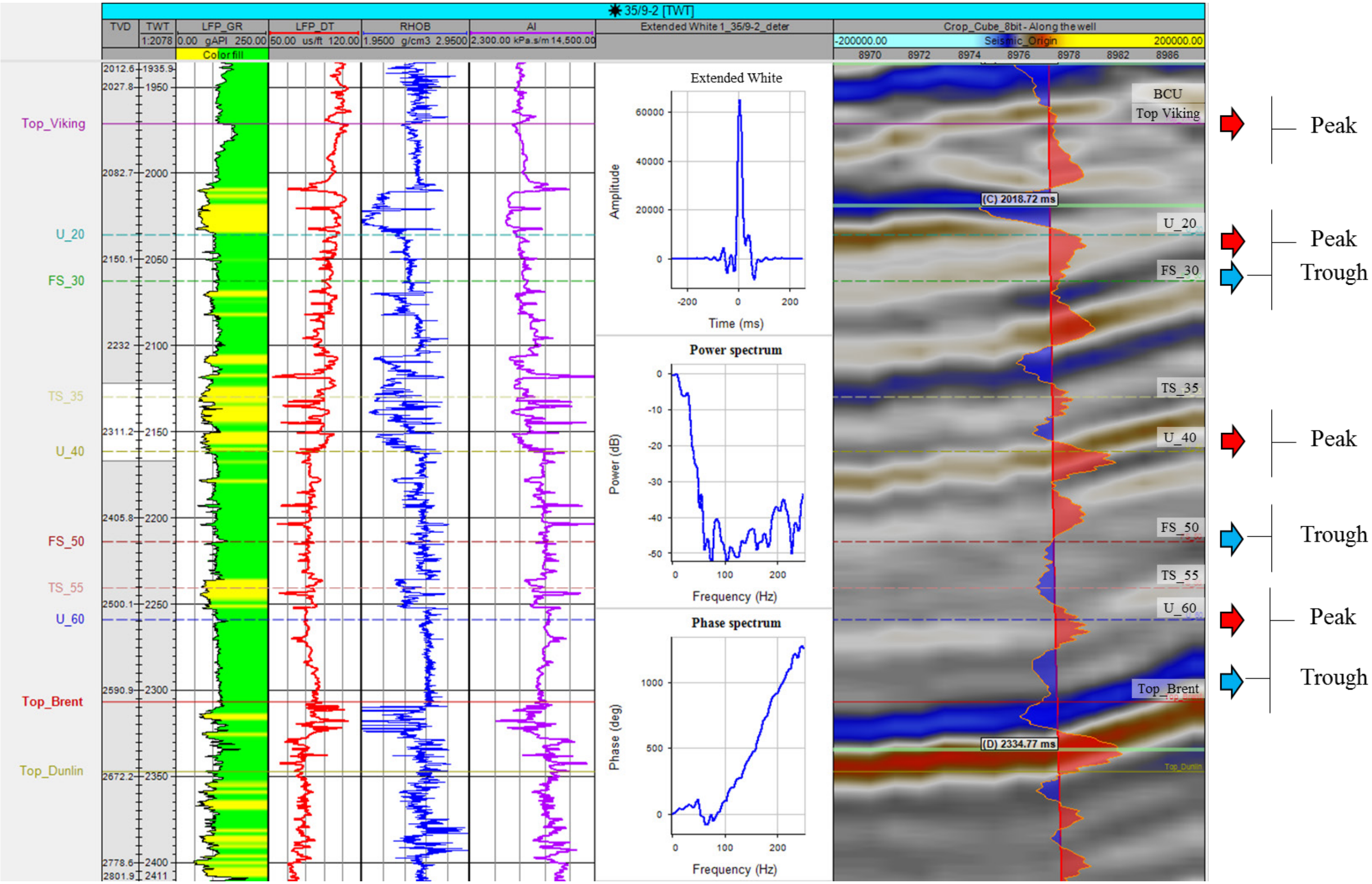


Figure 16. The type well 35/9-2 shows the well to seismic calibration result. The well was penetrated all units from the BCU to the Top Brent. Wavelet extracted by the extended white algorithm. Unconformities and MFS are shown on seismic data while the MRS of TS_35 and TS_55 are below the seismic resolution. Red The seismic is in normal polarity. Red peaks correlate to hard reflectors of U_20, U_40 and U_60 and Blue troughs correlate to soft reflectors of the Top Viking, FS_30, FS_50 and the top Brent.

4. Observations and Interpretations

The observation part of this study area was based on well log and seismic interpretations. Primary objectives of this part can be divided into three part:

1) To understand the geological setting and the sequence stratigraphy of the study area.

2) To observe and interpret important geological features which support depositional environments in the discussion part.

3) To highlight the potential petroleum area of the Horda platform that can be used for the further exploration purposes.

The first results described well log interpretations. Six well correlation panels covering the entire study area were selected (Figure 17). Interpretation of 18 key wells was used to guide the seismic interpretation. Figure 18 and Figure 19 show the overall lithological trend and thickness of the middle to late Jurassic strata in the SE-NW and SW-NE directions, respectively. Due to high tectonic activities during the middle to late Jurassic, wells in the main depocenter were selected for reference lines (Figure 17). Seven stratigraphic surfaces were identified in the interval of interest namely, Top Brent, U60, FS50, U40, FS30, U20 and BCU (Figure 18; Figure 19).

The surface interpretation from well sections was extrapolated to the seismic data. There are six stratigraphic units identified in the seismic data, which are Unit 1 (Top Brent-U60), Unit 2 (U60-FS50), Unit 3 (U50-FS40), Unit 4 (U40-FS30), Unit 5 (FS30-U20) and Unit 6 (U20-BCU) (Figure 23; Figure 24) Seven two-way-time (TWT) structural maps were generated, and also six isochrone maps. Two seismic profiles in the NE-SW and SE-NW directions represent the interpreted units on the seismic tied key wells (Figure 20; Figure 21).

Biostratigraphic data was also integrated into this study. Most of selected wells have biozone log, which assisted unit classification by ages and increased the accuracy of correlation, especially in thick sandstone layers (Figure 18; Figure 19).

The time structural maps show the paleogeography changes over time (Figure 23). Major faults controlled the depositional centre of the study area. These faults mainly orientated in the N-S, NE-SW, and E-W directions. Tectonic activity and fault control affected the sequence stratigraphy framework. The fault terminologies were assigned by NPD (NPD, 2018) (Figure 17). The study area comprised four major structural elements based on the well and the seismic interpretation, which were the Troll area, the Bjorgvin Arch, the Uer Terrace and the Lomre Terrace (Figure 17).

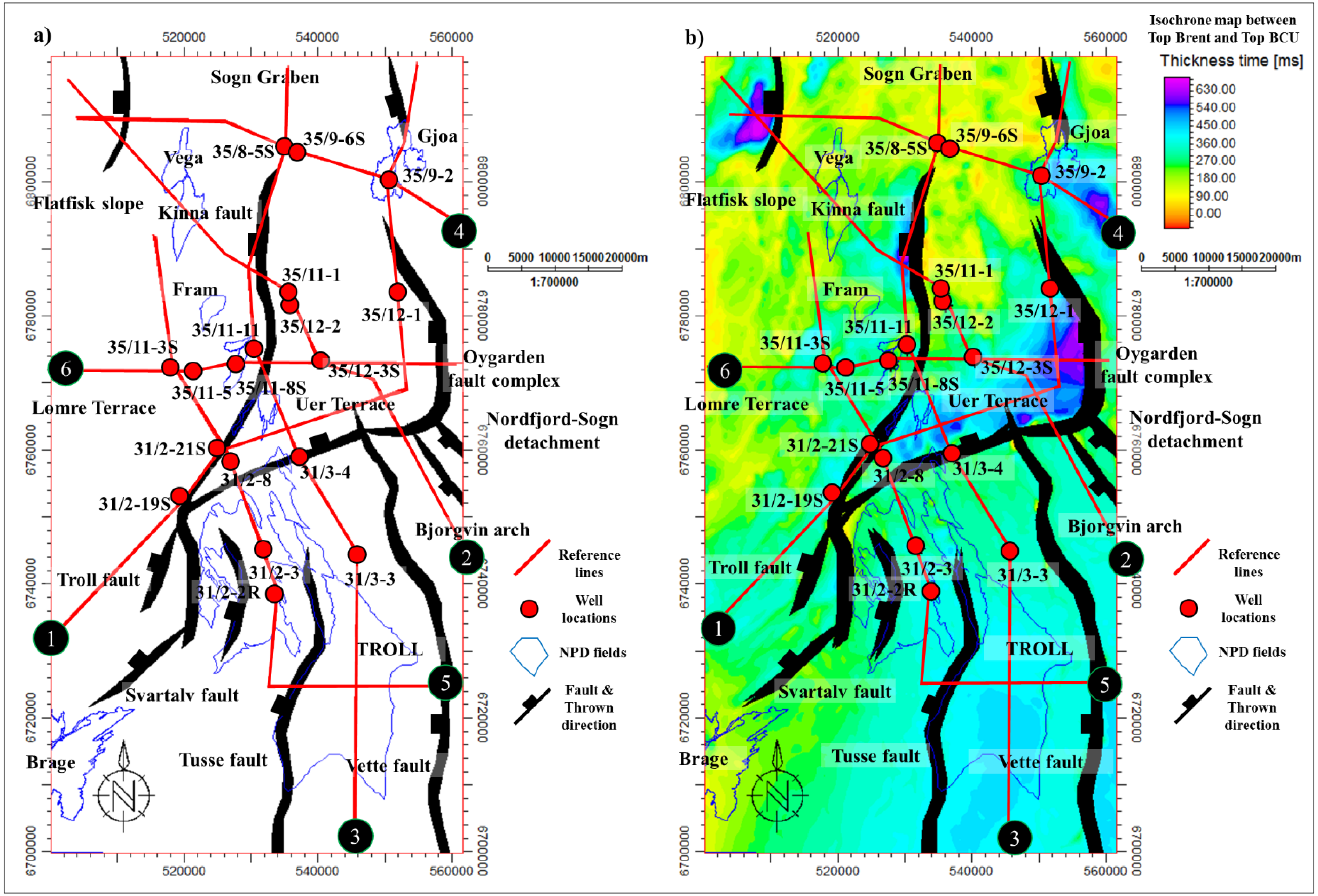


Figure 17. Reference lines represent both seismic interpretation and well correlation with well locations, NPD fields and main faults. a) The base map shows references lines with faults and NPD fields. b) Isochrone map between the BCU and the top Brent illustrates main depocenters of the study area. The references lines are selected across high thickness and depocenters areas to show thick sediment packages for stratigraphic study. The BCU and the top Brent in this map were generated by quick look interpretations in order to pick key wells. The version for stratigraphic study was interpreted again during the horizon interpretation process.

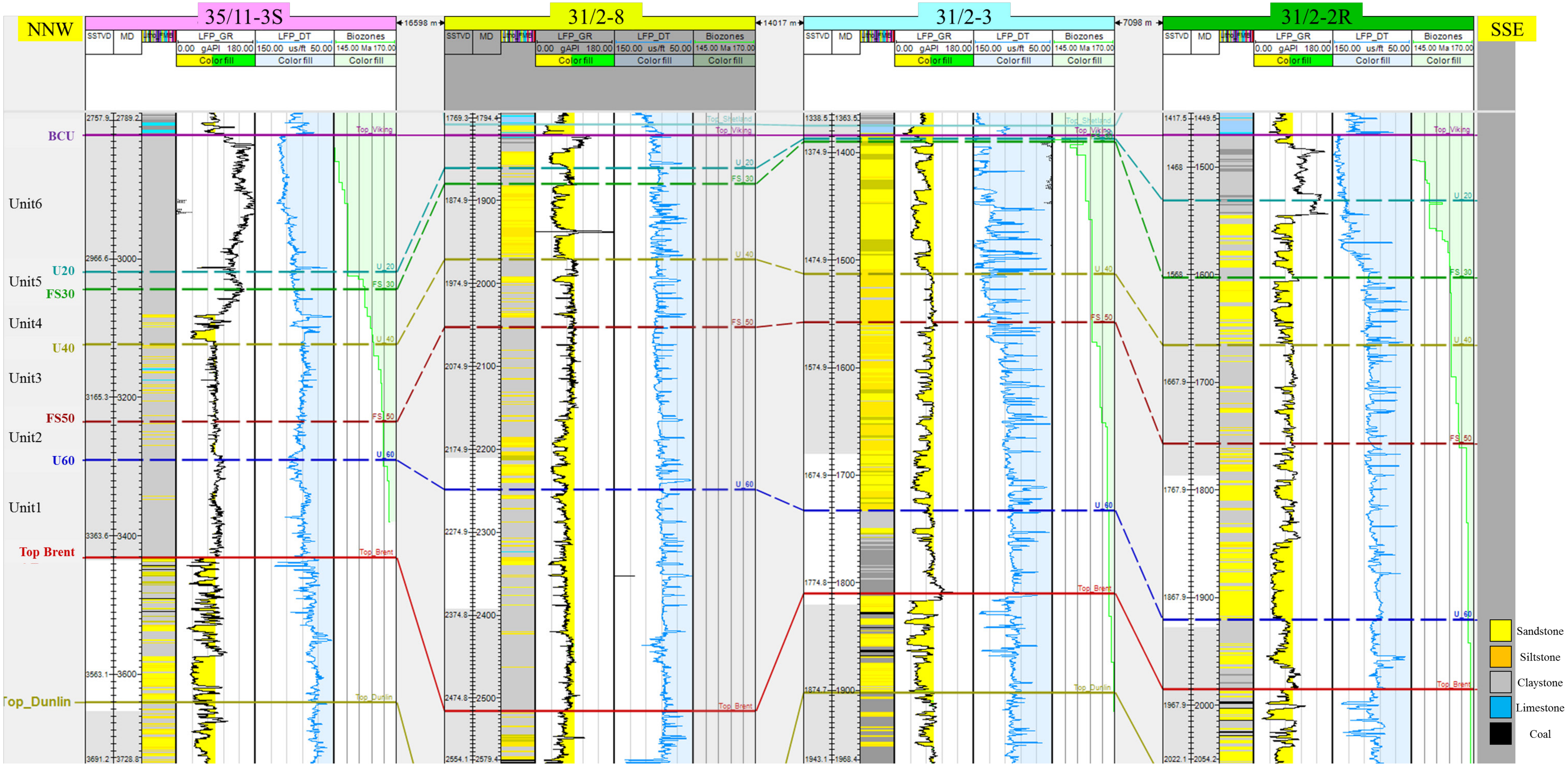


Figure 18. The well panel of reference line 5 (Figure 17) shows a correlation in the NNW-SSW direction. All wells were flattened on the BCU. The study interval is in the middle to late Jurassic. The panel shows overall lithological trends and thicknesses of the study interval. Stratigraphic units were divided using GR, DT, lithological and biozones logs. There are seven stratigraphic surfaces in the study interval which are BCU, U20, FS30, U40, FS50, U60 and Top Brent. Six stratigraphic units consist Unit 1, Unit 2. Unit 3, Unit 4, Unit 5 and Unit 6. The correlation show high thickness variation in the study interval. The well 31/2-3 presents a condensed section in the Unit 6. Abbreviations: U – unconformity; FS – flooding surface.

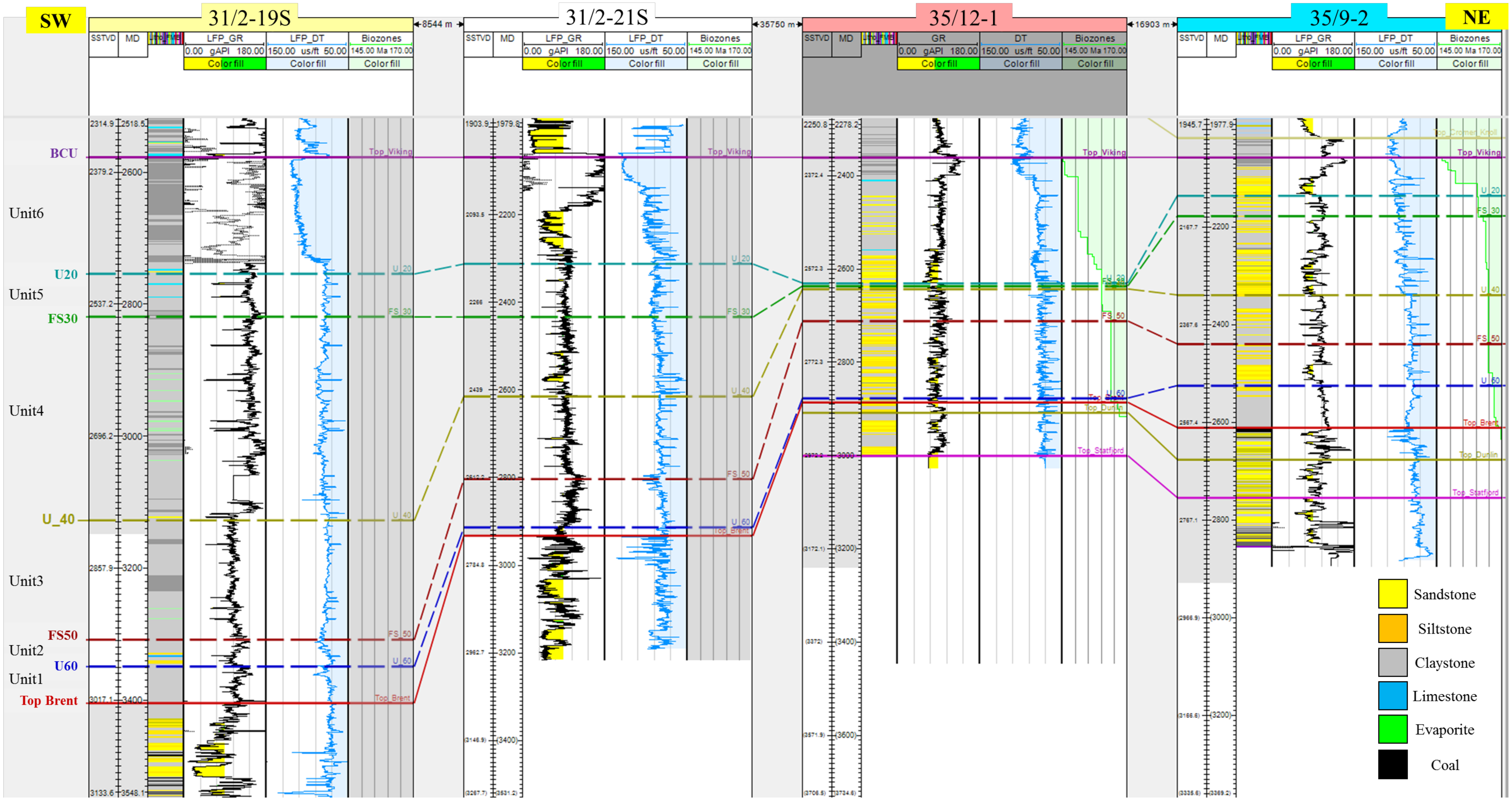
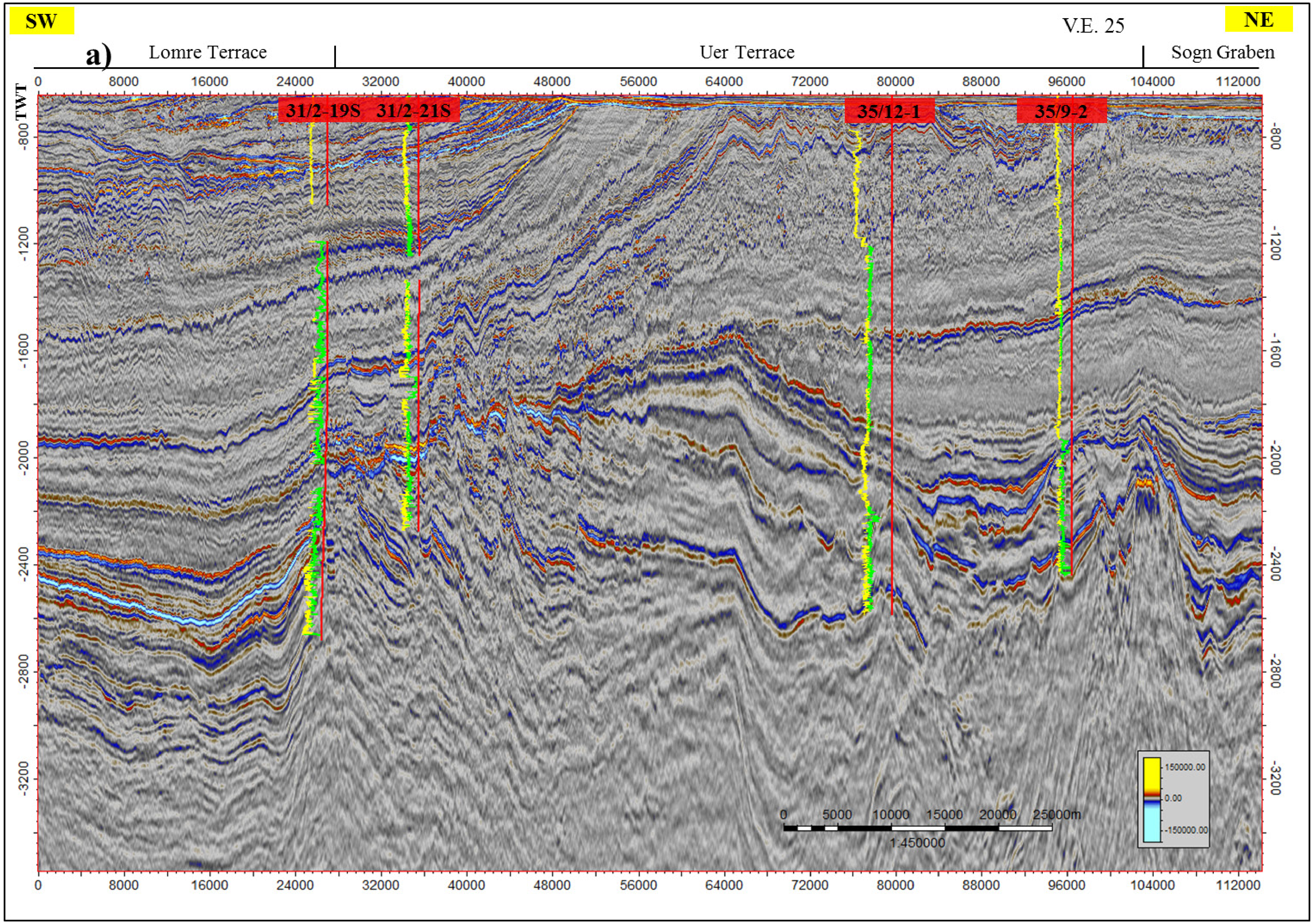


Figure 19. The well panel of reference line 1 (Figure 17) shows a correlation in the SW-NE direction. All wells were flattened on the BCU. The study interval is in the middle to late Jurassic. The panel shows overall lithological trends and thicknesses of the study interval. Stratigraphic units were divided using GR, DT, lithological and biozones logs. The correlation shows seven stratigraphic surfaces in the study interval which are BCU, U20, FS30, U40, FS50, U60 and Top Brent. Six stratigraphic units consist Unit 1, Unit 2. Unit 3, Unit 4, Unit 5 and Unit 6. The correlation shows condensed section in the well 35/12-1 in the Unit 5. The panel suggests structural inclination to the west which represents the basinward.


SW
NE
V.E. 25
a)
Lomre Terrace
Uer Terrace
Sogn Graben
TWT
31/2-19S
31/2-21S
35/12-1
35/9-2
0
8000
16000
24000
32000
40000
48000
56000
64000
72000
80000
88000
96000
104000
112000
-800
-1200
-1600
-2000
-2400
-2800
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0.00
-150000.00

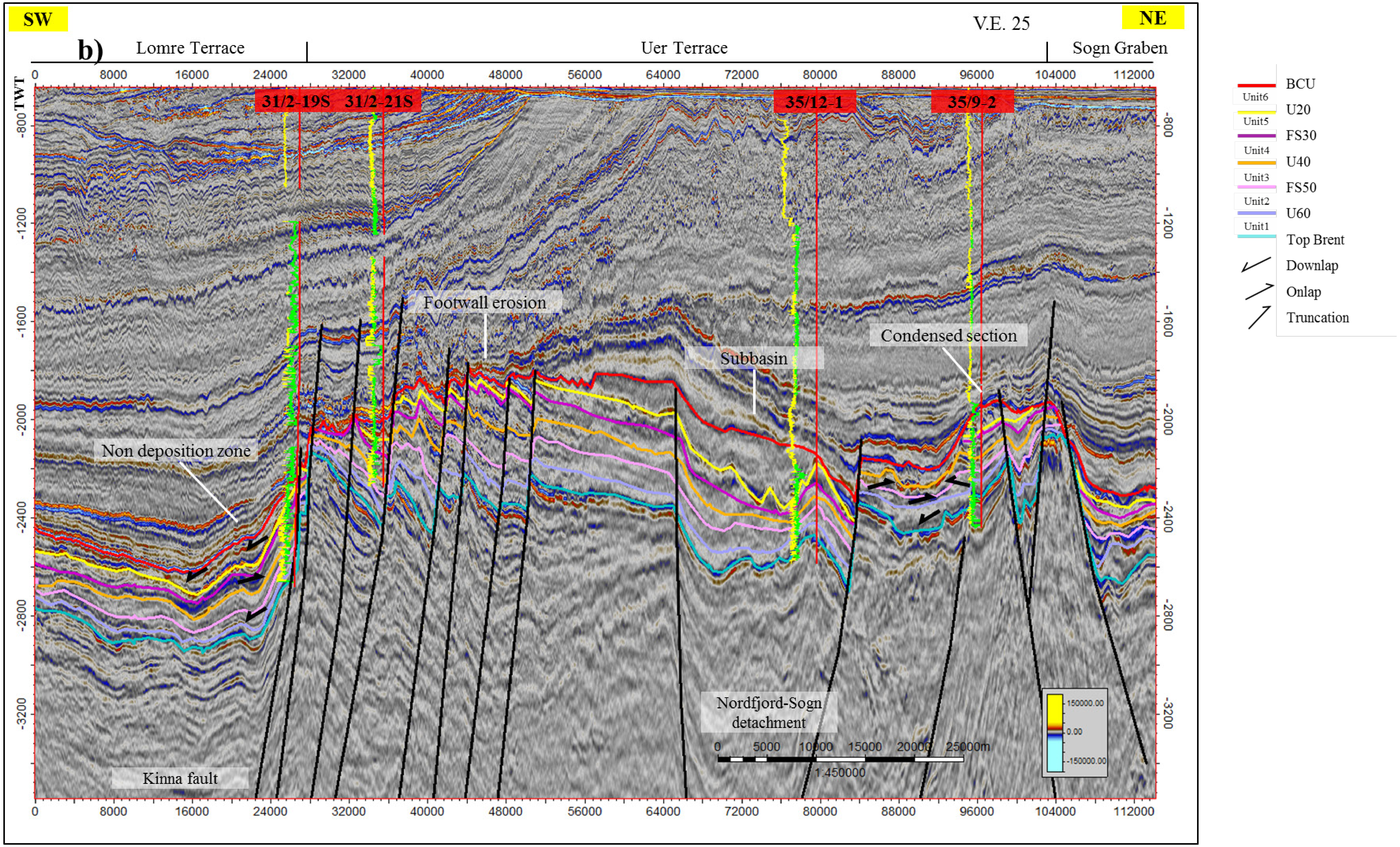
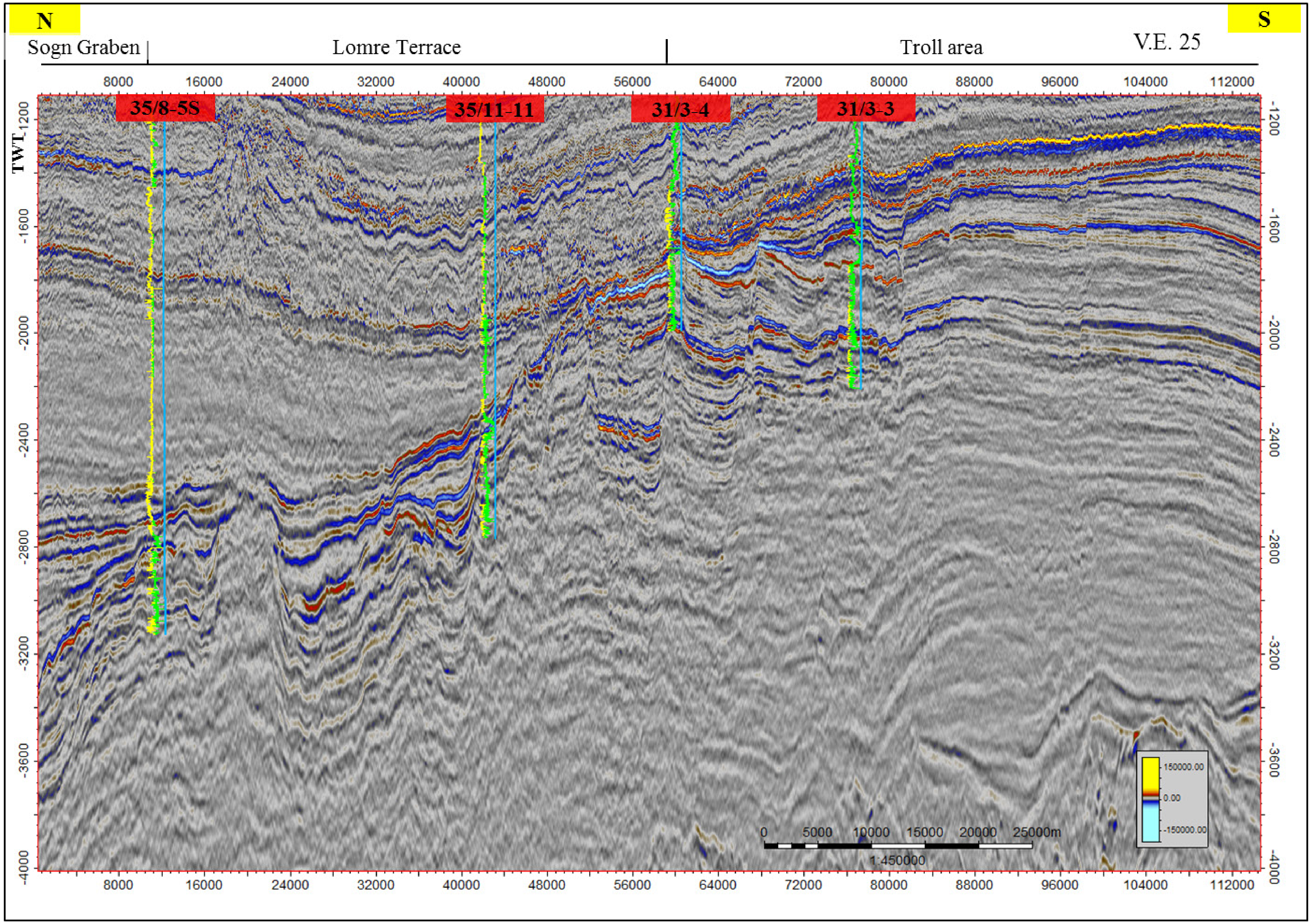


Figure 20. a) Uninterpreted seismic line and b) interpreted seismic line shows the reference line 1 (Figure 17). Seismic lines show the SW-NE profile, stratal patterns and geometries of the middle to upper Jurassic. There are four wells in the profile those are wells 31/2-19S, 31/2-21S, 35/12-1 and 35/9-2. Wells are overlaid with GR logs. All wells penetrate at high structures. The profile shows many condensed section, e.g. the Kinna fault and the NE. High topographic areas show large surface erosions, while downthrown blocks present non depositional zones. Seismic stratigraphic terminations are observed in the downthrown block along major faults. Sub-basin exists in the Uer terrace near the Nordfjord-Sogn detachment.


N
S
Sogn Graben
Lomre Terrace
Troll area
V.E. 25
35/8-5S
35/11-11
31/3-4
31/3-3
TWT
8000
16000
24000
32000
40000
48000
56000
64000
72000
80000
88000
96000
104000
112000
-1200
-1600
-2000
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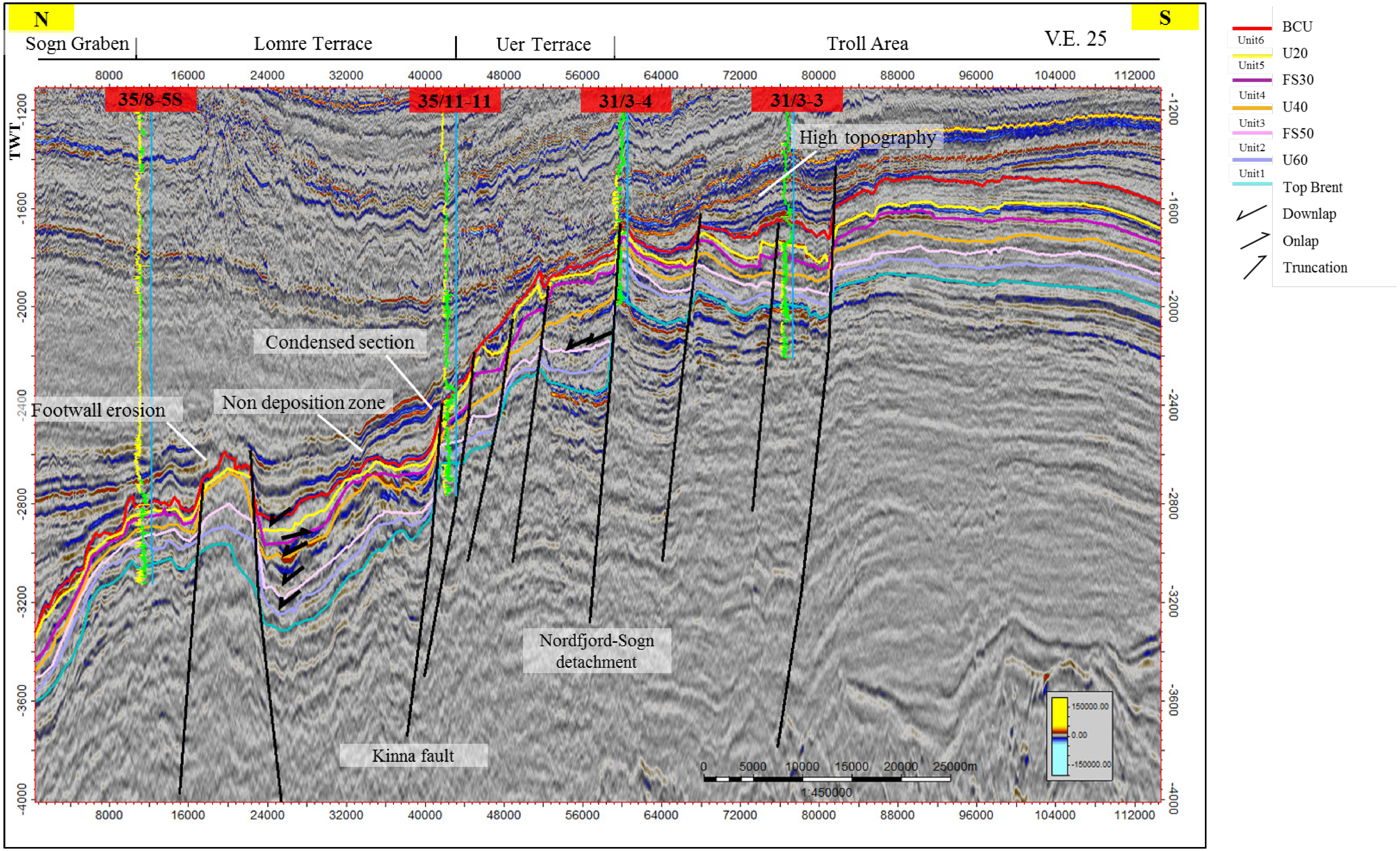
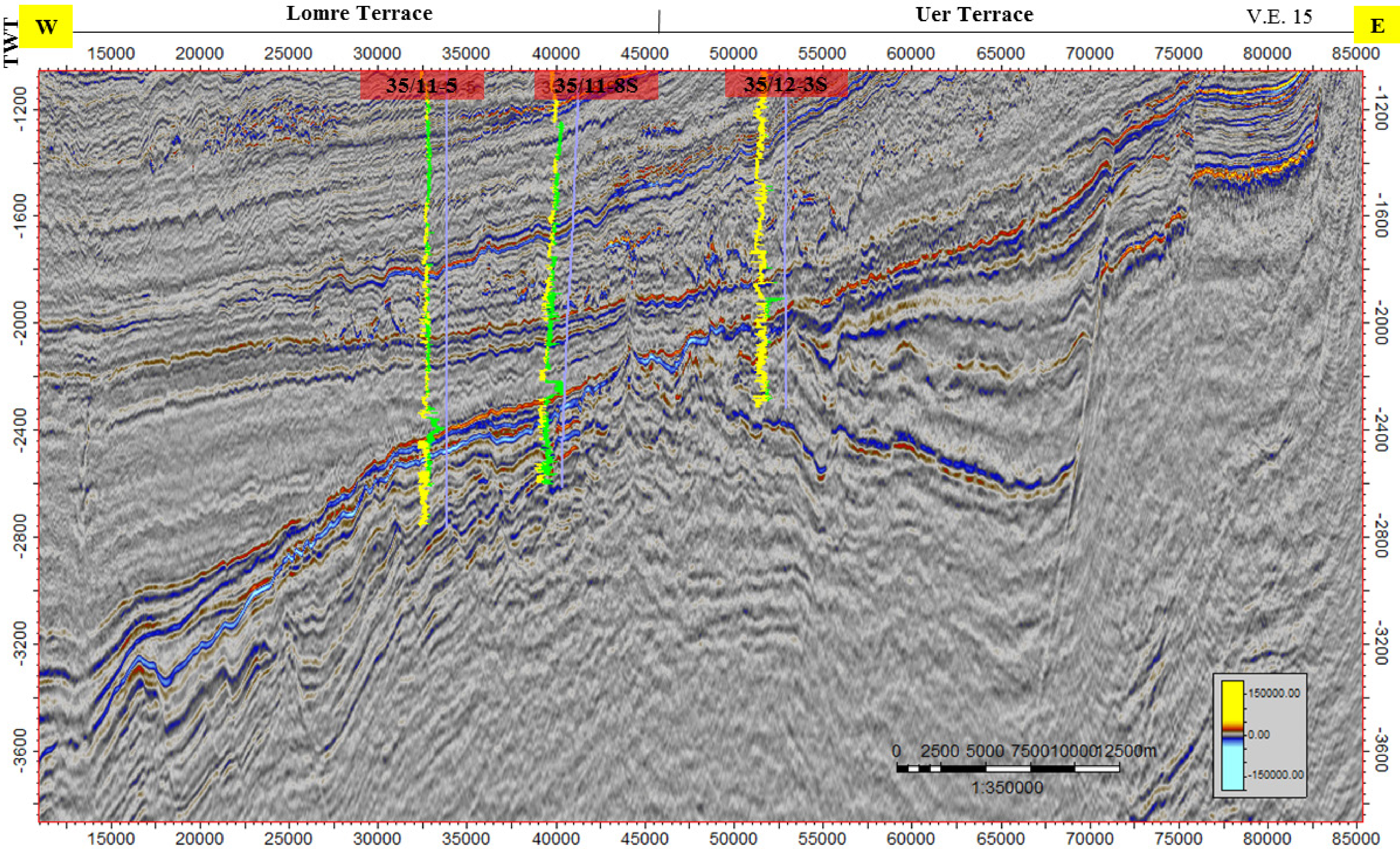


Figure 21. a) Uninterpreted seismic line and b) interpreted seismic line shows the reference line 3 (Figure 17). Seismic lines show the S-N profile, stratal patterns and geometries of the middle to upper Jurassic. There are four wells in the profile those are wells 35/8-5S, 35/11-11, 31/3-4 and 31/3-3. Wells are overlaid with GR logs. All wells penetrate at high structures. The profile shows structural incination dipping to the north where several erosion and condensed areas are observed. The deepest structure presents in the Sogn Graben and the shallowest structure is in the Troll area. Erosion zones exist at the Troll field, while non depositional zones represents along downthrown blocks into basinward such as the Uer terracce and the Lomre Terrace. Stratigraphic surfaces are clearly shown in the Lomter terrace where indicate the stratigraohic stacking pattern of the study area.


W
Lomre Terrace
Uer Terrace
V.E. 15
E
TWT
35/11-5
35/11-8S
35/12-3S
0 2500 5000 7500 10000 12500m
1:350000
150000.00
0.00
-150000.00

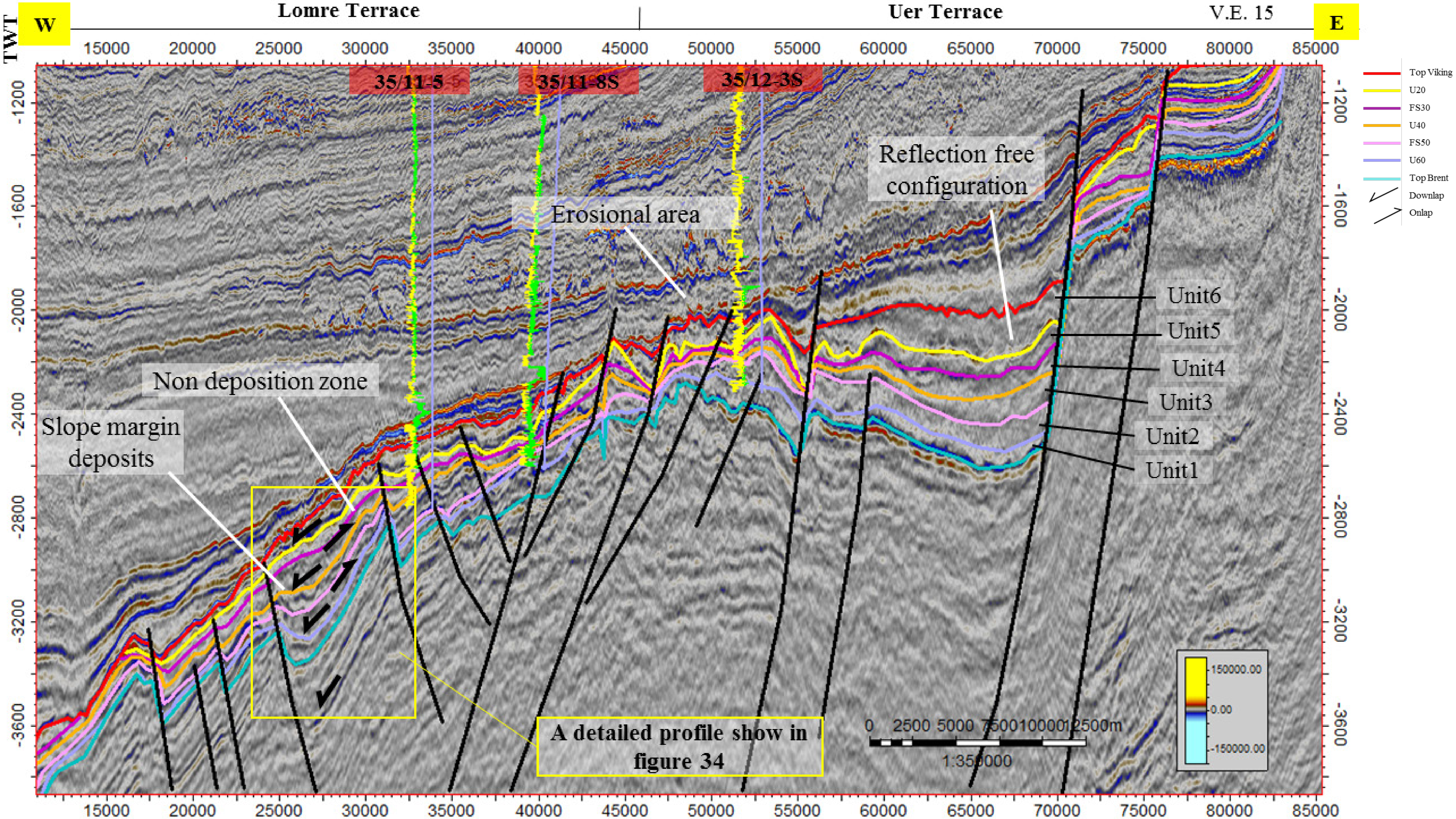


Figure 22. a) Uninterpreted seismic line and b) interpreted seismic line shows the reference line 6 (Figure 17). Seismic lines show the W-E profile, stratal patterns and geometries of the middle to upper Jurassic. There are three wells in the profile those are wells 35/11-5, 35/11-8S and 35/12-3S. Wells are overlaid with GR logs. The seismic profile shows a structural overview in the area of the Lomre Terrace and the Uer Terrace which inclines to the west. The deep inclination leads to slope sediment deposits in the Lomnre basin. Sub-basin exists in the Uer terrace near the Nordfjord-Sogn detachment.

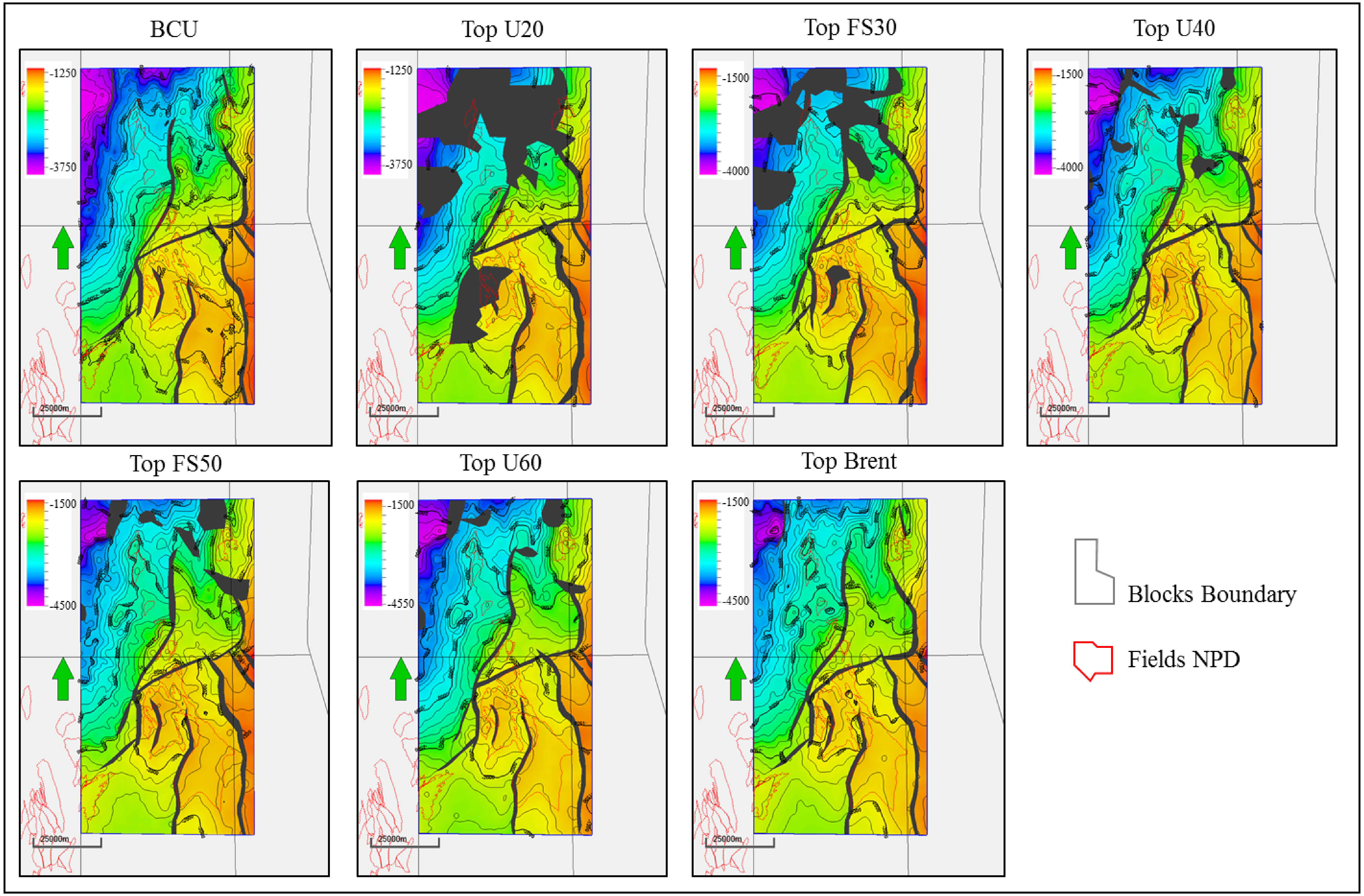


Figure 23. Time structural maps of BCU, U20, FS30, U40, FS50, U60 and Top Brent show the boundary and present-day topography of the study areas. High structures areas are at the SE such as the Troll *area*, the Bjorgvin Arch and the Øygarden fault complex zones. The structure inclines to the NW areas such as the Flatfisk Slope and the Lomre Terrace. The deepest area is in the Sogn Graben.

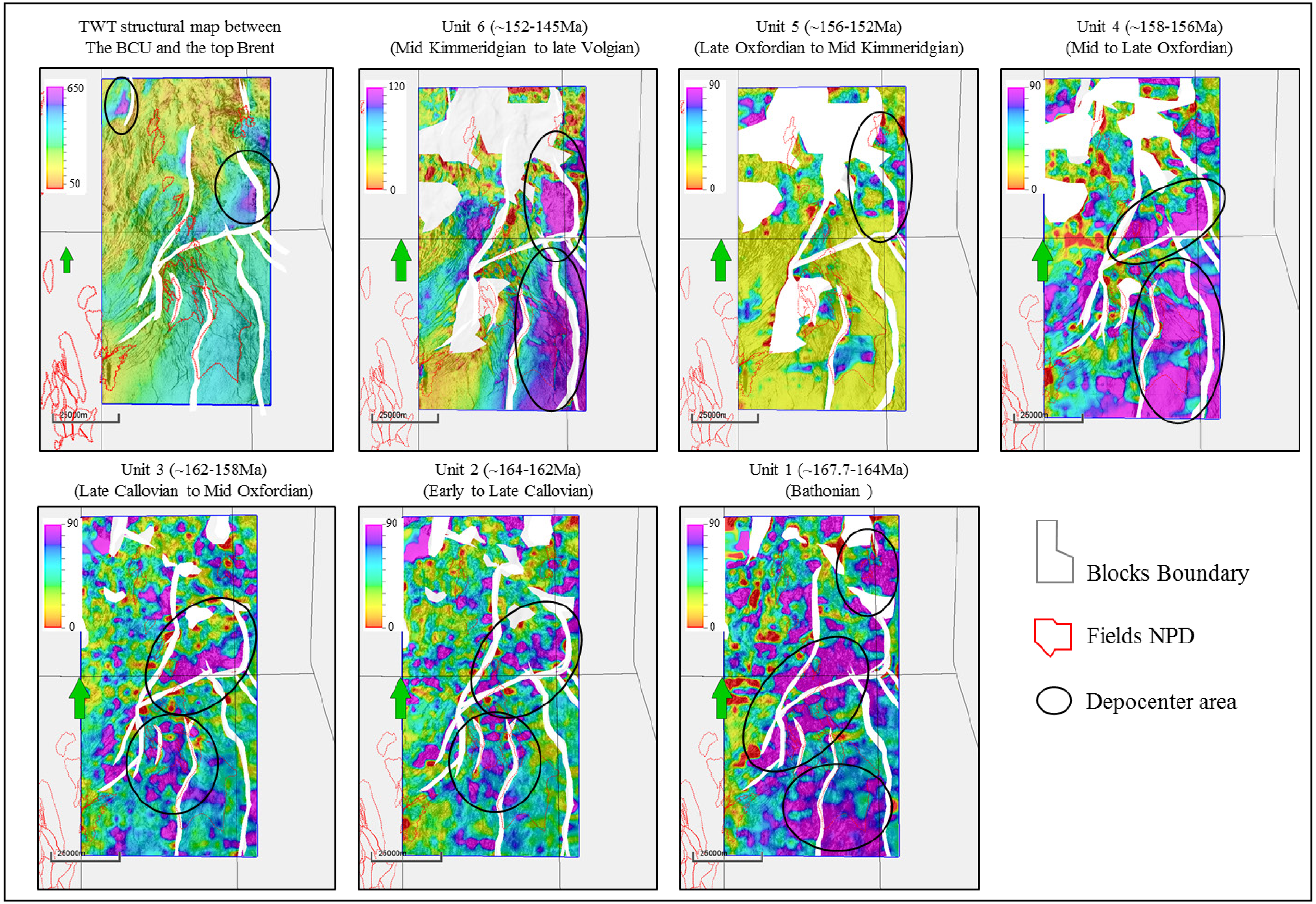


Figure 24. Isochrone maps overlay with variance attributes of the study area (middle to late Jurassic), Unit 6 (BCU-U20), Unit 5 (U20-U30), Unit 4 (U30-U40), Unit 3 (U40-U50), Unit 2 (U50-U60), and Unit 1 (U60 and Top Brent). The thickest value of the study interval is 650 ms (~1100 m). The isochrones map of the study interval shows the thickest sediment packages in the sub-basin along the Nordfjord-Sogn detachment and the Sogn Graben. Unit 1 shows depocenter areas at the Uer Terrace, the Troll and the Bjorgvin Arch, and then depocenters move to Unit 2 and Unit 3 which is a quiescence time. Depocenters of Unit 4, Unit 5 and Unit 6 show in the eastern part including the Bjorgvin Arch, the Uer Terrace and the Øygarden fault complex zone. White color represents faults and sedimentary hiatus zone.

4.1 Unit 1

Unit 1 is the oldest unit of this study. It is bounded by the Top Brent group at the base and U60 on the top (Figure 25). Unit 1 was deposited during the Bathonian (167.7-164.0 Ma) based on the lithological correlation and biostratigraphic data.

4.1.1 Observation from well sections

Unit 1 overlain on the sandstone dominated Brent group (Figure 25). Sandstones interbedded with coal of the upper Brent group are the main characteristic for Unit 1 base identification. The top Unit 1 is marked by U60 with the sharp boundary of sand progradation. The definition of this unit based on lithological change rather than biostratigraphic logs. Biozones data was used to define the boundary.

The overall lithology of Unit 1 is shale-dominated unit. It shifted from the sandy part in the upper Brent into the shaly part in Unit 1. Fine-grained sediment was deposited in the lower part and coarse-grained sediment was deposited at the upper part. Shale to silty claystone was interpreted at the lower and middle part of the unit. Claystones, siltstones and clean sandstones beds were interpreted in the upper part with a variable thickness from meter to ten meter scales. Thick sandstone sequences were found in the Troll area (e.g. wells 31/2-3 and 31/2-2R) whereas shales and siltstones were found in the northern part of the study area, e.g. the Uer Terrace (Figure 18; Figure 19). Thin limestone layers were found in several wells 31/2-8, 35/11-10, 35/11-11 and 35/11-1, which located in the Uer Terrace and the Lomre Terrace.

Gamma-ray log show a coarsening upwards stacking pattern with serrated shapes (Emery and Myers, 1996). The well correlation shows that the overall thickness trend of Unit 1 decreases from the SE to NW direction (Figure 25).

4.1.2 Observations from seismic profiles

Unit 1 is underlain by the soft reflection of the Brent group and overlain by the hard reflection U60 surface (Figure 16). Rock density and velocity change from the Brent horizon caused a significant variation in acoustic impedance. Therefore, high reflectivity contrast lead to a reliable interpretation of the top Brent. U60 shows medium to strong positive amplitudes and good continuity reflector.

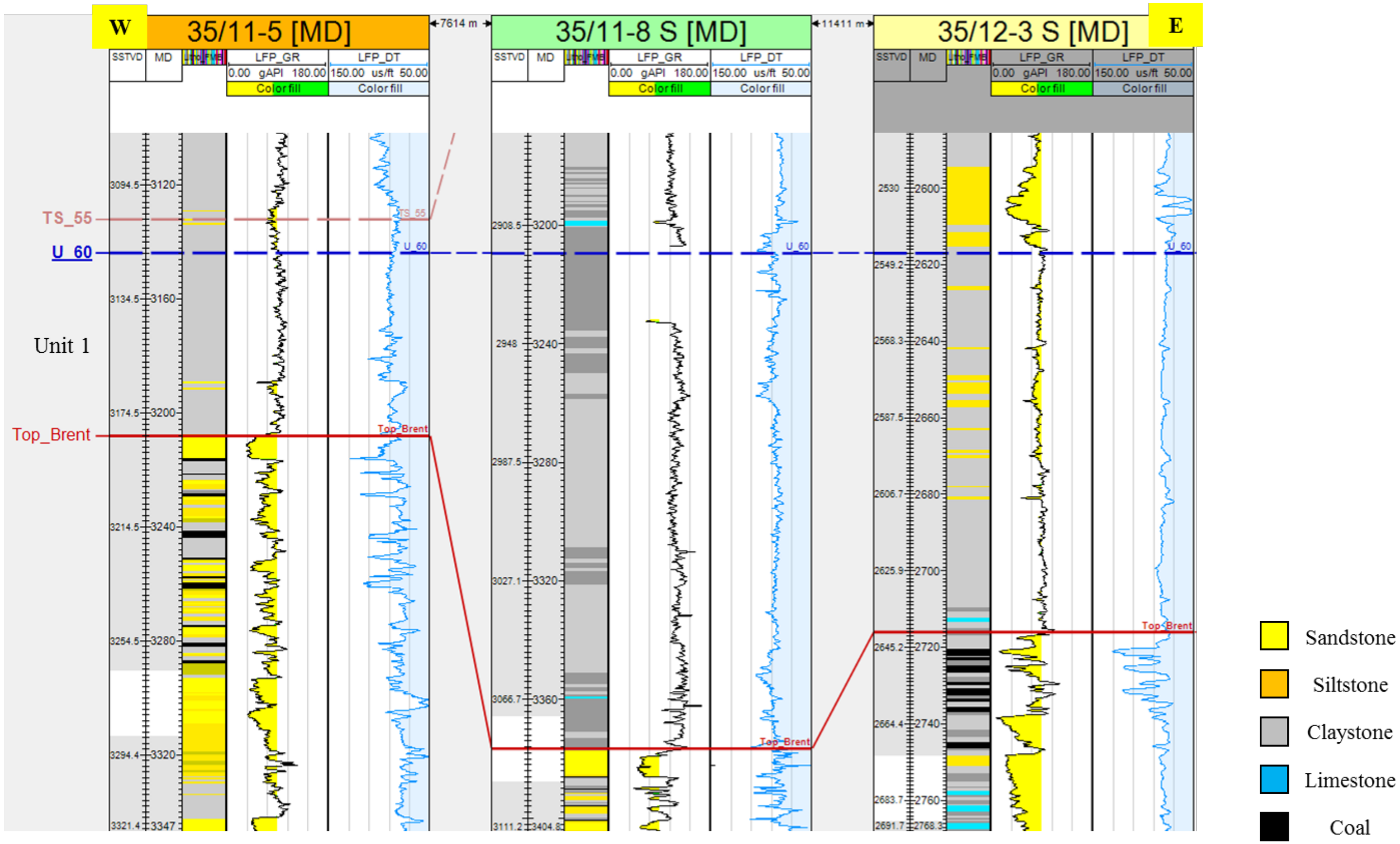


Figure 25. The well correlation shows log motif, lithological characteristics and thickness variation of Unit 1. The panel is flattened on U60 showing the correlation in the W-E direction. Lithological characteristics are dominated mudstone layers interbedded with thin sandstone layers. The panel shows unconformity at the base boundary, while the upper part shows more dominated sandy layers. The correlation shows less sandstone deposits to the west. GR logs show spiky trend with coarsening upward trends. The stacking patterns are in aggradation to small progradation at the upper part. The correlation panel represents the reference line 6 (See Figure 17).

Seismic sections show the depositional sequence dimming out westward toward the Lomre Terrace (Figure 20). The Flatfisk Slope consists of very thin layers of sandstones.

Small clinoforms are observed in the Troll area and the Bjorgvin Arch, where thick layers are deposited. Reflection configuration shows a subparallel pattern in the Troll area where sandstone progradation exists. Parallel to subparallel seismic facies were observed on the Lomre Terrace.

4.1.3 Observation from geologic maps and seismic attributes

Time structural maps of the Top Brent and U60 show the highest structure in the Bjorgvin Arch and the Troll area (Figure 23). The topography inclined in an NW direction towards the Lomre Terrace and the Flatfisk Slope. The Sogn Graben and the Ryggsteinen Ridge show the Jurassic truncation at the northern area (Figure 20). The truncated surfaces indicate the existence of paleotopography that led to post-depositional erosion.

The isochrone map of Unit 1 shows main depocenters at the Troll area and the Uer Terrace (Figure 24; Figure 26). The average thickness of this unit is 60 ms from the time structural map and around 100 m approximately from key wells. The calculation used average velocity from sonic logs. The thickest part from the time structural map was in the Uer Terrace with a thickness value larger than 100 ms and 166 m.

Seismic attribute maps show high amplitude values mainly on the western Troll area. Prograding clinoforms were seen in two areas (Figure 26; Figure 27). The southern Lomre Terrace shows the brightest amplitudes, where thick homogeneous shale are deposited (Figure 21; Figure 27).

4.1.4 Interpretation of Unit 1

Unit 1 was deposited during the Bathonian age, which previously was interpreted to be the inter-rifting phase of the Jurassic. The thickness between two Tusse fault blocks show less variable when compared to the others unit. The low variation thickness against fault can be an inter-rifting characteristic (Figure 29.). Stacked sandstone inferred a high sediment influx in the Troll area and the Bjorgvin Arch (Figure 25). The lithological change from sandstones to shales toward the west suggests that sediment source was from the east. The sediments supply less to the west due to due to low accommodation space and the distance from sedimentary sources (Figure 20; Figure 21; Figure 26; Figure 27). Downlap termination at the Lomre Terrace shows high RMS amplitude. The downlap surface at the Lomre Terrace was created by increased accommodation space and gravity flow of the shale sediments deposited along the Troll fault (Figure 27). However, it was no significant tectonic activity during this inter-rifting period. The domination of shale at the Lomre Terrace explains the distal part of a depositional system. The Troll fault caused an accommodation space and minor progradation at the downthrow fault block.

Also, the coarsening upward in the Troll well data represents sequences of sand prograding system, which supports sediment sources from the east. The highest sedimentation rate is inferred in the northern Troll area due to the high net to gross rate. (31/3-4 and 31/2-8). The Uer Terrace represents an average sedimentary input ratio with assumed lack of sandstones and with shaley bed (Figure 18; Figure 19). The Uer Terrace interpreted to be a distal shelfal area separating shallow and offshore marine environments.

Truncated layers were found at the northern Uer Terrace and likely representing a paleotopography during the deposition of this unit. The erosional surface identified in the seismic section supports that the unit was subaerial exposed above the sea level after deposition.

In summary, this unit is interpreted as a highstand system tract with representing normal regression. The upper boundary is bounded by U60 subaerial unconformity (SU). The change of shallow marine to deep marine deposits and truncation found at the top Brent horizon represents an unconformity shoreface ravinement (SR-U) (Posamentier et al., 1988). This unit represents the lower part of the Heather C and the Krossfjord formation where the Heather represents mudstone deposit, and the Krossfjord represent the sandstone intervals. The type section of this unit is the well 31/2-8 where the complete coarsening upward were found.

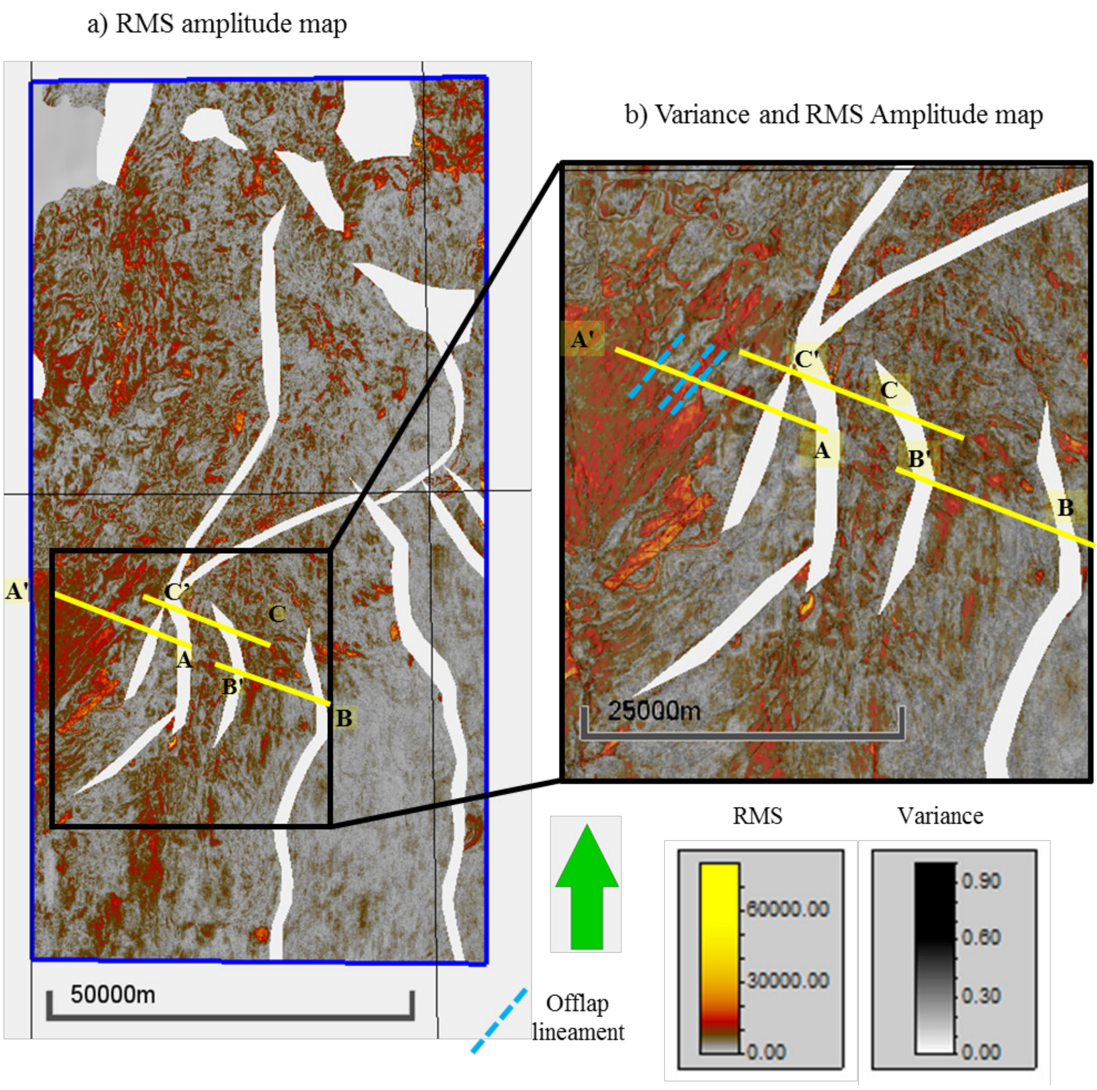


Figure 26. a) RMS amplitude map, b) Superimposed variance and RMS amplitude maps. The attribute map show overall high amplitudes in the Lomre Terrace and the Flatfisk Slope. Low amplitudes present in the Bjorgvin Arch and the eastern Uer terrace. High amplitude values indicate tuning thickness effect that suggests merging of seismic reflectors. It is a good hint to find stratigraphic termination in those area. The attribute maps show offlap lineaments with high RMS amplitude values in the Lomre Terrace. Two seismic sections which are A'-A and B'-B are selected to display stratigraphic features in profiles.

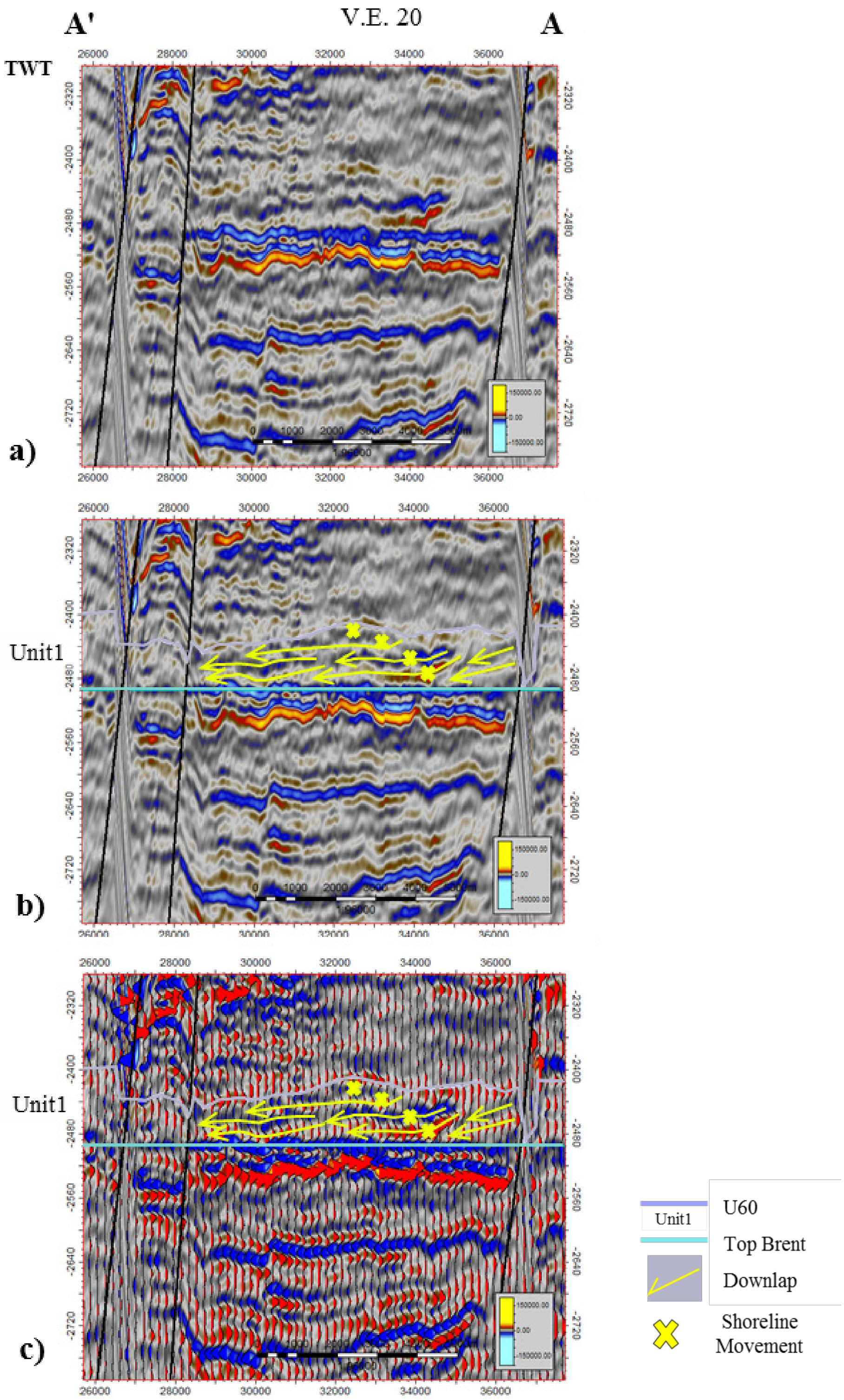


Figure 27. Seismic profiles from A'-A in the Lomre Terrace and the Troll Area. a) uninterpreted flattened seismic section b) interpreted flattened seismic section on the top Brent horizon. c) Seismic wiggle flattened the section on the top Brent horizon. The surface terminations shows downlap clinoforms to the west. The reflection amplitude is higher at the upper part of Unit *1. The shoreline movement shows progradation toward west from the Troll area into the Lomre Terrace.*

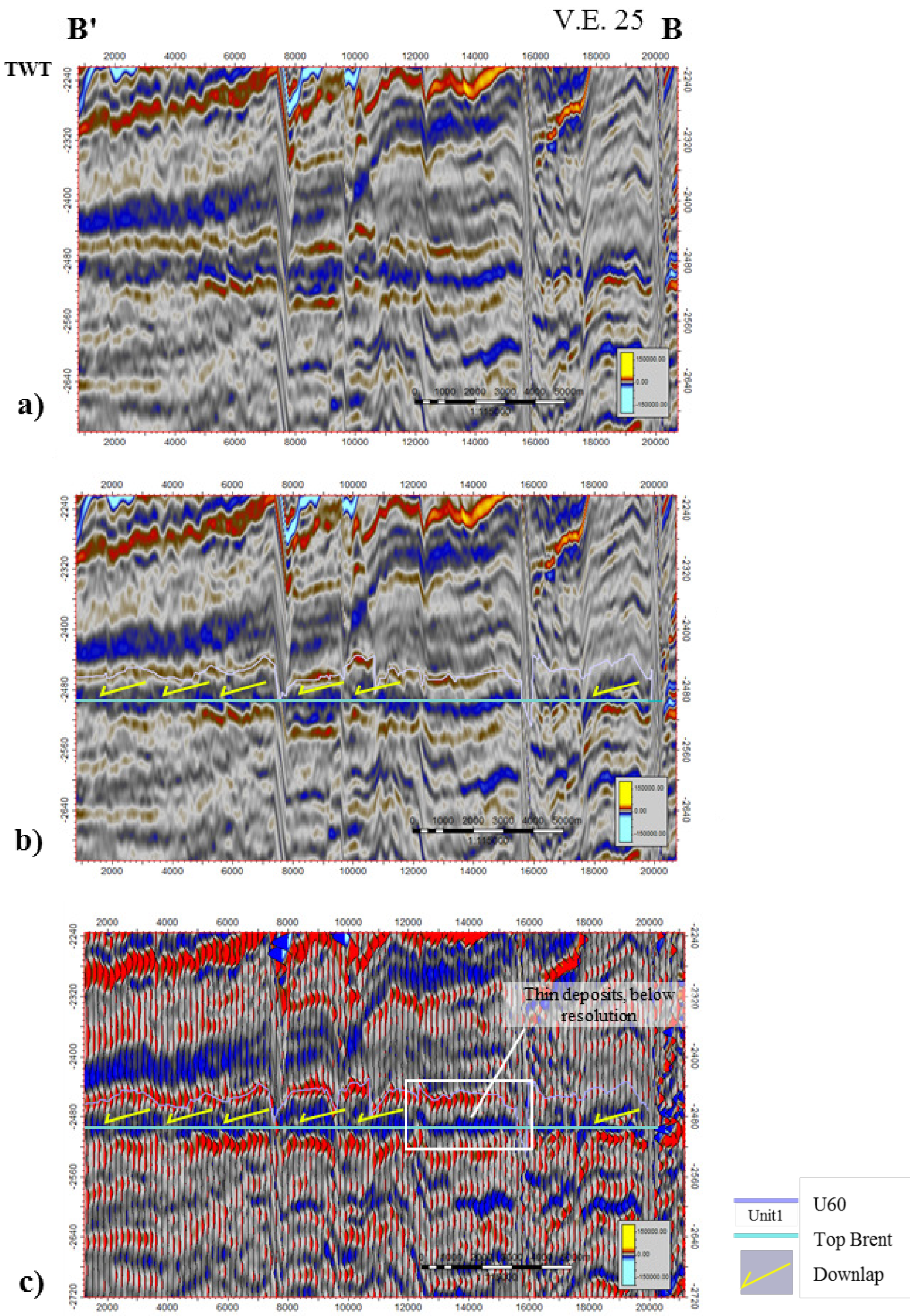


Figure 28. Seismic profiles from B'-B in the area of Bjorgvin Arch and the Troll area a) uninterpreted flattened seismic section b) interpreted flattened seismic section on the top Brent horizon. c) Seismic wiggle flattened the section on the top Brent horizon. The surface terminations shows downlap clinoforms to the west. Seismic wiggle amplitude shows tuning reflectors in the white box. It might represent thin layer deposits below the tuning thickness.

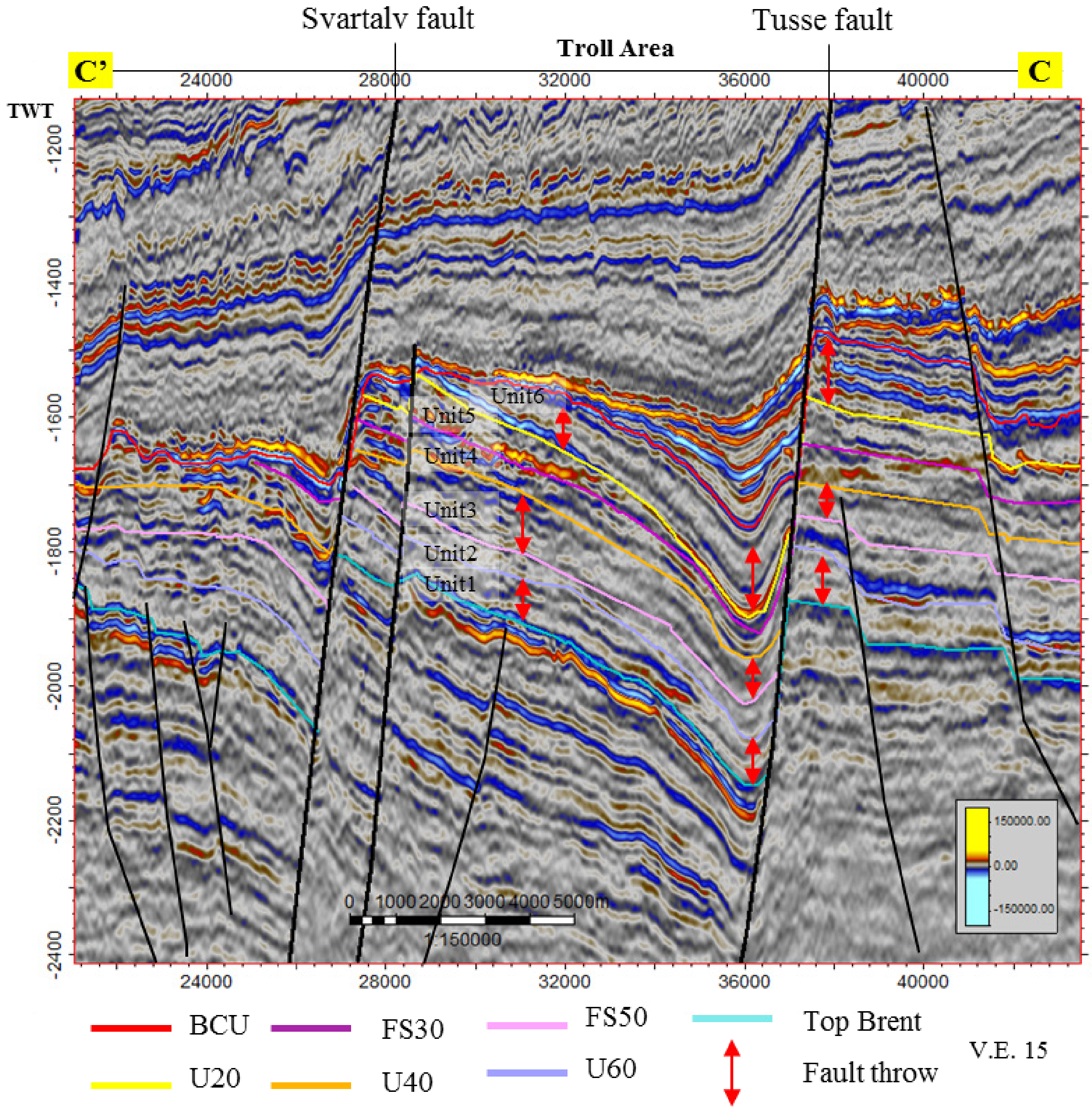


Figure 29. An interpreted seismic profile across the Troll field from C'-C. The central compartment are bounded by the Svartalv and the Tusse faults. The Tusse fault shows downthrown block sediments increases against the fault plane. It suggests several active periods during the middle to late Jurassic. Thickness highly increases along the fault plane since Unit 3 to Unit 6 which indicates the syn-tectonic period.

4.2 Unit 2

Unit 2 is bounded by underlying U60 and overlying FS50 stratigraphic surfaces. The age of the biostratigraphic data is interpreted to be between 164-162 Ma, which represents the early to late Callovian. Unit 2 is divided into two subunits, which are the Unit 2.1 and Unit 2.2. The stacking pattern shows progradation-aggradation-retrogradation features (Figure 30). The sub-units can only be identified in the well logs due to the thickness below the seismic resolution.

4.2.1 Observation from well sections

The base of Unit 2 is defined by a lithological change from shale-dominated with thin sandstone layers to thick sand-dominated layers at the top. The main criteria for the classification of the lower boundary is the biozone ages and lithological change. The upper boundary of Unit 2 is a maximum flooding surface (FS50), which has a geological age around 164 Ma.

The lithology of Unit 2.1 shows interbedded sandstone with siltstone layers in the southern part, especially in the Troll area. The northern part of the study area shows more shale and sandy siltstone packages (Figure 30). Limestone layers are observed at the Uer Terrace and in the north (e.g. wells 35/11-11, 35/8-5S, and 35/9-6S). Few meters of limestone beds are interbedded with shales to siltstone.

Unit 2.2 is dominated by shale. Shale interbedded with siltstone is observed in the Uer Terrace while sandstone sequences are observed in the eastern area. Around the Troll area, wells 31/2-3, 31/2-2R, and 31/3-3 show thick siltstone interbedded with clean sandstone beds. The thickness of this unit is around 5-13 meters.

The GR log shows a typical stacking pattern of Unit 2.1 that is mostly in blocky shape and Unit 2.2 that is in bell shapes, which suggests an aggradation above the maximum regression, then followed by the retrogradation. The sonic log (DT) displays a steady velocity decrease upward (e.g. wells 31/2-3, 31/2-8, and 35/11-1) (Figure 30). The lithological changes from clean sandstone in Unit 2.1 to shaley to silty sandstone in Unit 2.2. Limestone layers present in the Uer Terrace. The overall thickness of Unit 2 is decreased from the SE to the NW direction (Figure 30).

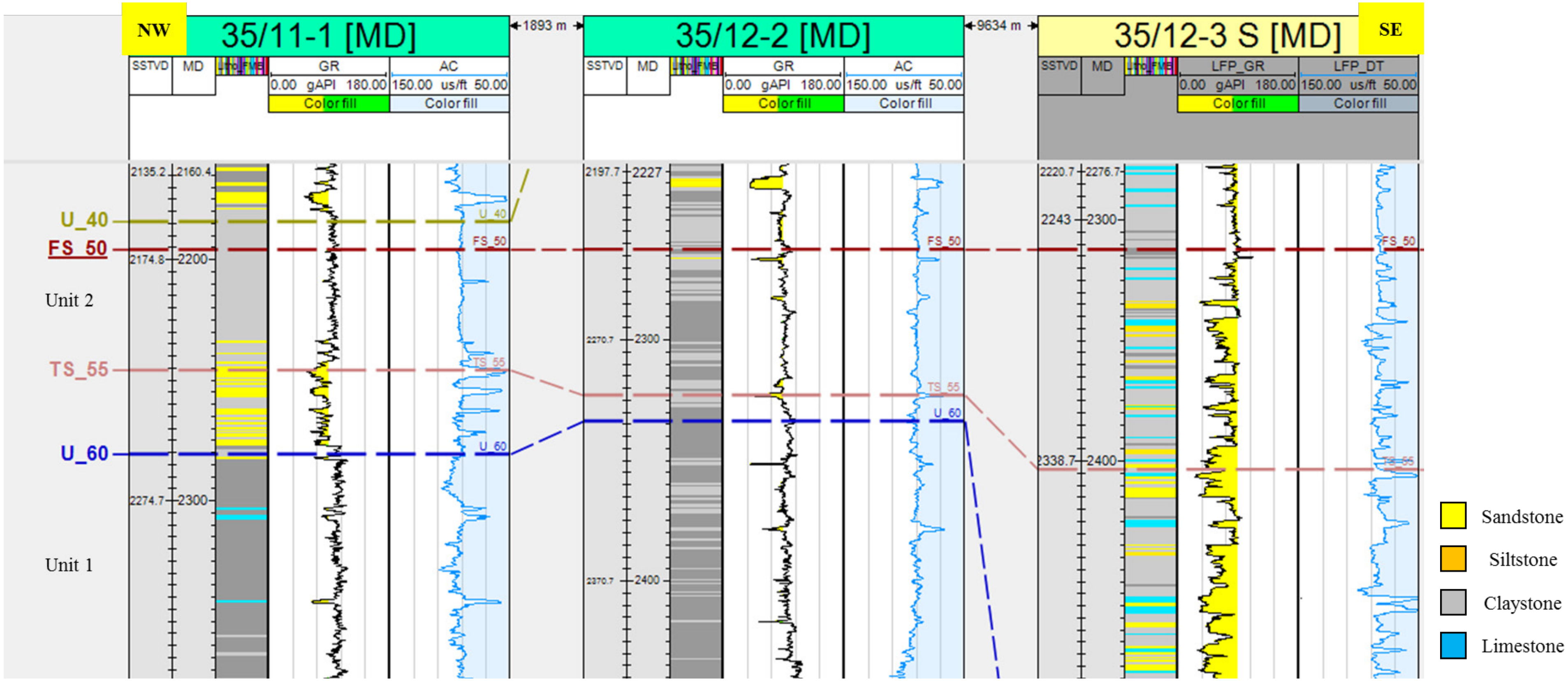


Figure 30. The well correlation shows log motif, lithological characteristics and thickness variation of Unit 2. The unit comprises FS50, TS55 and U60. The panel is flattened on FS50 surface showing the correlation in the NW-SE direction. Lithological characteristics are mainly sandstone layers at the lower part and fining upward deposition to mudstone layers at the top. Thick sandstone layers show at the east with sandstone interbedded with thin limestone beds as found in the well 35/12-3S. GR logs show fining upward trends. The panel shows unconformity of U60 at the base and MFS at the top. TS55 indicates changes from coarsening upward to fining upward GR trends. The stacking patterns are progradation at the base, then aggradation and retrogradation at the upper part. The correlation panel represents the reference line 2 (See Figure 17).

4.2.2 Observations from seismic profiles

Unit 2 is bounded below by the hard reflector of top Unit 1 and above by the soft reflector of FS50 (Figure 16). FS50 surface shows in general low to medium continuity. The sequence consists of thick layers in the Troll area as described in Unit 1. The unit thickness pinches out from the NE to the SW direction. The seismic configuration of unit 2 is parallel to subparallel with high continuity in the Troll area while the northern Uer Terrace shows poor continuity and chaotic patterns. Both downlap and onlap surfaces are identified on the Lomre Terrace near the Troll fault (Figure 31; Figure 32). The Uer Terrace has a localised depositional systems, especially along the Nordfjord-Sogn detachment.

4.2.3 Observation from geologic maps and seismic attributes

The time structural map of FS50 shows a similar structure to U60. The highest structure are at the Bjorgvin Arch, the Vette fault, and in the Troll area (Figure 23Figure 23.). The deepest part is in the Flatfisk Slope. Unit 2 is relatively thin in thickness and constant throughout the entire study area. An average thickness of Unit 2 is around 50 ms in the time domain and 80 m in the depth domain. The depositional centre shifted from the Bjorgvin Arch toward the Uer Terrace and the northern Troll area (Figure 24).

Seismic RMS and variance attribute maps show both high values over the Troll field, while the Lomre Terrace has high amplitude values but low variance values. The variance map has a high value in the Bjorgvin Arch along a SE-NW direction (Figure 31). This can represent high sandstone deposition by higher variance values from nearby areas. It is suggested that the sediment was sourced from the SE direction. The rest high amplitude areas are expected to serve insignificant geological feature, which was the result of the limited seismic resolution by the tuning thickness effects.

4.2.4 Interpretation of Unit 2

The thickness of this unit is relatively constant which is due to deposition during the inter-rifting period. The shifting of depocenter to the Uer Terrace was possibly caused by a small reactivation of the Vette fault and Nordfjord-Sogn during the early Callovian to the early Oxfordian. The time structural map displays a larger missing section in the north Uer Terrace. It suggests that paleotopographic high in the north indicates erosional areas (Figure 24). The amplitude map is integrated with the well data. The well shows thick shale deposition in the Lomre area, which is confirmed by high RMS amplitude values and low variance values. Shale can result in high RMS amplitude value when they have a negative amplitude value higher than seismic resolution. It usually shows high distribution covers the area.

In summary, unit 2 represents lowstand and transgressive system tracts. From the well logs, Unit 2.1 represents a lowstand system tract, and Unit 2.2 represents a transgressive system tract. However, sub-unit thickness is below the seismic resolution; therefore, it cannot be interpreted on the seismic data. The maximum regressive surface RS55 is the boundary between two subunits, which was identified in the well interpretation. The onlap surface is observed in the Lomre Terrace, which indicates a transgressive event (Figure 31; Figure 32). The base of Unit 2 is marked by truncation on the top Unit 1. The top of Unit 2 is overlain by a maximum flooding surface FS50. Sedimentary influx is interpreted from seismic sections, which suggests that the sediment source is in the proximal part at the SE and the distal part is in the shale-dominated sequences at the Lomre Terrace. Unit 2 correlates to the Krossfjord and the Fensfjord formations. The section of this unit presents in wells 31/2-8 and 35/12-3S (Figure 18; Figure 30).

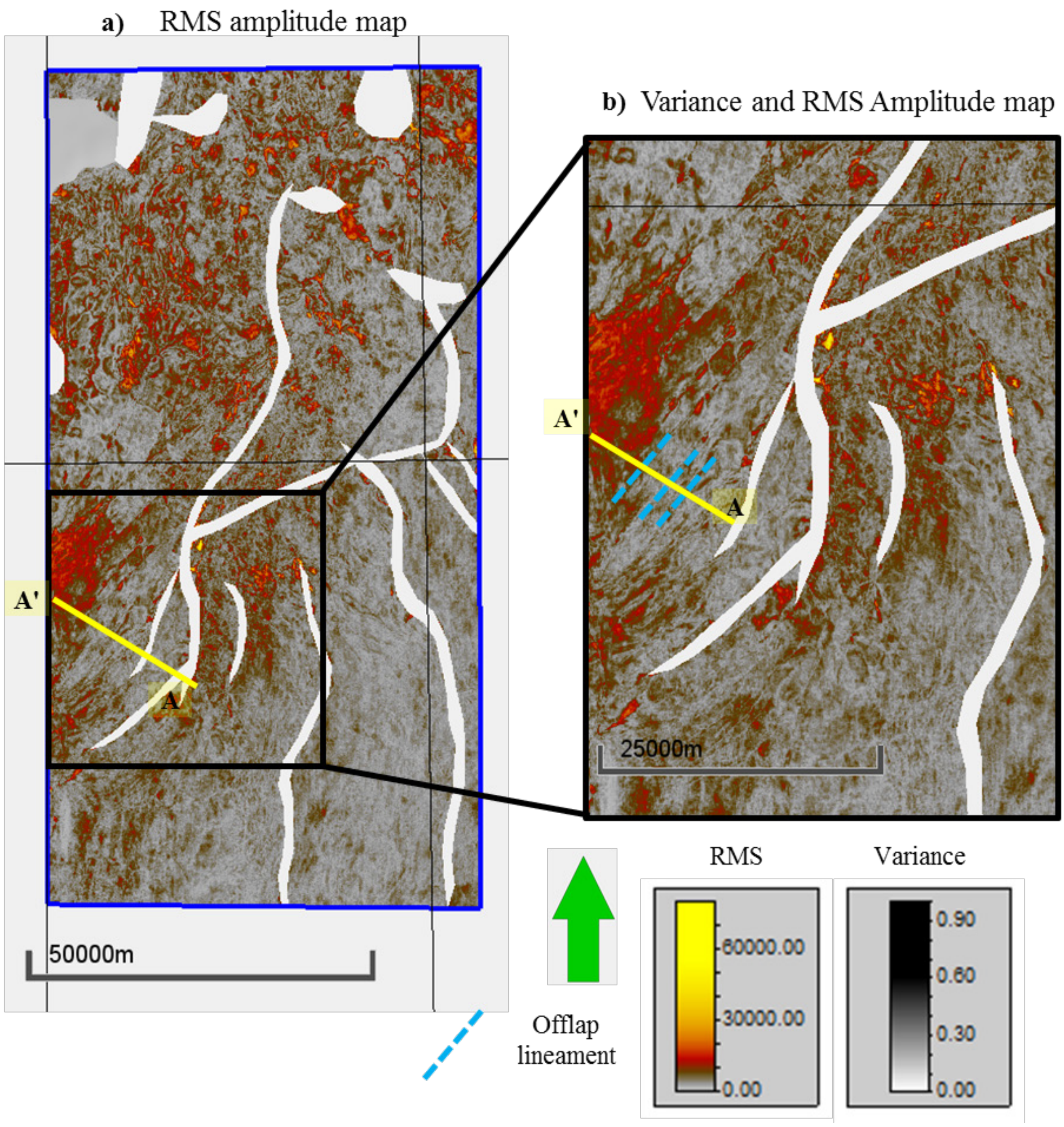


Figure 31. a) RMS amplitude map, b) Superimposed variance and RMS amplitude maps. The attribute maps show overall high amplitudes in the Lomre Terrace and the Flatfisk Slope. Low amplitudes present in the Bjorgvin Arch and the eastern Uer terrace. The Lomre Terrace presents high amplitude at the downdip area, while low amplitude presents in the updip area of the Lomre Terrace. The attribute maps show offlap lineaments in the Lomre Terrace. A seismic section A'-A are selected to display stratigraphic features in the profile.

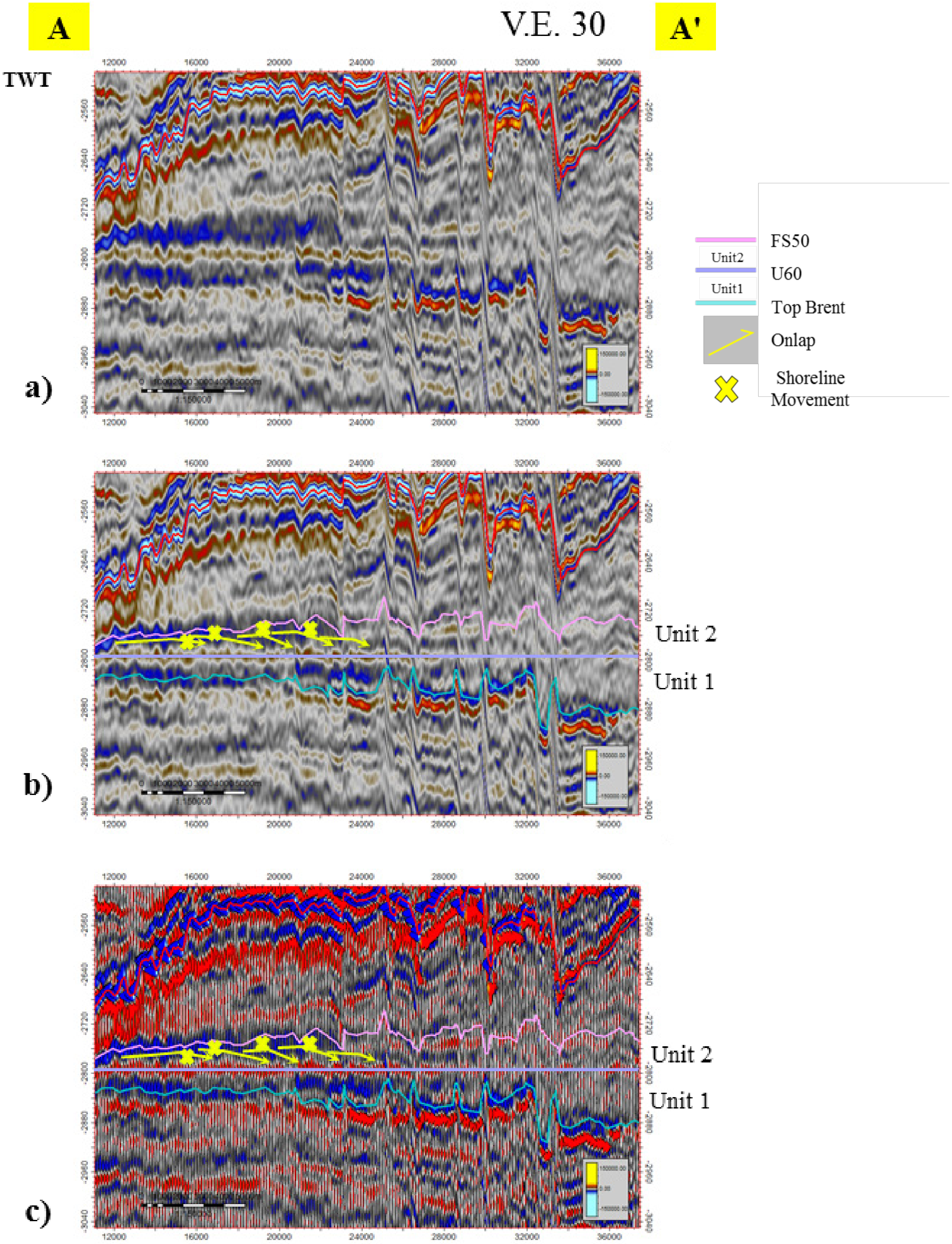


Figure 32. Seismic profiles from A-A' in the area of the Lomre Terrace a) uninterpreted flattened seismic section b) interpreted flattened seismic section on U60. c) Seismic wiggle flattened the section on U60. The surface terminations show onlap to the east. The shoreline movement presents retrogradation stacking pattern. The reflection amplitude has more positive value toward the east. High negative amplitude value represents thick soft sediment deposits such as mudstone, claystone layers.

4.3 Unit 3

Unit 3 is bounded by the underlying FS50 and overlying U40. Depositional age is assigned to between 162-158 Ma (the late Callovian to the middle Oxfordian).

4.3.1 Observation from well sections

Biostratigraphic data of this unit is in low confidence and unclear in stratigraphic. However, it suggests an approximate age between the middle Callovian to the early Oxfordian. The lithology is mainly shale dominated, except in the Troll area where siltstones and sandstones are deposited with a thickness around 4-7 meters. Limestone does not exist within this unit. The Uer Terrace contains a mud-dominated sequence in the well 31/2-19S (Figure 33). Moreover, the well 31/2-19S presented a sulfate rock at the lower part of the unit. Sulfate rock gives a very low GR, low DT and high acoustic impedance contrast (AI). The Troll area and the Øygarden fault complex area deposited thick sandstone beds. The sandstone beddings in the GR log are in blocky and symmetrical shapes (e.g. wells 35/9-2 and 35/12-1). The DT log shows an overall constant velocity. The stacking pattern is mostly aggradation (Figure 33).

4.3.2 Observations from seismic profiles

Unit 3 is bounded by the negative impedance and soft reflection of the F50 at the base and the positive impedance and hard reflection of U40 at the top (Figure 16). The U40 is characterised by strong amplitude and high continuity. The internal seismic character consists of medium to strong amplitudes which are subparallel at the Troll area, and chaotic weak amplitude at the Bjorgvin Arch. The thickness of this unit is relatively constant. However, gross thickness in the Lomre Terrace and the Flatfisk Slope is larger than the Troll area and the Uer Terrace (Figure 20; Figure 21). The Uer Terrace displays high erosion except in the sub-basin near the Nordfjord-Sogn detachment (Figure 34). The seismic configuration is subparallel in the depocenter with wedge shape geometry from the east to west in the sub-basin (Figure 20; Figure 22). The seismic facies is characterized by subparallel, medium to low continuity and weak amplitudes. Downlap surfaces can be found along the Nordfjord-Sogn detachment and at the slope along the Kinna fault (Figure 22; Figure 34).

4.3.3 Observation from geologic maps and seismic attributes

Unit 3 is overlain by the U40. The time structural map shows similar paleotopography as the underlying FS50 and U60 (Figure 23). The highest structure of unit is in the Troll area and the Bjorgvin Arch. The basin deepened to the NW. The Uer Terrace shows missing section in the north that possibly indicates a change in tectonic activity. For example, the isochrone map shows a thicker depocenter developed along the Nordfjord-Sogn detachment fault. However, the average thickness of this unit is similar to Unit 2 at 50 ms in the time domain and 84 m in the depth domain (Figure 24).

4.3.4 Interpretation of Unit 3

The interpretation infers tectonic reactivation in Unit 3. There are several areas showing increase in thickness against the fault plane such as the Nordfjord-Sogn detachment and the Kinna fault (Figure 24; Figure 29; Figure 34). The reactivation resulted in a higher thickness of Unit 3 near the Nordfjord-Sogn detachment compared to Unit 2. The lithological trend and sedimentary facies represents a shallow marine depositional environment at the Troll area and the Uer Terrace (Figure 33). Thick sandstones in the well 35/12-1 indicate the sedimentary influx was higher in the north compared to a more southern sediment influx in the south previously (Figure 34). The syn-rifting opened more accommodation space for the basin. However, a larger sedimentary hiatus indicated high paleotography came later during the post-rift stage, then became eroded.

Coarsening upwards sequences of interbedded sandstone and mudstone layers suggest the end of sea level rise and the start of shoreline progradation (*Figure 6*; Figure 33; Figure 34). The unit is interpreted as a highstand system tract. Sulfate rocks at the well 31/2-19S indicate short rapidly sea level dropped that resulted in shallow marine deposits in the closed environment (Goldhaber, 2003) (Figure 33). The type sections of Unit 3 are in wells 31/2-19S, 35/9-2 and 31/2-2R at the Lomre Terrace, the Uer Terrace, and the Troll area, respectively. The unit is capped by a subaerial unconformity of U40.

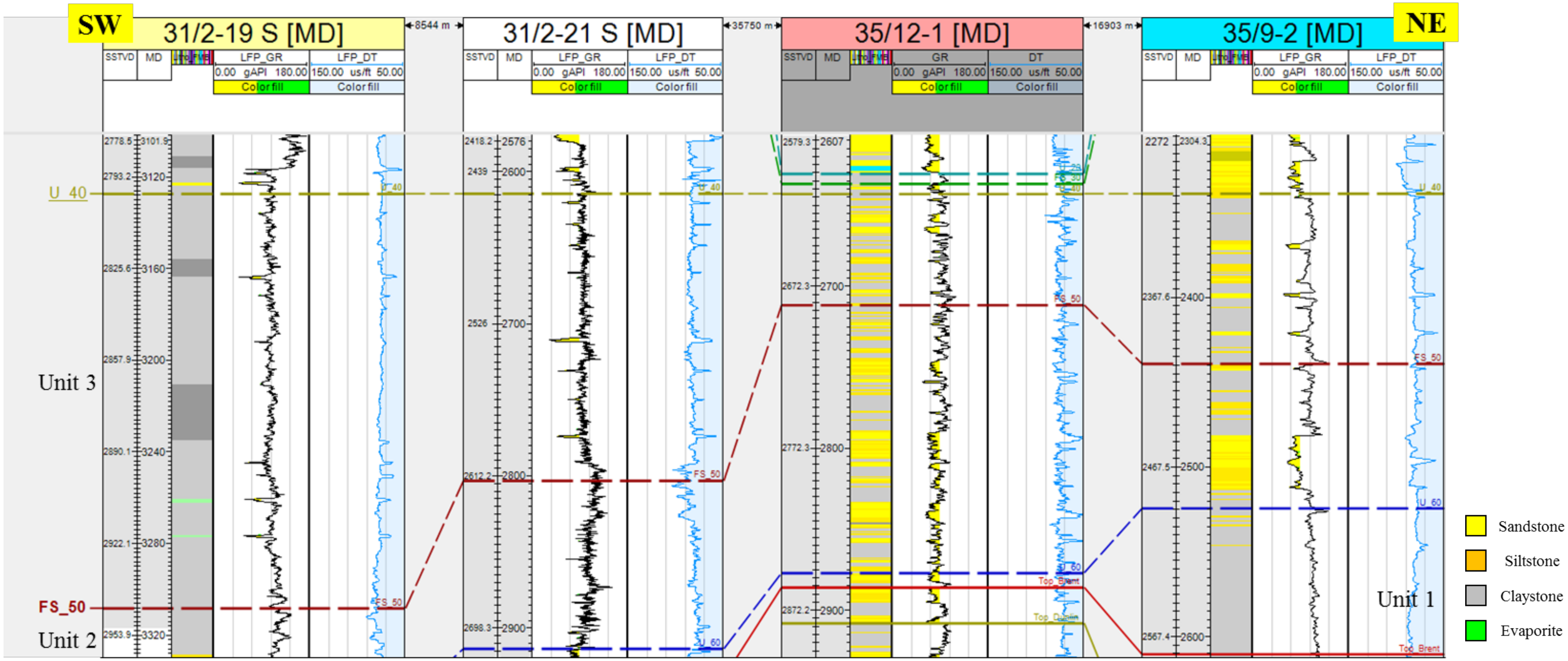


Figure 33. The well correlation shows log motif, lithological characteristics and thickness variation of Unit 3. The unit comprises U40 and FS50. The panel is flattened on U40 which is a sequence boundary. The correlation panel shows in the SW-NE direction. Lithological characteristics are interbedded sandstone and mudstone layers. The lithology variation clearly shows dominated sandstone layers at the east and mudstone layers at the west. GR log shows spiky and serrated curves with coarsening upward trend as displayed in the well 35/12-1. The stacking patterns are aggradational. The correlation panel represents the reference line 1 (See Figure 17).

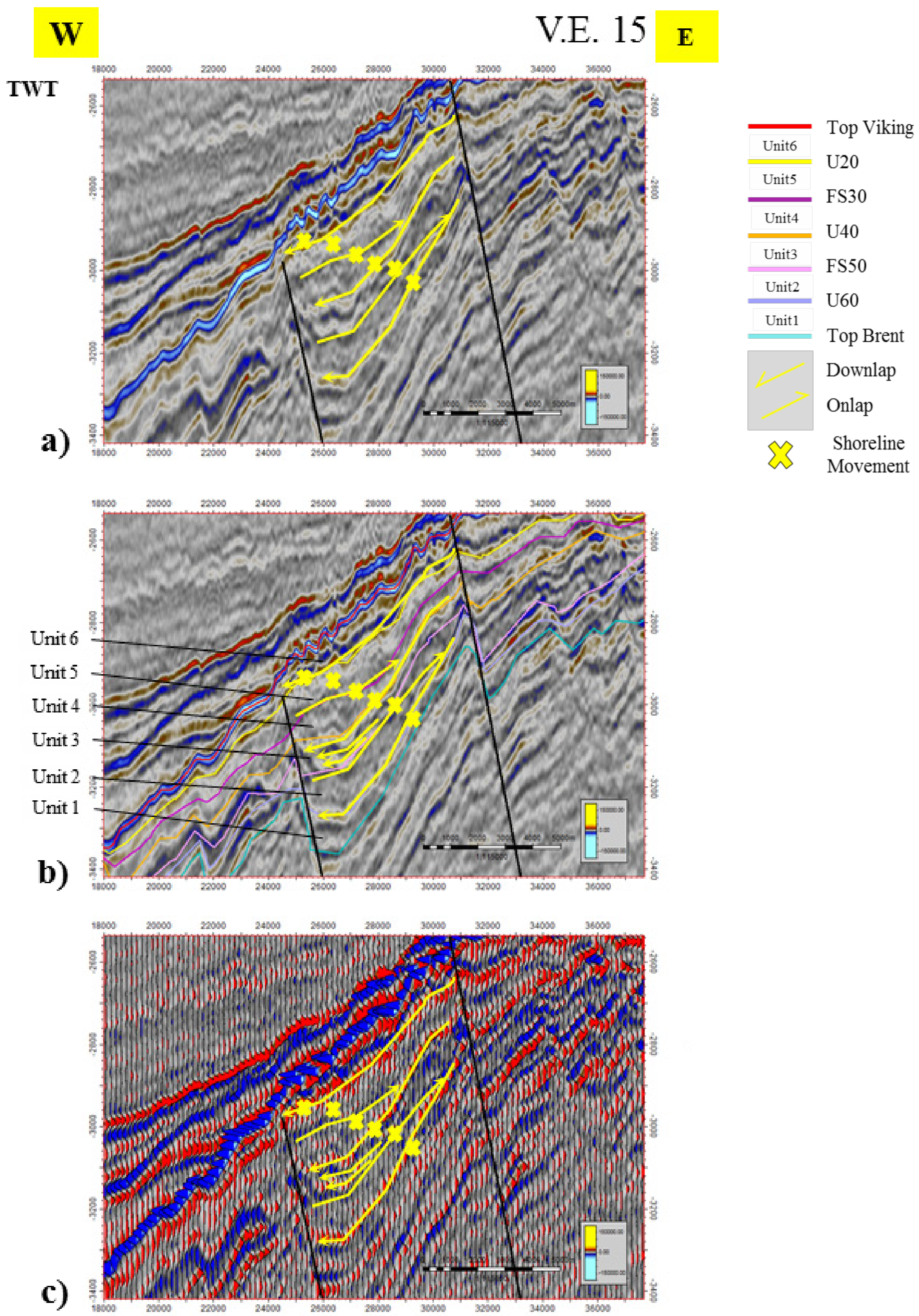


Figure 34. Seismic profiles from W-E in the area of the Lomre Terrace where slope sediment deposits. a) uninterpreted seismic section b) interpreted seismic section. c) Seismic wiggle section. The seismic reflector terminations display following the cycle of mean sea level change from Unit 1 to Unit 6. The stacking pattern in this area is always progradational. Seismic sections display stratigraphic termination surfaces of each Unit. Unit 3 shows the small downlap clinoform in the seismic section during the HST. The surface terminations shows downlapping to the west.

4.4 Unit 4

Unit 4 is bounded by the underlying U40 and the overlying FS30. The top Unit 4 was eroded by the BCU in some areas, for example, the highest point of the Troll field (e.g. 31/2-8 and 31/2-3) and a large part the northern Uer Terrace and the Flatfisk Slope. The biostratigraphic age is interpreted between 158-156 Ma, which is during the middle to late Oxfordian (Figure 18; Figure 19).

4.4.1 Observation from well sections

The boundary of Unit 4 are surrounded by clayey and silty sediment packages. Mudstones to siltstones deposited below Unit 4. The upper surface was capped by mudstones and siltstones deposits above the FS 30. Biostratigraphic data is an effective tool to define the age of this unit. It indicates a reliable age range from the top and the base boundaries (Figure 18; Figure 19). Unit 4 is divided into two sub-units. The lower part is Unit 4.1, which consists of thick sandy dominated sequences. The Troll area has thick sand packages ranging from 5-30 meters (31/2-8, 31/2-3, and 31/3-1). The northern Uer Terrace also consists of thick sandstone packages ranging from 5-15 meters (35/9-2). The GR log mainly shows a blocky shape sandstones. The stacking pattern is aggradational in Unit 4.1. Thin limestone and dolomite layers are found in the northern Uer Terrace in wells 35/9-6S, 35/11-1 and 35/12-3. The upper part is sub-unit 4.2, which shows fining upward sequence (Figure 35). Spiky shape in DT log indicates a sharp change from thick sandstones to interbedded thin mudstones to siltstones. Sandstones pinched out toward west as shown in correlation panels (Figure 18; Figure 19; Figure 35). The thickness of Unit 4 was relatively higher than other units. Prograding sandstone sequences is found extensively distribution toward the Flatfisk Slope (Figure 35).

4.4.2 Observations from seismic profiles

The hard reflector of U40 bounds Unit 4 at the base and the soft reflector of FS30 at the top. FS30 surface amplitude shows medium to poor continuity in the Uer Terrace and the Flatfisk Slope, while a strong reflector presents only in the Troll area (Figure 20; Figure 21). The large flat spot in the Troll area and the Bjorgvin Arch affected the reflector continuity, and it led to uncertainty of the surface picking (Figure 36). The large flat spot has a length of 12 km covering the Troll area and the Bjorgvin Arch. The unit thickness is relatively thick covering the Uer Terrace, the Troll area, and the Bjorgvin Arch. The thinnest areas are in the Lomre Terrace and the Flatfisk Slope (Figure 24). Seismic configurations generally show strong amplitudes, medium to good continuities with mainly parallel to subparallel shapes. Oblique prograding clinoforms is visible in the Uer and Lomre Terraces. Major downlap surfaces are identified in the Lomre Terrace and also in the Bjorgvin Arch where sediment sources transported from major active faults such as the Øygarden fault complex and the Vette fault (Figure 36; Figure 37; Figure 39; Figure 41). The upper part is indicated by onlap features in the Lomre Terrace. The upper part of Unit 4 is a transgressive surface in the well and log interpretation (Figure 35; Figure 36; Figure 37; Figure 38; Figure 40).

4.4.3 Observation from geologic maps and seismic attributes

Time structural maps of Unit 4 consists FS30 and U40. FS30 shows similar structures as previously mentioned surfaces. The thickest part is located on the Flatfisk Slope, and the shallowest area is in the Troll area and the Bjorgvin Arch (Figure 23; Figure 24). There is a larger missing section in the northern Uer Terrace. Depocenters were widely distributed covering a large area of the Uer Terrace, the Troll area and the Bjorgvin Arch. The average thickness is 60 ms in the time domain and 91 m in the depth domain (Figure 24). Variance maps suggest that main faults strike along the NE-SW direction in the Lomre Terrace and the SE-NW for the Troll area, the Bjorgvin Arch, and the Uer Terrace.

In the south, high amplitude values represent stack sandstones at the Troll area. Offlap lineaments on the Lomre Terrace represent the surface terminations of this unit in the seismic profiles (Figure 37; Figure 38). In the north, both spectral decomposition and RMS amplitude maps show a potential turbidity flowing from the Kinna fault into the Lomre Terrace and the Flatfisk Slope (Figure 37; Figure 42).

4.4.4 Interpretation of Unit 4

The large missing section in the northern Uer Terrace began forming during the deposition of Unit 4. This might infer to both unconformity high tectonic activity and the sea level drop (Snedden and Liu, 2010) during this period (*Figure 6*). The thickness map shows thick sediments highly distributed throughout the area, which inferred to major fault movements during Unit 4 (Figure 24). The thickness indicates higher rifting during Unit 4. The wedge-shaped geometry in the downthrown blocks also confirm the evidence of tectonic rifting phase (Figure 29).

Downlap features indicates the direction of sediment source was from the east at the Bjorgvin Arch and the Øygarden fault complex toward west. It suggests the proximal part of the system is in the Uer Terrace and the Troll area (Figure 37; Figure 38; Figure 39; Figure 41). The turbidite channel displays incising features and channel cut in seismic profiles (Figure 38; Figure 41; Figure 42). The interpretation of the turbidite channel represents a shefal marine environment on the Lomre Terrace, and the Flatfisk Slope. In contrast, the Troll area and the Uer Terrace were in a shallow marine environment. The results from spectral decomposition 9-27-45 Hz enhance turbidity facies features (Figure 37; Figure 38; Figure 41; Figure 42). Paleotopographic high during the active stage of the Kinna fault created a steep dipping toward the Flatfisk Slope, which caused sediments transported through the bypass area and deep marine sandstone deposits. The channel-cut, unconformity and tuning effect from the seismic profile confirmed slope bypass environment. The width of the channel from the seismic profile is about 3 km (Figure 42).

The large flat spot in the Troll field suggests the existence of huge hydrocarbon accumulation (Figure 36). Hydrocarbon reserves in the Troll field are gigantic when looked at the hydrocarbon column height above the flatspot. The flat spot line is used as a good indicator for hydrocarbon contact layers which shows a prominent character in both well and seismic data due to the sharp change of velocity in DT and AI (Sheriff et al., 1995). However, the flatspot can make an uncertainty for sequence stratigraphy interpretation since the structural reflectors are disturbed by hydrocarbon effect. Both FS30 and U40 needs an interpretation with a robust geological model rather than only following reflectors.

In conclusion, Unit 4 consists of lowstand and transgressive system tracts. It is bounded by the unconformity U40 at the base and the maximum flooding surface FS30 at the top. The maximum regressive surface RS35 is the boundary in between two system tracts which is only identified in the well interpretation. Offlap lineaments from seismic attributes are good indicators for the stratigraphic terminations. Prograded features on the Lomre Terrace supports the LST interpretation, while onlap features on top of FS30 in the upper part indicate the TST interpretation (Figure 37; Figure 38; Figure 39; Figure 40; Figure 41). The type section of this unit is in the well 31/2-2R for the LST distal part and in the well 35/11-3S for the TST.

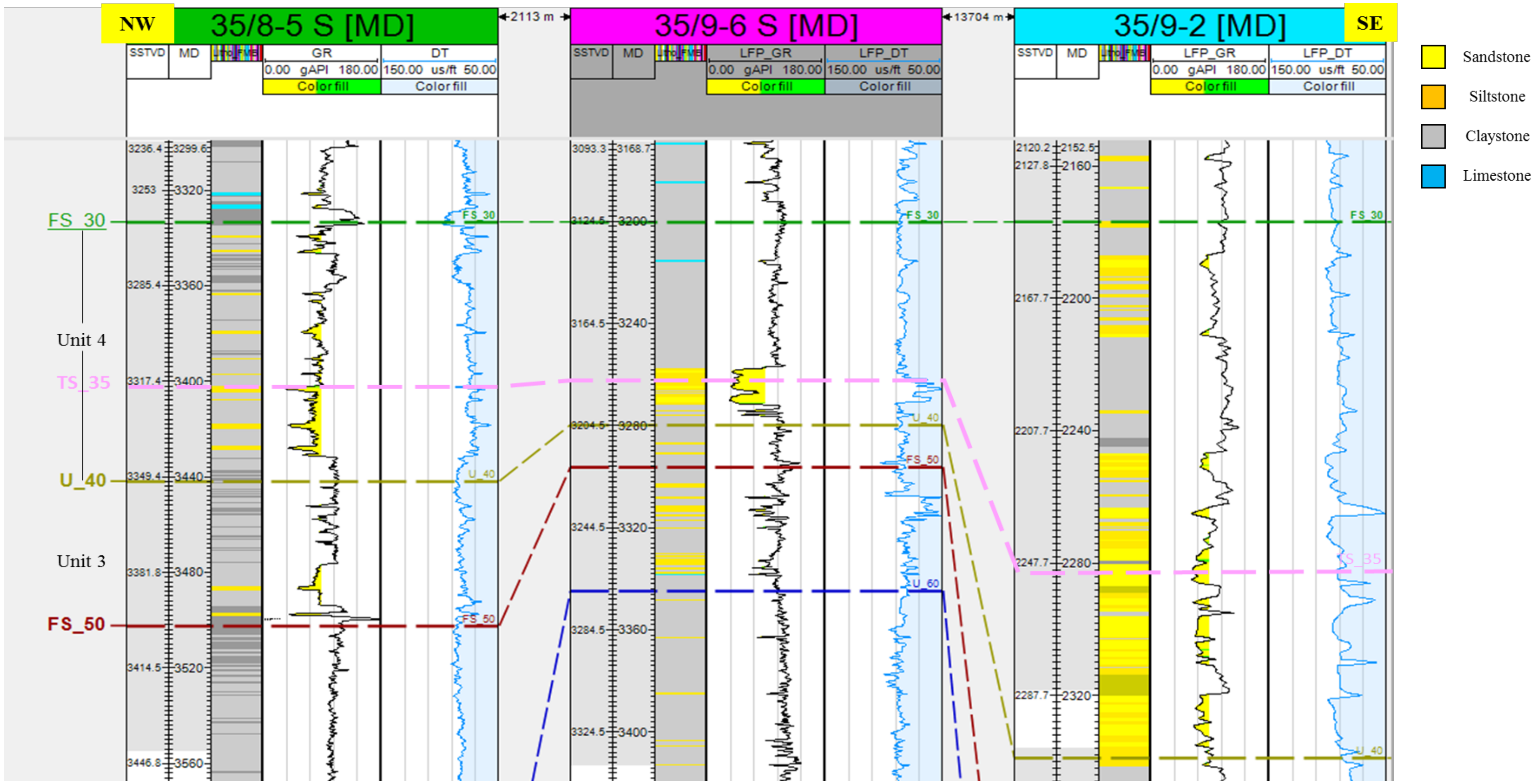


Figure 35. The well correlation shows log motif, lithological characteristics and thickness variation of Unit 4. The unit comprises FS30, TS35 and U40. Unit 4 is divided into two sub-units. The panel is flattened on FS30. The correlation panel shows in the NW-SE direction. Thickness variation decreases to the west. Condensed section is observed in the well 35/9-6 that represents paleotopographic high. Lithological characteristics are interbedded sandstone and mudstone layers. The lithology variation clearly shows dominated sandstone layers at the east and interbedded sandstone and mudstone layers at the west. GR log shows fining upward trend as displayed in the well 35/8-5S. The stacking patterns are progradation at the base, then aggradation and retrogradation at the upper part. The correlation panel represents the reference line 4 (See Figure 17).

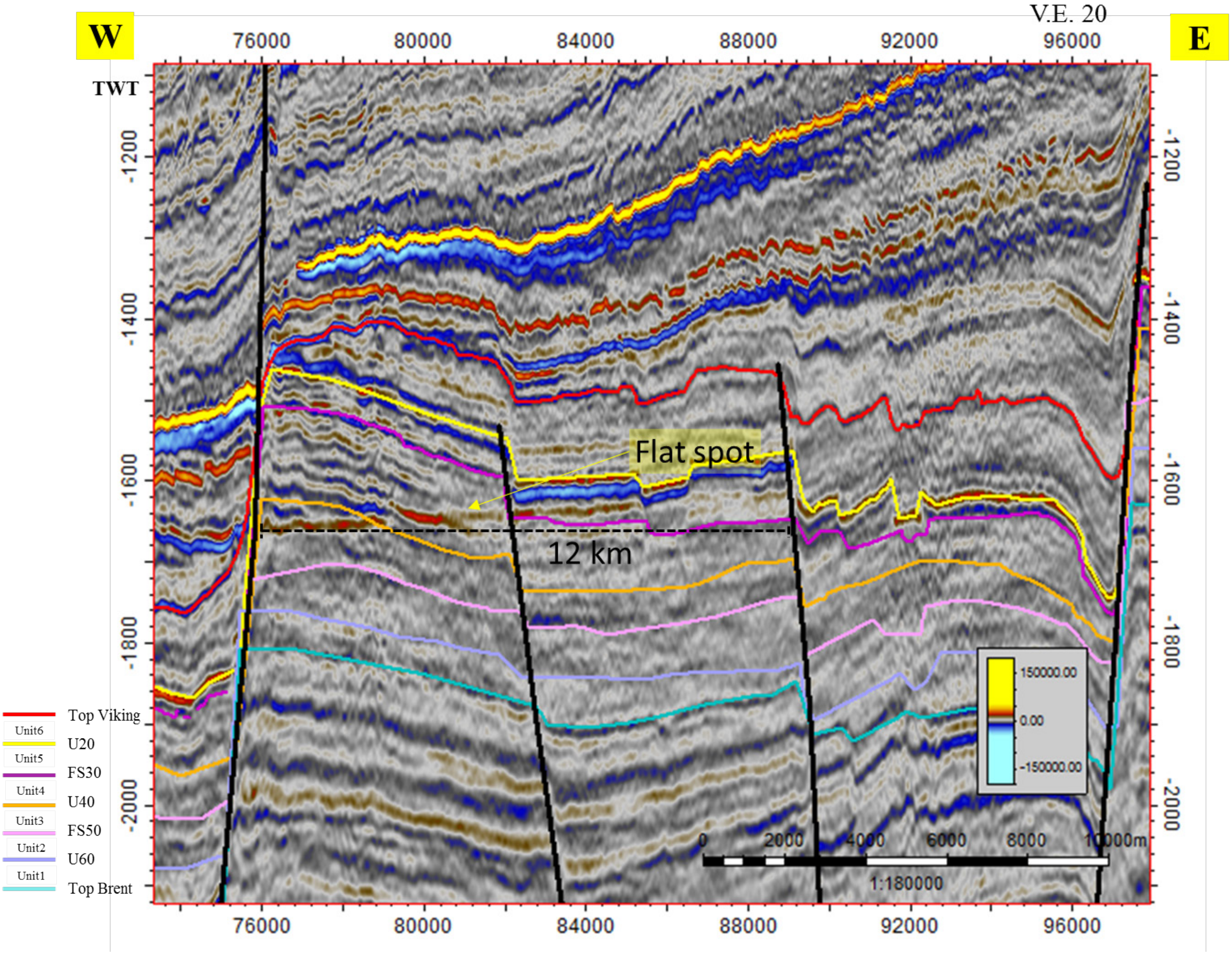


Figure 36. Unit 4 shows flat spot line in the Troll area. The flat spot lies in between two major faults, the Vetter and the Tusse faults. The length of flatspot is 12 km. The large flat spot on the Troll represents vast hydrocarbon reserves in the south of the study area. The flat spot suggests both the hydrocarbon contact and the hydrocarbon column height below the BCU.

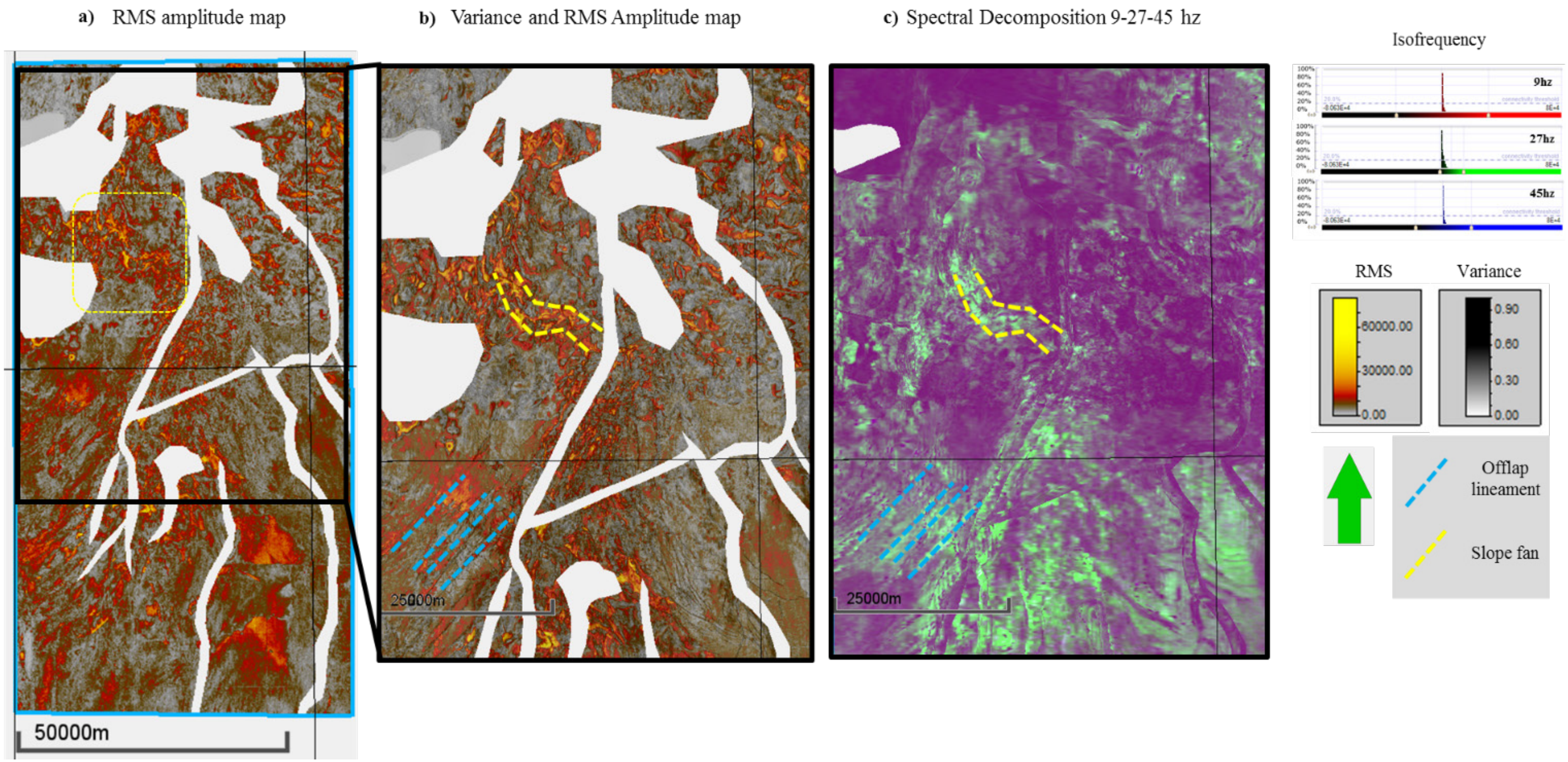


Figure 37. a) RMS amplitude map, b) Superimposed variance and RMS amplitude maps, c) Spectral decomposition map. The RMS amplitude map shows high values in the Lomre Terrace and the Troll area. The RMS attribute and the spectral decomposition supports high AI contrast from the flatspot and slope channel existence. The RMS present high amplitude value and the spectral decomposition presents channel feature after blending in red-green-blue bands. Attribute maps show offlap lineament which indicates progradational elements in the sotuhern Lomre terrace.

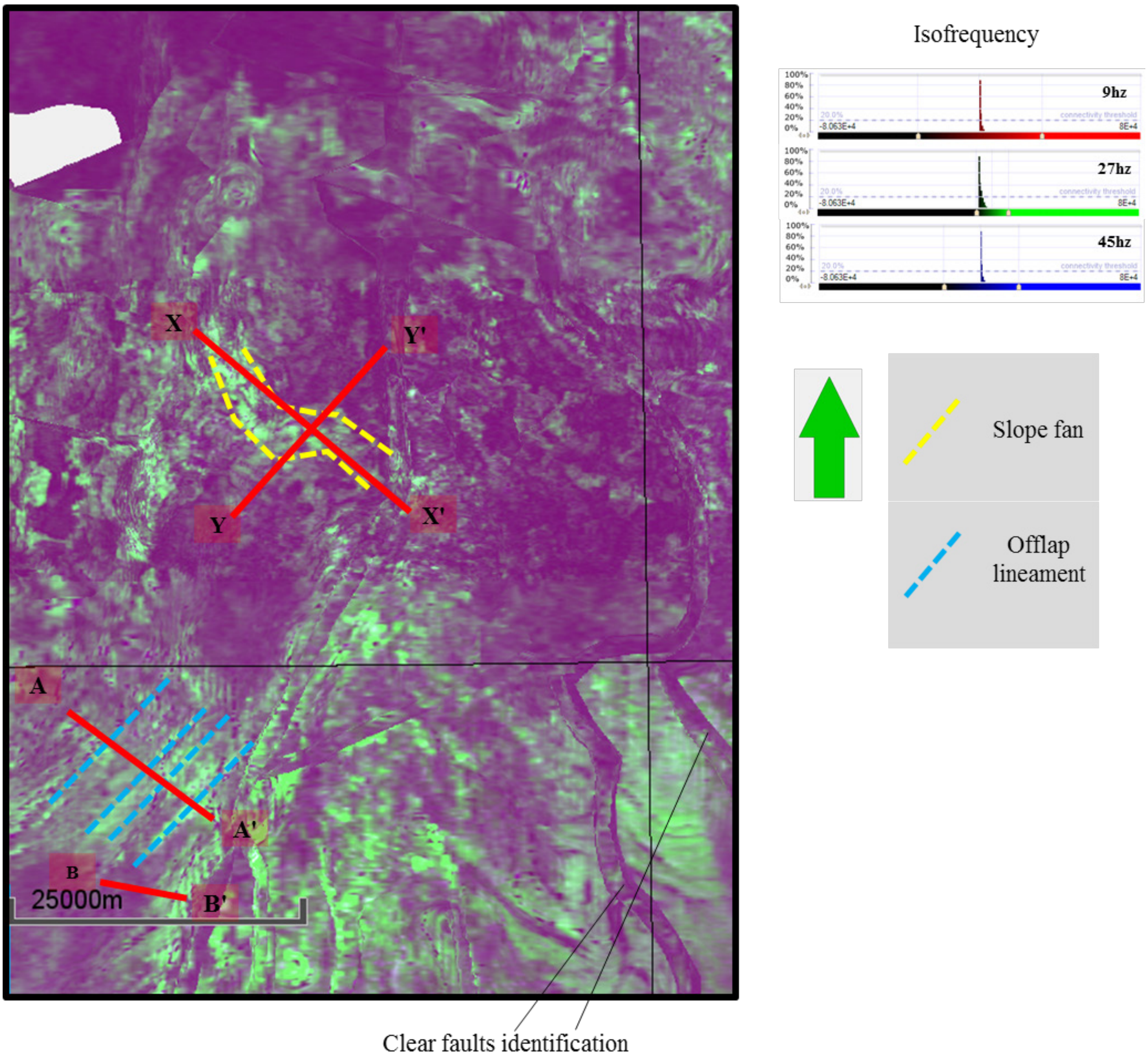


Figure 38. Spectral decomposition map blending in RGB bands of 9-27-45 Hz. The maps show the geological features such as slope channel in the northern Lomre Terrace and offlap linearments in the southern Lomre Terrace. Fault identification are enhanced after blending. Four seismic lines which are A-A', B-B', X-X' and Y-Y' are selected to display stratigraphic features in seismic profiles.

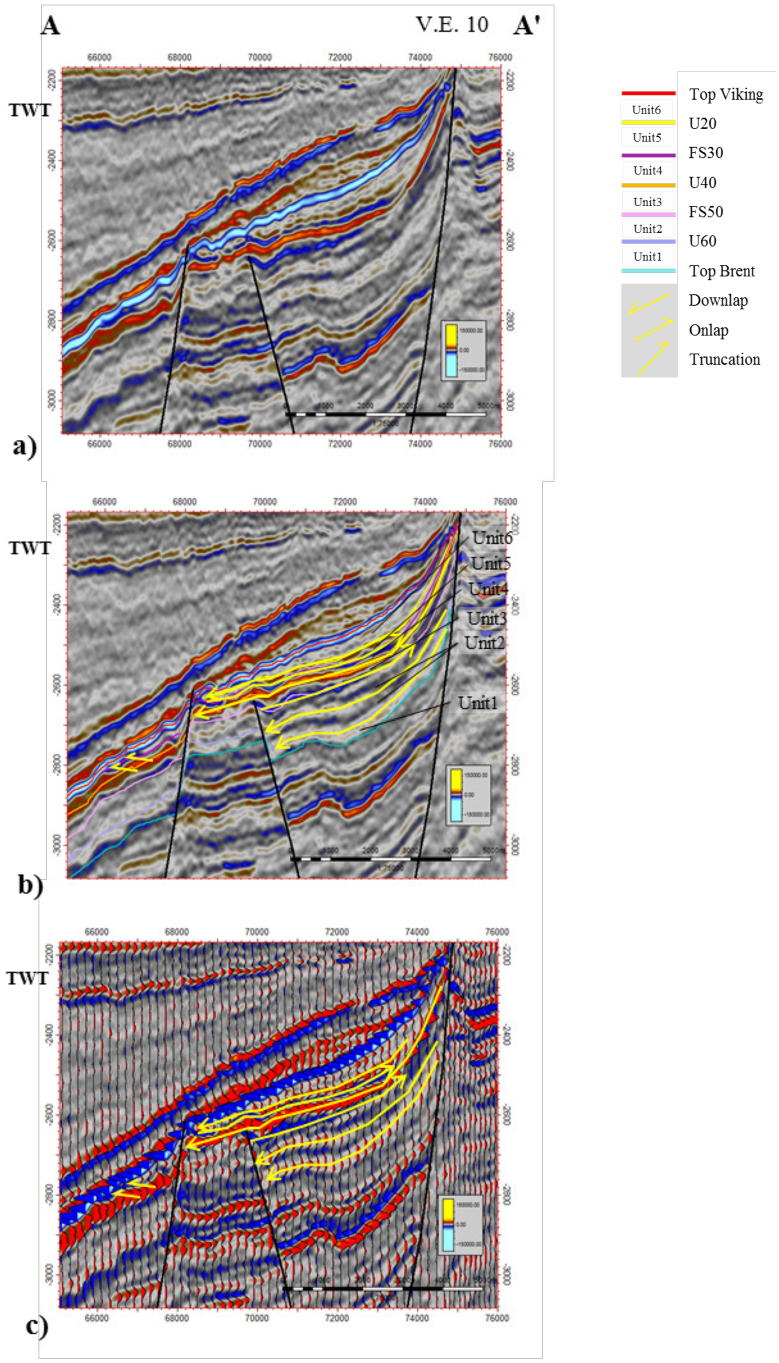


Figure 39. Seismic profiles of A-A' in the southern Lomre Terrace shows stratigraphic termination surfaces in the area including Unit 4. This southern Lomre terrace shows a gentle inclination compared to the northern Lomre Figure 34. (Figure a) uninterpreted seismic section b) interpreted seismic section. c) Seismic wiggle section. Seismic reflector terminations display following the cycle of mean sea level change from Unit 1 to Unit 6. The upper part of Unit 4 is found directly below an truncated surface. It indicates that the effect from BCU is shown until this unit. There is no internal reflector of Unit 4 in this area, the observation found a downlap surface at the base of Unit 4 and onlap surface at the top Unit 4.

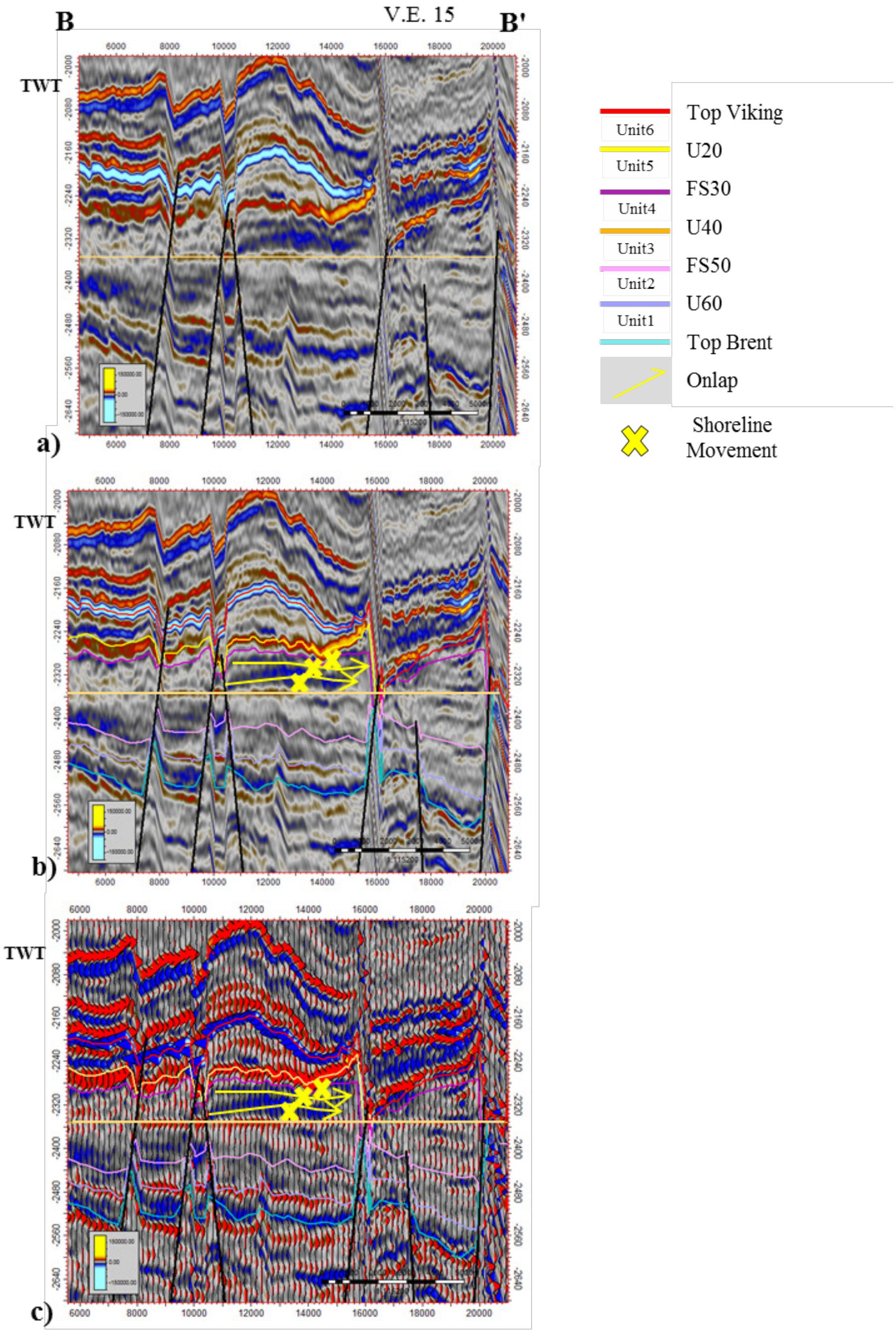


Figure 40. Seismic profiles of B-B' in the southern Lomre Terrace shows stratigraphic termination surfaces in the area. a) uninterpreted flattened seismic section b) interpreted flattened seismic section on U40. c) Seismic wiggle flattened the section on U40. Seismic profiles display onlap surfaces above U40 toward east. The shoreline movement shows retrogradation stacking pattern.

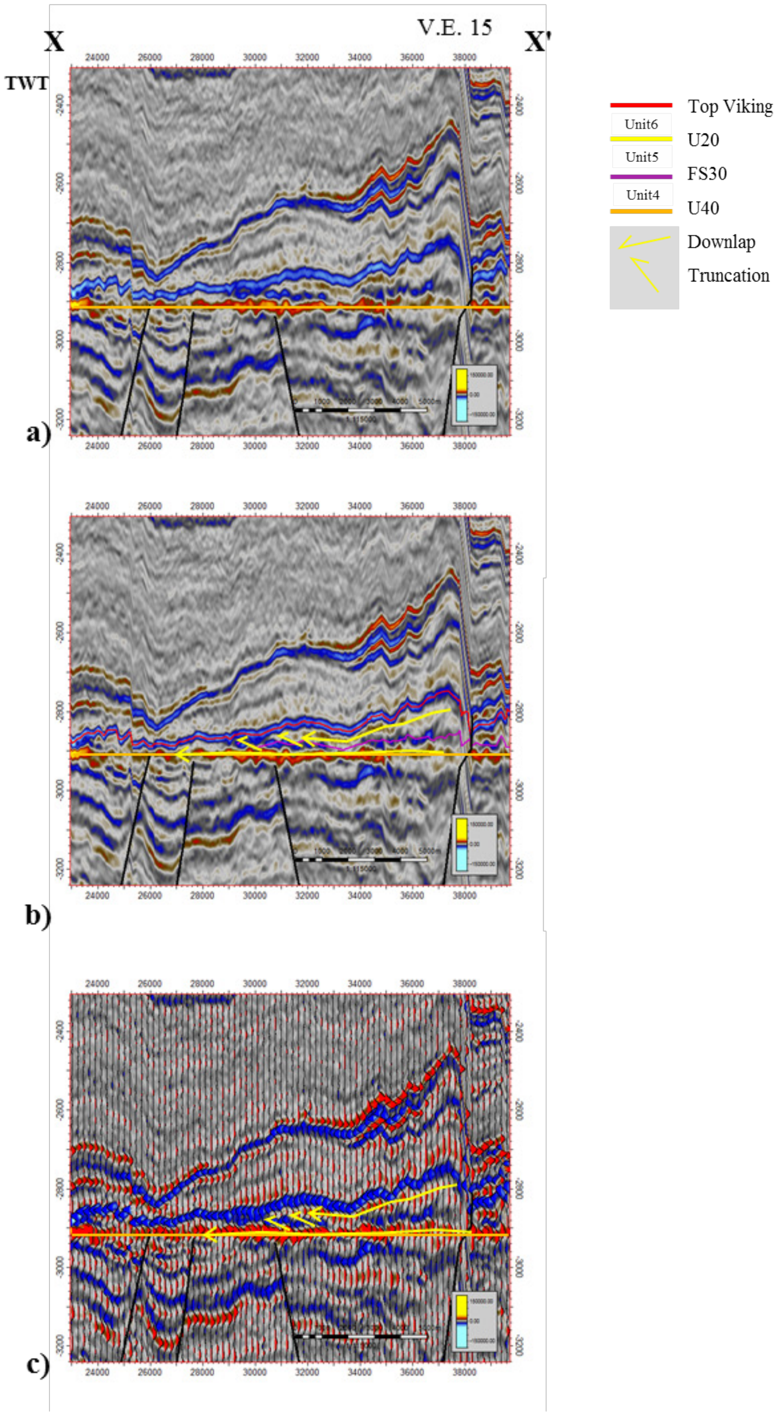


Figure 41. Seismic profiles of X-X' in the northern Lomre Terrace shows stratigraphic termination surfaces along the slope channel. a) uninterpreted flattened seismic section b) interpreted flattened seismic section on U40. c) Seismic wiggle flattened the section on U40. Seismic profiles display downlap surfaces above U40 toward east, then truncated surface at the distal part. Downlap surfaces represents an existence of slope channel in the Fram area. The shoreline movement shows retrogradation stacking pattern. Unit 4 is interpreted into two sub-units which are LST and TST. Both downlap and onlap clinoforms can be found in this unit depending on the seismic resolution in each area.

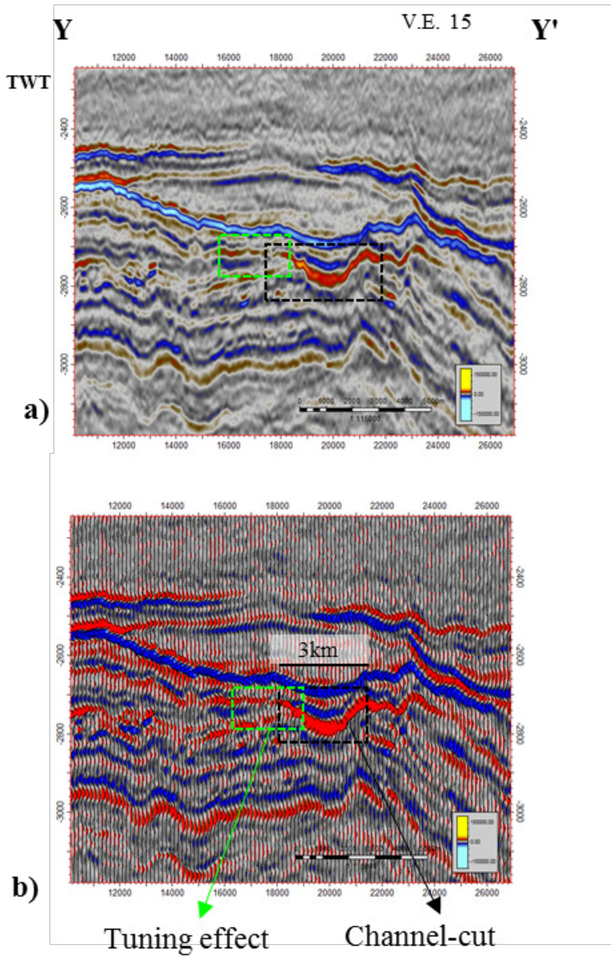


Figure 42. Seismic profiles of Y-Y' in the northern Lomre Terrace. a) seismic amplitude cut across the slope channel c) Seismic wiggle cut across the slope channel. Seismic profiles display the features of channel cut and tuning effect. Tuning effect exists at the channel edge when the channel pinched out until below seismic resolution. The channel cut indicates downward erosion into former mudstone deposits. The seismic shows very high AI contrast in the channel cut area. The width of channel is 3 km.

4.5 Unit 5

Unit 5 is bounded by at the underlying flooding surface FS30 and overlying unconformity U20. Similarly to Unit 4, the large area in the Troll area, the northern Lomre Terrace and the northern Uer Terrace show sedimentary hiatus. Most part of top Unit 5 was contacted directly below the U20 while in some area the BCU eroded deep until Unit 5. The unit age based on the biostratigraphic data is assigned to 156-152 Ma (the late Oxfordian to the middle Kimmeridgian).

4.5.1 Observation from well sections

In some areas, the absence of sediment preservation results in an unclear interpretation in the upper boundary. The upper part age is vaguely between the early to middle Kimmeridgian. Biostratigraphic data show inconsistent in age whereas the lithology shows clear shifting. It led to an overlapped age between Unit 5 and Unit 6 (Figure 18; Figure 19). Unit 5 is relied on lithostratigraphic data for the top and base identifications. The upper boundary of Unit 5 shows a significant change from fine-grained deposits to thick sandstone layers (Figure 43). The sharp change of DT values help defining the upper boundary of Unit 5 (Figure 43). The lower boundary age of Unit 5 is assigned at 159-156 Ma and the upper boundary at 152-150 Ma.

The main lithology of Unit 5 is interbedded sandstone-siltstone and mudstone with some rare thin limestone layers. The sandstone layers dominated at the Troll area where sandstone and siltstone parasequences were deposited up to 10 meters. Mudstone was mainly deposited at the Uer and the Lomre Terraces. The well 35/9-2 displays a few meters of sandy layers interbedded with mudstone to siltstone layers. The sandstone layers pinch out toward NW. Carbonate layers are found in wells 35/8-5S and 35/9-6S (Figure 43). GR log motifs are serrated shapes. The stacking pattern is the coarsening upward. However, lithology was not clearly pinched out. DT log is observed to be relatively constant. The lithological variation of lithology is quite hard to observe due to unit thickness is relatively thin. Thick sequences are observed near the major faults (e.g. Nordfjord-Sogn detachment).

4.5.2 Observations from seismic profiles

Unit 5 is bounded by FS30 at the base and U20 at the top. U20 surface is a hard reflector, very high amplitude and good continuity. Strong amplitude reflectors are distributed widely entire study area. Good continuity reflector aided to a consistent surface interpretation (Figure 20; Figure 21). The FS30 characterized by soft reflectors. The unit thickness is relatively thin, especially in the Troll area, the northern Lomre and the northern Uer Terraces where significant hiatus is identified (Figure 24). The thickest part exists in the Bjorgvin Arch and the Uer Terrace. Truncated surfaces within this unit are observed (Figure 44). Downlap surfaces are observed in the Troll area and the Lomre Terrace (Figure 44; Figure 45). The shoreline movement in the aggradation-progradation patterns (Figure 45).

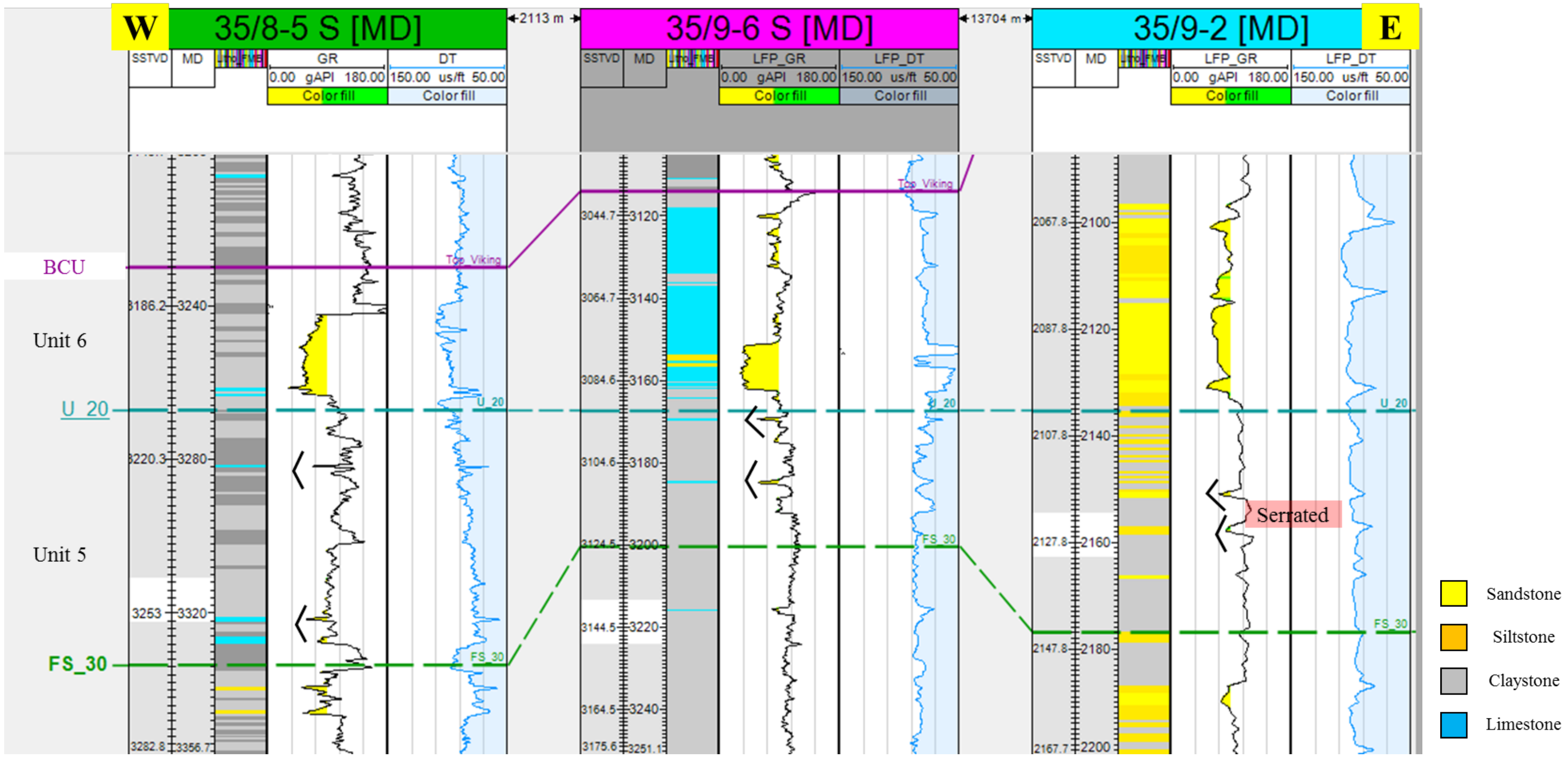


Figure 43. The well correlation shows log motif, lithological characteristics and thickness variation of Unit 5. The unit comprises U20 and FS30. The panel is flattened on U20. The correlation panel shows in the W-E direction. Thickness variation gently changes to the west. The correlation shows paelotopographic high at the well 35/9-6S. Lithological characteristics are interbedded sandstone and mudstone layers, with thin limestone layers in the well 35/8-5S. The lithology variation shows dominated sandstone layers at the east and dominated mudstone layers with thin limestone layers at the west. GR log shows coarsening upward trend in the east but fining upward at the west. The stacking patterns are aggradational and progradational at the upper part. The correlation panel represents the reference line 4 (See Figure 17).

Seismic configurations generally show low to medium amplitude, low continuity with subparallel reflectors. High amplitude, medium to good continuity and parallel reflectors can only be observed on the Troll area. In the Lomre Terrace, an internal reflector of Unit 5 was merged with the strong reflector of U20 by the tuning effect. The top boundary was overlain parallel to the base boundary as showed in the seismic profile (Figure 45). Prograding oblique shape can be observed in the Lomre Terrace and the Bjorgvin Arch. Several truncations are presented along the Troll fault which is an evidence of unconformity U20 (Figure 45).

4.5.3 Observation from geologic maps and seismic attributes

Time structural maps of the flooding surface FS30 and the unconformity U20 bounded Unit 5. The structural trend of this unit is similar to the others with a dipping toward NW. The deepest area is on the Flatfisk Slope (Figure 23). The sedimentary hiatus in the northern Uer Terrace and the Troll area are larger when compared to previous units (Figure 23). Unit 5 is the thinnest preservation in average which is only 31 ms in the time domain and 45 m in the depth domain. The isochrone map shows a depocenter in the northeastern Uer Terrace, and a small sub-basin is observed along the Nordfjord-Sogn detachment (Figure 24).

Variance attribute map indicates fault orientations within the study area (Figure 46). The Lomre Terrace shows main fault direction to be along the NE-SW. The Troll area and the Bjorgvin Arch shows minor faults orientation in the NW-SE direction. Small faults systems are observed in both NE-SW and SE-NW direction at the Uer Terrace, the northern Troll area, and the Bjorgvin Arch (Figure 46).

4.5.4 Interpretation of Unit 5

The BCU and U20 causes the top Unit 5 time hiatus. However, the top reflector of Unit 5 is very strong in seismic data due to high AI contrast from the unconformity (Figure 20; Figure 21; Figure 22). The reflector of top Unit 5 is identified by hard reflector at the top and soft reflector at the base. The thickness is relatively thin toward south. Low thickness explains strong reflector amplitude when reflectors of Unit 5 merged with an amplitude value of U20 (Figure 20; Figure 44; Figure 45). Huge increase of the downthrown block thickness against the Kinna fault indicates high tectonic rifting during the deposition (Figure 29). The Vette and Tusse faults, controlled NW-SE fault orientations in the Troll area and the Bjorgvin arch. The effect from the Nordfjord-Sogn detachment movement created small synthetic and antithetic faults in both NE-SW and SE-NW direction at the Uer Terrace, the northern Troll area and the Bjorgvin Arch (Figure 46).

The significant unconformity at the top unit corresponding to low thickness of this unit, as it affected sedimentations during the rifting period. The onlap terminations at the Troll fault indicate high erosion from subaerial unconformity at the upper boundary (Figure 20; Figure 21). In addition, large area of sedimentary hiatus also indicates paleotopographic high at the north (Figure 23; Figure 24).

This unit is mainly dominated by mudstone. Sandstones layers still exist in the Troll area in wells 31/2-2R, 31/3-1, and 31/3-4 (Figure 18). It is suggested the sedimentary influx came from the SE and E. The proximal part of the system is at the Øygarden fault complex and the Troll area, while the distal region is in the Lomre Terrace and the Flatfisk Slope.

In summary, Unit 5 is highstand system tract. Unit 5 can be correlated to the top of Sognefjord formation, where sea level began to rise throughout the study area (Snedden and Liu, 2010) (*Figure 6*). The type sections are shown in wells 31/3-4 and 35/11-5.

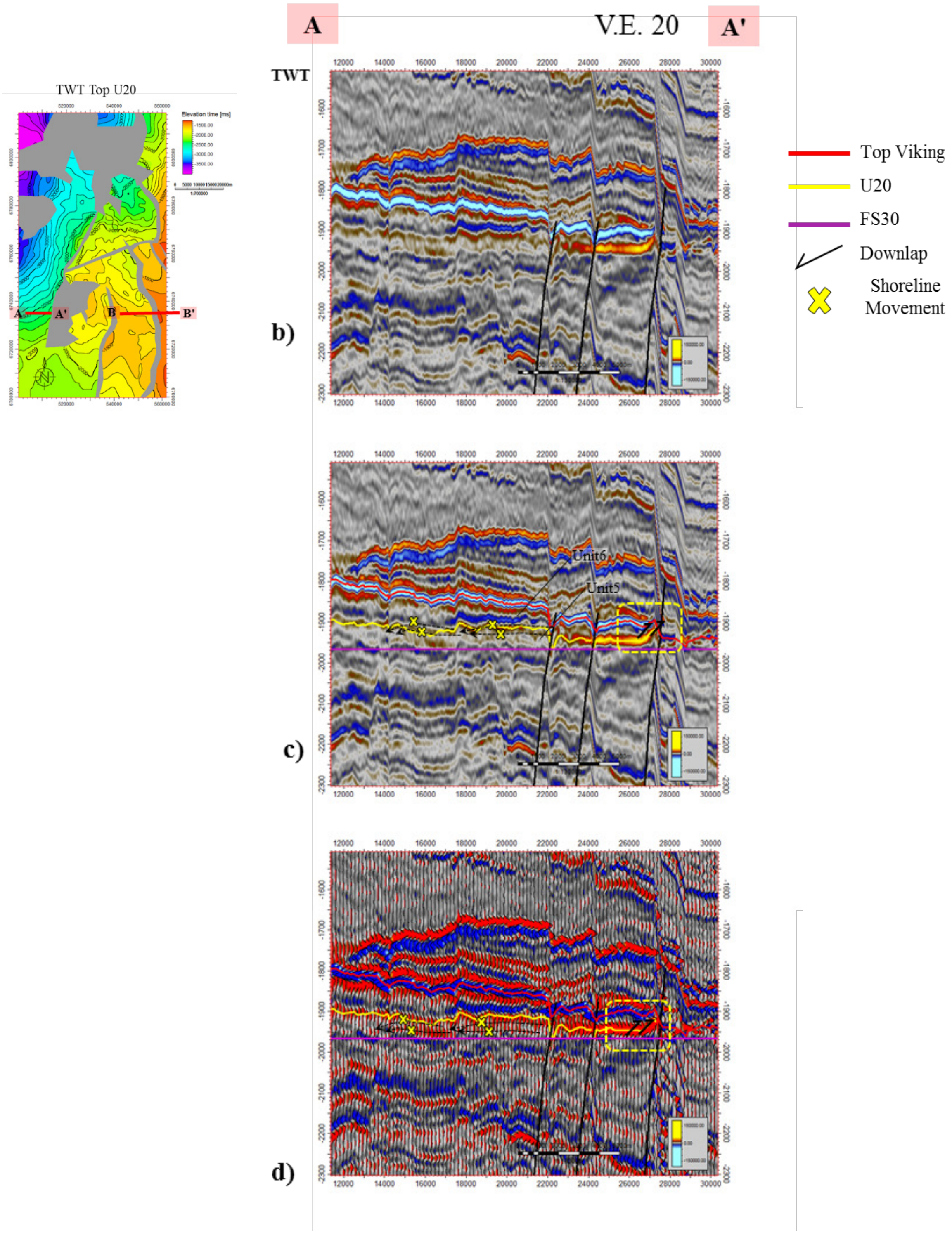


Figure 44. Seismic profiles from A-A' in the Lomre Terrace. a) uninterpreted flattened seismic section b) interpreted flattened seismic section on FS30. c) Seismic wiggle flattened the section on FS30. The surface terminations shows downlap clinoforms to the west. Truncated surface exists at the downthrown of major fault. It indicates a large erosion of U20 at the upper boundary. The shoreline movement has a small progradation toward the west.

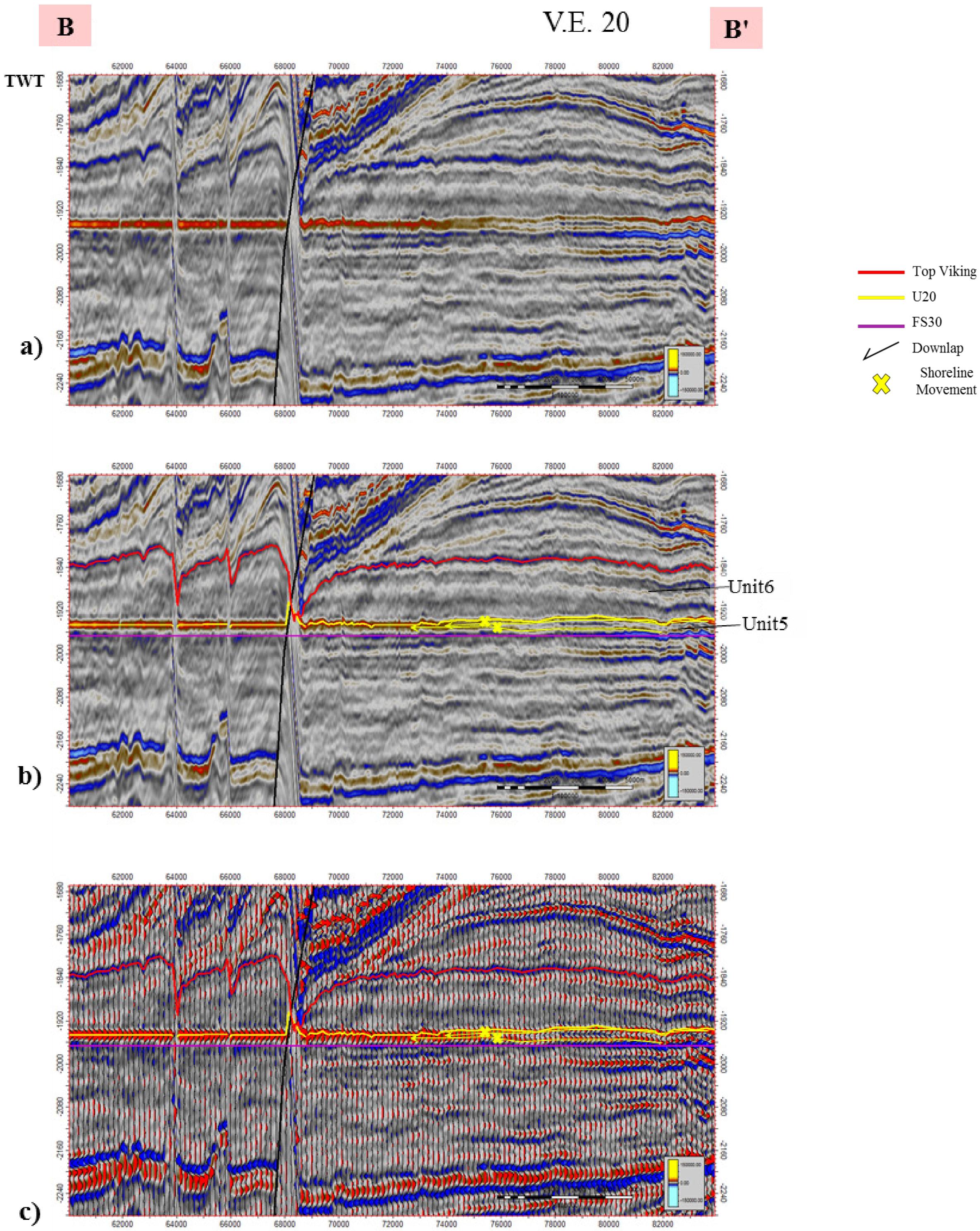


Figure 45. Seismic profiles from B-B' in the Troll area and the Bjorgvin Arch. a) uninterpreted flattened seismic section b) interpreted flattened seismic section on FS30. c) Seismic wiggle flattened the section on FS30. The surface terminations shows downlap clinoforms to the west. The shoreline movement has a higher progradation toward west than in the Lomre Terrace (Figure 44). This indicates that the proximal part of source is at the east.

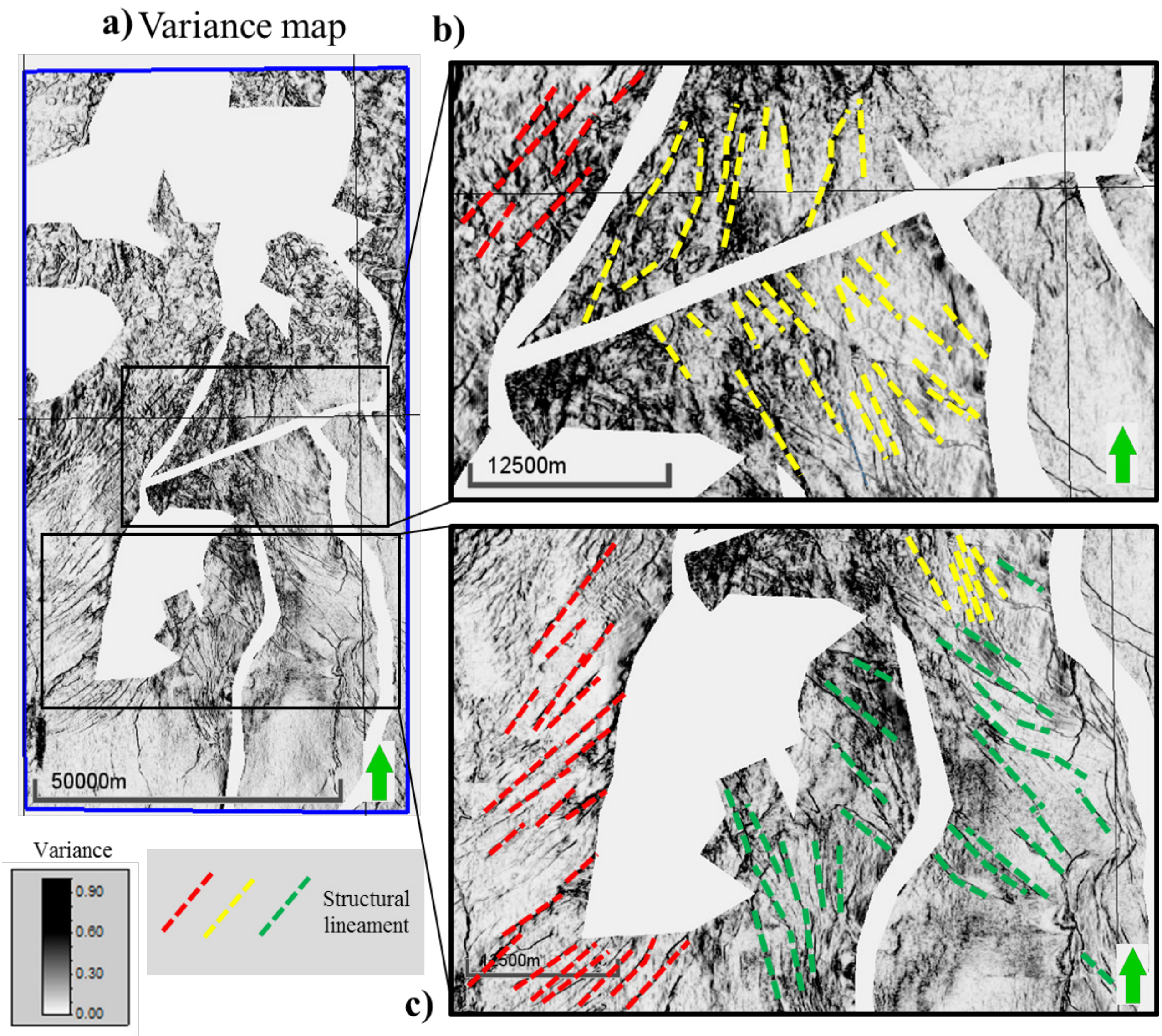


Figure 46. a) variance attribute maps of Unit 5 illustrate structural lineaments of the study area. b) and c) there are four main fault orientations from variance attributes which are NW-SE, SW-NE, W-E and N-S directions. All major faults of the study area are in the N-S direction except the Nordfjord-Sogn detachment which orientates in the W-E direction. Minor faults are classified into each area. The Uer Terrace presents faults in SW-NE orientation. The Lomre Terrace presents fault in SW-NE orientation. The Troll area shows fault orientations in the NW-SE direction.

4.6 Unit 6

The youngest unit of this study is Unit 6. It is bounded by U20 at the base and the BCU at the top. Biostratigraphy shows that the age of Unit 6 is between 152 and 145 Ma (the middle Kimmeridgian to the late Volgian). However, the ages of the top boundary are still unclear and vary due to a significant time gap from the BCU (Kyrkjebø et al., 2004).

4.6.1 Observation from well sections

The BCU is the main characteristic for upper boundary correlation. The upper boundary remains uncertain for the biological age. Therefore, the top boundary relied on an unconformity rather than the biological data (Figure 47). The BCU eroded most of the unit sequence in the Troll area, the northern Uer Terrace and the Flatfisk Slope. The lower boundary is correlated by U20 which is a significant unconformity between mudstone packages and thick sandstone layers. However, sandstones units are not distributed throughout the area, therefore, biostratigraphic data is introduced to help identifying the base boundary in some area.

The main lithology of Unit 6 is offshore mudstone and shale deposits except in the Uer Terrace where sandstone and carbonate layers exist. Sandstone to siltstone layers and also a thin layer of limestone were additionally found in specific areas at the northern Uer Terrace and the Lomre Terrace. Sandstone was mainly deposited at the lower part of the unit in wells 35/9-2 and 35/12-3S at the NE (Figure 19). The thickness of the sandy packages reached be up to 13 meters. Carbonate is observed interbedded with mudstone layers in the well 35/11-8S at the Uer Terrace (Figure 47). The southern and the western part of the study area show mainly mudstones and shales. The stacking patterns of Unit 6 are coarsening upward sequences and then changed to fining upward sequences until the BCU (Figure 47). Unit 6 can be subdivided into 6.1 and 6.2 sub-units. However, Unit 6.2 was mostly eroded by the BCU, then it is not consistent for observation. GR logs show blocky shapes at the lower part and bell shape at the middle part. DT logs show upward increasing value.

4.6.2 Observations from seismic profiles

Unit 6 is bounded by the soft reflector of the BCU and the hard reflector of U20. Most of the top Unit 6 surface were eroded by the BCU. Therefore, the top boundary was picked as the unconformity. High erosion area included the Troll area, the Sogn Graben, the northern Uer Terrace and the Flatfisk Slope (Figure 20; Figure 21; Figure 22). The top Unit 6 presents only in the sub-basin at the eastern Uer Terrace (Figure 20). The reflector free configuration is observed in sub-basin area of the Uer Terrace. The lithology in the sub-basin is interpreted as shales to siltstones. There was no well drilled into this basin.

The BCU has very strong amplitude and good continuity due to the sharp changes of lithologies between the Viking group and the base Cromer Knoll group. The unconformity forms a strong reflector that makes the interpretation more consistent. The unit thickness is relatively thick with an average thickness around 70 ms. Thick deposits distributed over the entire area, especially at the east. The thickest sedimentary package is observed in the eastern Uer Terrace (Figure 24Figure 21.). The reflector configurations of the thick package are reflector free. The Troll area and the Lomre Terrace display medium to strong amplitude with high continuity and parallel to subparallel (Figure 20; Figure 21). Prograding clinoforms are present on the Lomre Terrace with a complex sigmoid oblique geometry (Figure 39). Downlap terminations are observed in the Bjorgvin Arch (Figure 22; Figure 26; Figure 34). Truncated surface terminations exist underneath the BCU, especially in the Troll area. Thickness increases at the downthrown block against fault plane indicates active tectonic movements (Figure 29).

4.6.3 Observation from geologic maps and seismic attributes

The BCU is the largest unconformity event throughout the North Sea (Ziegler, 1975). The BCU surface is the strongest reflector within the study area. Most parts of the upper Unit 6 were eroded, and then created a large time gap at the top boundary. The top Unit 6 exists only in high thickness area, i.e. sub-basin of the Uer Terrace (Figure 20; Figure 24). Main depocenters were in the Bjorgvin Arch, the Troll area, the Uer Terrace and the eastern Lomre Terrace. The depocenter along major faults suggested fault activity and creation of accommodation space (Figure 24). The time structural map of the BCU is similar to other surfaces. In term of dip and azimuth, the highest structure is in the Bjorgvin Arch, and the main structure inclines to the NW direction (Figure 23). The isochrone map is relatively thick with the value of 70 ms in the time domain and 97 m in the depth domain. Unit 6 has the highest average thickness of the study interval (Figure 24).

Variance attribute displays SW-NE fault orientations on the Lomre and the Uer Terraces, and the SE-NW in the Troll area and the Bjorgvin Arch. The RMS attribute maps show high values on the Lomre Terrace, the Flatfisk Slope and the Troll area (Figure 48).

4.6.4 Interpretation of Unit 6

Unit 6 was deposited during a rifting climax. The thickness highly increased along hanging wall fault block is a concrete evidence of rifting. In addition, high erosions and large fault throws suggested the rifting climax in this unit (Figure 29). Most faults were highly active, and they resulted in paleotopographic highs in the east that led to a big erosion and non-deposition from the east toward west (Figure 20; Figure 21; Figure 22). Sandstone layers in Unit 6 suggests the erosion and re-deposition during the transgression (Figure 18; Figure 19). It infers to paelotopographic highs which formed during the rifting climax. The BCU created a big time gap from a large erosion at top Unit 6. The BCU and U20 bounded the unit with an angular unconformity. The unconformity showed in both seismic profiles and log data (Figure 20; Figure 21).

The base level rose rapidly after the early Kimmeridgian time (Snedden and Liu, 2010) and this increased accommodation space in the west (*Figure 6*). The shoreline retreated following the sea level rise. Unit 6 is correlated to the Draupne formation. Offshore organic mudstones deposited in the Lomre Terrace and the Flatfisk Slope caused the high RMS amplitude when generated the attribute close to the BCU reflector (Figure 48). Reflection configurations are mainly parallel to sub parallel amplitude and reflection-free due to high homogenous lithology of offshore mudstone deposits (Figure 49).

The thick mudstone represents an open marine environment. The offshore marine environment penetrated landwards until the Bjorgvin Arch (Figure 48; Figure 49). Sandstone deposits existed only in the Uer Terrace and the northern Troll area. Carbonates deposits were found at the northern Uer Terrace. Sediments influx came from the east which is suggested by sandstone layers in the well 35/12-3S (Figure 47). Unit 6 is interpreted as a LST at the lower part, then rapidly changes to TST by sea level rise (*Figure 6*). However, top Unit 6 was mostly eroded by the BCU, so there is a big gap for TST of this unit, especially in the east. Wells 31/2-21S and 31/3-1 are type sections of this unit.

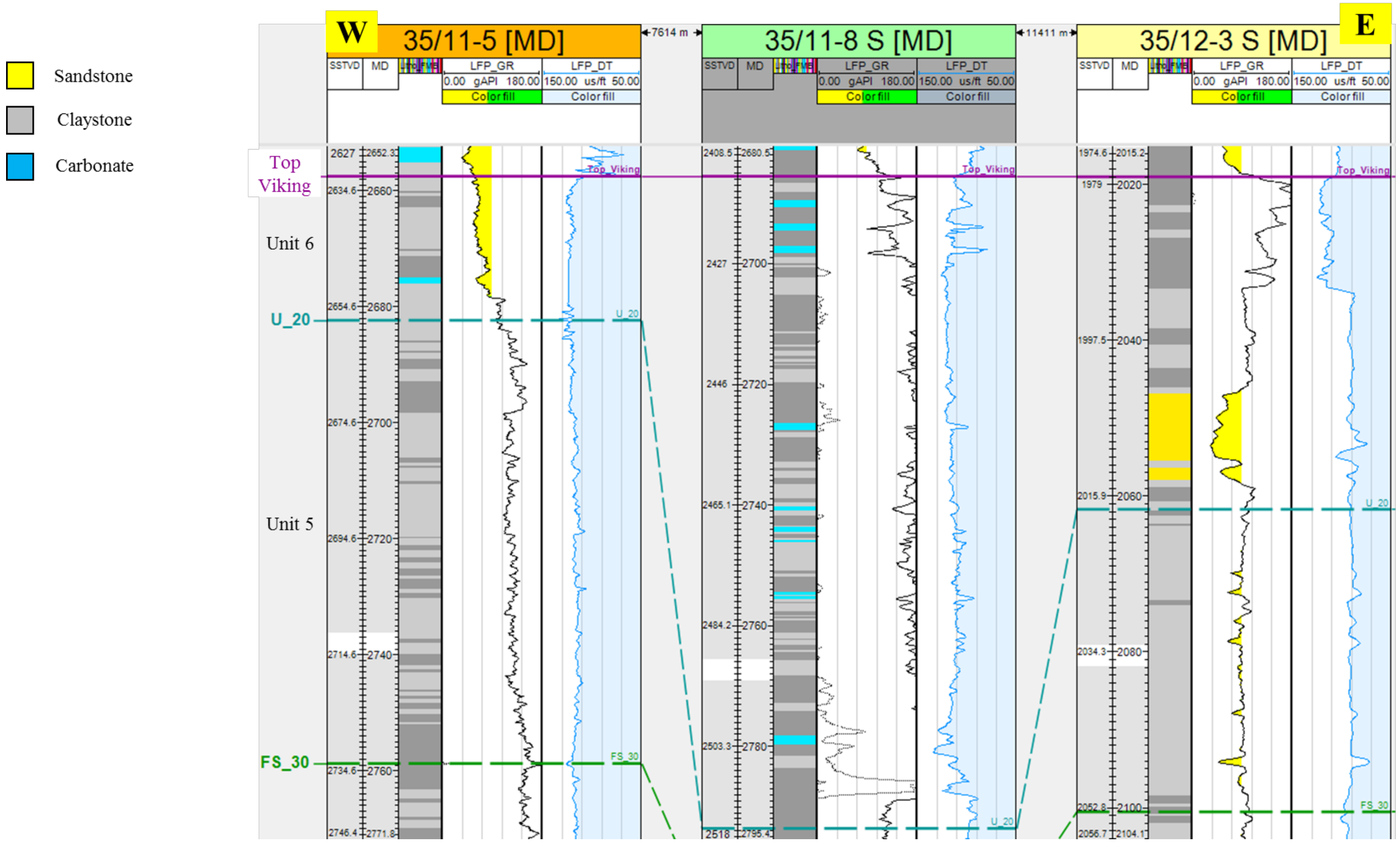


Figure 47. The well correlation shows log motif, lithological characteristics and thickness variation of Unit 6. The unit comprises U20 and BCU/Top Viking. The BCU shows a large erosion at the top of Unit 6. The panel is flattened on BCU. Thickness variation is higher at the east. Lithological characteristics are thick mudstone layers with thin carbonate layers. Sandstone layers are found at the east and rapidly shifted to mudstone. The log characteristic shows high GR with low DT. This unit is correlated to high sea level change at the late Jurassic. GR log shows fining upward trend as displayed in the well 35/12-3S. The correlation panel represents the reference line 6 (See Figure 17).

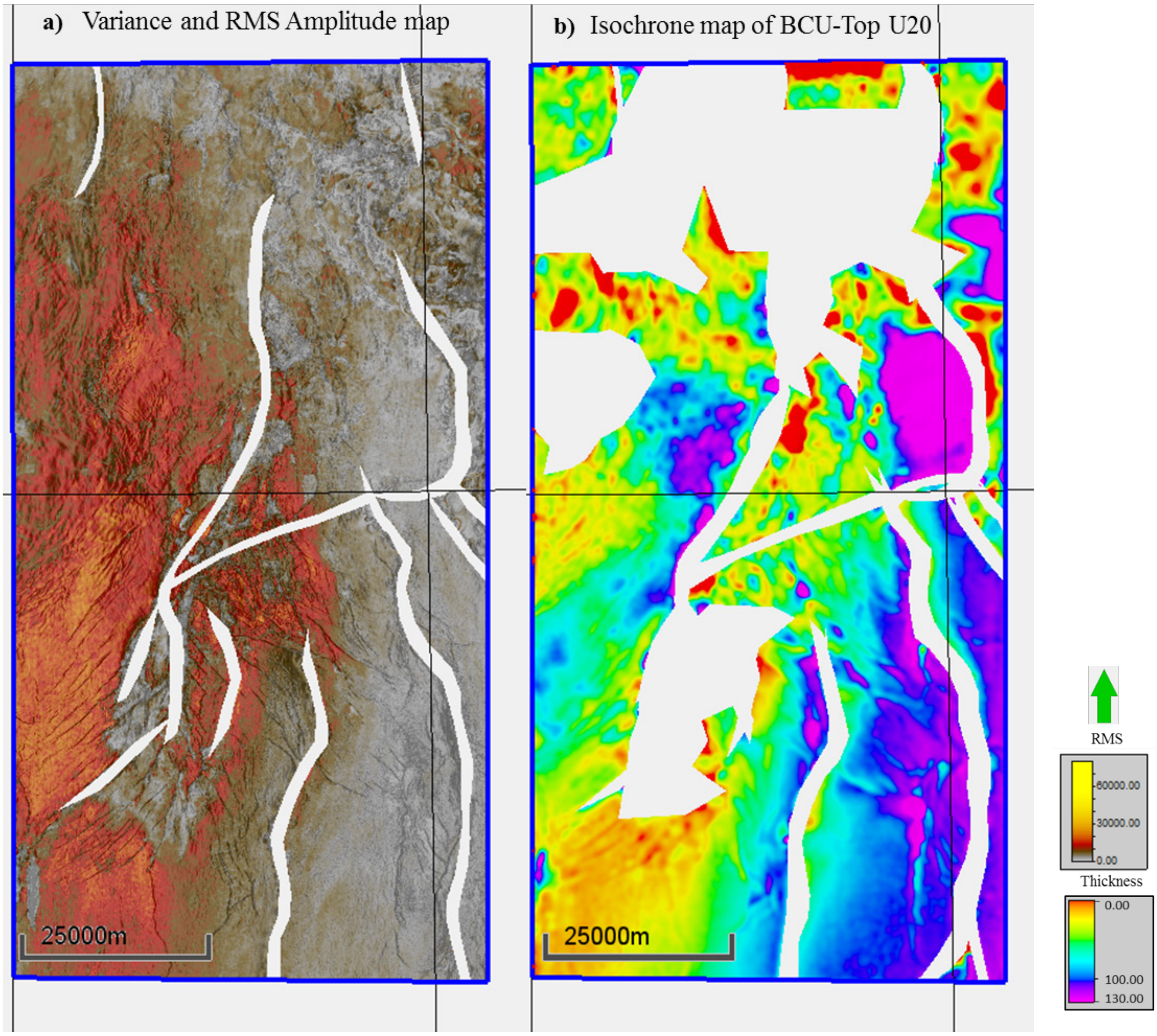


Figure 48. a) superimposed variance with RMS amplitude map of Unit *6. The RMS amplitude map shows the edge of thick to thin mudstone. The bright amplitude values are presented in the Lomre Terrace and the Faltfisk Slope. High amplitude value caused by tuning effect. b) Time isochrone map displays depocenters of* Unit *6 which indicates high active faults during* Unit *6.*

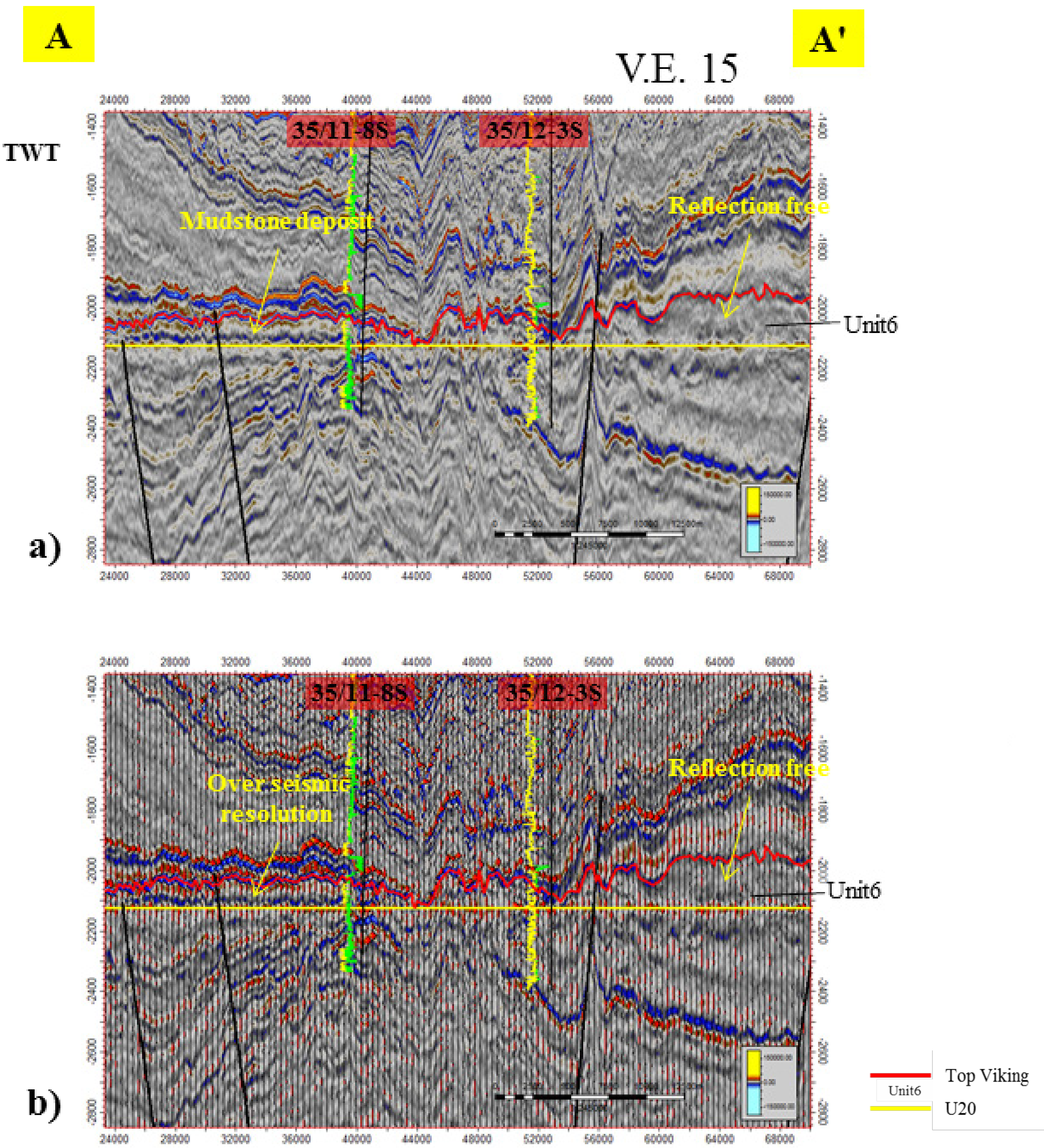


Figure 49. Seismic profiles from A'-A across the Lomre and the Uer terraces. a) Flattened seismic section on U20 b) Seismic wiggle flattened on U20. Seismic profiles illustrate effect from tuning event. Mudstone deposition in Unit 6 causes high negative amplitude values. It results in a bright negative amplitude in the seismic profile. Negative seismic amplitude much enhances the RMS value when generates the attribute map. The eastern Uer Terrace also shows an example of reflector free where low seismic contrast is found in the sub-basin. The lithology in the reflection free could be either massive sandstone or deep marine mudstone. Seismic profiles represent the reference line 6 (See Figure 17).

4.7 Chronostratigraphic diagram

Chronostratigraphic is constructed based on the well correlation panel of the reference line 5 (Figure 17; Figure 19). Chronostratigraphic diagram aims to illustrate the relationship of the depositional system and stratigraphic surfaces in both time and distance dimensions. Stratigraphic units are identified from log data, well correlation panel and the seismic provided the information between wells.

Based on the well and seismic interpretation, five sequence boundaries and two MFS are observed. The summary of the system tracts and unit classifications is shown in the Figure 50. The chronostratigraphic diagram illustrates the stacking pattern in the study interval. The progradational stacking pattern are in Unit 1, Unit 2.1, Unit 3, Unit 4.1, Unit 5 and Unit 6.1. The retrogradational stacking pattern are in Unit 2.2, Unit 4.1 and Unit 6.1 (Figure 50).

Unit 1 is the oldest unit in the Bathonian age. Shallow marine sandstones show progradation from the Troll to the Uer Terrace. The progradation continues to the Unit 2 where sea level curve reach the maximum fall. However, the observation shows that sandstones are still prograded until Unit 3 and Unit 4 even the sea level shows rising. This leads to an interpretation of high sedimentary influx during the late Callovian to the mid Oxfordian. Another evidence of the sedimentary influx is deep marine sandstone deposits in Unit 4 that formed in the Lomre Terrace. Deep marine sandstone might be caused by a down dip of the Kinna fault hangingwall block (Figure 17) during the syn-tectonic. In addition, high sediments influx rate during the Oxfordian transported sediment into the distal area. Seismic and attribute observations of Unit 4 support the existence of slope channel in the area (Figure 37; Figure 41; Figure 42). Unit 5 is the thinnest unit of this study. The observation in the chronostratigraphic diagram shows high absence of sediment in most part. The Troll area and the Uer Terrace illustrate the largest absence areas. Sedimentary absence continues until the top Unit 6 which is the BCU. However, shallow sandstone deposits are observed in the lower part of Unit 6 in wells 31/2-8 and 31/2-2R. It suggests the sediment transportation rate is still high in the Troll and the Uer terrace during the sea level rise. The assumption of sediment tramsportation can be either from the sediment source at the east or eroded and redeposited sediments from paleogeographic high in the local area.

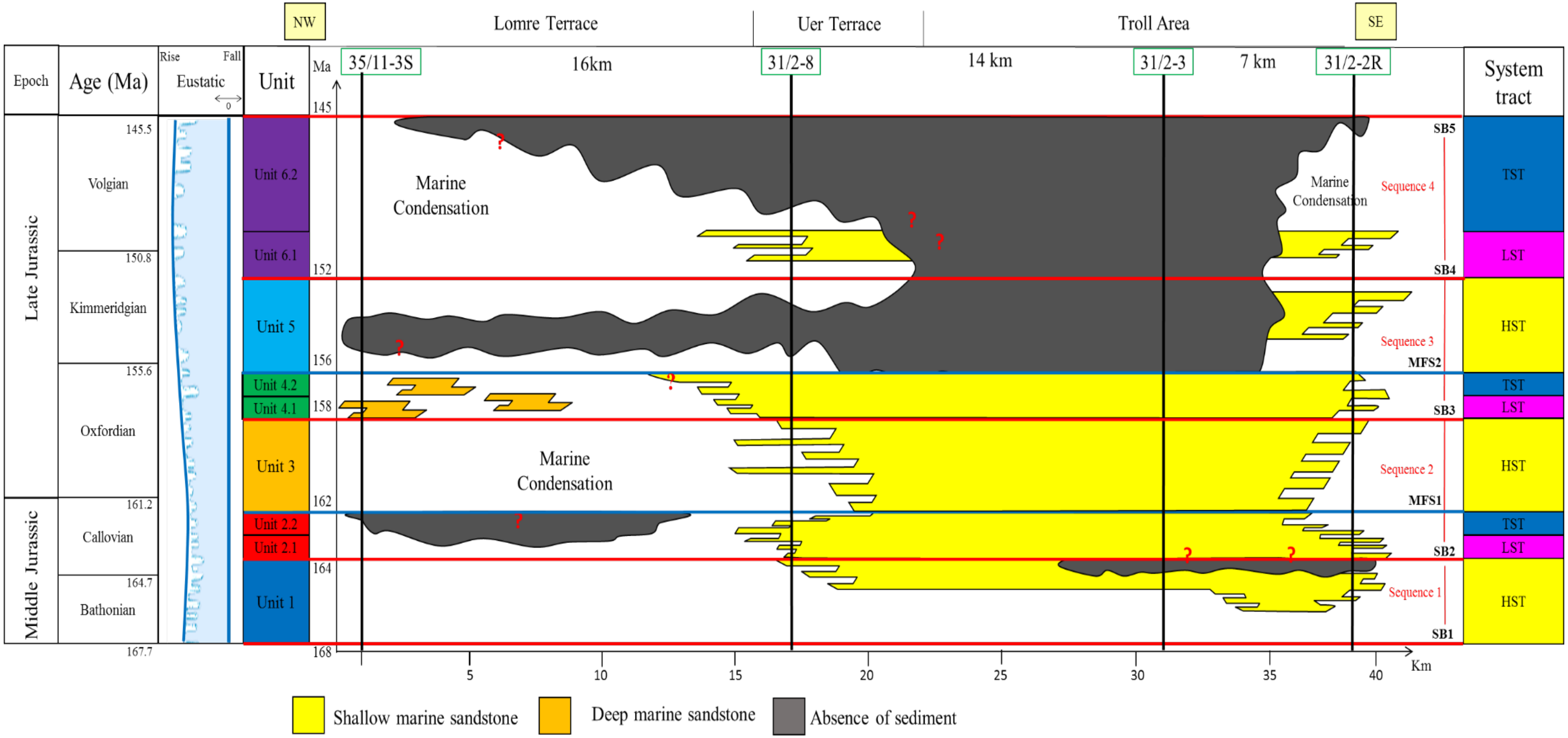


Figure 50. The chronostratigraphic chart of the study area illustrates in the NW-SE direction. The chronostratigraphic chart generated from the well correlation panel of the reference line 5. The chart represents a depositional schematic during the middle to upper Jurassic. Areas comprise the Troll area, the Uer Terrace and the Lomre Terrace. There are four sequences in the chronostratigraphic chart with five sequence boundaries and two MFS. The depositional sequences were prograded to the NW direction following the eustatic trend from Snedden and Liu, (2010). The location of the reference line is shown in Figure 17.

4.8 Seismic Facies Analysis

Seismic facies analysis was applied in each unit to describe in more detail of the internal seismic reflectors and configurations. This study used the facies analysis geometry from Roksandic (1978) and Ramsayer (1979) (Figure 11). The facie analysis was characterised into three elements: A was the characteristics of the upper boundary, B was the characteristics of the lower boundary and C was the internal reflection pattern of the sequence. The study also combined parameters of seismic reflectors such as reflection continuity, amplitude, and frequency from Mitchum et al., (1977) in association with seismic facies classification. The summary of seismic facies is described in Table 1.

4.8.1 Seismic Facies 1

Seismic facies 1 is bounded by an erosional truncation at the top boundary and the concordant at the base boundary. The internal reflections are parallel to subparallel. The reflection amplitude and frequency are moderate to high. The reflection continuity is fair to good. Facies1 is found in the eastern part of the study area along the Øygarden fault complex area and the eastern of Bjorgvin Arch which locate close to the proximal area of the sedimentary source. Sediments are in progradational and aggradational stacking patterns, which represents the shallow marine environment in a marginal/deltaic setting.

4.8.2 Seismic Facies 2

An erosional truncation bounds seismic facies 2 at the top boundary and a downlap surface at the base boundary. The internal reflections are subparallel with sigmoidal shapes. The reflection amplitude is moderate to high with poor to fair reflection continuity. The reflection frequency is moderate to high. The facies 2 is mainly sandstone dominated in a shallow marine environment which comprises interbedded siltstone and mudstone deposits. It is mainly found in the Troll area and on the Uer Terrace. It is interpreted as a shallow marine progradational sandstone deposits in prodelta/upper shoreface.

4.8.3 Seismic Facies 3

The seismic facies 3 is bounded by concordant surfaces both for the top and base boundaries. The reflection configuration is parallel. The reflection amplitude is moderate to high. The reflection continuity is fair to good, and the reflection frequency is moderate to high. Seismic facies 3 is sandstone dominated. The sedimentary facies is interpreted as sandbars within a wave-dominated shoreline. The sequence is stacked in an aggradational pattern. This facies is also shallow marine sandstones. This facies mainly presents in the Troll area and the Bjorgvin Arch. The depositional environment is upper shoreface/lower shoreface.

4.8.4 Seismic Facies 4

Seismic facies 4 is bounded by concordant surface. The internal reflection configuration is chaotic. Seismic facies 4 contains the shallow marine carbonate lithology. Carbonate layers reduce the quality of seismic reflection, which may be the cause of the chaotic configuration of this facies. The reflection amplitude is low to moderate. The reflection continuity is poor. The reflection frequency is low. The sedimentary facies is interpreted as carbonate layers in a shallow marine environment in the shelf margin area. The facies is founded in the Uer and the northern Uer Terrace. The depositional environment is the lower shoreface. However, the carbonate composition interpretation is still in controversial, since previous works interpreted the chaotic configuration in this area as cemented siliciclastic sediments (Vollset et al., 1984).

4.8.5 Seismic Facies 5

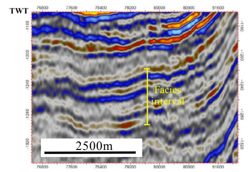
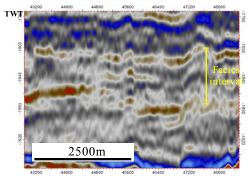
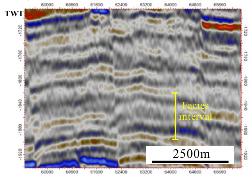
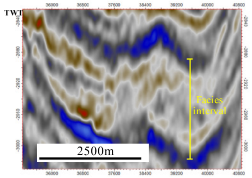
Seismic facies 5 is bounded by a concordant surface at the top boundary and an onlap surface at the base boundary. Prograding clinoforms are presented with a sigmoidal shape and surrounded by parallel reflectors in nearby areas. The reflection amplitude is moderate to high. The reflection continuity is relatively poor to fair, and the reflection frequency is moderate to high. The channel sandstone deposition surrounds by mudstones may cause high contrast reflects in the seismic profile. The sedimentary facies is interpreted as the channel sandstone fills in an upper slope setting. Facies 5 deposited in a turbidite deposits environment at the Flatfisk Slope and the Lomre Terrace.

4.8.6 Seismic Facies 6

Seismic facies6 is bounded by concordant in both top and base boundary surfaces. The reflection configuration is parallel to subparallel. The amplitude is low to moderate. The reflection continuity is poor to fair, and the frequency is low. Facies 6 consists mainly of mudstone to siltstone deposits. The lithofacies is observed as silty and muddy sediments in the basinward. Facies 6 presents in the western part of the study area such as the Lomre Terrace and the Flatfisk Slope. The environment of the facies 6 is offshore marine.

4.8.7 Seismic Facies 7

Seismic facies 7 is characterized by reflection-free configuration. The reflection amplitude is relatively low. The reflection continuity is poor. The frequency is low. Facies 7 can be found in the subbasin along the Nordfjord-Sogn detachment zone. The sedimentary facies is ambiguity. The reflection free indicates homogeneous sequences that could be either offshore mudstone or massive sandstone layers. There is no well penetration of this facies. The depositional environment is concluded as an offshore/basin center.

Seismic facies	Upper boundary	Lower boundary	Internal reflection configuration	Reflection Amplitude	Reflection Continuity	Reflection Frequency	Sedimentary facies	Environmental interpretation	Facies to Depositional environment interpretation	Seismic Example Vertical exaggeration :20
1	Erosional truncation	Concordant	Parallel to subparallel	Moderate to High	Fair to Good	Moderate to High	Sandstone sediments at the mouth bar deposits	Shallow marine delta aggradation	Marginal Marine/Deltaic	
2	Erosional truncation	Downlap	Subparallel and Sigmoidal shape	Moderate to High	Poor to Fair	Moderate to High	Prograded sand or silt sheet in the prodelta at the shelf margin	Shallow marine progradational sandstone in prodelta/shoreline	Lower/Upper Shoreface	
3	Concordant	Concordant	Parallel	Moderate to High	Fair to Good	Moderate to High	Aggraded sandbar in the wave dominated shoreline	Shallow marine sandstone in shoreline	Lower/Upper Shoreface	
4	Concordant	Concordant	Chaotic	Low to Moderate	Poor	Low	Carbonate deposits at the shelf margin	Shallow marine carbonate or calcareous sandstone	Lower Shoreface	

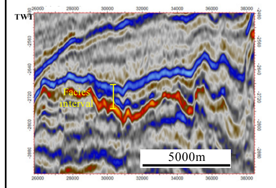
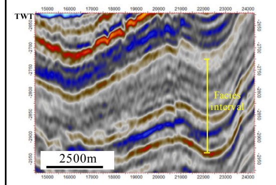
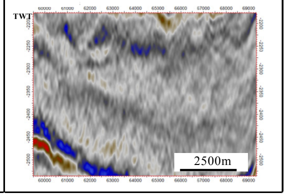
5	Concordant	Onlap	Prograding clinoform, Parallel	Moderate to High	Poor to Fair	Moderate to High	Channel sandstone in the slope area	Slope channel fan-fill	Turbidite deposit	
6	Concordant	Concordant	Parallel to subparallel	Low to Moderate	Poor to Fair	Low	Muddy or shaly sheet deposit	Basinal silt and shale deposit	Offshore	
7	-	-	Reflection free	Low	Poor	Low	Deep marine mudstone or massive sandstone in the basin floor	Basinal deposits	Offshore/ basin center	

Table 4. Seismic in the study area are explained in seven facies. The parameters used for facies characteristics are an upper boundary, a lower boundary, internal reflection configuration, reflection amplitude, reflection continuity and reflection frequency. Sedimentary facies and environment are interpreted based on facies parameters. Seismic examples show the main characteristics of each facies in seismic profile.

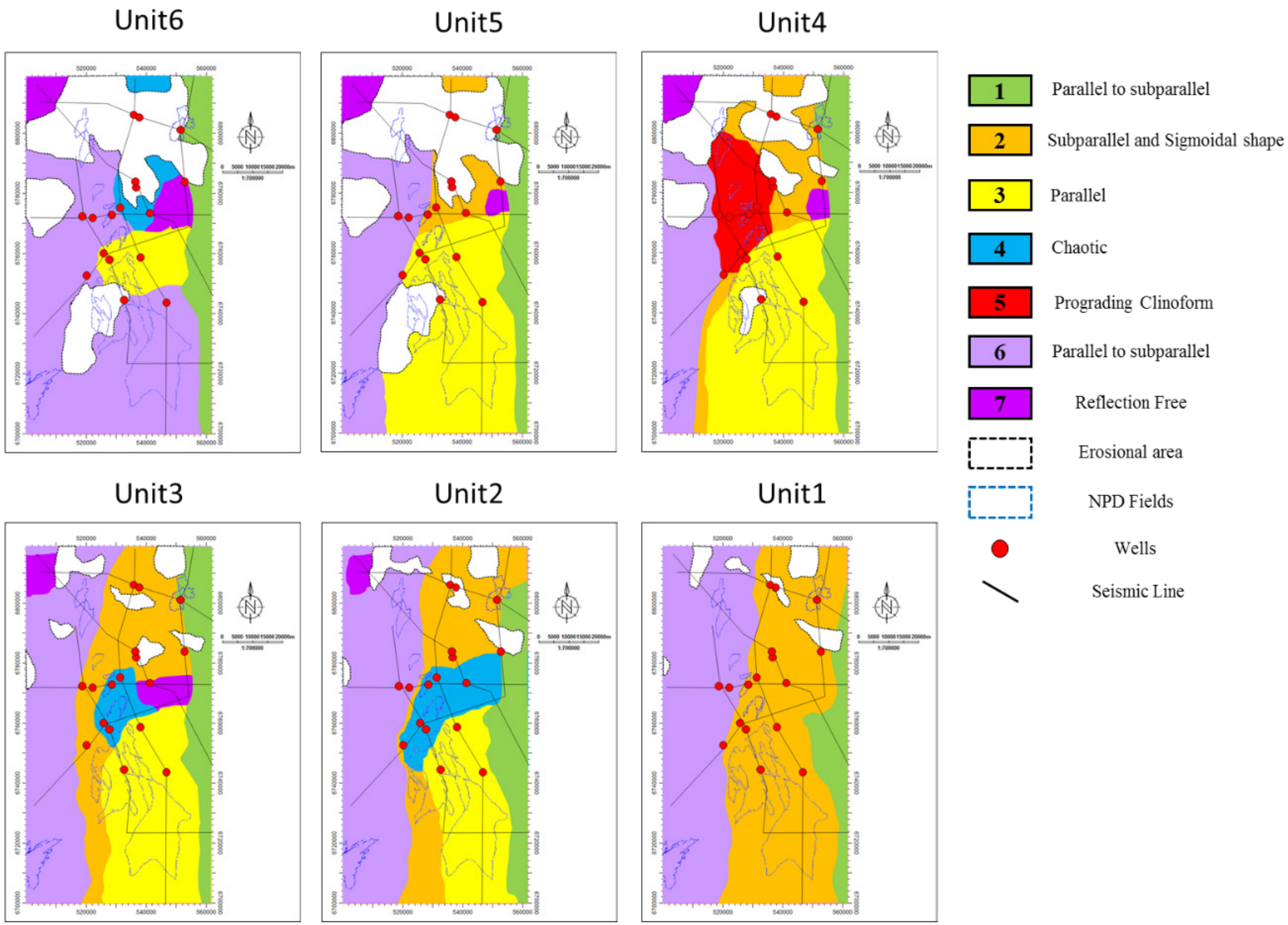


Figure 51. The seismic facies of each unit shown in the map view. Additional data is eroded/non-deposited areas, NPD fields, well locations and seismic lines used in this study. Inter-rifting tectonic phase is shown in Unit 1 to Unit 3, while the syn-rifting phase is shown in Unit 4 to Unit 6. Chaotic are observed in Unit s 2, Unit 3 and Unit6. The prograding clinoforms are only observed in Unit 4.

5. Discussion

This study divided the middle to late Jurassic into consistent sequence stratigraphy framework consisting of six units. The framework comprises of Unit 1 to Unit 6 from the Top Brent to the BCU. This discussion part describeb the choice of sequence stratigraphic methodology, sequence hierarchy and facies analysis, then led to the identification of depositional environment characteristics and inferred petroleum system elements.

5.1 Sequence stratigraphic framework integration

This study integrated sequence stratigraphic methods with complementary techniques such as stacking pattern, depositional trend, spatial, temporal distribution of strata and seismic facies analysis. The purpose of this integration was to get a robust stratigraphic framework and to be able to explain the depositional settings of the sedimentary filled basins.

Well stratigraphic interpretation was divided into more detailed sub-units for Unit 2, Unit 4 and Unit 6 which cannot be detected in the seismic data due to the limitations of seismic resolution.

The concept of sequence stratigraphic correlation was mainly based on Van Wagoner et al., (1988), which was classified as depositional sequence III (Catuneanu, 2006). The middle to late Jurassic covered the geologic time from the Bathonian (167.7 ma) to the Volgian (145 ma) ages. The deposition time was deposited during a low frequency (long duration) eustatic sea-level rise (Snedden and Liu, 2010). The stacking patterns showed a coarsening upward and progradational trend of the basin towards the west and land to the east (Figure 18; Figure 19). The interpretation indicated an apparent tendency of a first order cycle eustatic rise throughout the middle to late Jurassic time. The key evidence are GR and DT log trends that gradually increases to higher values for GR, and decreases to a lower value for DT logs.

The biostratigraphic data was crucial for the well interpretation to get the boundary age as correct as possible and to reduce the correlation uncertainties. The biostratigraphic data constrained the age of each depositional unit. Particularly, it aided in classification and correlation between similar depositional environments, e.g. the transition time between the tidal dominate shoreline in Unit 2 and wave-dominated shoreline in Unit 3. However, the interpretation was mainly based on the stacking pattern and lithostratigraphic data.

5.2 Tectonic and temporal variability

Interpretation results mainly show a syn-rift phase from seismic profiles and isochrone maps (Figure 24; Figure 29). The middle to late Jurassic was interpreted into intervening inter-rifting period during Unit 1 to Unit 3 which were correlated to the Bathonian to middle Oxfordian. The rifting reactivation event during Unit 4 to Unit 6 can be correlated to the middle Oxfordian to Volgian. The observation of fault movements and sedimentary thickness supports syn-rifting (Figure 29). The reactivation occurred after Unit 3 where unit thickness rapidly increased against fault (e.g. the Tusse fault) (Figure 24).

The Øygarden fault complex zone was the main fault at the basin boundary that controlled the basin opening in the east (Figure 17; Figure 20; Figure 22). Sediments were transported from the active margin in the east into the deeper areas in the west. The Kinna fault controlled paleotopographic highs between two area of the Uer Terrace and the Lomre Terrace. It resulted in high slope areas that formed turbidite deposits in Unit 4 when the time of high sedimentary influx.

Tectonic activity was a major influence on base level changes and sedimentary supply rates during the Upper Jurassic interval. It resulted in specific depositional environments and paleogeographic settings of each stratigraphic unit. The depositional environment of each unit was mainly interpreted by seismic facies analysis (Table 4; Figure 51). The depositional environment of the Troll and the Bjorgvin Arch was a marginal marine and delta where sediment sources transported from the lowland terrestrial area. The size of delta was developed during Unit 2 to Unit 4 due to the higher sedimentary influx and sea regression. The Troll area and the Uer Terrace were the transitional zones between upper shoreface and lower shoreface environments. Offshore marine and basin centre exists in the Lomre Terrace, the Flatfisk Slope and the sub-basin of the Uer Terrace where paleotopography was low (Figure 53). Turbidite deposits formed in the Lomre Terrace during the lowest eustatic level period of the study interval (Snedden and Liu, 2010) (*Figure 6*).

5.3 Sequence hierarchy

This study divided the upper Jurassic successions into a stratigraphic hierarchy down to the fourth order. The megasequence was defined on the scale of 100 million years which covered the entire Mesozoic period. The lower order eustatic sea level transgressed in this period (Snedden and Liu, 2010). The second order was the supersequence, which covered the middle to late Jurassic interval. This order covered 20-25 million years. The third order and parasequences (fourth order) covered 3-10 million and 0.1-3 million year, respectively (Table 5; Figure 52). The fourth order was used to define stratigraphic surfaces and stacking pattern of each unit, which led to stratigraphic units of the study interval. They were used to describe the depositional environments and the system tracts of each time interval. Sub-units can be divided more in unit 2, unit 4 and unit 6 but the resolution of the sub-unit can be observed only in the well log scale.

Seven stratigraphic units were defined from Unit 1 to Unit 6. Subunits were divided from Unit 2 (containing sub-units 2.1 and 2.2), Unit 4 (containing sub-units 4.1 and 4.2), and Unit 6 (containing sub-units 6.1 and 6.2) (Figure 52). Most of Unit 6 was eroded and therefore had some challenges with correlation from one basin to another. Stratigraphic surfaces of fourth orders were the main criteria to identify unit and sub-unit boundaries. The third order sequence model used to identify four depositional sequences. Each sequence was bounded by the sequence boundaries, which were the unconformities and their correlative surfaces. The sequences 2 and 3 were complete sequences including completed system tracts such as LST, TST and HST. The sequences 1 and 4 were not complete sequences since big erosion from the Top Brent, and the BCU resulted in only LST, and TST showed in sequence 4, and only HST showed in sequence 1 (Table 5Table 5). The second order identified two supersequences and the lowest order comprised one megasequence. The supersequence 1 consisted of Unit 1, Unit 2 and Unit 3. The supersequence 2 comprised of Unit 4, Unit 5 and Unit 6 (Table 5).

1st order >100 my	2nd Order 10-100 my	3rd Order 3-10 my	4th Order 0.1-3 my
Megasequence Mesozoic	Supersequence2 ≈ 12 my	Sequence4 ≈ 7 my	Unit6
		Sequence3 ≈ 6 my	Unit5
			Unit4
	Supersequence1 ≈ 10 my	Sequence2 ≈ 6 my	Unit3
			Unit2
		Sequence1 ≈ 4 my	Unit1

Table 5. The table of seismic sequence hierarchy of the middle to upper Jurassic. Sequence hierarchy of the lower orders are first and second orders and the higher orders are third and fourth orders.

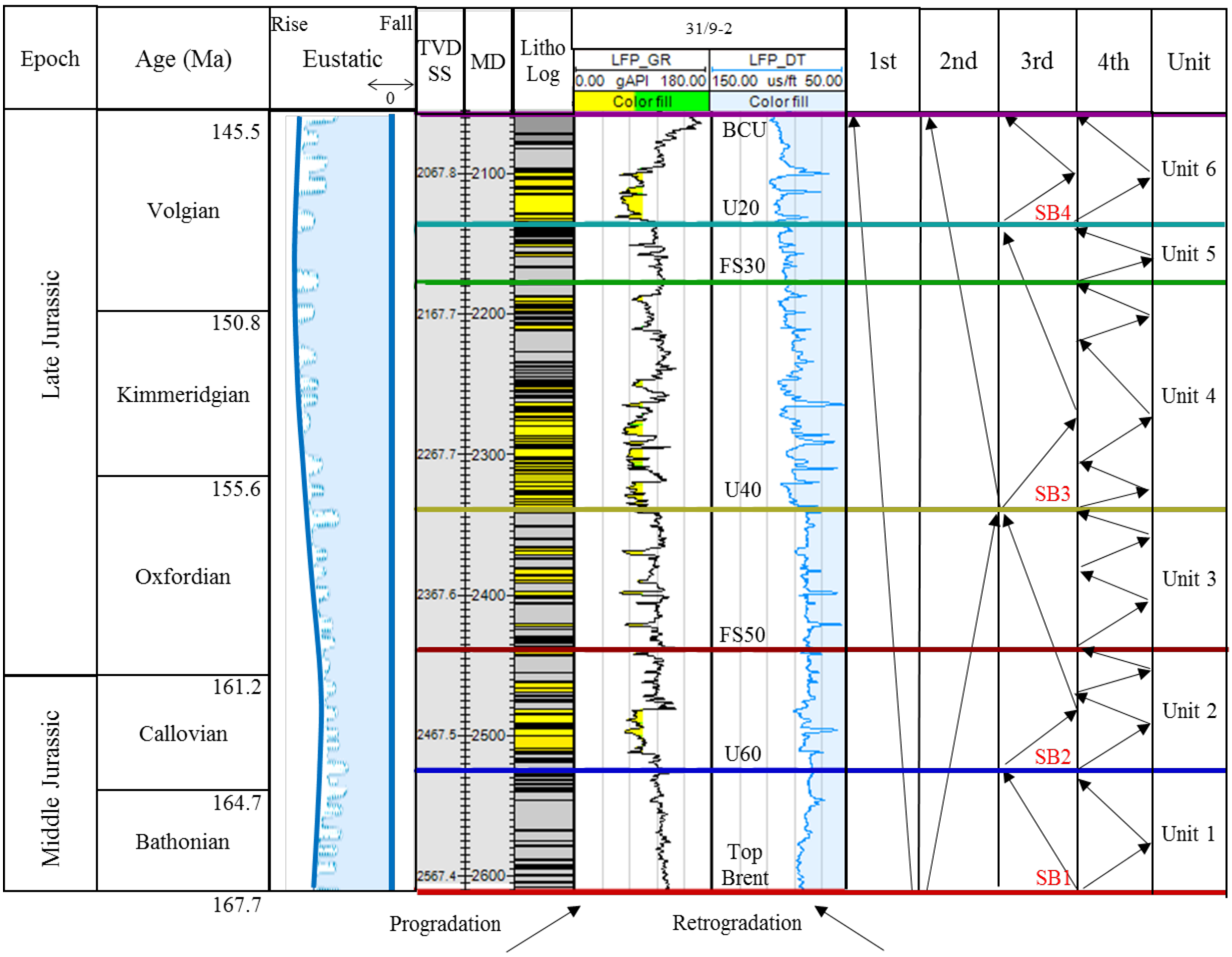


Figure 52. Interpretation of stacking patterns in well 31/9-2 shows frequency of each order from the first to the fourth order. Stratigraphic surfaces divide the study interval into six units. Stacking patterns were interpreted based on log data and eustatic history curve from Snedden and Liu, (2010).

5.4 Seismic facies analysis and paleogeography

The seismic interpretation and seismic facies analysis suggested five paleogeography settings; those are marginal marine/deltaic, upper shoreface, lower shoreface, offshore and turbidite deposits.

Unit 1 consists of shallow marine sandstones and deep marine mudstones. The boundary between the shallow and deep marine deposition is assumed to be divided at the Kinna and the Troll faults where the topography rapidly changed (Figure 20; Figure 22). Sediments are mud-dominated with a coarsening upward trend, which represents the HST in log interpretation (Figure 25). Unit 1 is bounded by the downlap surface at the top and truncation at the base. Unit 1 can be correlated with the transition between the Heather and Krossfjord formations. The seismic unit comprises facies 1, 2 and 6 which have parallel to subparallel configuration (Table 4; Figure 51). Parallel configuration represents low energy depositional environments while subparallel indicates low to medium energy deposition. The sediment deposition relies on to the sedimentary influx and subsidence rates. This meant that the depositional setting became more distal and deeper water. In addition, the evidence of constant sediment thickness along the fault plane also supported the summary that Unit 1 was deposited during the inter-rifting period. However, progradations are observed from the east to west in the Lomre Terrace and the Troll Area. The Sedimentary sources of Unit 1 came from the east as shown in clinoforms (Figure 26; Figure 27; Figure 28; Figure 44; Figure 45).

Unit 2 was also interpreted as being deposited in the inter-rifting period. It comprises both lowstand and transgressive system tracts. The LST can be explained by the downlap surface at the base with the FS at the top and TST is overlain by MFS, then changed to a prograded sequence of HST of Unit 3. The well correlation showed sandstone layers at the lower part and pinched out to the west. The upper part of the unit shows fining upward sequence that indicates the retrogradation of the shoreline with onlap surfaces in seismic (Figure 18; Figure 32). The high sedimentary influx into the basin during deposition of this unit resulted in downlap clinoforms in the lower part, which later changed to aggradation and retrogradation when the sea level rose (Figure 18; Figure 19; Figure 30). The inferred shoreface movement is in line with the interpretation of Snedden and Liu, (2010). They referred to a slow third order relative sea level rise during the early to middle Callovian. Unit 2 comprises facies 1, 2, 3, 4, 6 and 7 (Figure 51). Facies 3 represents the proximal sediments that were sourced from the SE part of the Bjorgvin Arch and the Øygarden fault complex zone. Shallow marine carbonates were interpreted in the northern Uer Terrace where there was a lower shoreface with low current energy (Figure 53). The progradation of the shoreline created an extensive shallow marine environment covered the Uer Terrace, Bjorgvin Arch and the Troll area (Figure 53). It can be correlated with the Krossfjord formation. The isochrone map showed the depocenter of this unit moved from the Bjorgvin Arch to the Uer Terrace which indicates the active area of the Nordfjord-Sogn detachment. This increase the accommodation space in the Uer Terrace.

The syn-rifting period started during deposition of Unit 3. The tectonic activity dominated the depositional settings by creating local basins and emergent highs that formed the source for sediments and barriers to flow. However, the rifting was not very active until deposition of Unit 4 and Unit 5. The depocenter of Unit 3 was still in the southern Uer Terrace (Figure 24). Movement of the Nordfjord-Sogn detachment zone created a deep local basin along the downthrown block (Figure 22). This depocenter contains the reflection-free configuration of the seismic facies 7 (Table 4). Reflection-free represents high homogenous lithology that leads to low seismic contrast. This inferred to the massive sandstone deposits rather than mudstone in this unit since this area was located near to the source of sediment and it was surrounded by sandstone in other wells from log interpretation.

Unit 3 represents the highstand system tract. It is bounded by the MFS at the base and downlap surface at the top. This system tract is in line with the mean sea level curve of Snedden and Liu, (2010) (*Figure 6*). The interpretations indicated that the marginal area expanded westward and created even more extensive shallow marine sandstone area. Well data shows more prograded sandstone to the Lomre Terrace than in the Unit 2 and also downlap surfaces in the clinoforms (Figure 33; Figure 34). This suggested a larger sediment influx, especially in the Uer Terrace. Unit 3 can be correlated to the Fensfjord formation.

Syn-rifting continued to Unit 4 and Unit5 with an inferred higher rifting rate. The low base level and the active Kinna fault during the middle Oxfordian dominated the depositional environment of Unit 4 by created more slope at the fault plane (*Figure 6*; Figure 29). High sediment influx during this unit can be observed from thick sandstone sequences in the Uer Terrace. Exceeded sediments were transported into the Lomre Terrace and the Flatfisk Slope as a turbidite flow and showed in large downlap clinoforms. The sedimentary flows were transported through bypass areas and created deep marine sandstones deposits in the slope channel. Channel features in the seismic profiles represent deep marine sandstone depositions (Figure 37; Figure 39; Figure 40). The isochrone map of Unit 5 suggested that most faults were active during the late Oxfordian to the middle Kimmeridgian and caused the large accommodation space in the area (Figure 24). The seismic profiles also show increasing sediment thickness against fault throws (Figure 20; Figure 21; Figure 22). Unit 4 is interpreted to consist of both a lowstand system tract and transgressive system tract. This unit is the only one that shows prograding clinoforms facies (Table 4; Figure 51). This unit is interpreted as a transitional depositional setting with the turbidite fan basinward and the shoreface area at the east. Unit 4 also had a large delta area which indicated massive supply sources from land. It can be correlated to the Fensfjord formation and its equivalents. A larger erosional area in the north suggests an uplift of the study area after the deposition (Figure 23; Figure 53).

Unit 5 was deposited during the middle Oxfordian to the middle Kimmeridgian time interval. However, most of the unit has an extensive erosional area due to the tectonic rifting during the late Jurassic that resulted in the thin sediment packages and information to see in well and seismic data. The main lithology is mudstone-dominated (Figure 43). The well correlation shows thin sandstone interbedded with the mudstones at the lower part and then coarsening upward to thicker sandstone layers at the upper part. High mudstone dominated from well data indicate tide-dominated shoreline at the upper shoreface. The higher net-to-gross dominated environment at the upper part represents more wave-dominated or deltaic environment as seen in the well 35/9-2 (Figure 43). Facies 1, 2, 3, 6 and 7 are found within this unit (Figure 51). The depositional environment of this unit is interpreted as shallow marine, and the transitional zone was located west of the Kinna and the Troll faults. The influence of paleotopography highs at the Troll and the Kinna faults blocked the sediment transport. In addition, small synthetic and antithetic faults in the area increased the relief of the paleotopography. This also explains the turbidite fan deposition in Unit 4 and not in Unit 5. Unit 5 was deposited during the highstand system tract. It can be correlated with the Sognefjord formation.

Unit 6 is the youngest unit of the study area. The deposition can be correlated with the rift climax. The ultimate evidence is the major time gap at the BCU Volgian surface (Kyrkjebø et al., 2004). This unconformity resulted in a regional erosion throughout the study area (Figure 20; Figure 21; Figure 22). Offshore mudstones is the main lithology of this unit. This unit represented the lowstand system tract in the lower part, which was influenced by rapid relative sea level rise (Figure 47) and the transgressive system tract at the upper part. However, many areas have an extensive missing time gap of the transgressive system tract due to the large erosion of the BCU and it not show in the well data (e.g., the well 35/9-2 and 35/12-3S) (Figure 43; Figure 47). Thick mudstone layers in association with high sea level curve supports the correlation between Unit 6 and the Draupne formation which is the main source rock of the Northern North Sea (Vollset et al., 1984). There are five seismic facies present in this unit: facies1, 3, 4, 6 and 7. The well data shows shale dominated with fining upward sequence at the upper part. Unit 6 represents a shoreline retrogradation. This was caused by rapid eustatic sea level rise during the late Jurassic (Snedden and Liu, 2010) (*Figure 6*). Deep marine mudstones are penetrated landward (e.g. wells 35/11-8S) (Figure 47), and it confirmed the deep marine environment as shown in the paleogeographic map (Figure 53). However, there was a shallow marine environment close to the Nordfjord-Sogn detachment (e.g. 35/12-3S). Isochrone map shows the depocenter in the Uer Terrace that suggests the active of Nordfjord-Sogn detachment. The accommodation created from fault led to sandstone deposits along the fault plane. The well 35/12-3shows sandstone layers deposit in the Unit 6. Carbonate beds were observed on the northern Uer Terrace which represented cemented shallow marine depositional beds. The areas to the north are still poorly understood due to the erosion at BCU and therefore missing section.

The early post-rifting stage began after deposition of Unit 6 during the early Cretaceous, which is inferred from the onlapping patterns of the overlying sediments (Gabrielsen et al., 2001).

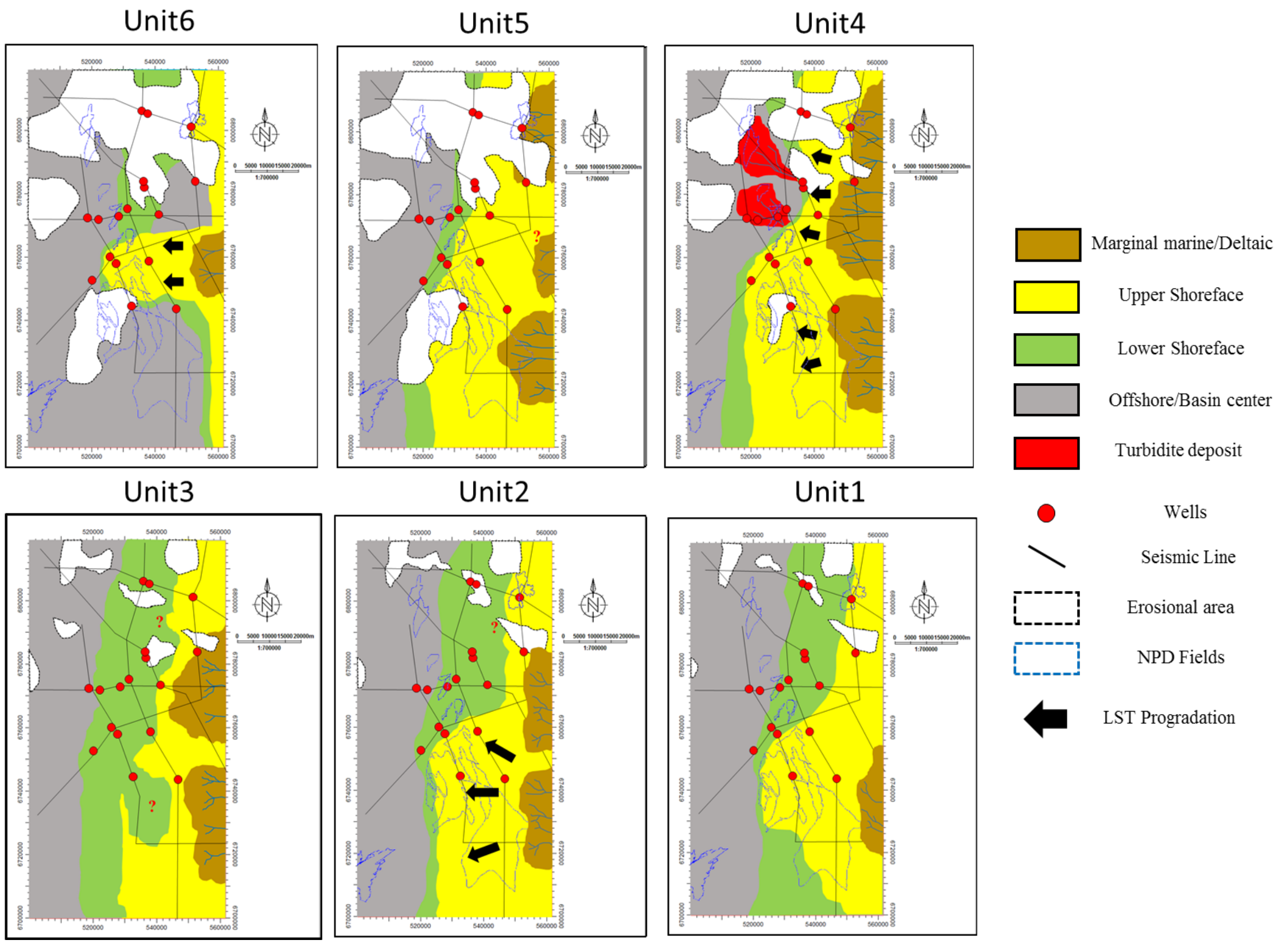


Figure 53. Depositional environments of each units are shown in the paleogeographic maps. There are four main depositional environments, which are marginal marine/deltaic, upper shoreface, lower shoreface, offshore/basin center and turbidite deposits. The sediment sources comes from the east. The source of sediments shows in the NE direction during Unit 4 and Unit 5. All units illustrate basinward progradation except unit 6 which shows landward progradation.

5.5 Petroleum System Analysis

The understanding of the depositional model and sequence stratigraphy is an essential part for determining the hydrocarbon potential. The stratigraphic framework describes litho-facies, temporal and spatial distribution of different units and linking it up to the tectonic evolution and eustatic sea level variations through time. Main outcomes of this study, such as interpretations, chronostratigraphic charts and paleogeographic maps, can be used to predict the distribution of the different petroleum system elements. Petroleum elements comprise of source, reservoir, trap, seal and migration.

5.5.1 Source Rocks

The characteristics of the source rocks are fine-grained sediments with high organic matter deposited in anoxic conditions. The potential source rock is evaluated by the total organic carbon (TOC) which is always highest in shales and mudstones (Peters, 1986). Mudstone dominated units are Unit 1, Unit5 and Unit 6. Unit 6 itself had the best condition for the source rock quality since it was deposited mainly in the deep offshore marine. Unit 1 and unit 5 were interpreted as highstand system tracts which deposited dominated mudstone layers at the lower part of units. These all units had a potential to generate source rock. However, the highest rank of the source rock can be classified from Unit 6, Unit 5 and Unit 3. The main criteria for classification was the shale content from GR log which is the highest in Unit 6, then Unit 5 and Unit 3 (Figure 47). Thick mudstone beds indicate a low energy environment in an offshore area. In combination with the seismic facies 6 which is parallel to subparallel. The facies also support the low energy depositional deposits that can preserve parallel bed with high organic matter (Figure 51). Unit 6 can be the highest potential source rock in the study interval. Unit 1 and Unit 5 are second candidates for source rock presence since they also are mudstone dominated formations. However, Unit 1 and Unit 5 have more sandstones, mudstones and siltstones interbedded and they are therefore more diluted with lower TOC (Figures 4.14 and 4.22). The seismic facies shows generally parallel to subparallel reflectors, but also sigmoidal clinoforms have been observed within these units in some areas. The uncertainty for units 1 and 5 is contributed by the quality of mudstone, in which the organic components are not as high as a deep marine shale (Figure 53). The deposition was interrupted by sedimentary sources, which came from the east during the high sedimentary supply period.

The source rock areas are located on the Lomre Terrace and the Flatfisk slope where an offshore marine environment was present (Figure 53). In addition, the local depocenter along the

Nordfjord-Sogn detachment zone is another potential area for a source rock presence since here is the thickest sediment package of Unit 6 within the study area (Figure 18). However, the reflection-free facies in the local basin of Nordfjord-Sogn detachment indicates either turbidity currents that disturbed organic matter deposition or very low energy environment that can preserve shale. There is no well penetrate into the area to prove the quality of source rock.

Unit 6 can be correlated to the Draupne formation (Vollset et al., 1984). The source rock analysis suggested a very high-quality source rock in Unit 6. The samples from the Draupne formation shows the rocks to be very high organic-rich mudstones with TOC content around 6%. The hydrogen index has a range from 200 to 400 mg/g of TOC (Kubala et al., 2003).

Unit 3 and Unit 5 are correlated to the Heather formation, which was deposited in between sandstone reservoirs. The dark grey mudstone with abundant carbonate beds also represents a potential source rock (Vollset et al., 1984). The lab result from the Heather shales showed a lower TOC content than for the Draupne formation. The TOC is around 2-2.5% (Goff, 1983) and the hydrogen index is from 100 to 200 mg/g TOC (Kubala et al., 2003).

5.5.2 Reservoir rocks

The Horda platform has great depositional environment for the reservoirs. The previous interpretations has concluded with shoreface and deltaic depositional environments. Facies and paleogeographic maps give a summary of shallow marine sandstone progradation from the active rift shoulder of the Øygarden fault complex zone and further to the east (Figure 51; Figure 53). All units contain reservoirs, especially in the Troll area and the Bjorgvin Arch which were proximal to the main sedimentary influx areas. Reservoir units are ranked from the best Unit 4, Unit 3 and Unit 2 based on the sandstone thickness and quality of sand.

Unit 4 was deposited during the syn-rift reactivation in combination with base level drop during the middle Oxfordian (Snedden and Liu, 2010). This event was the primary cause for high sandstone progradational rate towards the west and created a bypass area for turbidity deposit across the Lomre Terrace and the Flatfisk slope. Clean and thick sandstone reservoirs were deposited in a wave-dominated shoreline environment in the landward areas. These reservoirs form high quality reservoirs and this include the Troll area, the Bjorgvin Arch and the Uer Terrace (Figure 51; Figure 53).

Unit 3 and Unit 2 are secondary reservoir candidates. Tectonic activity is one of the main factor for generating reservoir quality in term of accommodation spaces and sediment sources from active margin side. Unit 3 was deposited during the early syn-rifting period, and Unit 2 was deposited during the late inter-rifting period. Both were interpreted as the tidal dominated shoreface environment. Even if both units are reasonable reservoirs, Unit 2 has more shale dominanted than Unit 3. Laminated layers of sandstones and shales within Unit 2 may decrease reservoir quality (Figures 4.12 and 4.14). The other units also contain good reservoirs in some limited areas where sandstones are deposited during high sedimentary influx time and high energy regime. Thin sandstone layers in other units have low potential. Therefore, they are not mentioned here.

5.5.3 Trap

Tectonic activity is the main factor that affected the trapping elements. Fault geometry in this area is rotated normal fault blocks along the extensional basin (Partington et al., 1993; Rattey and Hayward, 1993). Complex development of major faults and minor synthetic-antithetic faults provided a high potential for structural trapping. The stratigraphic traps are also possible but they are not of focus for this study. The stratigraphic traps are expected locally. Tectonic activity created high structures for hydrocarbon entrapment at the Troll area and the Bjorgvin Arch during the post-rift stage (Figure 23; Figure 29; Figure 46) (Gabrielsen et al., 2001).

5.5.4 Seal

The seal quality is defined as excellent in the Horda platform, especially Unit 6. Seal is divided into two types: top seal and lateral seal. Unit 6 was claystone-dominated, which was deposited in the offshore environment (Figure 53). The thick mudstone layers of Unit 6 behave as a robust cap rock for hydrocarbon reservoirs for underlying units. However, Unit 6 is not presented everywhere within the study area. Instead, it was eroded by the main unconformity, the BCU, in the Troll area, the Bjorgvin Arch and the northern Uer Terrace (Figure 23; Figure 47). Therefore, the top seal quality in these areas relys on the development of mudstone from the later stage. The Åsgard Formation in Lower Cretaceous was deposited above the BCU in wells 35/9-2, 35/9-5, and 31/2-2 (Isaksen and Tonstad, 1989). The Åsgard Formation behaved as the top seal in the Troll area and the Bjorgvin Arch. The main evidence for effective top seal was a flatspot feature in seismic data (Figure 36). The large flat spot indicate an enormous hydrocarbon accummulation which make the Troll a world-class hydrocarbon field. Another possible top seals are the transgressive system tract of Unit 2 and Unit 5. They can be correlated to the Heather ‘B’ and ‘C’. These mudstone layers can represent a top seal for the Krossfjord and the Fensfjord formations.

The lateral seal is also a key factor for hydrocarbon storage. Sand-shale juxtaposition form the lateral seal potential. The shallow marine environments presented here contains interbedded sandstones, siltstones, and shales which could aid the sand-shale juxtaposition formed during fault movements (Figure 20; Figure 21; Figure 22).

5.5.5 Timing and Migration

Timing and migration is the last element for hydrocarbon prospectivity. They areessential elements to determine hydrocarbon existence. The hydrocarbon has to migrate to the reservoir at the proper time after the trap formed. Migration prior to the formation of traps leads to the leak off from the reservoirs. As discussed previously, the primary source rock of the study area is the offshore mudstone in Unit 6, to the Draupne Formation. Seismic sections show structural highs at the central and southern part of the study area (Figure 20; Figure 21; Figure 22). Hydrocarbons were mainly kept in the present-day high structure areas including the Horda platform, the Uer Terrace, and the Bjorgvin Arch (Figure 23). However, the observations show a high erosional area in the north. The northern Horda platform is assumed to be a structural high in the past. The southern high paleotopography could have been uplifted during the post-rift stage; then hydrocarbons were generated and migrated to the structure at a time after the structure was completely sealed by the cap rocks. The Neogene tilting resulted in the inclination of the Horda Platform to the west, which could have created the pathway for hydrocarbon migration into hydrocarbon fields along porous carriers. Hydrocarbon was generated from the main kitchen area in the Viking Graben and the Sogn Graben when it reached an expulsed temperature (Larter, 1997).

6. Conclusion

This study aimed to investigate the seismic sequence stratigraphy of Upper Jurassic on the Horda platform. Multiple of stratigraphic frameworks were integrated into the study such as sequence stratigraphy, lithostratigraphy, chronostratigraphy and biostratigraphy. Well correlation, seismic interpretation, seismic attribute analysis and seismic facies analysis were primary methods applied to characterise the depositional environment of the studied Upper Jurassic interval.

Depositional sequences are controlled by three regime variables, which are influenced by sediment supply, eustatic sea level and tectonic setting. The first order base level was controlled by eustatic sea level rise, while the second order included two sea level fall events. The depositional sequences were aligned with the eustatic curve from Snedden and Liu, (2010). The interpretation shows one megasequence, two supersequences and four depositional sequences for the study interval.

The sequences stratigraphic framework illustrate seven stratigraphic units from the middle to late Jurassic interval: Unit 1 (Bathonian), Unit 2 (Early to Late Callovian), Unit 3 (Late Callovian to Middle Oxfordian), Unit 4 (Middle to Late Oxfordian), Unit 5 (Late Oxfordian to Middle Kimmeridgian) and Unit 6 (Middle Kimmeridgian to Late Volgian). Stratigraphic unit interpretations were determined based on well correlation and seismic interpretation. The sequence hierarchy for the depositional sequence is in the third order. Seven stratigraphic surfaces comprise five unconformities and two flooding surfaces. There were three highstand system tracts, which are defined in Unit 1, Unit 3 and Unit 5. Three lowstand system tracts to transgressive system tracts were interpreted in Unit 2, Unit 4 and Unit 6.

The chronostratigraphic diagram was generated in order to explain depositional schematic of the study area during the middle to upper Jurassic. The result showed the relationship of stratigraphic regime variables in term of sedimentary supply and eustatic change. The diagram suggested highest sedimentary influx period was in Unit 4 from the evidence of turbidite deposits. Low sedimentary supply occurred during the Unit 1 to Unit 3 and it was increased following the syn-tectonic period.

Seismic reflection configurations were analysed to perform the seismic facies analysis in order to describe the paleo-depositional environment. Seismic facies analysis included the seismic boundaries, internal reflections, seismic amplitudes, frequencies and continuity. In this study, there were seven seismic facies identified and four types of paleo-depositional environments inferred.

Shallow and deep marine deposition characterized the Horda platform during the middle to late Jurassic. The seismic profiles show that the deeper part was in the west where the Lomre Terrace and the Flatfisk slope are located. Well correlation and seismic attribute maps indicate that main sedimentary sources was from the Øygarden fault complex zone and further to the east. Main sediment input area was from the southeast into the Troll area and the Bjorgvin arch. Sediment also transported from the east during the high tectonic activity in the active margin side. It generated deltaic environment in the E and NE of the study area. It is assumed that tectonic rifting activities and eustatic sea level controlled the sediment supply rate. During the syn-rifting, the influx rate increased in Unit 3 to Unit 6. Well and seismic observations indicated an inter-rifting phase during deposition of Unit 1 andUnit 2. Deposition of Unit 3 coincided with basin reactivation,Unit which reached the rift climax during the sedimentation of Unit 6. However, the highest sediment input rate was during deposition of Unit 4 (Callovian to Oxfordian) where eustatic sea level shows a rapid sea-level fall. Turbidite fan systems prograded onto the Flatfisk slope and the Lomre Terrace during this time. Submarine channels are observed in both well, seismic and attribute observation.

Four fault systems in the study area are associated with various tectonic stages, which include two major fault trends and two minor fault trends. Major faults such as the Troll Fault, the Kinna Fault, the Svartalv Fault, the Tusse Fault and the Vette Fault are oriented in the N-S direction (Figure 17; Figure 46). Seismic profiles show most major faults were created before the Middle Jurassic since they penetrated to deeper sections. Tectonic reactivation during deposition of Unit 3 created a different maximum horizontal regime which resulted in the reactivation of Nordfjord-Sogn detachment in the NE-SW direction. Two minor faults orientated in the NE-SW and NW-SE directions were observed against the Nordfjord-Sogn detachment in variance maps (Figure 46). This small faults increased the potential for petroleum storage in term of trap and lateral seals.

The study provides a summary of the petroleum significance of the Upper Jurassic interval. The main source rock was in Unit 6 which correlate to the Draupne formation. Mudstone deposited during the TST are generally good source rocks. Mudstone deposits interfingering with thin sandstones are correlated to the Heather formation, which deposited during HST. The Horda platform has high-quality reservoir rocks which are deposited in shoreface and deltaic environments. The turbidite dreposits are also good reservoirs candidate in the Lomre Terrace. The thickest sandstone reservoirs are in the Troll area and the Bjorgvin Arch, which was more proximal to the main sedimentary influx area. The reservoir formations are correlated with the Krossfjord, the Fensfjord and the Sognefjord formations. Many normal faults and small synthetic-antithetic faults created several trapping possibilities due to the high tectonic activity. The top seal is could be the mudstone formation of Unit 6 as well as the interbedded mudstones of other interval formation. Hydrocarbon charge happened during the post-rifting stage after the late Jurassic. The platform geometry was inclined into the northwestern part and this controlled the migration routes of the hydrocarbons. The hydrocarbons were generated in the deeper kitchen areas towards the west after reaching hydrocarbon expulsion conditions, which then migrated towards the highs to the east.

7. Recommendation

This study has synthesised the Upper Jurassic depositional environments of the Horda Platform from the sequence stratigraphic framework and linked it to the petroleum significance. Several applications from both geophysical and geological approaches were integrated into the study, but below further recommendations to improve the stratigraphic framework are mentioned.

The essential part of this study was the generation of consistent seismic and well interpretations to get an accurate unit division and lateral distributions. There are still many applications related to facies analysis that could be introduced in a future study to make more robust models. For example, the use of gross sand maps with dynamic data in combination with seismic attributes for a better understanding of the reservoir pathways or the use of quantitative interpretations from well log data can help lithological facies analysis. The quantitative interpretation could provide higher resolution of units and facies classifications than achieved by using only biostratigraphic and lithostratigraphic data. More focus on structural models and detailed fault interpretations are other recommendations that definitely could improve the stratigraphic framework models in the future.

8. References

Allen, G.P. and Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill; the Gironde Estuary, France. Journal of Sedimentary Research, 63(3), pp.378-391.

Amrizal, A. and Nordfjord, S., 2017, June. An Integrated Study of the Cretaceous Sequence Stratigraphic Development in the Northern Stord Basin, North Sea. In 79th EAGE Conference and Exhibition 2017.

Badley, M.E., Price, J.D., Dahl, C.R. and Agdestein, T., 1988. The structural evolution of the northern Viking Graben and its bearing upon extensional modes of basin formation. Journal of the Geological Society, 145(3), pp.455-472.

Bockelie, J.F., 1991. Ichnofabric mapping and interpretation of Jurassic reservoir rocks of the Norwegian North Sea. Palaios, pp.206-215.

Brown, A.R. 2003. Interpretation of three dimensional seismic data: AAPG memoir 42. 3rd ed., pp.368

Brown, S., Richards, PC. and Thomson, A.R., 1987. Patterns in the deposition of the Brent Group (Middle Jurassic) UK North Sea. In: J. Brooks and K.W. Glennie (Editors), Petroleum Geology of North West Europe. Graham and Trot- man, London, pp. 899-913.

Carter, R. M., Fulthorpe, C. S., Naish, T. R., 1998. Sequence concepts at seismic and outcrop scale: the distinction between physical and conceptual stratigraphic surfaces. Sedimentary Geology 122, pp.165–179.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R. and Giles, K.A., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews, 92(1-2), pp.1-33.

Catuneanu, O., Galloway, W.E., Kendall, C.G.S.C., Miall, A.D., Posamentier, H.W., Strasser, A. and Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsletters on stratigraphy, 44(3), pp.173-245.

CGG. 2018.
URL: http://www.cgg.com/en/Media-and-Events/Media-Releases/2016/11/Integrated-Geoscience-Unlocks-Potential-in-Northern-Viking-Graben (available from: 27.02.2017).

Christiansson, P., Faleide, J.I. and Berge, A.M., 2000. Crustal structure in the northern North Sea: an integrated geophysical study. Geological Society, London, Special Publications, 167(1), pp.15-40.

De'Ath, N.G. and Schuyleman, S.F., 1981. The geology of the Magnus oilfield. Petroleum geology of the continental shelf of north-west Europe, pp.342-351.

Deegan, C. E and Scull, B. J, (compilers), 1977 A proposed standard lithostratigraphi nomenclature for the Central and Northern North Sea. Rep. Inst. Geol. Sci., No. 77/25: Bull. Norw. Petrol. Direct., No. 1, HMSO, London

Doré, A.G., Lundin, E.R., Fichler, C. and Olesen, O., 1997. Patterns of basement structure and reactivation along the NE Atlantic margin. Journal of the Geological Society, 154(1), pp.85-92.

Duffy, O.B., Bell, R.E., Jackson, C.A.L., Gawthorpe, R.L. and Whipp, P.S., 2015. Fault growth and interactions in a multiphase rift fault network: Horda Platform, Norwegian North Sea. Journal of Structural Geology, 80, pp.99-119.

Embry, A.F., 1995. Sequence boundaries and sequence hierarchies: problems and proposals. Sequence Stratigraphy on the Northwest European Margin, 5, pp.1-11.

Embry, A.F., 2009. Practical sequence stratigraphy. Canadian Society of Petroleum Geologists, 81.

Emery, D. and K. J. Myers. 1996. Sequence Stratigraphy. Victoria, Australia: Blackwell Science Ltd., pp.291.

Færseth, R.B., 1978. Mantle-derived lherzolite xenoliths and megacrysts from Permo-Triassic dykes, Sunnhordland, western Norway. Lithos, 11(1), pp.23-35.

Færseth, R.B., 1996. Interference of Permo-Triassic and Jurassic stretching phases and associated megafault-blocks in the northern North Sea. J. Geol. Soc.(Lond.), 153, pp.931-944.

Færseth, R.B., Gabrielsen, R.H. and Hurich, C.A., 1995. Influence of basement in structuring of the North Sea basin, offshore southwest Norway. Norsk Geologisk Tidsskrift, 75(2-3), pp.105-119.

Faerseth, R.B., Knudsen, B.E. and Liljedahl, T., 1997. Oblique rifting and sequential faulting in the Jurassic development of the northern North Sea. Oceanographic Literature Review, 4(45), p.677.

Fossen, H., Hesthammer, J., Johansen, T.E.S. and Sygnabere, T.O., 2003. Structural geology of the Huldra field, northern North Sea—A major tilted fault block at the eastern edge of the Horda platform. Marine and Petroleum Geology, 20(10), pp.1105-1118.

Fraser, S.I., Robinson, A.M., Johnson, H.D., Underhill, J., Kadolsky, D., 2002. Upper Jurassic. In: Evans, D., Graham, C., Armour, A., Bathurst, P. (Eds.), The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London, pp.157-189.

Frazier, D.E., 1974. Depositional episode: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf basin. The University of Texas at Austin, Bureau of Economic Geology, Geological Circular, 74(1), p.28.

Furnes, H., Mitchell, J.G., Robins, B., Ryan, P. and Skjerlie, F.J., 1982. Petrography and geochemistry of peralkaline, ultrapotassic syenite dykes of Middle Permian age, Sunnfjord, West Norway. Norsk Geologisk Tidsskrift, 62(3), pp.147-159.

Gabrielsen, R.H., Færseth, R.B., Steel, R.J., Idil, S. and Kløvjan, O.S., 1990. Architectural styles of basin fill in the northern Viking Graben. Tectonic Evolution of the North Sea Rifts. Clarendon Press, Oxford, pp.158-179.

Gabrielsen, R.H., Kyrkjebø, R., Faleide, J.I., Fjeldskaar, W. and Kjennerud, T., 2001. The Cretaceous post-rift basin configuration of the northern North Sea. Petroleum Geoscience, 7(2), pp.137-154.

Gibbons, K., 1991. Use of variations in strontium isotope ratios for mapping barriers: an example from Troll Field, Norwegian continental shelf. 6th Eur. Symp. Improved Oil Recovery, Stavanger. Statoil, Vol. 1 pp. 205-211.

Goff, J.C., 1983. Hydrocarbon generation and migration from Jurassic source rocks in the E Shetland Basin and Viking Graben of the northern North Sea. Journal of the Geological Society, 140(3), pp.445-474.

Goldhaber, M.B., 2003. Sulfur-rich sediments. Treatise on Geochemistry, 7, p.407.

Graue, E., Helland-Hansen, W., Johnsen, J., Lømo, L., Nøttvedt, A., Rønning, K., Ryseth, A. and Steel, R., 1987. Advance and retreat of Brent delta system, Norwegian North Sea. Petroleum geology of north west Europe, pp.915-937.

Halland, E.K., Gjeldvik, I.T., Johansen, W.T., Magnus, C., Meling, I.M., Pedersen, S., Riis, F., Solbakk, T. and Tappel, I., 2011. CO2 Storage Atlas Norwegian North Sea. Norwegian Petroleum Directorate, PO Box, 600.

Haq, B.U., Hardenbol, J.A.N. and Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science, 235(4793), pp.1156-1167.

Harker, S.D. and Rieuf, M., 1996. Genetic stratigraphy and sandstone distribution of the Moray Firth Humber Group (Upper Jurassic). Geological Society, London, Special Publications, 114(1), pp.109-130.

Harms, J.C., Tackenberg, P., Pickles, E. and Pollock, R.E., 1981. The Brae oilfield area. Petroleum Geology of the Continental Shelf of North-West Europe. Heyden, London, pp.352-357.

Helland-Hansen, W. and Martinsen, O.J., 1996. Shoreline trajectories and sequences; description of variable depositional-dip scenarios. Journal of Sedimentary Research, 66(4), pp.670-688.

Helland-Hansen, W., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews, 94(1-4), pp.95-97.

Hellem, T., Kjemperud, A. and Øvrebø, O.K., 1986. The Troll Field: a geological/geophysical model established by the PL085 Group. In Habitat of hydrocarbons on the Norwegian continental shelf, pp.217-238. Graham and Trotman London.

Holgate, N.E., Jackson, C.A.L., Hampson, G.J. and Dreyer, T., 2013. Sedimentology and sequence stratigraphy of the Middle–Upper Jurassic Krossfjord and Fensfjord formations, Troll Field, northern North Sea. Petroleum Geoscience, 19(3), pp.237-258.

Holgate, N.E., Hampson, G.J., Jackson, C.A.L. and Petersen, S.A., 2014. Constraining uncertainty in interpretation of seismically imaged clinoforms in deltaic reservoirs, Troll field, Norwegian North Sea: Insights from forward seismic models of outcrop analogsCharacterization of Seismically Imaged Clinoforms Using Forward Seismic Models of Outcrop Analogs. AAPG Bulletin, 98(12), pp.2629-2663.

Holgate, N.E., Jackson, C.A., Hampson, G.J. and Dreyer, T., 2015. Seismic stratigraphic analysis of the Middle Jurassic Krossfjord and Fensfjord formations, Troll oil and gas field, northern North Sea. Marine and Petroleum Geology, 68, pp.352-380.

Hunt, D. and Tucker, M.E., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level'fall. Sedimentary Geology, 81(1-2), pp.1-9.

Husmo, T., Hamar, G.P., Høiland, O., Johannessen, E.P., Rømald, A., Spencer, A.M., Titterton, R., 2002. Lower and middle Jurassic. In: Evans, D., Graham, C., Armour, A., Bathurst, P. (Eds.), The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London, pp. 129-155.

Isaksen, D. and Tonstad, K. eds., 1989. A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea. Norwegian Petroleum Directorate.

Johns, C.R. and Andrews, I.J., 1985. The petroleum geology of the Unst Basin, North Sea. Marine and Petroleum Geology, 2(4), pp.361-372.

Johnsen, J.R., Rutledal, H. and Nilsen, D.E., 1995. Jurassic reservoirs; field examples from the Oseberg and Troll fields: Horda Platform area. Petroleum Exploration and Exploitation in Norway, 4, pp.199-234.

Jonassen, P., 2015. Fault Analysis Based on 3D Seismic Data from the Northern Horda Platform (Master's thesis).

Krivenko, N., 2014. Seismic interpretation at the Horda Platform, North Sea. Detailed characterization of Sognefjord Formation (Master's thesis, Institutt for petroleumsteknologi og anvendt geofysikk).

Kubala, M., Bastow, M., Thompson, S., Scotchman, I. and Oygard, K., 2003. Geothermal regime, petroleum generation and migration. The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London, pp.289-315.

Kwanjai, K., 2012. Structural Interpretation and Investigation of the Displacement Gradients of the Normal Fault System beneath the Horda Platform, the northern North Sea (Master's thesis).

KyrkjebØ, R., Gabrielsen, R.H. and Faleide, J.I., 2004. Unconformities related to the Jurassic–Cretaceous synrift–post-rift transition of the northern North Sea. Journal of the Geological Society, 161(1), pp.1-17.

Larter, I.H.S., 1997. Petroleum migration, alteration, and remigration within Troll field, Norwegian North Sea. AAPG bulletin, 81(2), pp.222-248.

Lervik, K.S., Spencer, A.M. and Warrington, G., 1989. Outline of Triassic stratigraphy and structure in the central and northern North Sea. In Correlation in hydrocarbon exploration, pp.173-189. Springer, Dordrecht.

Li, Y. and Zheng, X., 2008. Spectral decomposition using Wigner-Ville distribution with applications to carbonate reservoir characterization. The Leading Edge, 27(8), pp.1050-1057.

Macurda Jr, D.B., 1997. Carbonate seismic facies analysis. Carbonate seismology: Society of Exploration Geophysicists Geophysical Developments Series, 6, pp.95-119.

Marsden, G., Yielding, G., Roberts, A.M. and Kusznir, N.J., 1990. Application of a flexural cantilever simple-shear/pure shear model of continental lithosphere extension to the formation of the northern North Sea basin. Tectonic evolution of the North Sea rifts, pp.241-261.

Miall, A.D., 1995. Whither stratigraphy?. Sedimentary Geology, 100(1-4), pp.5-20.

Mitchum, R. M. Jr., P. R. Vail and J. B. Sangree, presence of a stratigraphic trap at Hortense Field 1977, Seismic Stratigraphy and Global Changes of Sea Level, Part 6: Stratigraphic Interpretation of Seismic Reflection Patterns in Depositional Sequences, In: Payton, C. E. cd., Seismic Stratigraphy - Applications to Hydrocarbon Exploration: AAPG Memoir 26, pp.117-133.

Mitchum, R. M. Jr., P. R. Vail and S. Thompson III, 1977, Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for StratigraphicAnalysis, In: Payton, C. E. cd., Seismic Stratigraphy - Applications to Hydrocarbon Exploration: AAPG Memoir 26, pp.53-62.

Nanda, N.C., 2016. Seismic data interpretation and evaluation for hydrocarbon exploration and production: A practitioner's guide. Springer, pp.171-183.

Nio, S.D. and Yang, C.S., 1991. Sea-level fluctuations and the geometric variability of tide-dominated sandbodies. Sedimentary Geology, 70(2-4), pp.161-193.

Norwegian Petroleum Directorate (NPD) - FactPages. 2018.
URL: http://factpages.npd.no/factpages/Default.aspx?culture=en (available from: 05.03.2018).

Nummedal, D., Swift, D. J. P., 1987. Transgressive stratigraphy at sequence-bounding unconformities: some principles derived from Holocene and Cretaceous examples.

Olaussen, S., Larsen, B.T. and Steel, R., 1994. The Upper Carboniferous-Permian Oslo Rift; basin fill in relation to tectonic development.

Osborne, P. & Evans, S. 1987. The Troll Field: Reservoir geology and field development planning. In: Buller, A.T. & Kleppe, J. (eds) North Sea Oil and Gas Reservoirs. Graham & Trotman. London, pp.39–60.

Øvrebø, L.K., Kjennerud, T., Lippard, S.J., Rivenæs, J.C. and Hamborg, M., 2001. Forward depositional modelling of the Cretaceous post-rift deposits in the northern North Sea. Norwegian Journal of Geology/Norsk Geologisk Forening, 81(3).

Partington, M.A., Mitchener, B.C., Milton, N.J. and Fraser, A.J., 1993, January. Genetic sequence stratigraphy for the North Sea Late Jurassic and Early Cretaceous: distribution and prediction of Kimmeridgian–Late Ryazanian reservoirs in the North Sea and adjacent areas. In Geological Society, London, Petroleum Geology Conference series (Vol. 4, No. 1, pp. 347-370). Geological Society of London.

Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis. AAPG bulletin, 70(3), pp.318-329.

Pigott, J.D., Kang, M.H. and Han, H.C., 2013. First order seismic attributes for clastic seismic facies interpretation: Examples from the East China Sea. Journal of Asian Earth Sciences, 66, pp.34-54.

PITMAN III, W.C., 1978. Relationship between eustacy and stratigraphic sequences of passive margins. Geological Society of America Bulletin, 89(9), pp.1389-1403.

Platt, N.H., 1995. Structure and tectonics of the northern North Sea: new insights from deep penetration regional seismic data. Geological Society, London, Special Publications, 80(1), pp.103-113.

Plint, A. G., 1988. Sharp-base shoreface sequences and" offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea-level. Sea-level Changes: An Integrated Approach: SEPM Special Publication, 42, pp.357-370.

Plint, A.G. and Nummedal, D., 2000. The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. Geological Society, London, Special Publications, 172(1), pp.1-17.

Posamentier, H.W. and Allen, G.P., 1999. Siliciclastic sequence stratigraphy: concepts and applications (Vol. 7, pp. 212). Tulsa, Oklahoma: SEPM (Society for Sedimentary Geology).

Posamentier, H.W. and Kolla, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. Journal of sedimentary research, 73(3), pp.367-388.

Posamentier, H.W. and Vail, P.R., 1988. Eustatic controls on clastic deposition II—sequence and systems tract models.

Posamentier, H.W., James, D.P., and Allen, G.P., 1990, Aspects of sequence stratigraphy: recent and ancient examples of forced regressions: American Association of Petroleum Geologists Bulletin, v. 74, pp.742.

Ramm, M. and Ryseth, A.E., 1996. Reservoir quality and burial diagenesis in the Statfjord Formation, North Sea. Petroleum Geoscience, 2(4), pp.313-324.

Ramsayer, G.R., 1979, January. Seismic stratigraphy, a fundamental exploration tool. In Offshore Technology Conference. Offshore Technology Conference.

Rattey, R.P. and Hayward, A.B., 1993, January. Sequence stratigraphy of a failed rift system: the Middle Jurassic to Early Cretaceous basin evolution of the Central and Northern North Sea. In Geological Society, London, Petroleum Geology Conference series (Vol. 4, No. 1, pp. 215-249). Geological Society of London.

Ravnås, R. and Bondevik, K., 1997. Architecture and controls on Bathonian–Kimmeridgian shallow-marine synrift wedges of the Oseberg–Brage area, northern North Sea. Basin Research, 9(3), pp.197-226.

Ravnås, R., Nøttvedt, A., Steel, R.J. and Windelstad, J., 2000. Syn-rift sedimentary architectures in the Northern North Sea. Geological Society, London, Special Publications, 167(1), pp.133-177.

Rawson, P.F. and Riley, L.A., 1982. Latest Jurassic - Early Cretaceous events and the "Late Cimmerian Unconformity" in North Sea area. Bull. AAPG Bulletin, 66(12), pp.2628-2648.

Roberts, A.M., Yielding, G., Kusznir, N.J., Walker, I.M. and Dorn-Lopez, D., 1995. Quantitative analysis of Triassic extension in the northern Viking Graben. Journal of the Geological Society, 152(1), pp.15-26.

Roksandić, M.M., 1978. Seismic facies analysis concepts. Geophysical Prospecting, 26(2), pp.383-398.

Ryan, M.C., Helland-Hansen, W., Johannessen, E.P. and Steel, R.J., 2009. Erosional vs. accretionary shelf margins: the influence of margin type on deepwater sedimentation: an example from the Porcupine Basin, offshore western Ireland. Basin Research, 21(5), pp.676-703.

Ryseth, A., & Ramm, M., 1996. Alluvial architecture and differential subsidence in the Statfjord Formation, North Sea: prediction of reservoir potential. In Petroleum Geos cience 2.

Ryseth, A., 1989. Correlation of depositional patterns in the Ness Formation, Oseberg area. In Correlation in Hydrocarbon Exploration (pp. 313-326). Springer, Dordrecht.

Ryseth, A., 2001. Sedimentology and palaeogeography of the Statfjord Formation (Rhaetian-Sinemurian), North Sea. In O. J. Martinsen, & T. Dreyer, NPF Special Publications 10.

Schlager, W., 1992. Sedimentology and sequence stratigraphy of reefs and charbonate platforms. Continuing Education Course Note Series, Amer. Assoc. Petrol. Geol., (34), pp.71p.

Schlumberger, 2016. Petrel Seismic-to-Simulation Software Interpreter's Guide to Seismic Attributes. Schlumberger, Houston.

Sheriff, R.E. and Geldart, L.P., 1995. Exploration seismology. Cambridge university press. pp. 146.

Sloss, L., Krumbein, W., and Dapples, E., 1949.Integrated facies analysis. In: C. Longwell, (ed.). Sedimentary facies in geologic history. Geological Society America, Memoir 39, pp.91-124.

Snedden, J. W., and C. Liu., 2010. A Compilation of Phanerozoic Sea-level Change, Coastal Onlaps and Recommended Sequence Designations. American Association Petroleum Geologists, pp.3.

Sømme, T.O., Martinsen, O.J. and Lunt, I., 2013. Linking offshore stratigraphy to onshore paleotopography: The Late Jurassic–Paleocene evolution of the south Norwegian margin. Bulletin, 125(7-8), pp.1164-1186.

Steel, R. and Ryseth, A., 1990. The Triassic—Early Jurassic succession in the northern North Sea: megasequence stratigraphy and intra-Triassic tectonics. Geological Society, London, Special Publications, 55(1), pp.139-168.

Steel, R.J., 1993, January. Triassic–Jurassic megasequence stratigraphy in the Northern North Sea: rift to post-rift evolution. In Geological Society, London, Petroleum Geology Conference series (Vol. 4, No. 1, pp. 299-315). Geological Society of London.

Steel, R.J., 1993. Triassice-Jurassic megasequence stratigraphy in the Northern North Sea: rift to post-rift evolution. In: Parker, J.R. (Ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, Petroleum Geology Conference Series, 4. Geological Society, London, pp. 299-315.

Stewart, D.J., Schwander, M. and Bolle, L., 1995. Jurassic depositional systems of the Horda Platform, Norwegian North Sea: Practical consequences of applying sequence stratigraphic models. In Norwegian Petroleum Society Special Publications (Vol. 5, pp. 291-323). Elsevier.

Subrahmanyam, D. and Rao, P.H., 2008. Seismic attributes–A review. In 7th International Conference & Exposition on Petroleum Geophysics, Hyderabad (pp. 398-404).

Torsvik, T.H., Sturt, B.A., Swensson, E., Andersen, T.B. and Dewey, J.F., 1992. Palaeomagnetic dating of fault rocks: evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjord Fault, western Norway. Geophysical Journal International, 109(3), pp.565-580.

Vail, P. R., Mitchum, R. M. Jr., Thompson, S., III, 1977. Seismic stratigraphy and global changes of sea level, part four: global cycles of relative changes of sea level. American Association of Petroleum Geologists Memoir 26, pp.83–98.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J., 1988. Sea-level changes: An integrated approach. SEPMSea-level changes: an integrated approach, 42.

Vindenes, K.S., 2013. Sequence stratigraphic analysis of the Jurassic period on the Horda Platform, northern North Sea, using state-of-the-art 3D seismic interpretation-tools and methodologies (Master's thesis, University of Stavanger, Norway).

Vollset, J. and Doré, A.G. eds., 1984. A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea. Oljedirektoratet.

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

Whitaker, M., 1984, August. The usage of palynology in definition of Troll Field geology. In Reduction of uncertainties in innovative reservoir geomodelling.'Offshore'Northern Seas Conference (No. 6).

Yielding, G., Badley, M.E. and Roberts, A.M., 1992. The structural evolution of the Brent Province. Geological Society, London, Special Publications, 61(1), pp.27-43.

Ziegler, P.A., 1975. Geologic evolution of North Sea and its tectonic framework. AAPG Bulletin, 59(7), pp.1073-1097.

Ziegler, P.A., 1990. Geological atlas of western and central Europe. Geological Society of London.