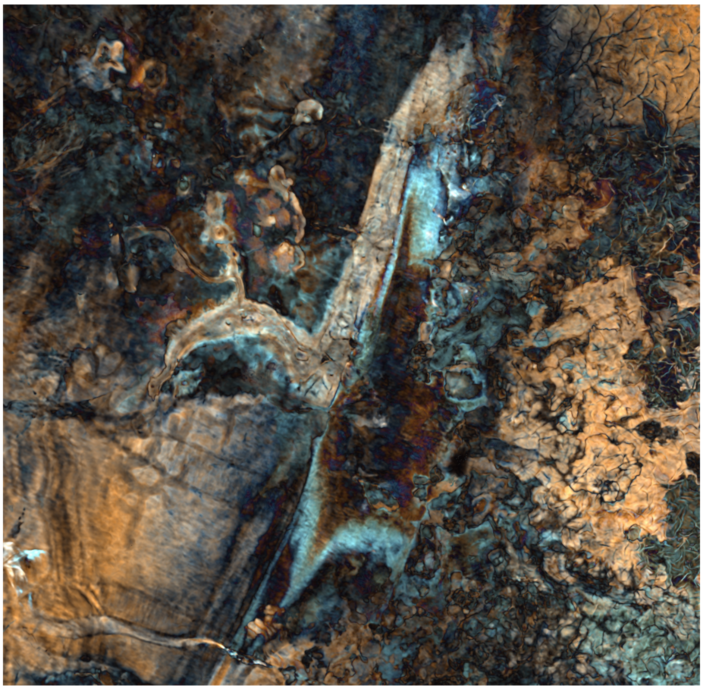
Kristin Wiig Helland-Hansen

Geological and geophysical characterization of the Oligocene stratigraphy in the Greater Alvheim Area, northern North Sea

Master's thesis in Petroleum Geoscience and Engineering
Supervisor: Christophe Serie
Co-supervisor: Gwenn Peron-Pinvidic
June 2023

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Geoscience and Petroleum



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AkerBP

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Abstract

A thorough understanding of the shallow stratigraphy is important to reconstruct the complete geological history of a basin while having significant implications for the energy transition, including petroleum exploration and CO2 storage projects which are all of major concern these days. An integrated approach based on geological and geophysical analysis has been used to study the local depositional systems of the post-Eocene stratigraphy in the Northern North Sea. Existing studies have highlighted some limitations with respect to data access and quality. The project has conducted a post-processing conditioning workflow that has removed noise and improved the seismic data quality. The conditioned seismic data has further been used for a detailed study focusing on Oligocene sands above the Alvheim field. A detailed seismic-lithostratigraphic subdivision of the Oligocene strata has been proposed with three main units separated by continuous regional surfaces. Each sequence has been characterised based on respective seismic terminations and seismic facies, in addition to attribute maps, including spectral decomposition and seismic relief. The integration of mapped horizons, seismic facies, and attributes with well data has been synthetised in a chronostratigraphic chart. The integrated results infer a new interpretation highlighting a more complex evolution of the late Oligocene with relatively quick spatio-temporal variations from marine to shallow marine depositional environment. These new interpretations may explain the challenges posed in previous overburden interpretations while providing an alternative depositional model explaining the development of the Ull Formation.

Sammendrag

En grundig forståelse av den grunne stratigrafien er viktig for å kunne rekonstruere den fullstendige geologiske historien til sedimentære basseng. Grunn stratigrafi kan være betydningsfull for dagens energiomstilling med tanke på leting etter og boring til petroleums forekomster og CO2-lagrings prosjekter. Lokale avsetningssystemer fra Post-Eocen stratigrafi i Nordlig Norsjø har blitt studert gjennom en integrert metode som kombinerer både geologisk og geofysisk analyse. Studiet har gjennomført en seismisk data kondisjonerings prosess for å fjerne støy og optimalisere data kvaliteten. Den kondisjonerte dataen har videre blitt brukt til et detaljert studie med fokus på Oligocen sander over Alvheim-feltet. En forbedret stratigrafisk inndeling av Oligocen intervallet har blitt foreslått og sekvensen har blitt delt inn i tre hovedenheter. Seismiske tolkninger, seismisk facies, attributt kart og brønn data har blitt kombinert og er visualisert i en chronostratigrafisk tabell. Resultatene antyder en ny tolkning av geologien som viser seg å være mer variert i sen Oligocen tid, med relativt raske tidsmessige og laterale endringer fra marine til grunn marine avsetningsmiljøer. Denne nye tolkningen kan forklare tidligere utfordringer med grunne tolkninger i området da disse sandene kan ha blitt feil-tolket som den dyp marine Ull-formasjonen.

Acknowledgement

This master's thesis has been written as the final work of my five years studying Petroleum Geoscience and Engineering at NTNU in Trondheim. It has been written in collaboration with Aker BP, and I am grateful for the opportunity to work with their data. Thank you, all helpful friends and colleagues in Aker BP, for your guidance and advice. I have learned so much! Thank you to my two supervisors, Christophe Serie and Gwenn Peron-Pinvidic, for your advice, feedback, and exciting discussions. Finally, I would like to thank my friends and family for all your support. A special thank you to Torgeir for believing in me and being the best Illustrator mentor!

Trondheim, June 2023

Kristin Helland-Hansen

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List of Abbreviations

NPD	Norwegian Petroleum Directory
NCS	Norwegian Continental Shelf
RMS	Root Mean Square
RGB	Red, Green, Blue (Spectral decomposition)
AC	Acoustic (Sonic log)
ACS	Shear Velocity
GR	Gamma Ray
DEN	Density
TWT	Two-way travel time
Hz	Hertz
Fm	Formation
ML	Machine Learning
Ms	Milli second
Ma	Mega annum (One-million years)
GDE	Gross depositional environment

1 Introduction

Basin evolution is an important part of Earth's history and studying the formation and development of sedimentary basins can provide key insights into the planet's geological evolution. Studying the characteristics of sedimentary depocenters can help deduct the depositional environments, tectonic processes, and climatic conditions of the past.
Stratigraphy is the study of rock layers (strata) within the Earth. Shallow stratigraphy refers to the layers of sedimentary rocks that are found near the surface, also known as the overburden rock controlling the burial history (Magoon, 2004). These younger stratigraphic sequences have typically been underexplored and additional detailed studies are important to fully understand the geological history of these recent geological times (Eidvin, et al., 2022). A thorough understanding of the shallow stratigraphy is important to reconstruct the complete geological history of the North Sea Basin, including the uplift and erosion of the Fennoscandian Shield. An improved understanding may have significant implications for the energy transition with respect to petroleum exploration and CO2 storage projects which are all of major concern these days.
This project explores the shallow stratigraphy in the Greater Alvheim region, located in the northern North Sea. The Greater Alvheim region represents a main exploration and production area along the NCS (Norwegian Continental Shelf) and currently subject to significant industry activity associated with drilling of exploration and production wells. This study aims to improve the current understanding of the post-Eocene stratigraphy and link local depositional systems to the regional basin evolution, through an integrated approach including geological and geophysical analysis.

This study focuses on the overburden accounting for up to 1,5 kilometres of sediment deposited from the Eocene to present day over the last 34Ma. This interval corresponds to approximately one fourth of the sediments preserved during the entire evolution of the North Sea. Studying the characteristics of the stratigraphy and the different layers in relation to each other can help us deduct the spatio-temporal changes of depositional environments characterizing the geological evolution of the basin.

In order to predict what we can find in the subsurface we need to understand how it was formed and what type of sediment should be expected to have been deposited at certain times. The interplay between tectonic processes and sedimentary deposition over geological time is called the tectono-stratigraphic evolution. This can be studied in terms of source-to-sink systems, which describe the erosional and depositional processes involved in moving sediment from one place to another through time and space. The shape and form of the landscape, known as the morphology, plays a critical role in determining the evolution of sediment fairways through time. Depositional environments are the result of the dynamic interaction between sediment supply, topography, bathymetry, water depth, sedimentary processes, and energy levels. The stratigraphic record is a succession of events representing short periods of erosion and deposition superimposed on longer-term allogenic control mechanisms including climate changes, sea level fluctuations, and tectonic activities (Sømme, et al., 2009).

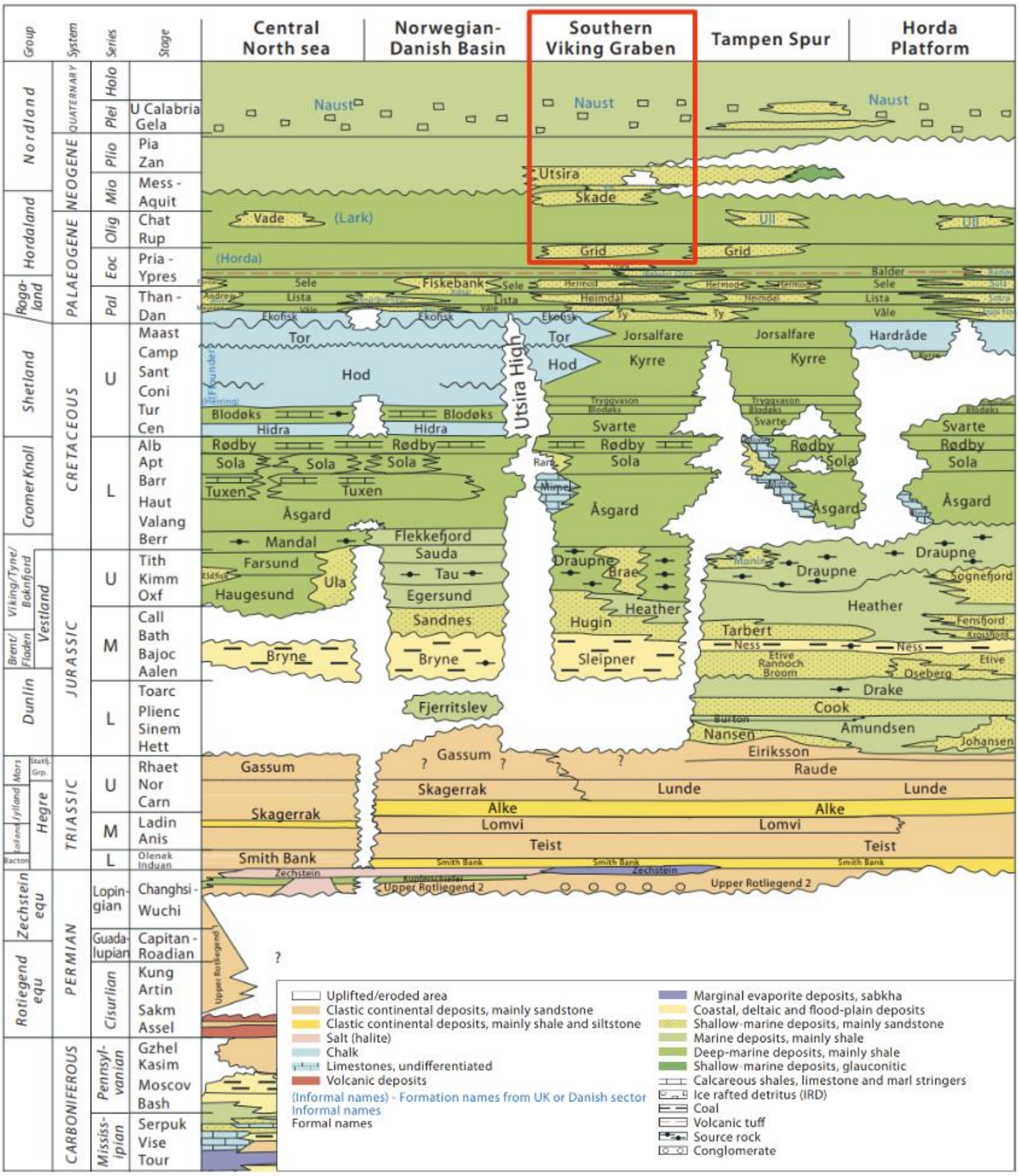


Figure 1-1 Regional stratigraphic column highlighting the studied interval from Paleogene to present day in the Greater Alvheim Area (NPD, 2014).

Detailed understanding of the overburden is of interest to the industry for several reasons. The depositional history and timing of the overburden have key implications for the evolution and the development of petroleum systems. A petroleum system consists of 5 main elements including source rock, reservoir rock, trap, seal, hydrocarbon generation and migration all of which are affected by the overburden and associated burial history. The amount and type of sediments that are deposited strongly influence the burial rate, compaction curves, and diagenetic processes, hydrocarbon generation and migration. Diagenesis and compaction control the reservoir quality while considering porosity and permeabilities. For example, the overburden thickness will affect the sedimentary load, while increasing compaction and decreasing porosity. In addition, the rate and timing of burial is key in understanding diagenetic processes that directly affect porosity and permeability. The spatio-temporal evolution of the overburden sequence can also have an impact on the burial evolution and associated source rock maturation, as well as recording subtle tilt affecting migration pathways, including secondary migration from paleo accumulation into present day accumulation.

Other implications that are of relevance to the industry include improving seismic imaging and mitigating drilling hazards. The overburden can play a large role in seismic imaging due to vertical and lateral velocity variations not captured during processing. Incorrect velocities can account for up to 30 meters of mismatch between depth migrated seismic and true depth in the shallow drilled sections (Aker BP, 2022). An improved understanding of the shallow geology can contribute to an updated overburden velocity model. Complex structures such as injectites are challenging to image and better knowledge of overburden velocities could significantly improve imaging during seismic reprocessing. Additionally, the overburden characterization is a key element when mitigating drilling hazards, considering highly permeable zones, faults, shallow gas, and over-pressured zones. Accurately identifying the presence of sand or shale is important when designing and optimizing a well path. There have been recorded instances of encountering unexpected sand or the absence of projected sand in the area. Improving the geological understanding of the overburden has the potential to mitigate drilling hazard and optimize costs during drilling activities.

Characterizing sandy formations and deposits in the overburden has an increasing importance for CO2 sequestration and storage projects. This technology, where emitted CO2 is captured and injected back into deep geological formations, is one of the solutions to reach the international climate change targets. Post-Eocene saline aquifers in the North Sea can potentially store significant amounts of CO2, and the need for a detailed geological characterization is now increasing (Eidvin, et al., 2022). Finally, with the growing demand for energy and high oil prices, it may also be of interest to focus on high-risk exploration targets, including post-Eocene sandy formations and units.

The Cenozoic sequence in the North Sea has been the subject of several studies, however, the majority of these are regional studies focusing on the big picture and broad trends. The main regional study was initiated by the Norwegian Petroleum Directorate (NPD) in the late 1980s. This integrated study of the Oligocene to Pliocene basins along the NCS, stretching from Svalbard in the north to the Norwegian-Danish basin in the south. The previous understanding of the shallow stratigraphic intervals was limited by the available data, and the NPD study investigates new and old data from more than 60 wells and boreholes covering the entire continental shelf (Eidvin, et al., 2022). The wells have been analysed for Sr isotopes and microfossils, and the stratigraphic data has been investigated in a regional context utilising log correlations and seismic interpretations (Eidvin, et al., 2022). The findings from these investigations have been documented in over 20 scientific articles and reports, which have been summarized in an interactive portal known as NPD Bulletin 10 (Eidvin, et al., 2013). These discoveries were then used to revise the lithostratigraphic nomenclature of the area, which was presented in 2022 (Eidvin, et al., 2022).

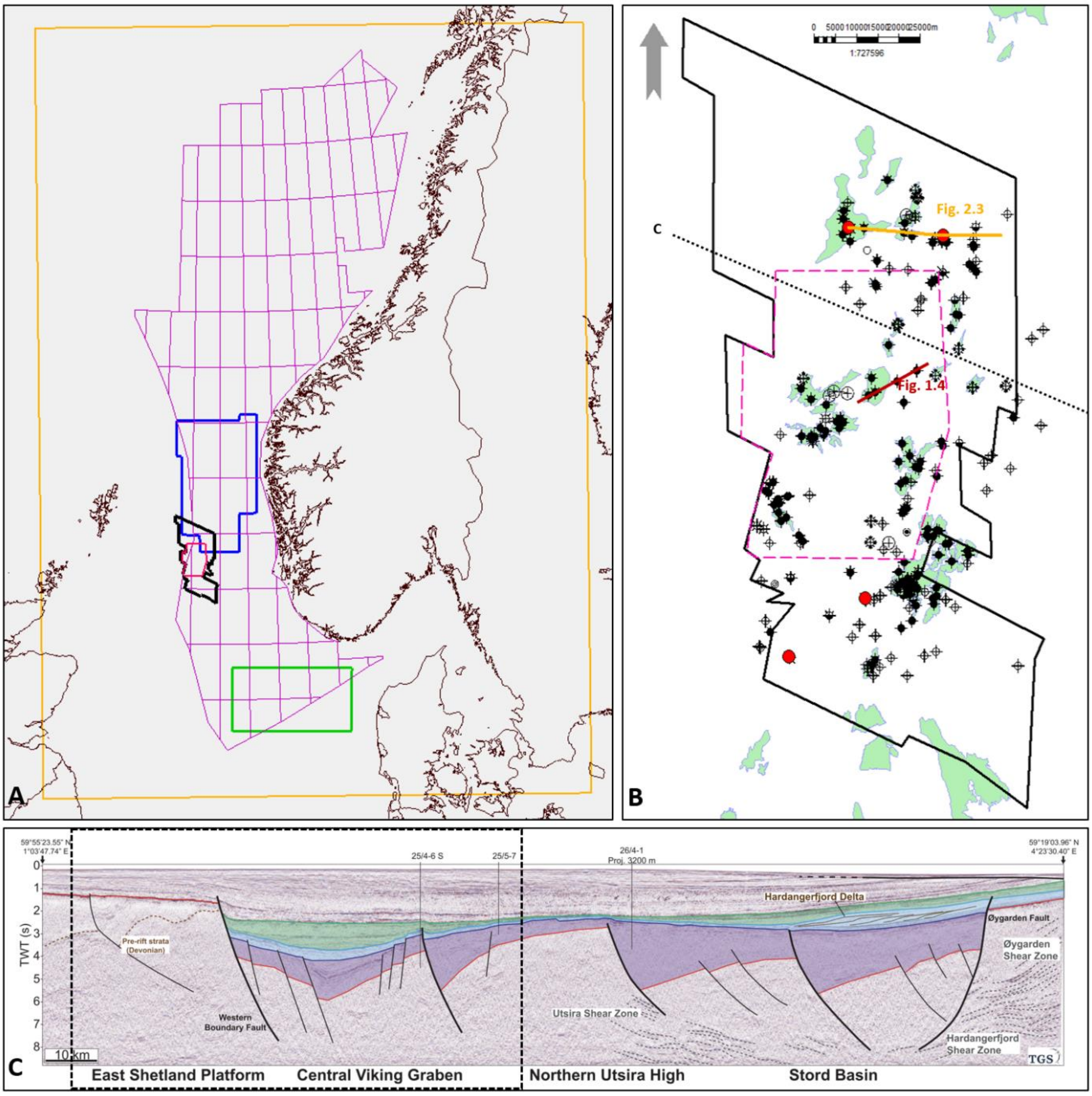


Figure 1-2: Overview map showing the outline of some of the main studies in the area including a regional interpreted cross section (C) from Phillips et al., 2019. Black polygons highlight the PGS16M01- survey and the outline of this study area. A: Yellow study outline by Eidvin et al., 2014, 2022, part of the full NPD study. Green study area by E.M. Jarsve et al., 2014. Blue study outline conducted internally in Aker BP in 2020. Pink polygon shows the outline of the internal study by Theodor Lien in 2018. B: Close up of study area including producing fields and exploration wells. The wells that have been studied in the NPD study have been highlighted in red. Location of previously interpreted seismic cross sections shown; C, Figure 1-4 and Figure 2-5. (Phillips, et al., 2019); (Eidvin, et al., 2014); (Eidvin, et al., 2022); (Jarsve, et al., 2014); (AkerBP, 2020); (Helland-Hansen, 2022).

Figure 1-3 shows a comparison of depth maps created before and after the NPD study. The re-dated well-data has substantially enhanced our understanding of the regional stratigraphy, but due to the regional extent of the study the focus is on the large sand deposits of the Skade and Utsira formations. The local and detailed stratigraphy of the lower Cenozoic has received less attention, and Figure 1-4 depicts current interpretations of Paleogene sand bodies within the Greater Alvheim region. The illustration shows the current difficulties associated with varied interpretations and imprecise well tops within the study area.

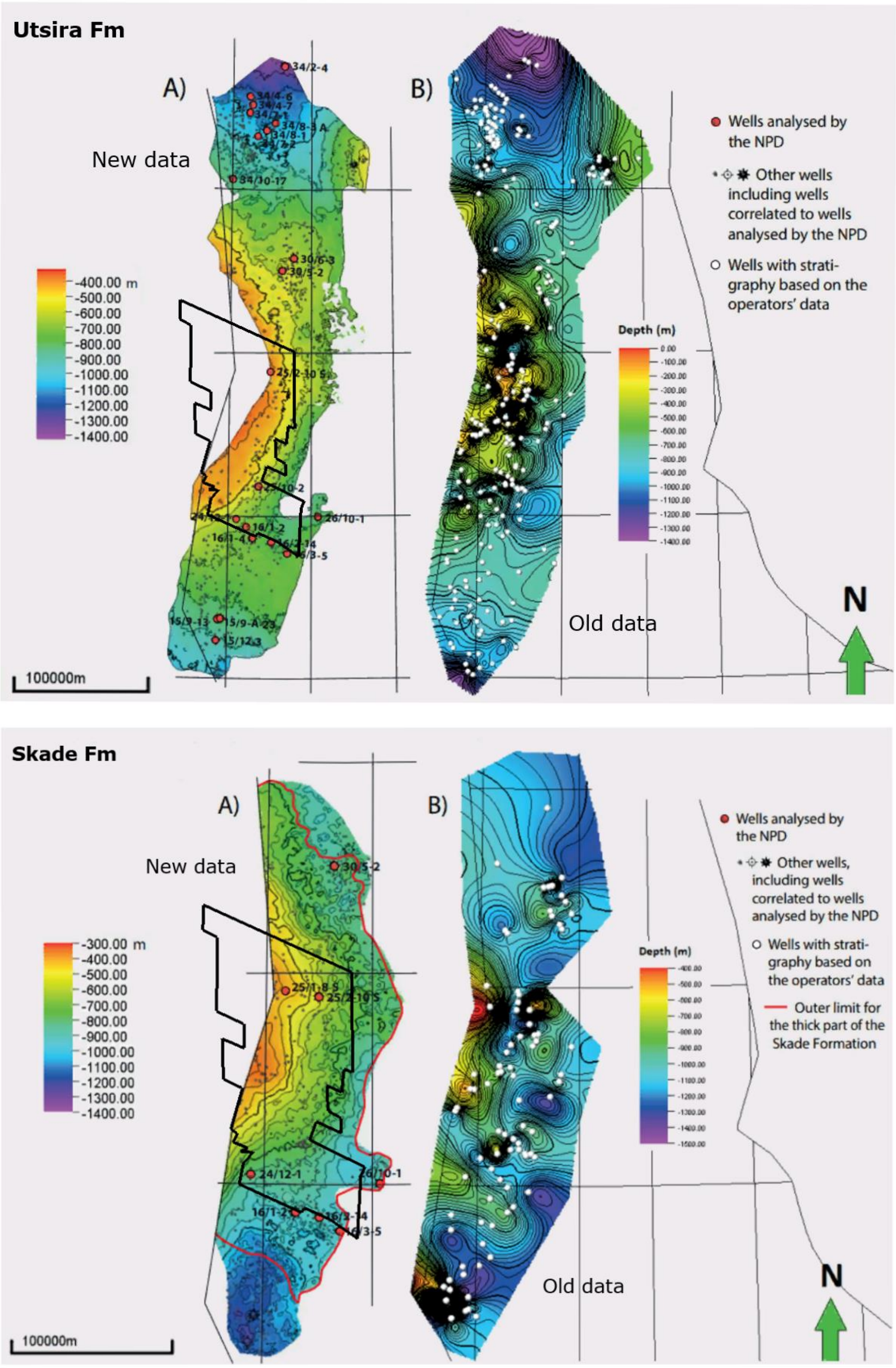


Figure 1-3: This figure is modified from the Eidvin et al., 2022 paper and shows the comparison of depth maps created based on A) the new wells analysed by the NPD study and B) the previous old well data obtained by oil companies' contracted consultants. The maps have been made for the Utsira formation Group and the Skade Formation. The outline of this study is shown by the black polygons. (Eidvin, et al., 2022).

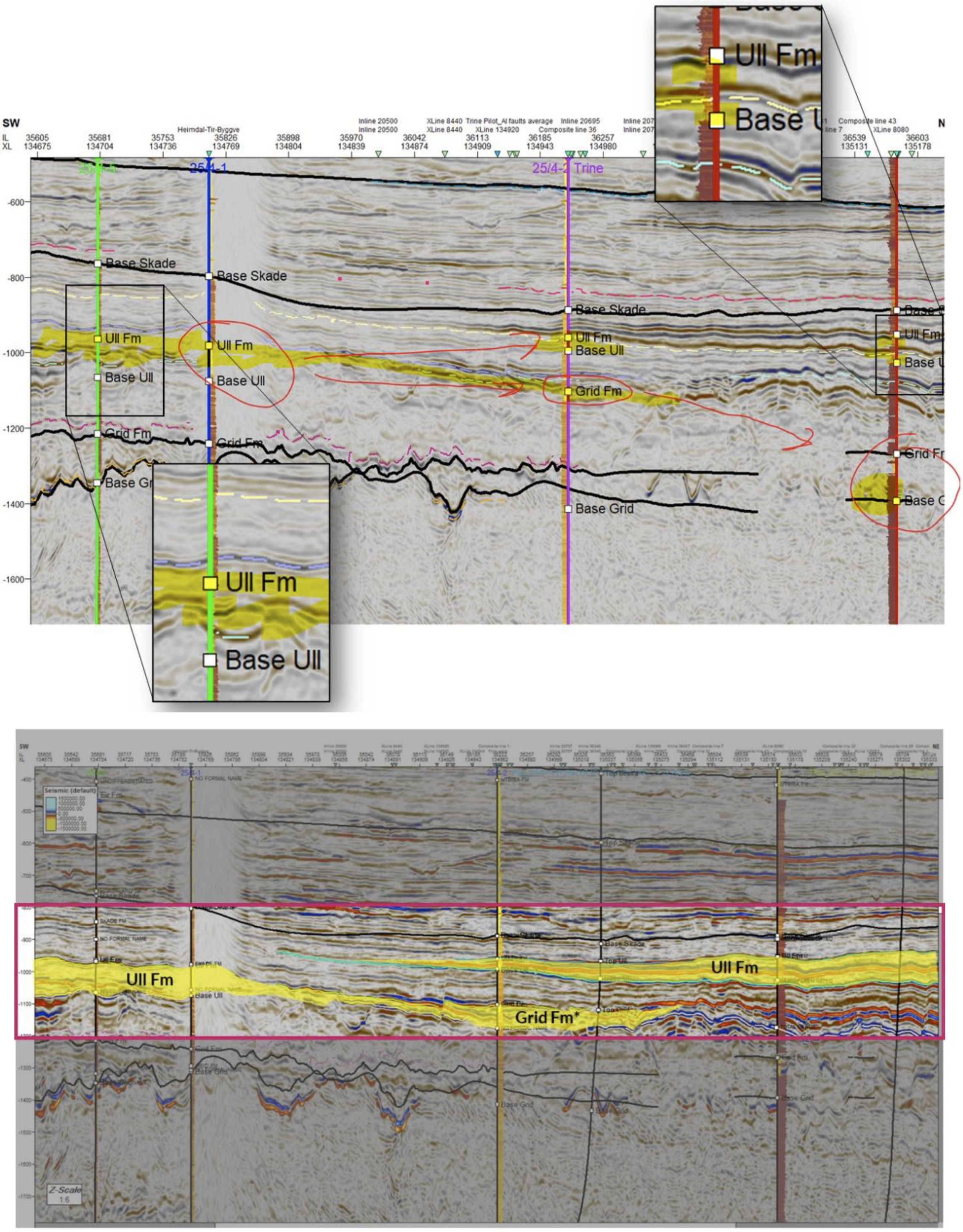


Figure 1-4: Interpretations from the internal Aker BP Alvheim overburden report showing the current difficulties associated with varied interpretations and imprecise well tops within the study area. The location of the cross sections can be seen in Figure 1-2. (Aker BP, 2022).

Aker BP has conducted a couple of internal studies to re-examine the shallow lithostratigraphic units above their main assets. In 2018, Theodor Lien completed Heidi Knudsen's research on the overburden over the Alvheim Field and the neighbouring fields, including Vilje, Volund, Boyla, and Skogul fields. The pink polygon in Figure 1-2(b) depicts the study's outline. An additional regional study was conducted further north in the Yggdrasil area (Figure 1-2) (AkerBP, 2020).

The current study area is delineated by the PGS16M01 seismic survey extent shown with the black polygon in Figure 1-2. The project was initiated in the summer 2022, through an internship at Aker BP and aimed to reassess Lien's work and extend it to the northern interpretations in the Yggdrasil area. Through seismic interpretation using Petrel and PaleoScan, an initial geological framework and a tectono-stratigraphic evolution was proposed for the area. The geology was challenging to interpret and there were several areas that would have been interesting to look at in more detail. The main internship findings pointed out that more work is needed to fully understand the local depositional processes and check the proposed stratigraphy. The interest was sparked, and the work continued through the specialisation project during fall 2022 (Helland-Hansen, 2022). A literature review was conducted, and the proposed stratigraphy was compared to previous regional work in the area. Most previous work have been focused on the larger depocenters with a more regional extent such as the Skade and Utsira formations (Figure 1-3). The specialisation project report confirms that there is a lot of sand sourced from the East Shetland Platform during the late Cenozoic, however the results from the initial geological mapping shows that there is more sand present in the Oligocene time than presented in the literature (Helland-Hansen, 2022). The sands of the Oligocene time have therefore been chosen for a detailed study through this master thesis project (Figure 1-5).

The goal for this project was to conduct a detailed study to bridge the gap between previous internal overburden assessments and consolidate the current regional understanding. This Master project report builds on the method proposed in the specialisation project and revises the initial geological mapping by adding more detail to the current regional understanding. One of the main limitations discussed in the specialisation report is the access to good quality data in the overburden and this project intends to improve the quality of the seismic data. The seismic data has been analysed and a post-processing conditioning workflow has been applied to remove noise. The well log data has also been analysed in more detail. Various methods including rock physics analysis and a machine learning algorithm has been applied for quality check and well log estimation. The improved data has further been used to do a detailed interpretation of the Oligocene sands above the Alvheim field. The interpretation results from the detailed study have further been compared and integrated in the regional geological framework.

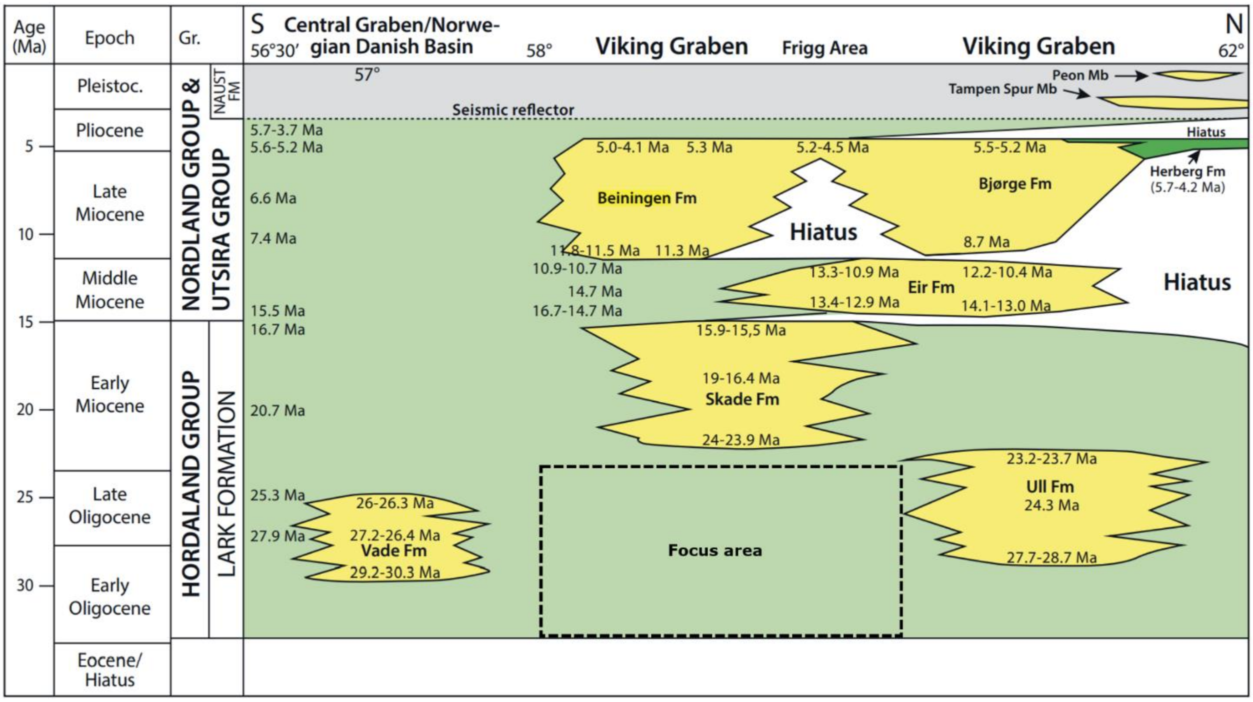


Figure 1-5: Post-Eocene Lithostratigraphy of The Norwegian North Sea proposed by the NPD study including ages from their re-dated wells. The focus area for this study comprises the Oligocene sediments in the Viking Graben Alvheim to Frigg field area. Modified from (Eidvin, et al., 2022).

2 Geological setting

The study area is in the northern North Sea, between 58° and 60° N (Figure 1-2). The primary industry quadrants studied are PL 24 and PL 25, which encompass both sides of the border between the UK and Norwegian territories. The region is known as the Greater Alvheim area and lies in the central part of the Viking Graben. The northern North Sea rift architecture is well documented in previous studies (Phillips, et al., 2019); (Underhill & Partington, 1993); (Færseth, 1996); (Ziegler, 1992). Regional cross-sections highlight the main setting of the Central Viking Graben bounded to the west by the East Shetland Platform, and the Utsira High to the east (Figure 1-2).

The tectonostratigraphic development of the North Sea is characterized by a series of successive extensional episodes, including an orogenic collapse in late Paleozoic times, and two main rift phases in the Mesozoic. The Permian-Triassic rift (RP1) represents the first phase of extension related to the breakup of Pangea, with the development of north-south trending basins characterized by a series of tilted half-grabens (Ziegler, 1990); (Færseth, 1996). These principal tectonic elements are seen in the Alvheim area with the main boundary faults striking in the North-South direction. The major depocenters during this rift period in the Stord and East Shetland Basin are delineated and to some extent (Sømme, et al., 2009) controlled by Devonian shear zones (Figure 1-2), (Phillips, et al., 2019). The second rift phase (RP2) in the late Jurassic to early Cretaceous was related to the collapse of the central North Sea thermal dome and the opening of the North Atlantic Ocean (Underhill & Partington, 1993); (Phillips, et al., 2019). The collapse of this dome is believed to have exerted regional tension that resulted in the development of the trilete North Sea rift system, which includes the Viking Graben, Moray Firth and the Central Graben (Davies, et al., 2001); (Bell, et al., 2014). The largest extension took place in the Viking Graben which becomes the main depocenter during RP2 with North-South trending terraces on either side (Odinsen, et al., 2000); (Bell, et al., 2014). A regional model for the multiphase evolution of the northern North Sea rift is shown in Figure 2-1 (Phillips, et al., 2019). During the later stages and following the RP2, the rift activity migrated northwards (Figure 2-1) (Phillips, et al., 2019). The Cretaceous was further dominated by thermal post-rift subsidence and the depocenters were dominated by passive infilling of pre-existing relief (Odinsen, et al., 2000). The deep Viking Graben had a large accommodation space and was the main depocenter during this time.

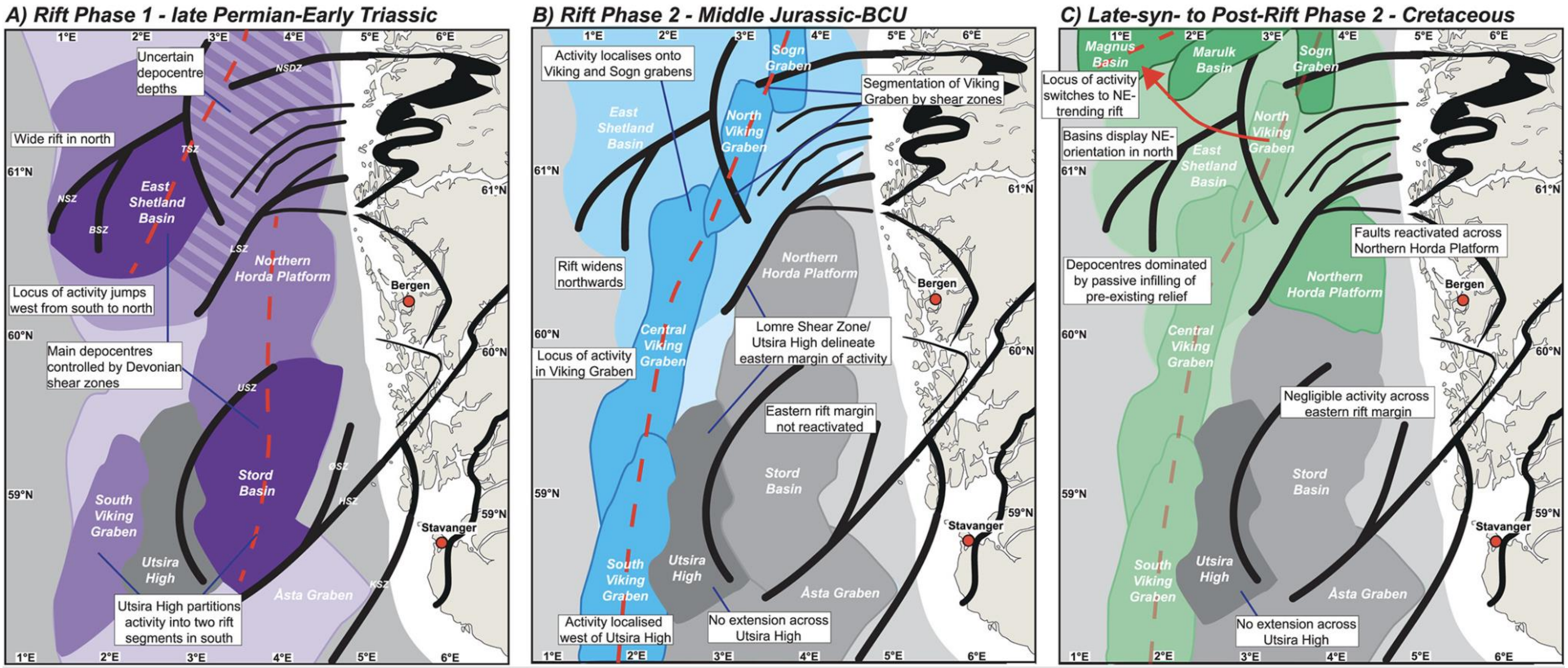


Figure 2-1: Regional model for the multiphase evolution of the northern North Sea from (Phillips, et al., 2019).

The thermally induced subsidence during the Cretaceous transitioned into a period of inversion. The inversion is interpreted to have occurred in response to a N-S- to NNW-SSE oriented transpressional stress regime, which was influenced by both the Alpine Orogeny and the initiation of opening of the North Atlantic (Jackson, et al., 2013); (Ziegler, 1987); (Vejbæk & Andersen, 1987); (Ziegler, 1990). The basin inversion is thought to have coincided with an eustatic sea-level rise and in response there was a reduction in clastic input to the basin during the Late Cretaceous (Jackson, et al., 2013); (Ziegler, 1990); (Sørenson, et al., 1992). In the Viking Graben area, there was an overall change from shallow marine conditions during the Late Cretaceous to deep marine during Early Paleogene (Michelsen, 1994); (Kyrkjebo, et al., 2001); (Jarsve, 2014).

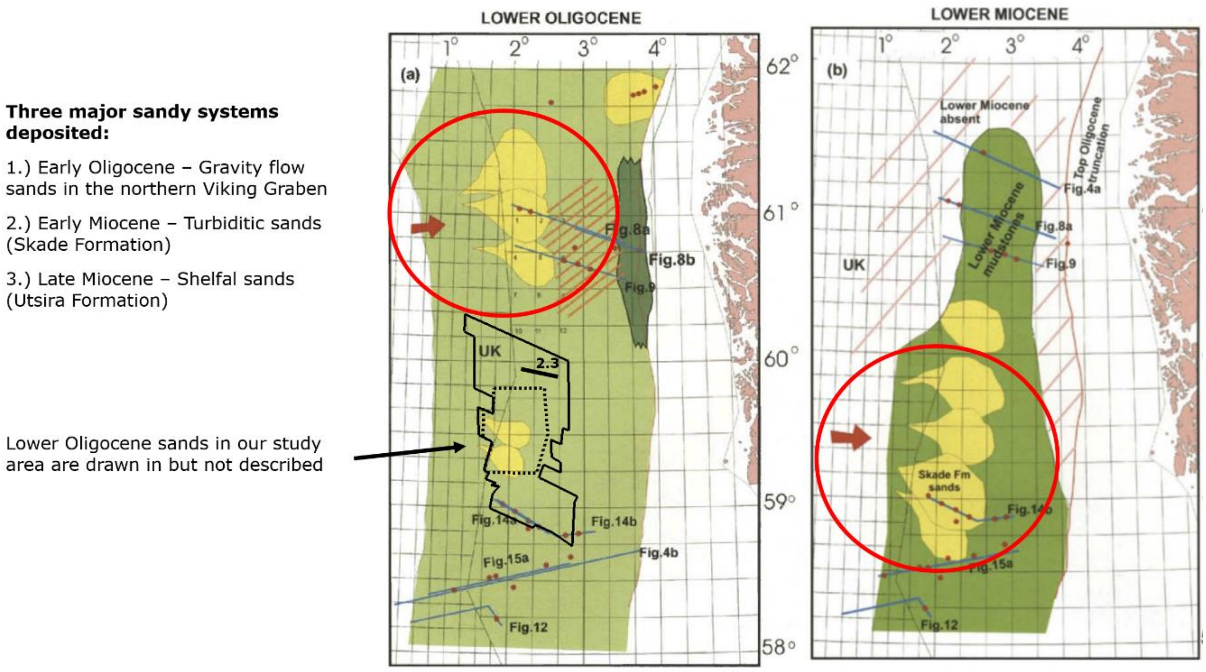


Figure 2-2: Three major sandy systems are interpreted to have been deposited from Oligocene through Miocene time. The maps from Rundberg and Eidvin, 2005 show the location of the mapped Lower Oligocene and lower Miocene sands. Lower Oligocene sands present in this study area are drawn in, but not described. The location of the interpreted cross section in figure 2.3 is shown.

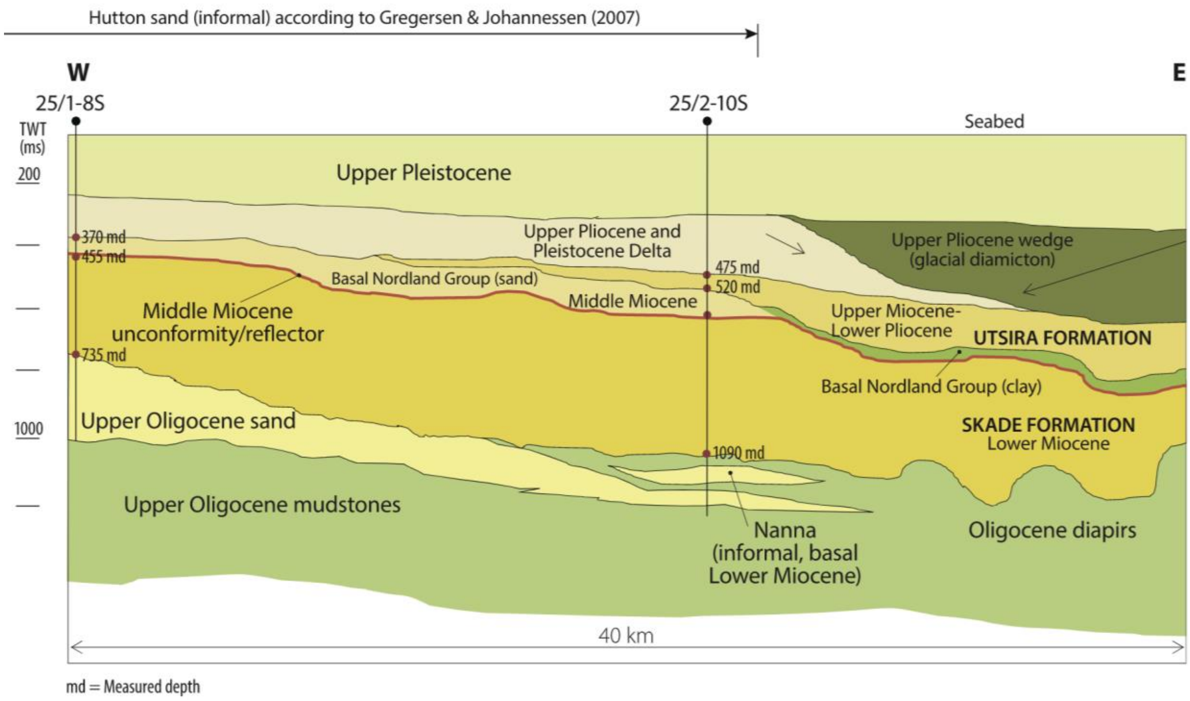


Figure 2-3: Geo-section from Eidvin et al. 2014 showing the interpreted sand formations sourced from the East Shetland Platform from Oligocene to present day (Eidvin, et al., 2014).

During Cenozoic times, the North Sea was an epicontinental basin, surrounded by higher areas of southern Scandinavia, the British Isles and Central Europe (Gregersen & Johannessen, 2007). The basin experienced different phases of tectonic inversion resulting in uplift and erosion (Rundberg, 1989); (Jordt, et al., 1995); (Gregersen, et al., 1997); (Fyfe, et al., 2003); (Gregersen & Johannessen, 2007). The North Atlantic breakup in the Paleocene- Eocene time resulted in the uplift of the Fennoscandia and Shetland-Scottish area. The uplifted areas were eroded while providing increasing sediment supply recorded by the progradation of deltaic sequences in the North Sea basin (Eidvin, et al., 2014); (Eidvin & Rundberg, 2007); (Eidvin & Rundberg, 2001); (Gregersen & Johannessen, 2007). The submarine fans of the Ty, Heimdal, Hermod, Odin and Frigg formations were deposited, and the sediment loading resulted in a further deepening of the basin (Aker BP, 2022). The progradation is thought to have continued into the Oligocene and Miocene but was more confined to the depocentres which varied through time (Eidvin & Rundberg, 2007); (Eidvin & Rundberg, 2001); (Gregersen & Johannessen, 2007); (Rundberg & Eidvin, 2005). Several pulses of coarse clastic sedimentation are found in the sedimentary record from this time (Eidvin, et al., 2014); (Rundberg & Eidvin, 2005) and the main depocenters typically contain 200-600 meters of Oligocene to Lower Pliocene sands (Eidvin, et al., 2022). Rundberg and Eidvin highlight three major sandy systems that were deposited from Oligocene through Miocene time; 1) Gravity flow sands in the Nothern Viking Graben deposited during early Oligocene, 2) Turbditic sands of the Skade formation in the lower Miocene and 3) Shelfal sands of the Utsira formation in the late Miocene (Figure 2-2). Figure 2-3 is from the Eidvin et al. 2014 paper and shows a geosection of the main interpreted sand formations sourced from the East Shetland Platform from Oligocene to present day. The sands are interpreted to be delta sands that constitute the outer delta front of a sand system on the UK side, informally called the Hutton sand (Gregersen & Johannessen, 2007); (Eidvin, et al., 2022). These sandy deposits are interpreted to have been deposited in response to uplift of the East Shetland Platform and southern Fennoscandia. The uplift was caused by a compressive structural regime on the Mid-Norwegian margin which was initiated by major plate reorganisations at the end of Eocene time (Figure 2-4) (Rundberg & Eidvin, 2005). More than 1500 meters of sediments were deposited through Miocene to recent times in the central and northernmost part of the North Sea (Rundberg, 1989); (Jordt, et al., 1995); (Gregersen & Johannessen, 2007). The late Cenozoic depositional systems were partly controlled by regional basin subsidence of the Viking graben area and episodic marginal uplift (Rundberg, 1989); (Jordt, et al., 1995); (Gregersen & Johannessen, 2007); (Fyfe, et al., 2003).

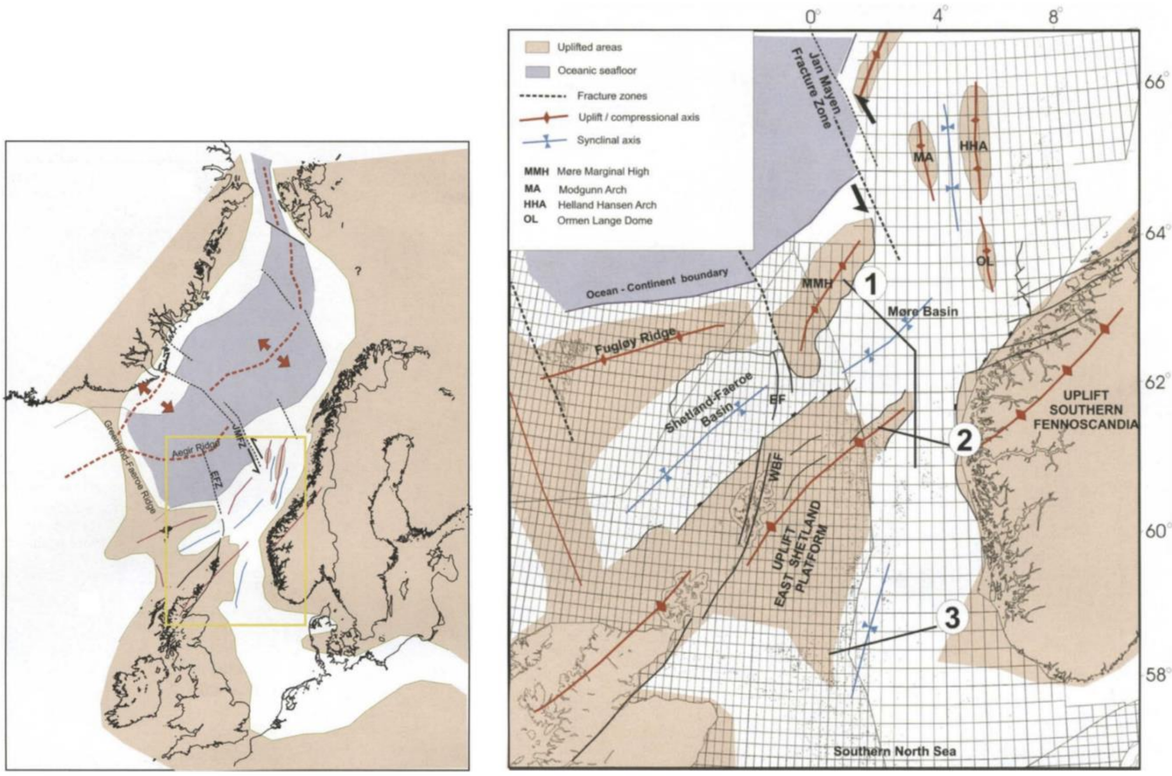


Figure 2-4: Structural map by Rundberg and Eidvin, highlighting the main areas that were affected by uplift during the Oligocene – Miocene time (Rundberg & Eidvin, 2005).

The interplay between tectonic and climate driven erosion makes it difficult to quantify their relative influence on sediment production, which has led to contrasting interpretations of the geological evolution of many areas, including the North Atlantic region (Anell, et al., 2009); (Anell, et al., 2010). The Oligocene to Miocene deposits in the North Sea can be interpreted as a response to the surrounding Scandinavian hinterland or Shetland platform's tectonic uplift (Rundberg & Eidvin, 2005). Alternatively, they can be explained by non-tectonic processes like sedimentary progradation, ocean current rearrangement, or eustatic and/or climate changes (Laberg, et al., 2005); (Eidvin, et al., 2022). Jarsve et al., studied the Oligocene sedimentary succession in the eastern North Sea and argue that the creation and infill of accommodation spaces here are related to both tectonic processes and climate change (Jarsve, et al., 2014).

3 Data

This study is primarily based on the PGS16M01-PGS15917VIK three-dimensional (3D) seismic survey. This full fold polygon was re-processed in 2015 by PGS Geophysical AS, Imaging Oslo and merges several surveys to cover an approximate area of 11684 square km. The main surveys used for this multi-client project are the GeoStreamer® surveys acquired from 2009 to 2013. The conventional surveys used to extend and fill inn holes were acquired in 1996 and 2005-2006 (PGS ASA, 2017) The full re-processed survey outline can be seen in figure 3-1 and covers the Viking Graben from the Frigg field in the north to part of the Johan Sverdrup field in the south.

The seismic data is zero phase and follows the Aker BP standards, with positive amplitudes indicating an increase in acoustic impedance and negative amplitudes indicating a drop in acoustic impedance. Positive peaks are displayed in blue, whereas negative troughs are shown in red. The frequency spectrum calculated for the detailed study area from 0 to -1500 ms shows a dominant frequency ranging from approximately 25-50 Hz (Figure 3-2). The velocity model shows average velocities ranging between 1800-2300 m/s which gives a vertical resolution (λ/4) of ~11–18 m and a horizontal resolution (λ/2) of ~23–36 m.

The project also includes all the exploration wells drilled within this area. Figure 3-3 shows all the exploration wells within the 24^{th} and 25^{th} quadrants. The wells studied in this detailed study are chosen based on their location compared to the main interpreted sand body and the well log data available (Figure 3-3). The wells studied in the regional NPD study are shown in red and include biostratigraphic data. The purple wells have been studied in the sub regional study and used for well to seismic correlation. There are a lot of wells in the area, however the available well log data at the shallow depth of interest is variable.

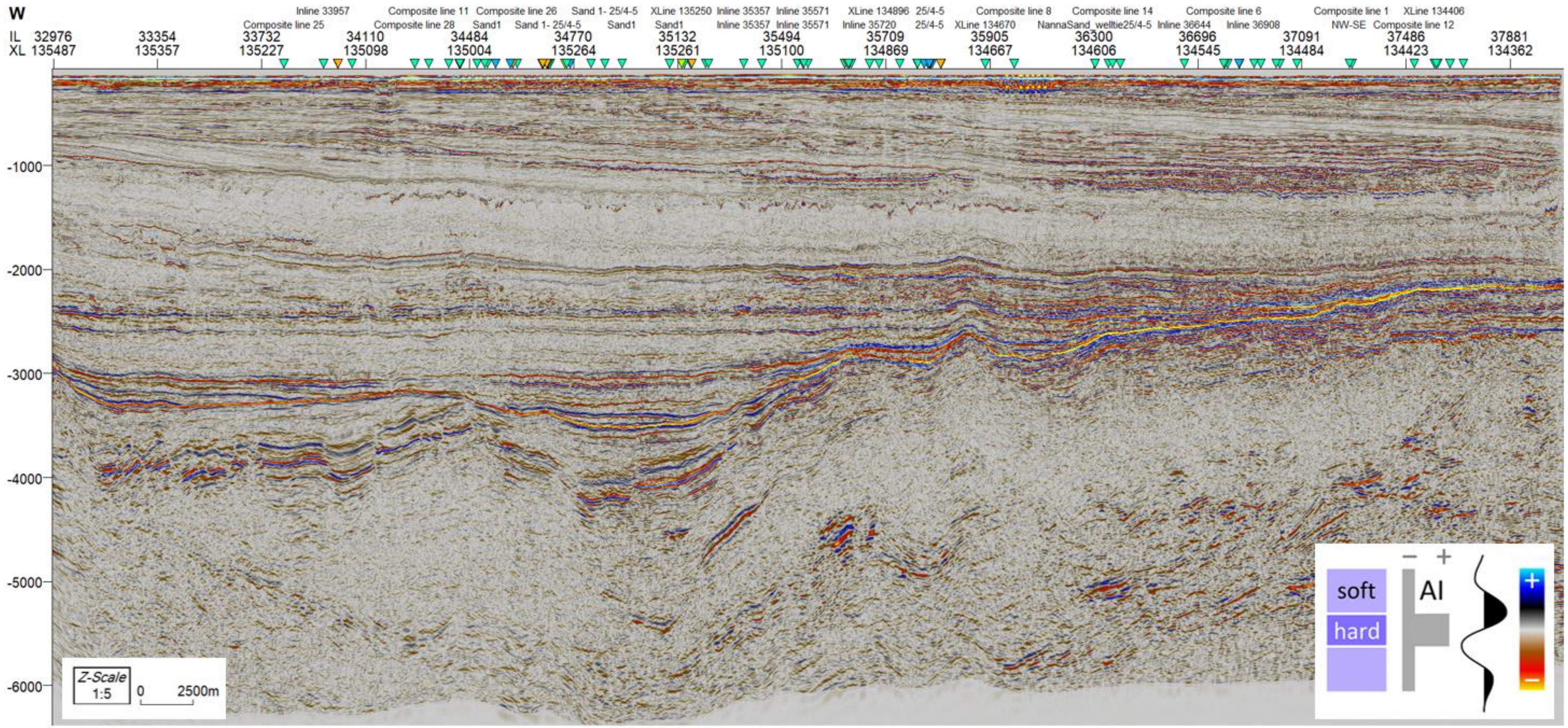


Figure 3-1: PGS16M01-PGS15917VIK full survey cross section. Location shown in Figure 3-3.

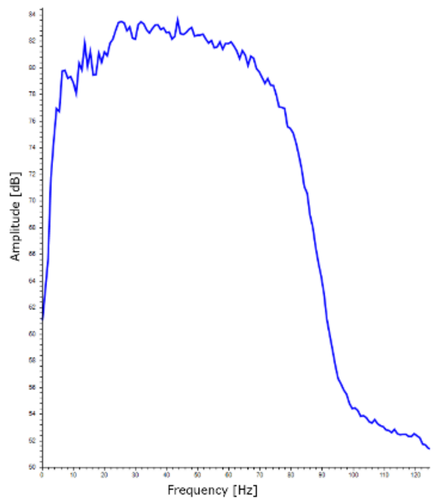


Figure 3-2: Frequency spectrum of detailed study area from 0 to -1500 ms.

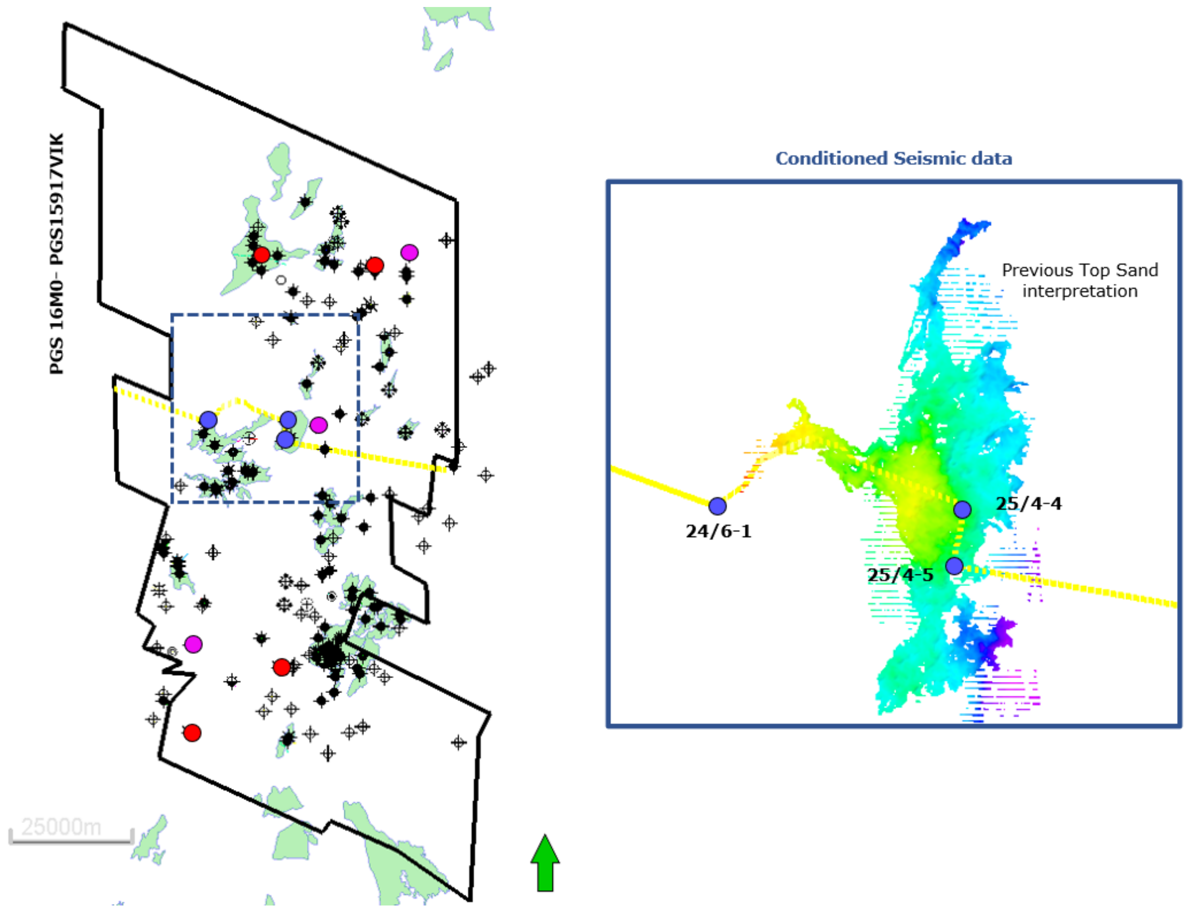


Figure 3-3: PGS16M01-PGS15917VIK full survey including outline of the conditioned seismic data. Producing fields and exploration wells in the area are displayed. Red wells are included in the NPD study, the purple wells have been studied in the sub regional study and the blue are the main wells for this focused study. The composite line that has been used to display the seismic cross sections has been chosen to follow the previous Top Sand interpretation.

4 Methodology

The methodology of this study is based on the iterative workflow developed in the specialisation project (Helland-Hansen, 2022). The integrated workflow has been applied at different scale based on the scope of the project from sub regional to local scale. This section will present the methodology used for this focused study of the Oligocene sands.

The first step of this focused study was to update the quality of the seismic data. This has been done through a denoise conditioning workflow in the software Avary. The conditioning procedure consists of a detailed geophysical analysis comprising seven main steps. When the seismic was updated, the main integrated workflow has been applied to the conditioned seismic in the focused area. The workflow is based on three main steps including (1) seismic mapping, (2) well-seismic calibration, (3) predictive seismic stratigraphy (Figure 4-1). The first step is seismic mapping based on seismic termination geometries, seismic facies and derived seismic characteristics. The mapping has been done using the software Petrel and PaleoScan and the approaches of seismic stratigraphy defined in R.M. Mitchum et al. (1977). The second step includes calibrating the seismic facies to stratigraphy and lithology by studying well-log data and cuttings. The seismic sequence stratigraphic framework is tied to the well data for age control and lithostratigraphic correlation. The third step consists of integrating all the findings and use these interpretations to predict depositional environments away from well control. The final stage of this study was then to compare the detailed study results to the sub regional interpretations and previously studied literature. The goal is to be able to bring more details for the regional understanding.

This section will first present the geophysical work that was done through the conditioning workflow and then proceed to the workflow and methods applied in the detailed interpretation study.

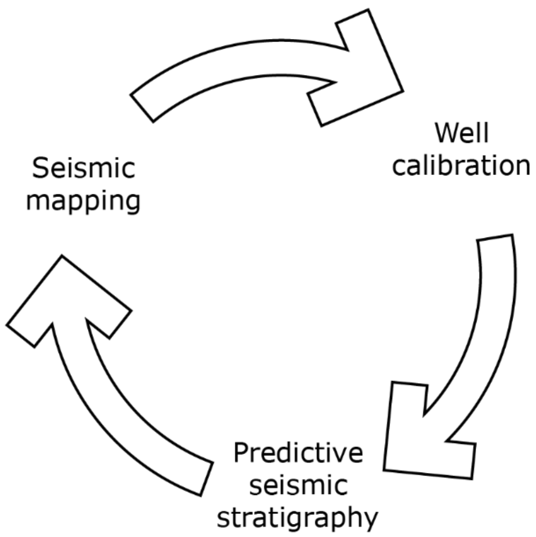


Figure 4-1: Iterative and integrated workflow developed and modified by (Helland-Hansen, 2022).

4.1 Conditioning

Seismic conditioning is a pre-processing procedure that seeks to make the data suitable for further analysis and interpretation. Conditioning the seismic data is also a good way of understanding the data you are interpreting in more detail. The original PGS survey is a regional survey processed with a purpose of imaging the deeper prospective stratigraphic intervals. This seismic data is therefore not optimized for the frequency content and noise present in the overburden sequences. The goal of the conditioning process is to tailor the processing and noise removal steps for the detailed study target area. Conditioning of the data is also a necessary procedure before conducting an inversion of the data (the inversion is not covered in this project but is proposed for future work).

The conditioning for this project has been done in the Cegal software called Avary. A denoise workflow has been conducted to remove noise and enhance the quality of the overburden sequence. The conditioning has been conducted for a cropped volume of the PGS survey, covering the main Oligocene sand body interpreted in the regional study (Figure 3-3). The conditioned volume covers approximately 900 km^2 and spans 0–1500ms in depth. The focus has been on optimizing the seismic around the sands located at depths of -600 to -1200ms.

4.1.1 Conditioning workflow

The conditioning workflow applied consists of seven steps. First a bandpass filter is applied to remove high frequency noise. A de-stripe filter is designed to remove acquisition and processing footprints. Two de-noise filters are applied to remove random noise while preserving the structure and amplitudes. Bandwidth matching is conducted to ensure that all partial angle stacks have approximately the same frequency content. Finally, time alignment and relative phase balancing is applied to account for shifts in phase and time due to attenuation.

One of the most important things to keep in mind when conducting these conditioning steps is to not remove any geologic reflection events. The filtering steps should only remove noise and artifacts. An effective way to check this is to compute a delta volume that shows the difference between the original volume and the filtered volume. This method has been the main quality check (QC) during the conditioning procedure. The changes made to the seismic were analysed after every processing step to understand what part of the signal was being removed to avoid removing primary signal.

4.1.1.1 Bandpass filter

A bandpass filter is designed to remove noise and unwanted signals from the seismic data while preserving the desired frequency range. By removing unwanted signals, such as background noise, instrument noise, or signals from sources other than the target subsurface, the bandpass filter can enhance the signal-to-noise ratio and reveal essential features and structures in the subsurface. The bandpass filter's design depends on the seismic data's specific characteristics and the features of interest. The centre frequency and bandwidth of the filter can be adjusted to target specific frequencies or frequency ranges. An Ormsby filter was applied on the near data stack to filter out high frequency noise. The parameters used for the Ormsby filter design can be seen in Figure 4-2. The delta cross section shows the high frequent “ringing” noise that has been removed (Figure 4-3).

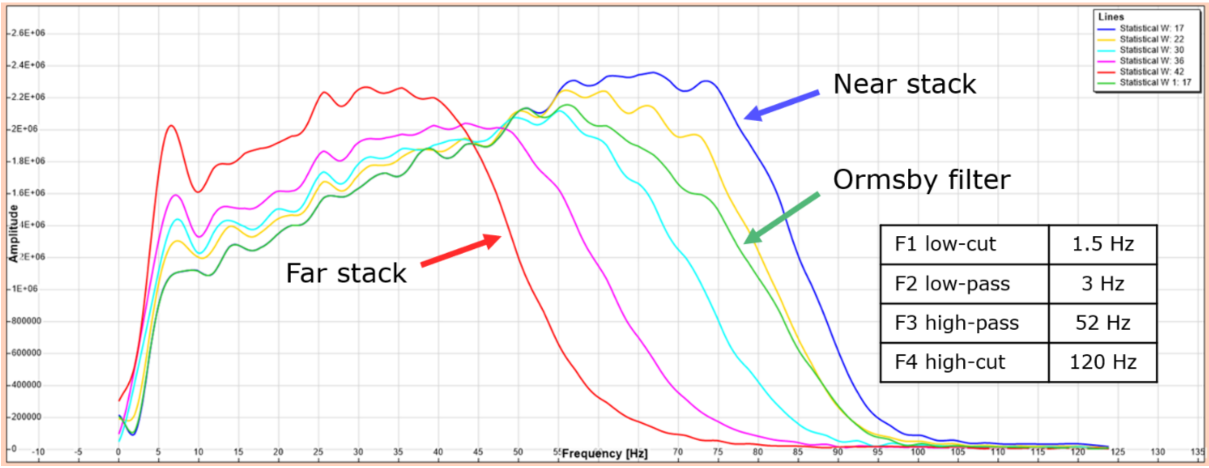


Figure 4-2: Frequency spectrums of the partial angle stacks extracted from the area of interest between -600 to -1200ms. The Green spectrum shows the Ormsby filter that has been designed and applied through the Bandpass filter step in the conditioning workflow.

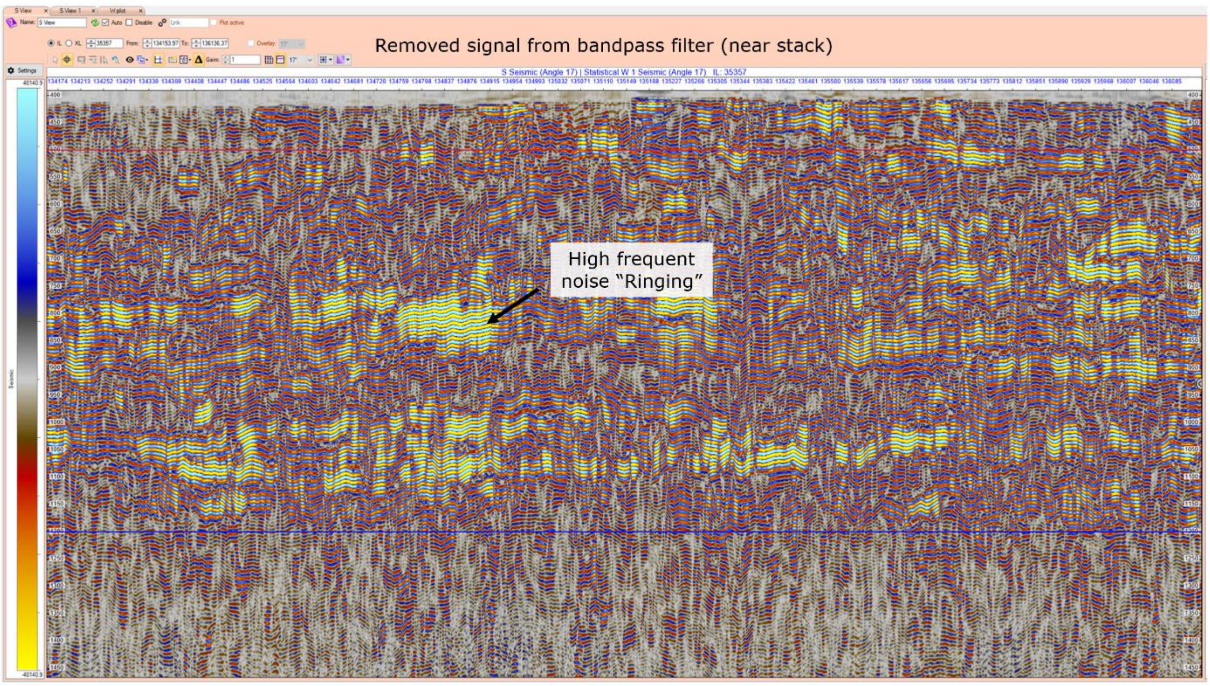


Figure 4-3: Delta cross section displaying the signal that has been removed by the bandpass filter on the near stack. High frequent “ringing” noise can be seen.

4.1.1.2 De-stripe filter

A de-stripe filter was used to remove the effects of acquisition footprints. Acquisition footprints are linear grid patterns on 3D seismic time slices that reflect parts of the acquisition geometry used in the seismic survey. They are typically seen on shallow time slices or horizon amplitude maps and can mask actual amplitudes, affecting interpretation, AVO analysis, and reservoir characterization (Chopra & Larsen, 2000); (Marfurt, et al., 1995); (Marfurt, et al., 1998). There are several reasons for these stripes, but two general types can be distinguished. One type may be categorized as depending on the details of the acquisition geometry, and the other type as those arising from signal processing problems (Chopra & Larsen, 2000); (Drummond, et al., 2000). Examples of signal processing related footprint noise can be a combination of migration aperture, spatially aliased migration noise and diffraction noise. The acquisition footprints are removed in the Fourier domain because here it is easier to distinguish noise from the data. The wavenumber in the inline direction is plotted against the wavenumber in the crossline direction in a Fourier transformation (FFT)-plot (Figure 4-4). The centre of the FFT-plot represents the geological data, while localized peaks can indicate the presence of footprint noise. The footprint noise is removed by creating a mask over the localized peaks and a smoothing parameter is applied to avoid sharp edges.

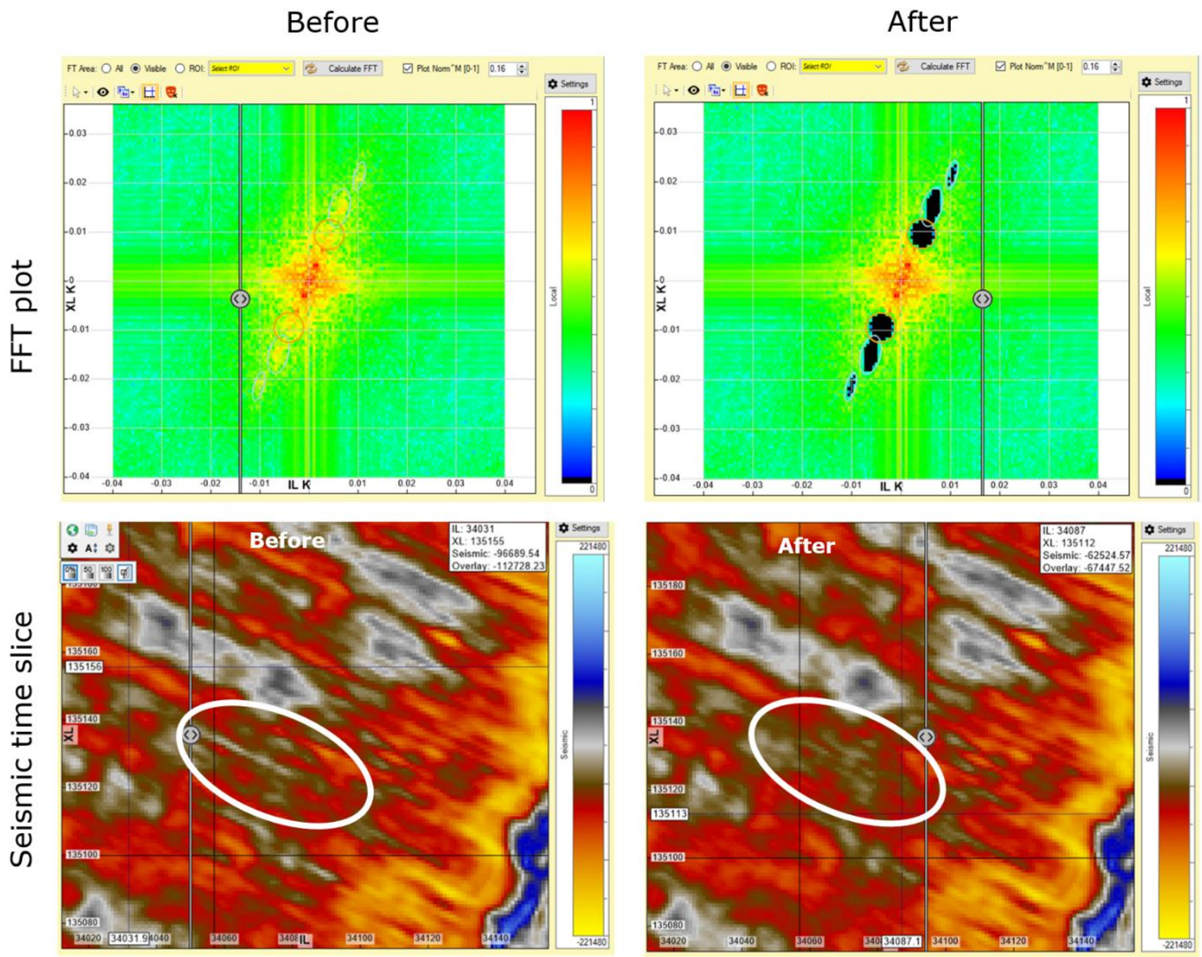


Figure 4-4: The Fourier transformation plot where the de-stripe filter is designed and a seismic time slice showing before and after the filter has been applied.

4.1.1.3 De-noise filters

De-noise filters are applied to remove unwanted random noise from the data. In this workflow two denoise filters are applied. The first denoise filter is called MSMTM and is short for Multi-Stage Median Modified Trimmed Mean. This is a structurally oriented filter that utilizes spatial stacking to enhance the signal to noise ratio and reduce random noise (Avary, 2022). The geological structure of the data is taken into account to preserve both the structure and amplitude through the spatial stacking process. The dip-angle of the steepest dipping geological feature is measured, and the filter makes sure to preserve structural features that have a lower or equal dip-angle. The MSMTM filter combines two filters. The first stage sharpens and maintains fine details like lineaments, while the second smoothes to reject random noise. The alpha parameter balances the weight of the two stages. If alpha is too low the seismic will be sharpened and can look like Lego blocks. When alpha is too high the local fine detail amplitude may not be preserved.

The second de-noise filter applied is an Anisotropic Tensor Diffusion De-noise (ADF) filter. This is a 1-step filter that can dampen random noise while still preserving edges and reflector strengths. This filter does not have any dip constraints and is often used after the 2-step MSMTM denoise filter. A mild ADF is run after the MSMTM to reduce the undesired Lego-block artifacts that can be introduced in the MSMTM when using a low alpha value to preserve the detailed amplitude.

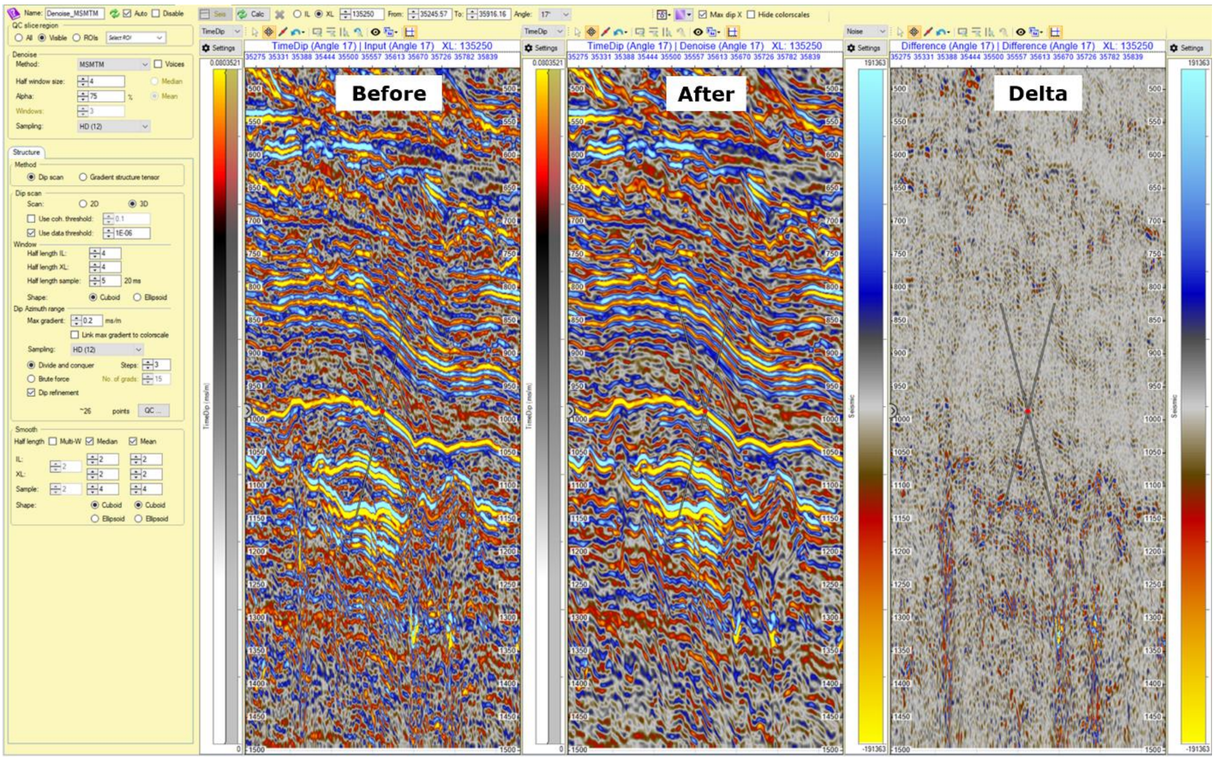


Figure 4-5: Seismic cross sections displaying; Before, After and removed signal from the MSMTM denoise filter.

4.1.1.4 Bandwidth matching

Bandwidth matching performs spectral balancing across the defined partial angle stacks to ensure they all have approximately the same frequency content. The analysis is performed over selected traces to create a balancing operator, which is then convolved with every trace in the volume to match the frequencies (Aker BP, 2022).

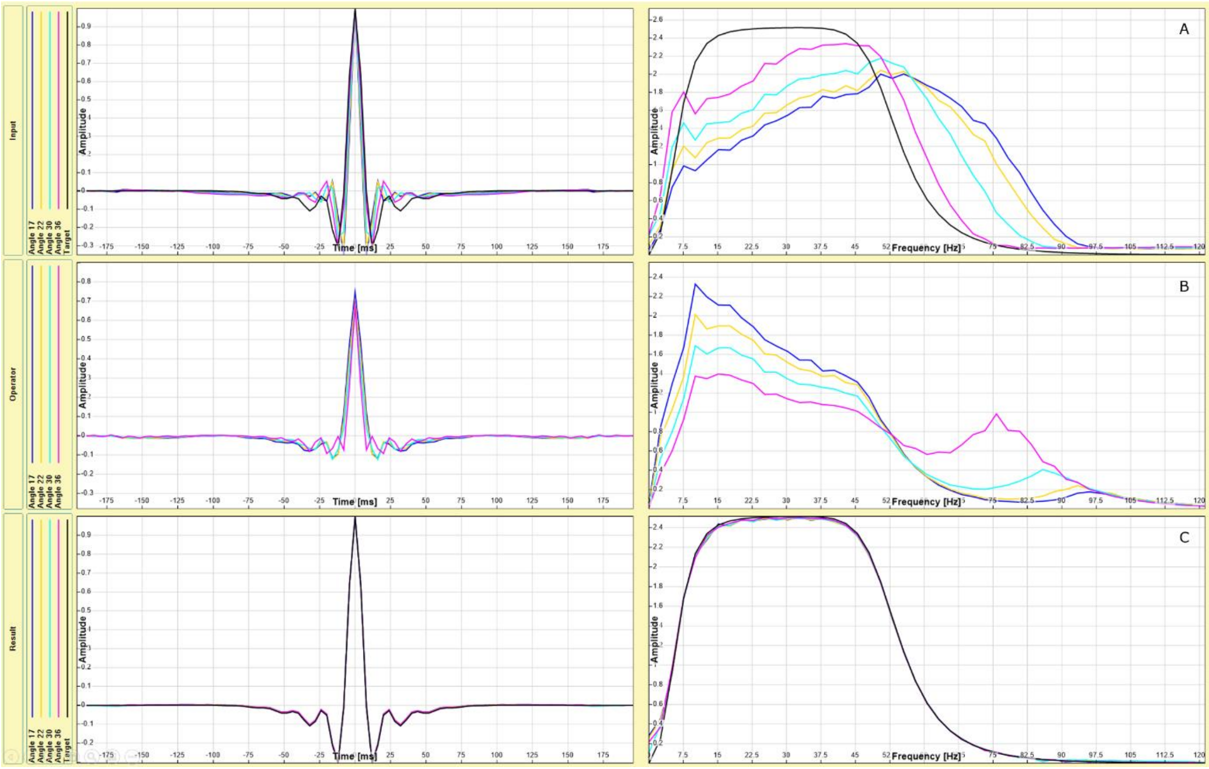


Figure 4-6: Wavelet and frequency spectrums of the partial angle stacks before and after bandwidth matching. A: Wavelet and frequency spectrums before bandwidth matching. B: Balancing operator that has been convolved with the data. C: Resulting wavelet and frequency spectrum.

4.1.1.5 Time alignment and Relative phase balancing

The two last steps of the conditioning process were Time alignment and relative phase balancing. A weighted time shift is applied to the angle stacks that are misaligned in time. The data is aligned relative to a selected reference stack. Relative time shifts are applied for every sample in every trace (Avary, 2022). The amplitude and phase spectrum of the wavelet can be significantly impacted by traveling through the subsurface. The phase will be rotated and shifted in time depending on the attenuation, which varies with the lithology and state of consolidation (Simm & Bacon, 2014). The relative phase balancing element compares the phase of partial angle-stack traces, to correct phase and time shifts between stacks (Avary, 2022).

4.2 Seismic mapping

The first step of the detailed interpretation is seismic mapping. The mapping is based on seismic termination geometries, seismic facies and derived seismic characteristics. The mapping has been done using the software Petrel and PaleoScan and the approaches of seismic stratigraphy discussed in R.M. Mitchum et al., (1977).

4.2.1 Seismic stratigraphy

Seismic stratigraphy is a technique for interpreting stratal information from seismic data and reconstruct paleogeography (Mitchum, et al., 1977); (Vail, et al., 1977). Stratigraphy and depositional facies are interpreted from the seismic data through mapping seismic sequences and studying the seismic facies reflection patterns. Seismic sequences are mapped based on seismic reflection terminations such as erosional truncation, toplap, onlap, and downlap (Figure 4-7). Seismic facies units are groups of seismic reflections with differing characteristics from adjacent groups. The differing parameters can include configuration, amplitude, continuity, frequency, and interval velocity (Figure 4-8) (Mitchum, et al., 1977). Seismic facies units and their lateral extent can be used to interpret depositional environments because the differing reflection patterns are controlled by varying energy of the depositing medium and different lithological content (Mitchum, et al., 1977). The use of sequence stratigraphic methods when studying the basin evolution in a sedimentary basin has the advantage that the basin dynamics can be inferred directly from observations and can be defined as a model independent approach (Glørstad-Clark, et al., 2011); (Jarsve, 2014).

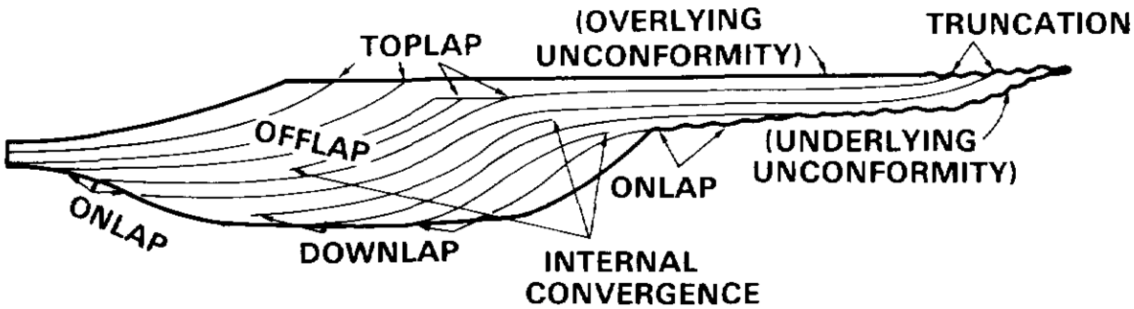


Figure 4-7: Seismic stratigraphic reflection terminations within idealized seismic sequence from (Mitchum, et al., 1977).

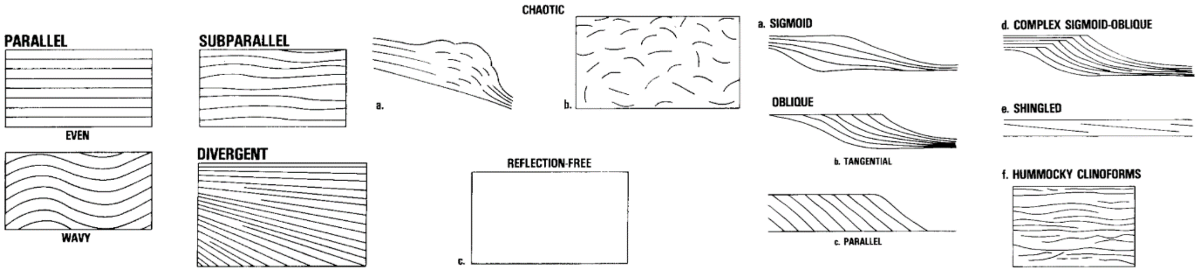


Figure 4-8: Seismic facies characteristics from (Mitchum, et al., 1977).

4.2.2 PaleoScan

PaleoScan is a seismic interpretation software based on a semi-automated approach developed by the company Eliis. This software has been used as a supplement to traditional interpretation in Petrel to improve the quality of the mapped sequences and create continuous surfaces throughout the volume.

A model-grid is created based on a global minimization algorithm, where the seismic points are merged based on the similarity of the seismic wavelets and their relative distance (Pauget, et al., 2009); (Lacaze, et al., 2011); (Lutome, et al., 2022). A 3D model-grid was computed from the base to the top of the interpreted Oligocene sequence. The geoscientist's task is further to refine the auto-tracked model-grid by marking horizons that make sense geologically and should be used to constrain the geometry of the model. The previously interpreted horizons from Petrel were imported to constrain the model. It has been shown that the more detailed horizon constraints are given, the better the resulting GeoModel will be (Lutome, et al., 2022). When the horizon constrains are picked the software will use the model-grid and marked constraints to create a 3D geological model that fits the data. The Model-Grid to GeoModel process can be updated and revised as many times as needed. Three GeoModels were created in this project. One on the original regional PGS seismic volume and two on the conditioned volume, with and without constraints. The next step in the workflow is to create a stack of horizons based on the GeoModel. A stack of 200 horizons that follow and honour the geometries of the GeoModel was created. The PaleoScan horizons are laterally continuous, but they are not based on the seismic reflectivity. It is therefore important to evaluate their time consistency when interpreting. Surface attributes and spectral decomposition blending was further applied to all 200 surfaces and used for further interpretation.

4.2.3 Attributes

Seismic attributes are measurable properties or characteristics that can be computed or implied from the seismic data (Subrahmanyam & Rao, 2008). The attributes highlight specific geological or geophysical features in the data and can for example enhance variations in rock properties, sedimentary facies, structural features or flid content. There are many types of attributes, and they can be derived from or related to the basic seismic information of time, amplitude, frequency, and attenuation (Brown, 2001). Seismic attributes are used as tools during interpretation to extract meaningful information form the seismic data. It is however important to remember that all the attributes available are not independent pieces of information but, simply represent a limited amount of basic information (Brown, 2001).

The main attributes derived in this project is a seismic relief attribute and a spectral decomposition blend. Seismic relief is an amplitude derived attribute closely linked to the more common root mean square (RMS) amplitude attribute. It was derived by Bulhoes in 2005 and is optimized for visualizing and enhancing geology (Bulhoes, 2005). Spectral decomposition is a frequency related attribute that can highlight layer thicknesses and stratigraphic variations (Roden, et al., 2015). This is done by decomposing the seismic signal into its constituent frequencies and allows the interpreter to see the amplitude and phase tuned to specific wavelengths (Othman, et al., 2016). The spectral decomposition is visualised with Red-Green-Blue (RGB) colour blended maps where each colour corresponds to a specified frequency range.

The frequencies used for the spectral decomposition blends of the detailed study area are based on the frequency spectrum analysis that was conducted for the regional study. The analysis was conducted using the software Petrel and GeoTeric for comparison. In Petrel the frequency spectrums of three wells were calculated between -20 ms and -1500 ms. The frequencies 10, 22 and 35 Hz were chosen based on the spectrums and with a spread around the dominant frequency of approximately 20 Hz. A frequency decomposition was also done in GeoTeric where various frequencies in both higher and lower ranges were tested. The most clear and defined blends were obtained using frequencies of 8, 19 and 36 Hz. The two different frequency ranges were further applied to a test surface to compare. There was little difference between the two frequency ranges and the frequencies 10, 22 and 35 Hz form the Petrel analysis were chosen.

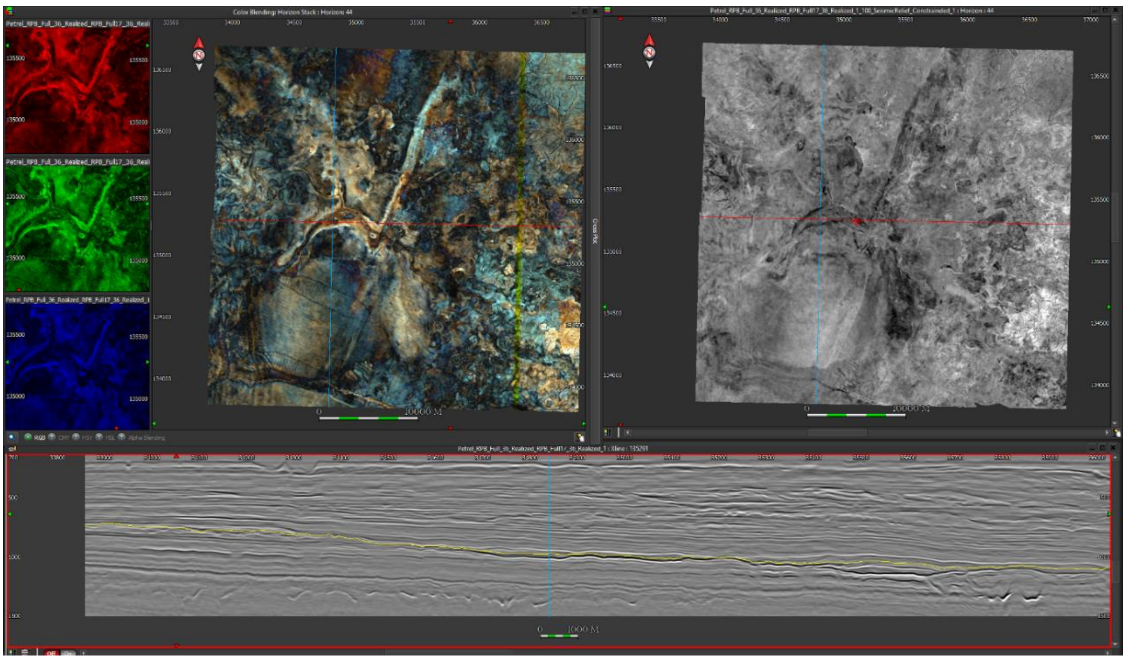


Figure 4-9: Spectral decomposition blend with frequencies 10, 22 and 35 Hz and Seismic Relief attribute map.

4.3 Calibration with well data

After seismic mapping the second step of the detailed interpretation is to calibrate the seismic facies with stratigraphy and lithology data from well logs. As mentioned in the data section the well log data availability at these shallow depths is limited and a lot of time has been spent on choosing and quality checking wells and well log data. Seismic to well ties have been conducted in Petrel to understand the variations in the seismic response with variations in lithology. The wells have been tied to both the original and the conditioned seismic data and the correlation has been compared.

To be able to create a seismic to well tie the well data should include some essential well logs. The most important are Acoustic Impedance (AC), Gamma ray (GR), Density (DEN), and a time-depth relationship. AC, GR, and time-depth relationships are available in all chosen wells however, the Density log has usually only been recorded for deeper stratigraphic sections. Several methods of creating synthetic well log data have been tested. Synthetic density data has been calculated using Gardner's equation which is based on the available Sonic velocity. An internal Aker BP machine learning (ML) software called Align has also been tested. Both a curve patching model and a lithology prediction model have been applied to the chosen wells. The models are trained on wells and well data covering the entire Norwegian continental shelf and uses the available well logs to predict missing sections. The curve patching model was used to create both synthetic density data and synthetic shear velocity (ACS). The model was quality checked by testing on nearby wells with measured density and ACS data. The ML lithology logs have been quality checked by comparing with the measured gamma ray logs and cuttings data recorded in the well logging reports.

4.4 Integration and Predictive seismic stratigraphy

The final stage has been to integrate the data from all the previous stages and use these results to predict the lithology and facies away from the areas with well control and interpret the gross depositional environments (GDE). A chronostratigraphic chart has been created by integrating the interpreted seismic sequences, facies, well logs and spectral decomposition blends. Proposed GDE maps have been created based on the chronostratigraphic chart and the spectral decomposition blends. The interpreted results have further been compared to analogues from Google Earth and related back to the results from the regional study and previous literature.

5 Results

This section will present the results and observations from the conditioning, detailed seismic mapping and well calibration. The following sections will present the integration of these results and following interpretations.

5.1 Conditioning

A conditioning procedure was conducted on a focused area of the PGS survey. The workflow applied was designed to remove noise and optimize the data quality for the area of interest. High frequent "ringing" noise, acquisition footprints, processing artifacts and random noise have been removed. Through this the signal to noise ratio has been enhanced. The frequency spectrums for each angle stack have been analysed and bandwidth matching have been applied to account for the large spread in frequencies and ensure that all the angle stacks contain approximately the same frequency content before stacking. The final stacked data compared to the original seismic data can be seen in Figure 5-1and 5-2. The conditioned seismic data is generally smoother and easier to interpret. Areas with little reflectivity looks cleaner and high amplitude reflectors are more prominent in the conditioned data.

The conditioned seismic volume was further used for detailed seismic mapping including the creation of attribute maps. The seismic relief attribute was conducted on both the original and the conditioned seismic data to compare the differences. Figure 5-3 shows two seismic relief attribute maps of the same horizon comparing the original and conditioned seismic data. The attribute map created with the conditioned data is smoother and less noisy than the original. Stripes in the original data most likely acquisition artifact are less prominent in the conditioned data and we see the direct effect of the de-stripe filter applied. The signal to noise ratio has clearly been improved as more details are visible in the conditioned seismic attribute map. Additionally, Figure 5-3 shows there are geological features that are only visible in the conditioned data.

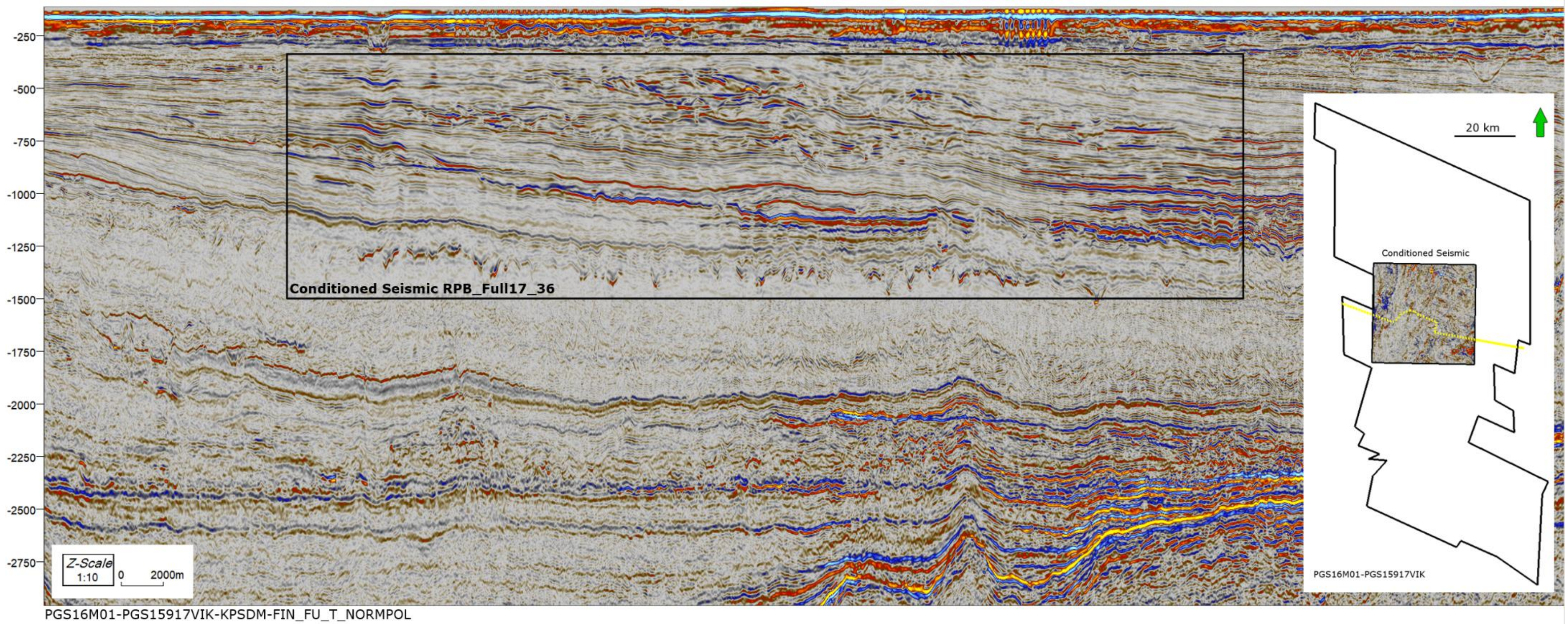


Figure 5-1: Conditioned seismic data compared to original full PGS16M01 survey

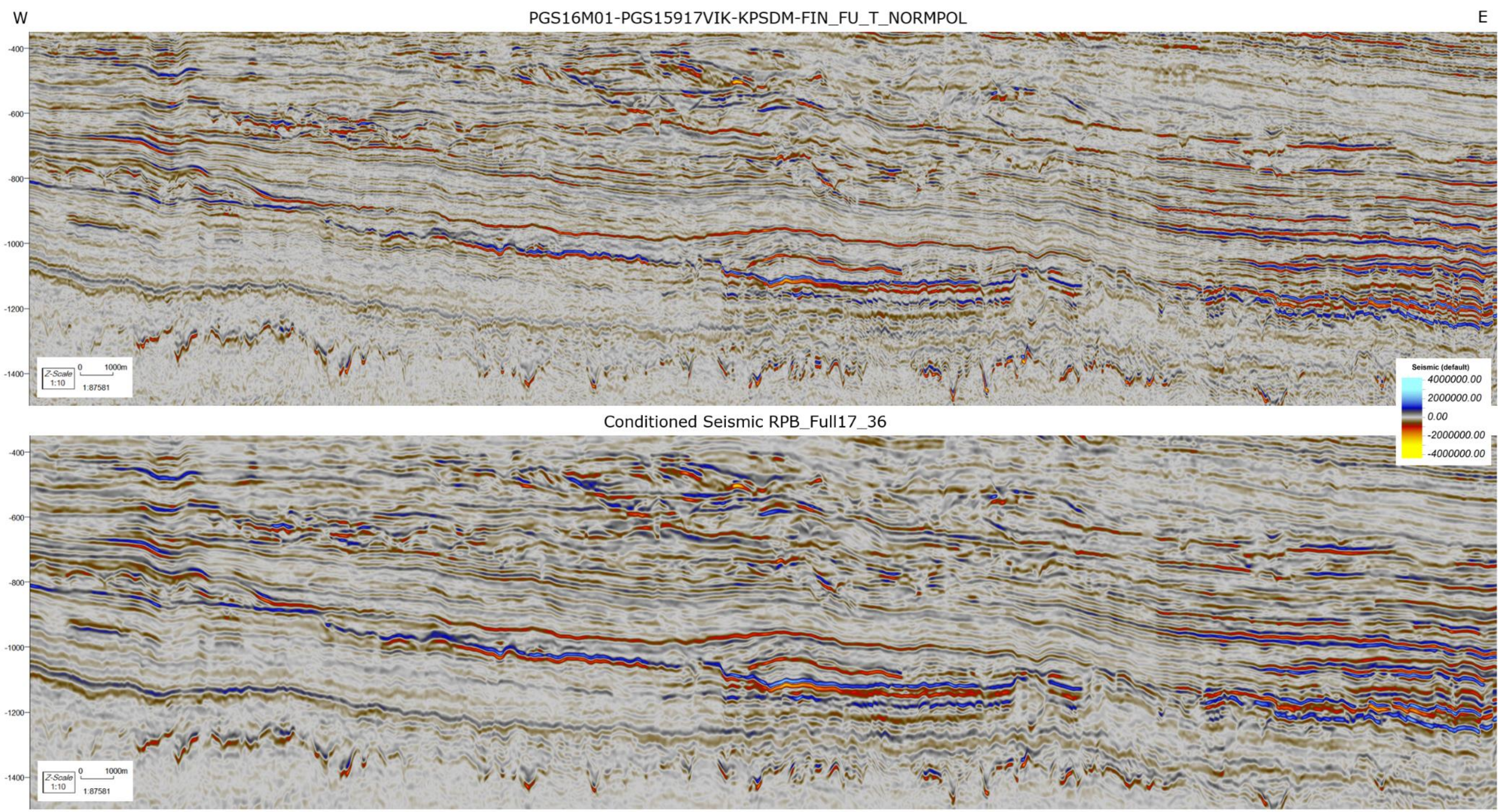
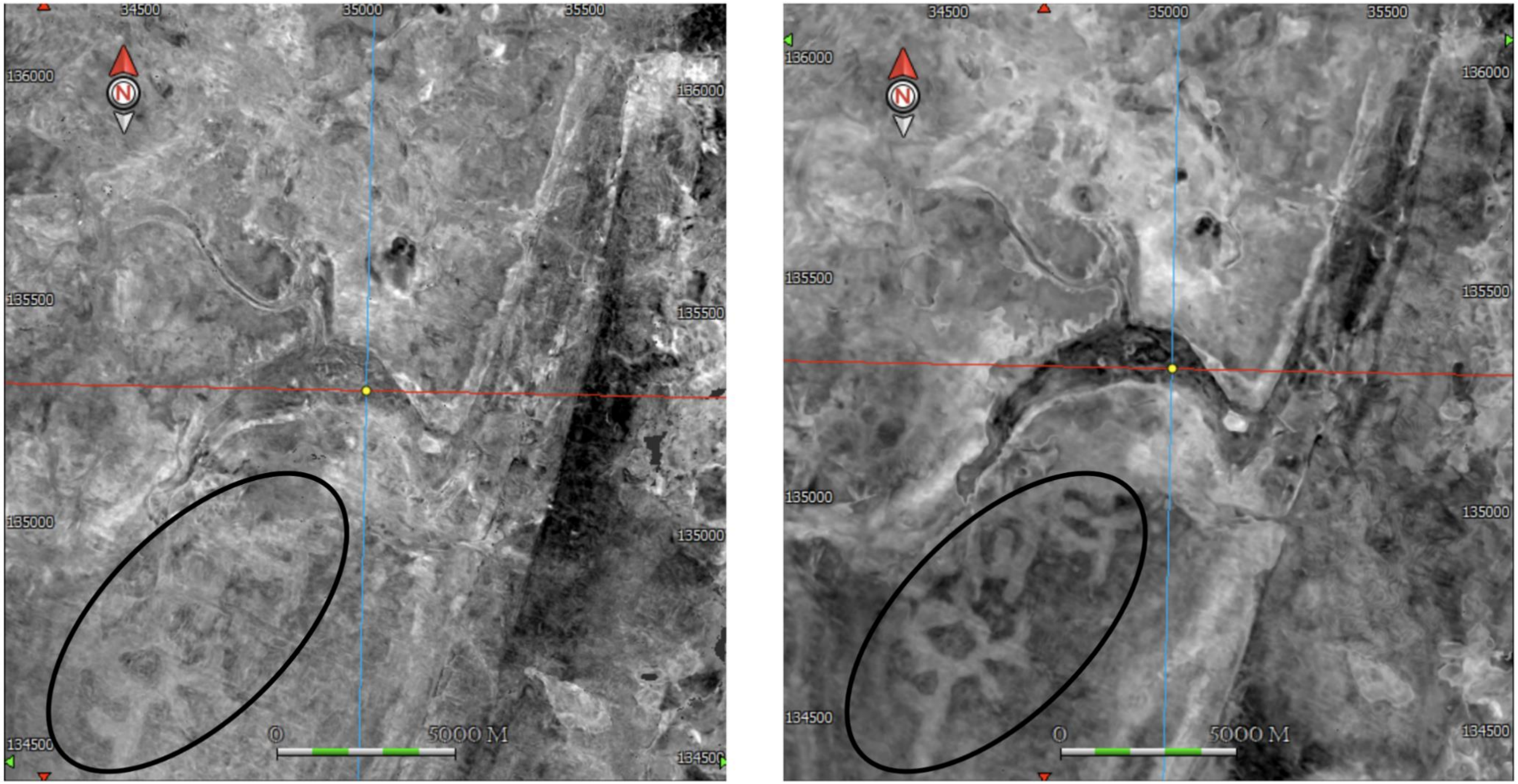


Figure 5-2: Seismic data before and after conditioning.

Original Seismic

Conditioned Seismic



Seismic Relief Attribute

Figure 5-3: Seismic relief attribute maps comparing the original and conditioned seismic data. Circle highlights the area where geological features are significantly more visible in the conditioned data.

5.2 Seismic mapping

The initial seismic mapping in Petrel was conducted on the conditioned seismic data and focused within the previously interpreted Oligocene sequence (Figure 5-4) (Helland-Hansen, 2022). The detailed seismic mapping resulted in ten final horizons displayed with different colours and labelled in stratigraphic order from Time 0 (T0) to Time 9 (T9) (Figure 5-7). Figure 5-5 shows the seismic section with and without mapped horizons.

The four regionally extensive and conformable horizons (T0, T2, T7 and T9) divide the interpreted section into three main units. A geo-section was created to visualize the mapped units (Figure 5-6). Unit 1, 2 and 3 are colour coded in the colours blue, orange and green. The main units are split into sub-units that are present locally in either the proximal or distal area. These are laterally extensive in either the distal, proximal and or the local area. Unit 1 and 3 contain mainly conformable horizons while unit 2 contains mainly unconformable horizons. Seismic facies within all units have been described and studied in detail. The eight main seismic facies (SF) have been labelled from SF1 to SF8. Figure 5-7 shows an overview of the characteristics and distribution of the mapped horizons, units, and seismic facies within the study area.

Spectral decomposition blends and seismic relief maps have been created for seven laterally continuous PaleoScan surfaces. The surfaces were created through the PaleoScan GeoModel and was guided by the initial horizons mapped in Petrel. The chosen surfaces were exported back to Petrel and their location and lateral extent relative to the main units is visualised in Figure 5-8.

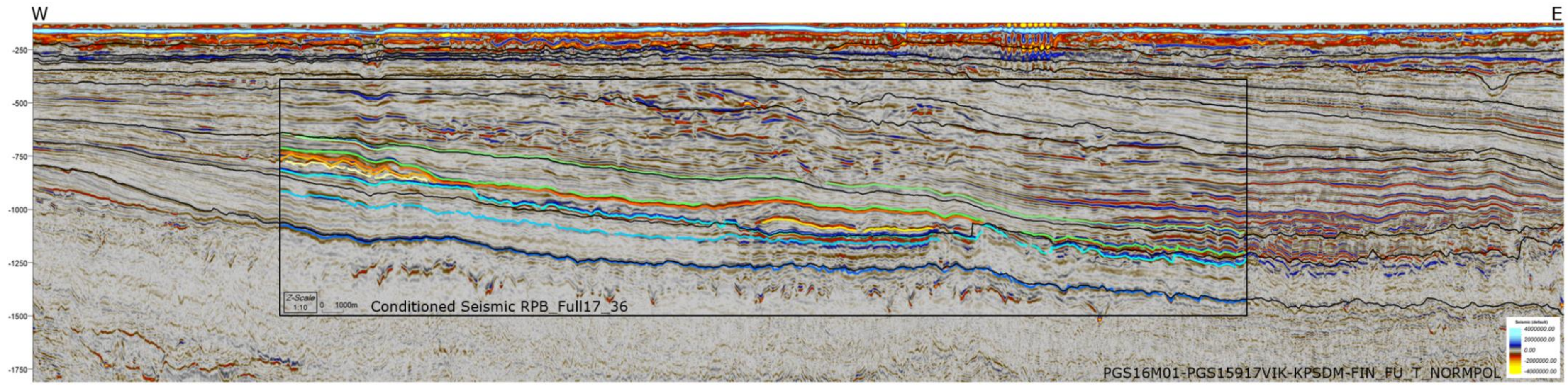


Figure 5-4: Seismic section comparing detailed study interpretations to previous sub-regional surfaces

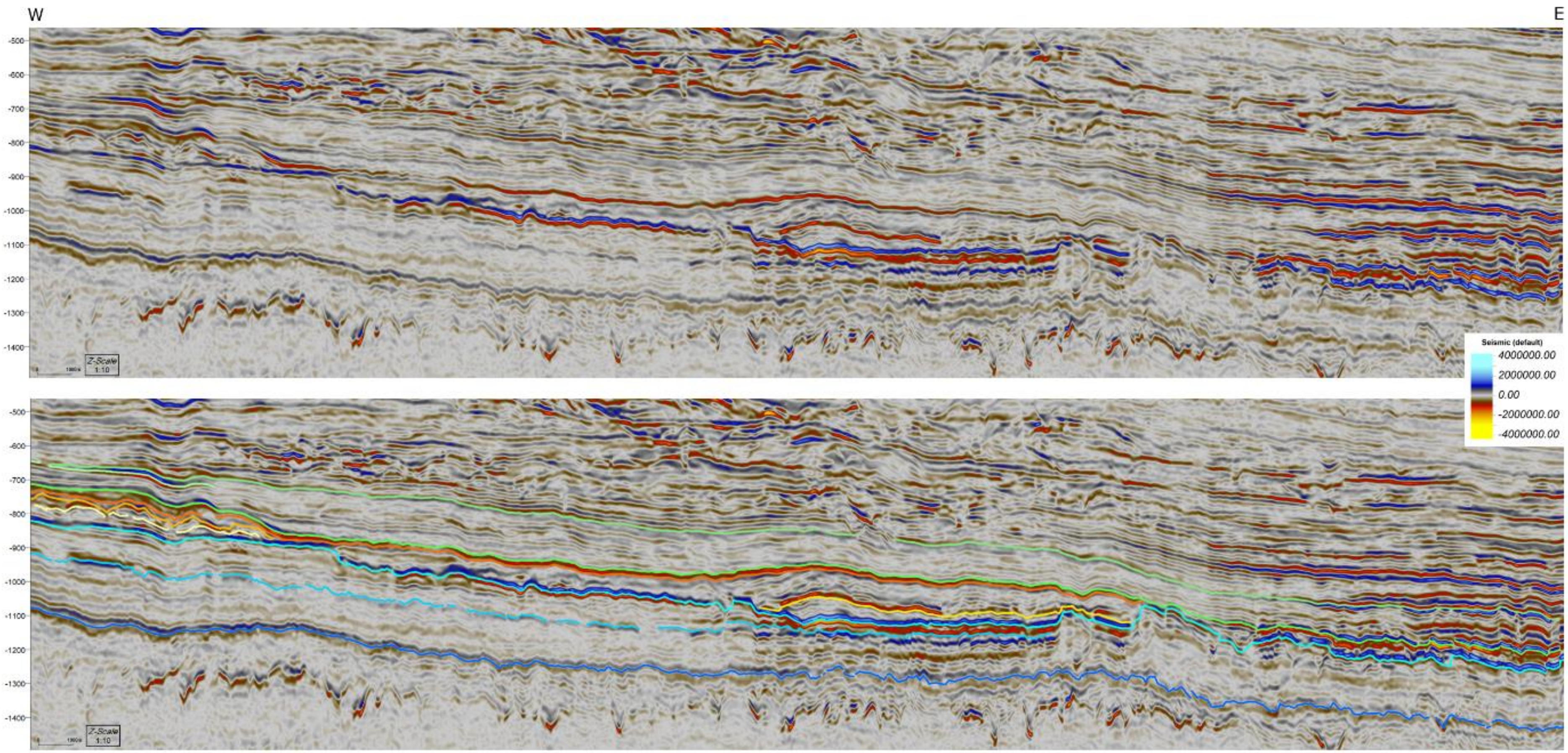


Figure 5-5: Seismic section with and without interpreted horizons.

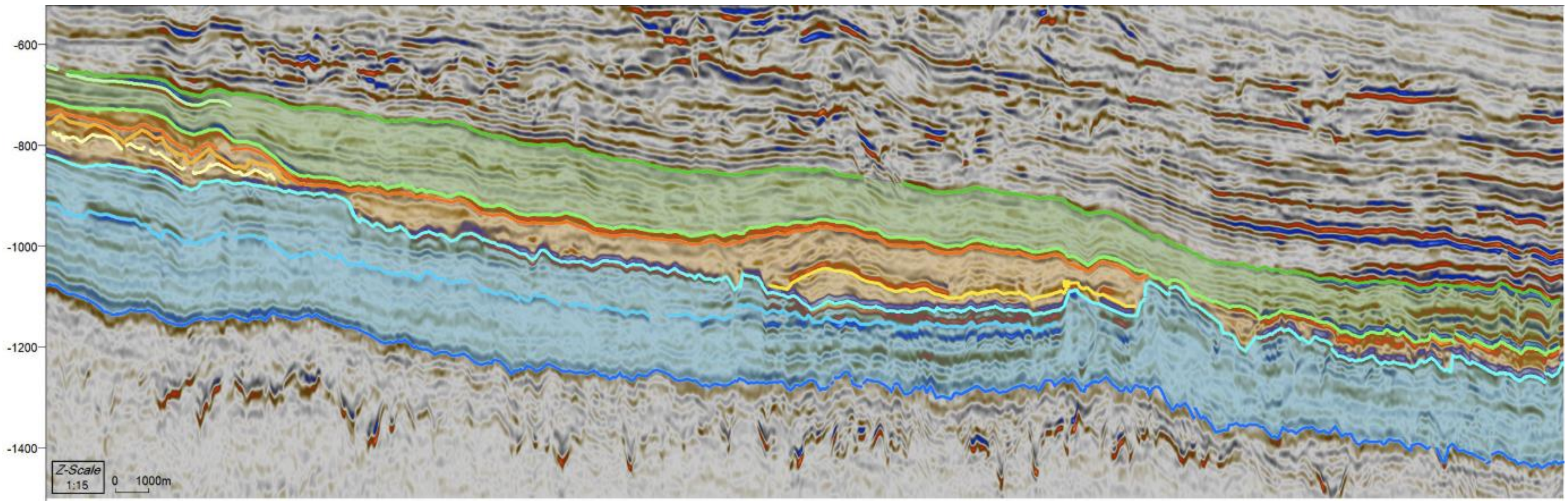


Figure 5-6: Mapped horizons and main units.

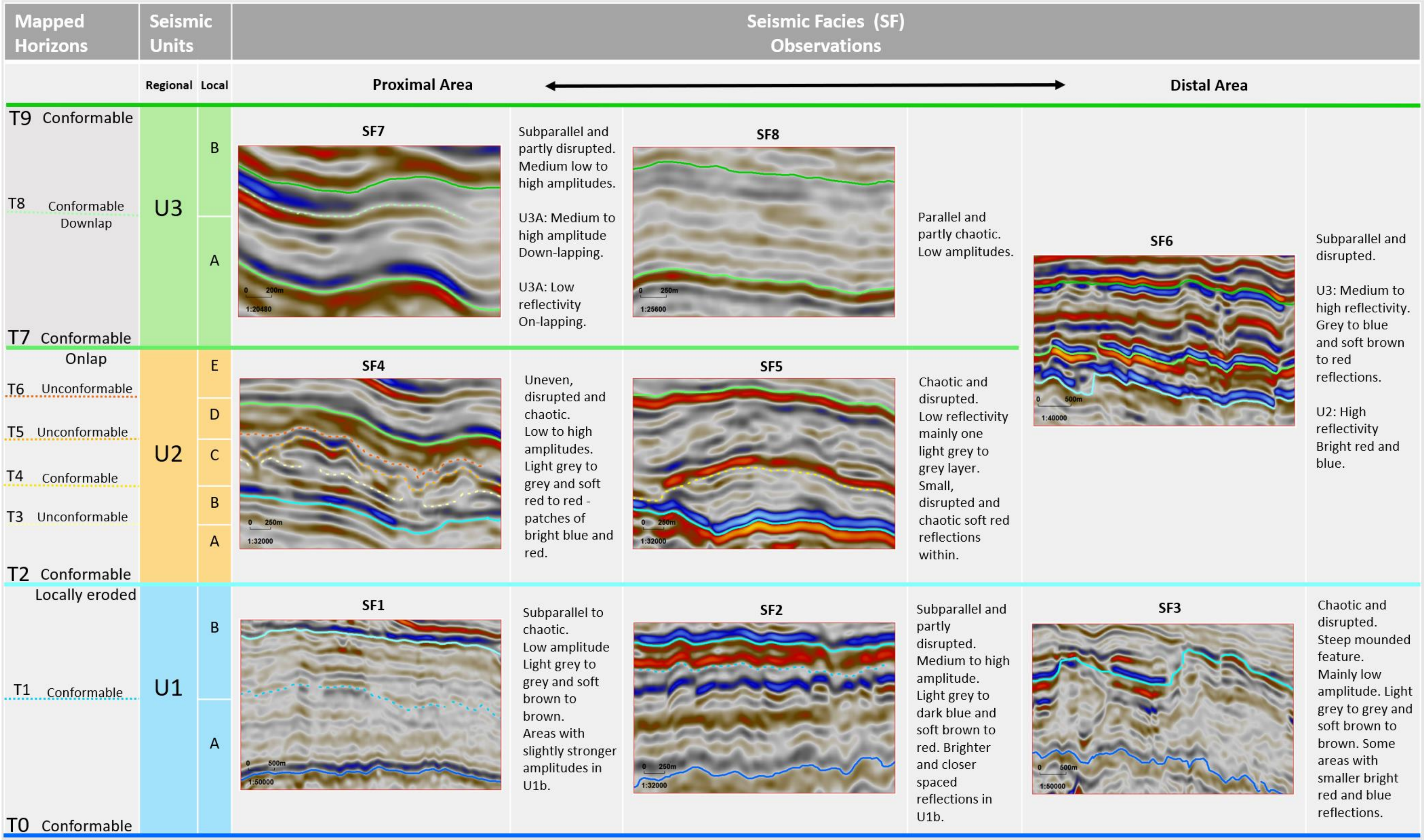


Figure 5-7: Seismic facies observations.

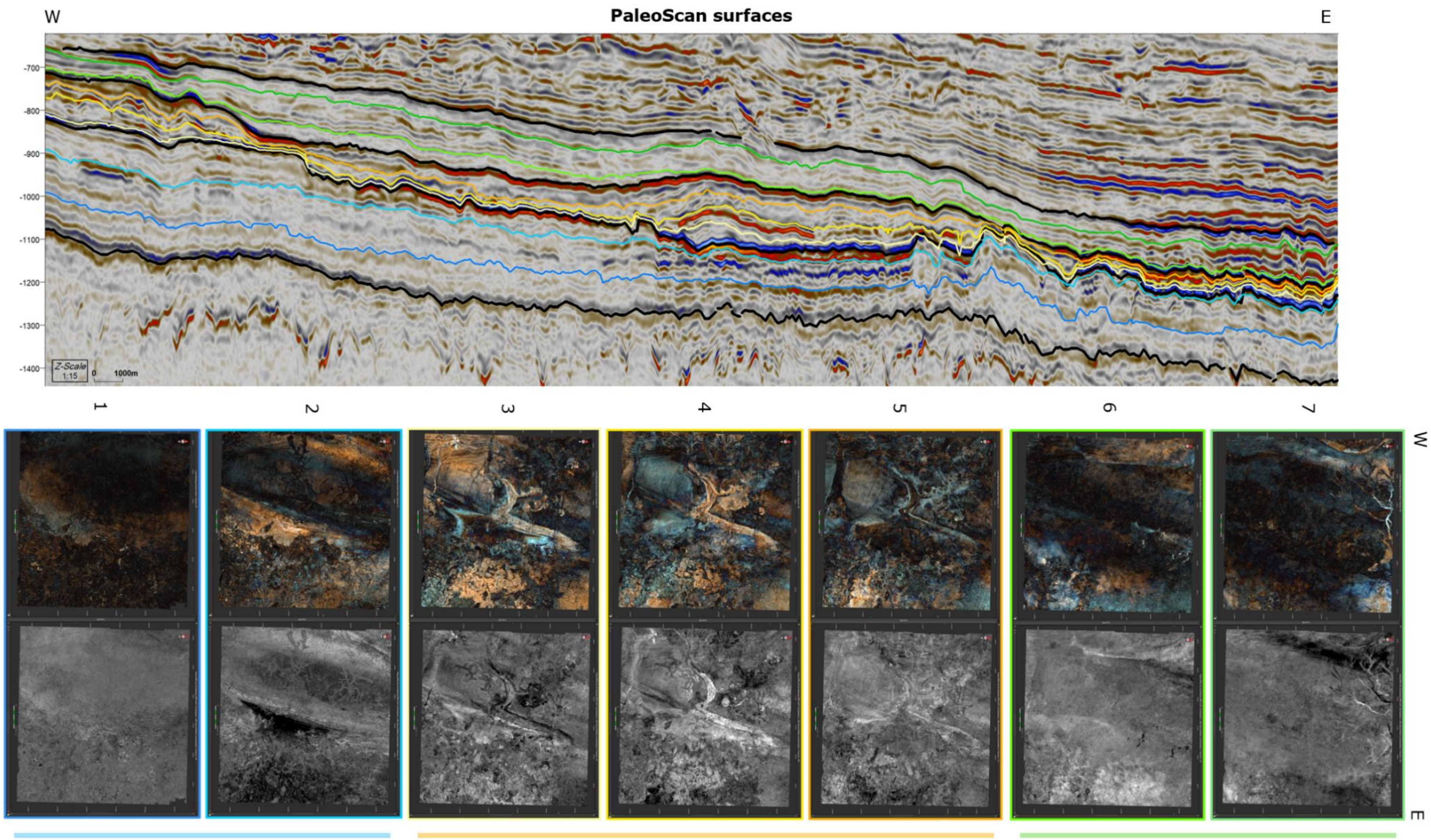


Figure 5-8: Chosen PaleoScan surfaces colour coded by main unit.

5.3 Well calibration

Well log analysis and seismic to well ties were conducted on the three main wells 24/6-1, 25/4-4 and 25/4-5. The cross-correlation in the depth window of -480 and -1400 ms, showed a maximum correlation factor of 0.430 for well 25/4-5. This is 0.1 higher than for the previously tied original PGS survey data. The resulting seismic to well tie, synthetic wiggle traces are visualised on the seismic in Figure 5-9 a.

Figure 5-9 b shows the lithology log created by the machine learning (ML) model compared to the originally recorded Gamma ray log. The calibrated logs are visualised on the seismic section with the previously presented detailed seismic interpretations. The ML lithology log is only able to separate sand from shale with two main classes. The cuttings information show that reality is more complex with several transition depths with more silty lithology. The sand interpretations from the ML lithology log correlate well with low GR values. Comparing the well log data to the mapped horizons show that unit 1 and 3 contain mainly clay while the boundaries of unit 2 correlate with the sandy sections in the well logs (Figure 5-9 b). The integration of the well log data with the cuttings is shown in a chronostratigraphic chart in the following section.

The age determination of these detailed interpretations are based on correlation with the sub-regional interpretations conducted for the full PGS16M01 survey (Figure 5-4). The wells used in this detailed study do not contain biostratigraphic data, however the sub-regional interpretations have been tied to the re-dated wells from the NPD study.

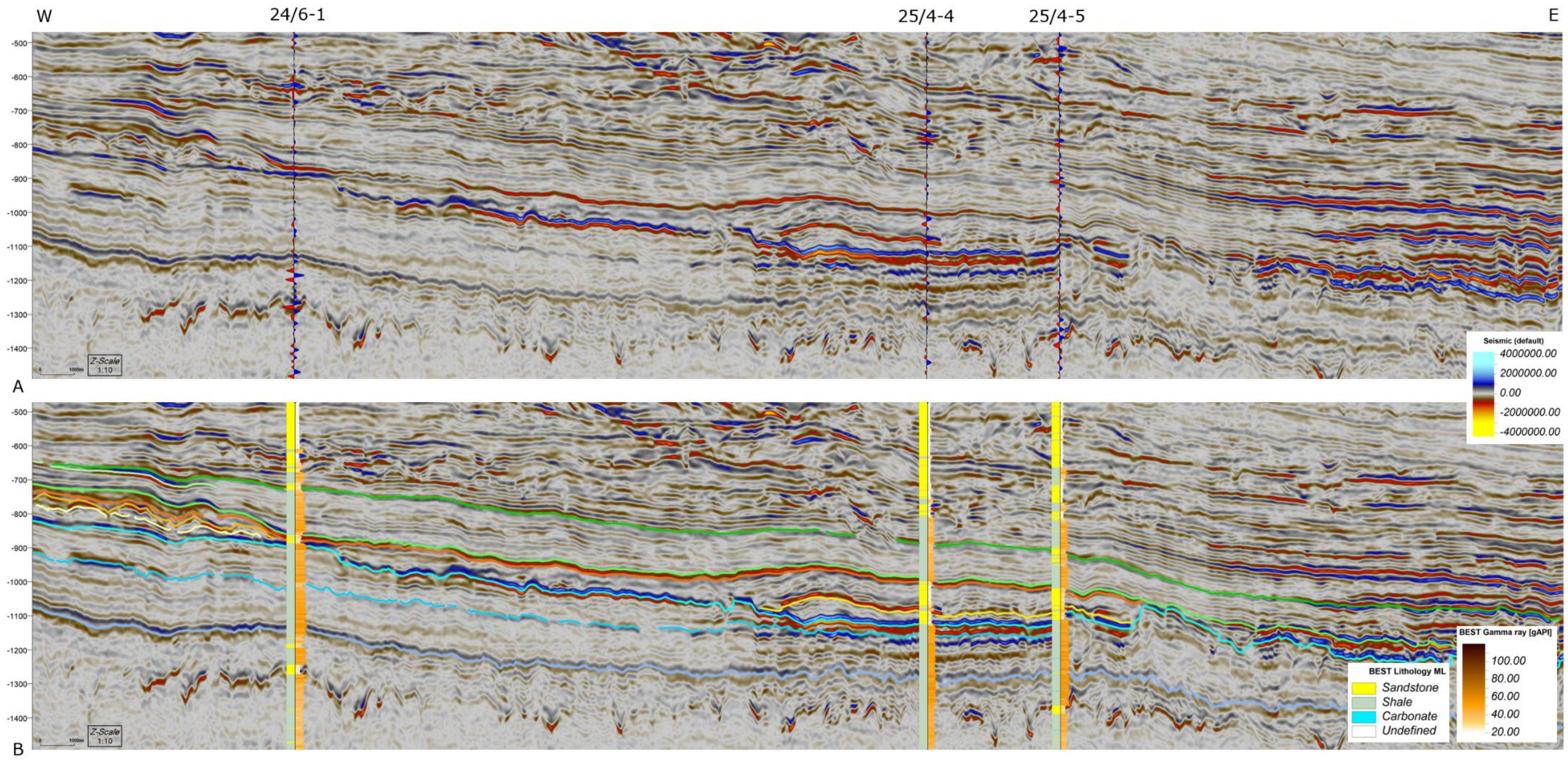


Figure 5-9: Seismic cross sections with wells. A: Displays the synthetic seismic wiggle trace from the well ties.
B: ML lithology log, Gamma Ray log and Interpreted horizons.

6 Discussion

The goal of this study has been to add more detail to the current understanding of the post-Eocene overburden stratigraphy. These younger stratigraphic sequences have typically been underexplored and more detailed research is important to fully understand the geological history of these recent geological times (Eidvin, et al., 2022). The limited stratigraphic understanding has led to conflicting interpretations and imprecise well tops illustrated in Figure 1-4 from the current internal Aker BP overburden report. Most of the research conducted has been at a regional scale, while this study focused on a smaller area in more detail to fill in the gap with the aim for these details to add insight into the understanding of the regional basin history and spatio-temporal evolution. This section will discuss how the previously presented data and results have been integrated and interpreted and their impact on understanding the geologic development. The interpretations made in this focused study will then be compared and discussed in relation to literature and previous work. Finally, the conditioning process results and well calibration will be discussed in relation to the limitations of the data.

6.1 Integration and Interpretations

The observations from the seismic mapping, facies descriptions, and the well data have been combined and used to create a chronostratigraphic chart (Figure 6-1). The chronostratigraphic chart, also called a Wheeler diagram, has been used to visualize the sequence stratigraphic interpretations. The relative geological time is displayed along the vertical axis, and distance is displayed along the horizontal axis. The chronostratigraphic chart shows the proposed stratigraphical units based on the geometries and regional extent of the mapped horizons and seismic facies. The Oligocene sequence is divided into three main units subdivided into local sub-units. The three main units are the most certain as these are bounded by regionally extensive and conformable surfaces. The sub-units are locally present in either the proximal or the distal domain.

The following interpretations have been made based on the chronostratigraphic chart and previous observations, including the mapped horizons, units, seismic facies (Figure 5-7), well logs, cuttings, and the PaleoScan surface attribute maps.

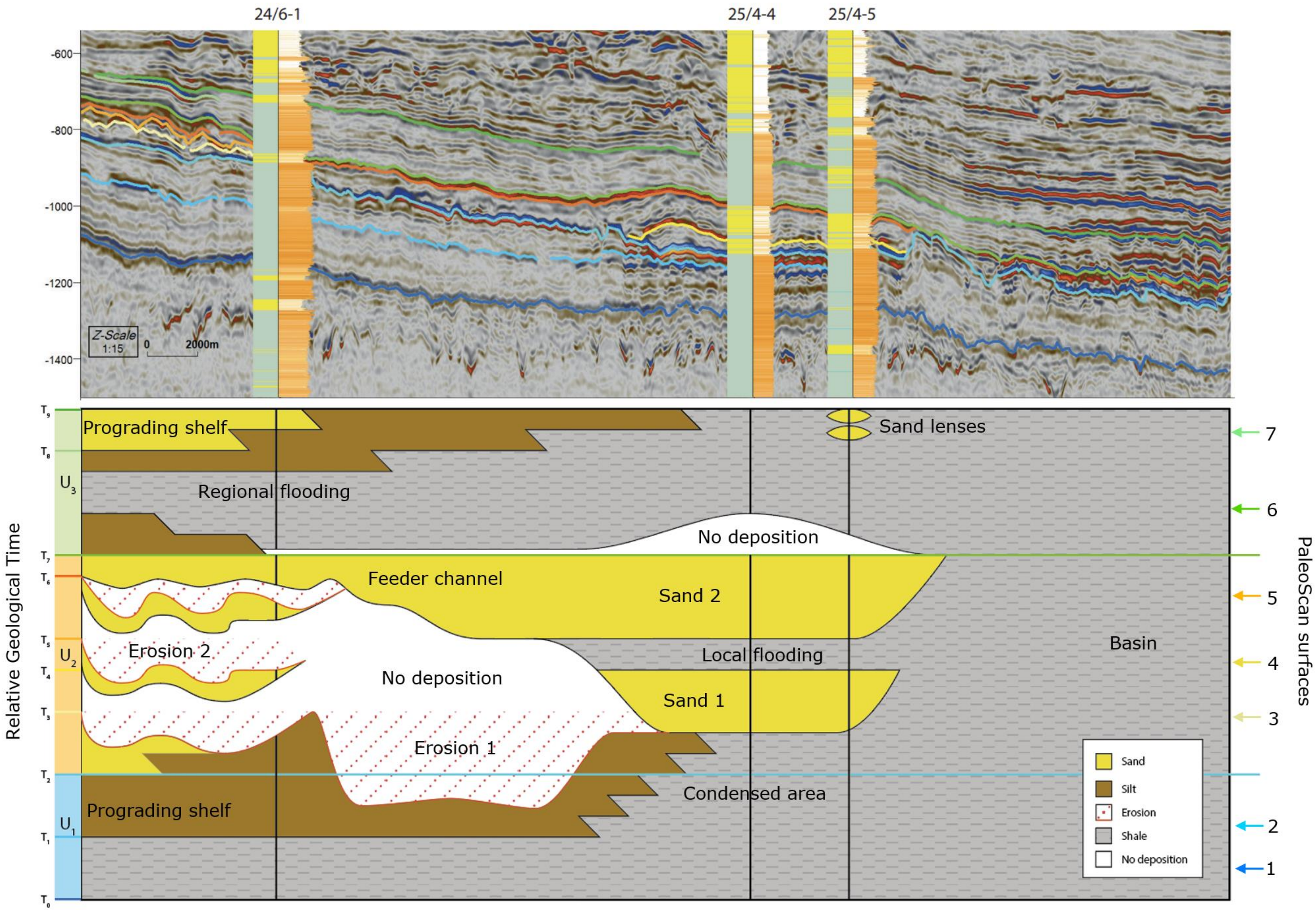


Figure 6-1: Chronostratigraphic chart visualizing the integration of data, observations, and interpretations.

Unit 1 is mainly interpreted as soft clay and basin floor sediments. The subparallel and partly disrupted facies (SF2) indicate polygonal faulting (Figure 5-7). These faults are commonly developed in mudstone sequences during early burial and diagenetic processes (Ogilvie, et al., 2015); (Goulty & Swarbrick, 2005). This type of seismic facies can indicate a basin floor environment. SF2 in Figure 5-7 seems to be compacted compared to SF1 in the proximal regime. This compaction is interpreted to be due to the overlying load of sand, and the polygonal faulting in this region may be enhanced due to this. The characteristics of the distal facies SF3 are interpreted to result from the compaction. The soft sediments may have been squeezed up and created mounded features in the distal area. Two main attribute maps from PaleoScan have been studied within this unit. The first surface confirms the observations from the seismic facies study with polygonal faulting on the basin floor. There are also some smaller bright points present, and these are thought to be the top of the underlying injectites. Overprinting of the overlying sand can be seen on the second attribute surface. The overprinting correlates to the compacted area described in the seismic facies table (SF2). Signs of a prograding shelf can be seen in the proximal area of section U1B, and this is interpreted to be the start of a transition from proximal marine conditions in unit 1 to potentially shallow marine conditions in unit 2. PaleoScan surface 2 shows a prograding sequence in the proximal area in addition to channel-like features on the interpreted shelf. These could also be overprinted from channels in the unit above (Figure 6-2).

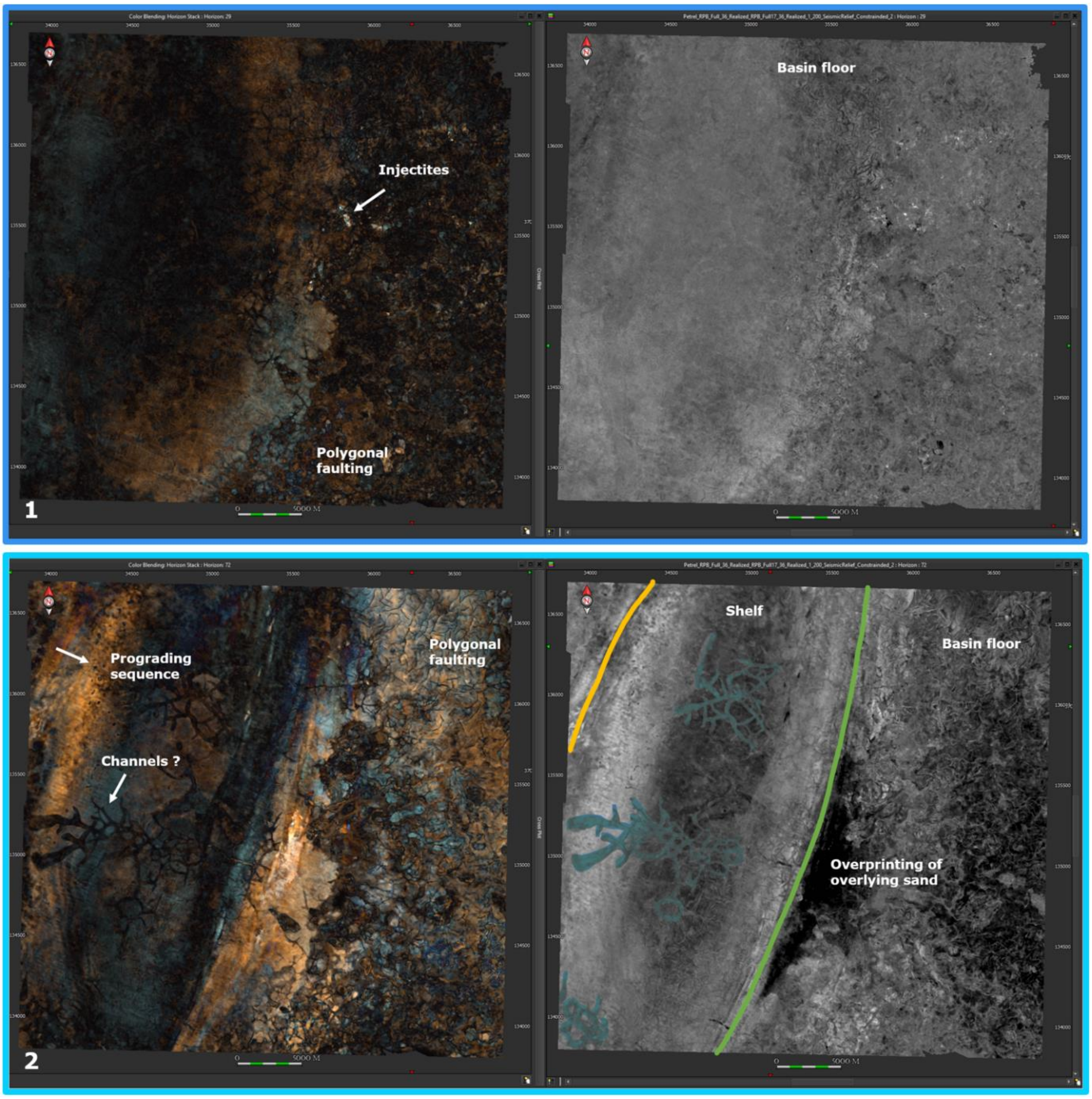


Figure 6-2: Spectral decomposition blend and seismic relief attribute maps of PaleoScan surfaces 1 and 2. Proposed depositional elements are annotated on the map.

Unit 2 contains a lot of detail and signs of a complex and dynamic depositional environment. The western proximal area is interpreted as several phases of prograding sediment and erosion. The PaleoScan attribute maps show complex channel systems eroding and transporting sediment from the shelf to the basin. Different depositional elements such as prograding sandbars (possibly dunes), river, swamp, and lake deposits prevail west of a lineament that can be interpreted as the paleo-coastline. Along the coastline towards the northeast apparent sandy facies can be mapped from the river mouth and north-eastward, indicating a sandy beachline, whereas southwest of the river mouth, the coastline appears less sandy at this point in time. From this, one can infer that waves and currents have transported sand from the river mouth in a northeast direction. In a distal easterly direction, seismic facies 5 show two mounded sand bodies separated by a layer of clay (Figure 5-7). The sand is interpreted to have been sourced from the up-dip erosion and appears to have been deposited in two separate phases. A local flooding event has possibly flooded the underlying sand body before sand body 2 was deposited, with a likelihood of a layer of clay within. The three attribute maps from this unit show the evolution of the deposited sand bodies ending in a large delta shape. The observation of seismic facies indicating rapid lateral variation from sub-aerial swamp, lake, and river deposits to a coastline and beach near sands proximal to the facies indicating a more distal marine environment eastwards, lead to the interpretation that this might have been a shallow marine environment potentially with tidal influence and a wave-dominated beachline. The distal area of unit 2 shows basin floor facies and the sands seem to have been deposited where the slope meets the basin floor, possibly a low-stand sand deposit. The sands seem to have been sourced through one main feeder channel that has eroded deep into the lower sediments of unit 1. There is also evidence of a southern feeder channel sourcing a similar but smaller type of deposit.

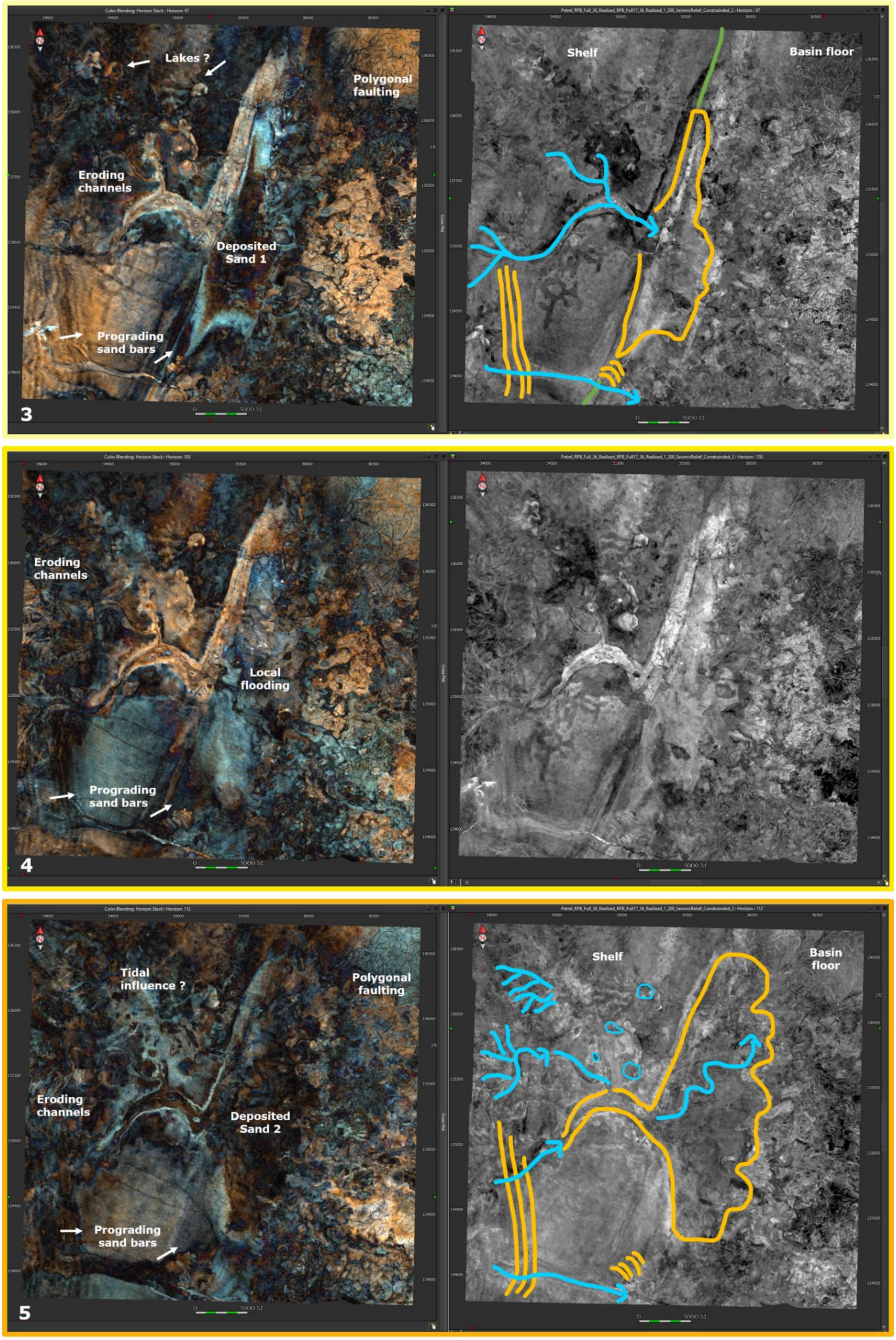


Figure 6-3: Spectral decomposition blend and seismic relief attribute maps of PaleoScan surfaces 3, 4 and 5. Proposed depositional elements are annotated on the map.

The transition from unit 2 to unit 3 seems to represent a transition back to a deeper marine environment. Onlapping characteristics of SF7 in unit 3A combined with shale present in all wells at this depth indicate that the whole region may have been flooded. Unit 3 has also been divided into two sub-units, representing two phases. SF7 shows a transition from on-lapping to down-lapping characteristics. The well logs show more silty sediments with lenses of sand in both the proximal and distal areas. The down-lapping, silty sediments in the proximal area indicate a new gradual shallowing of the area, and the lenses of sand present in well 25/4-5 may be correlated to the channels and potential sand bars interpreted from the attribute maps of PaleoScan surface 7. The distal area still shows signs of a basin floor environment with polygonal faulting, but there are phases of more sandy sections in the last stage of the unit.

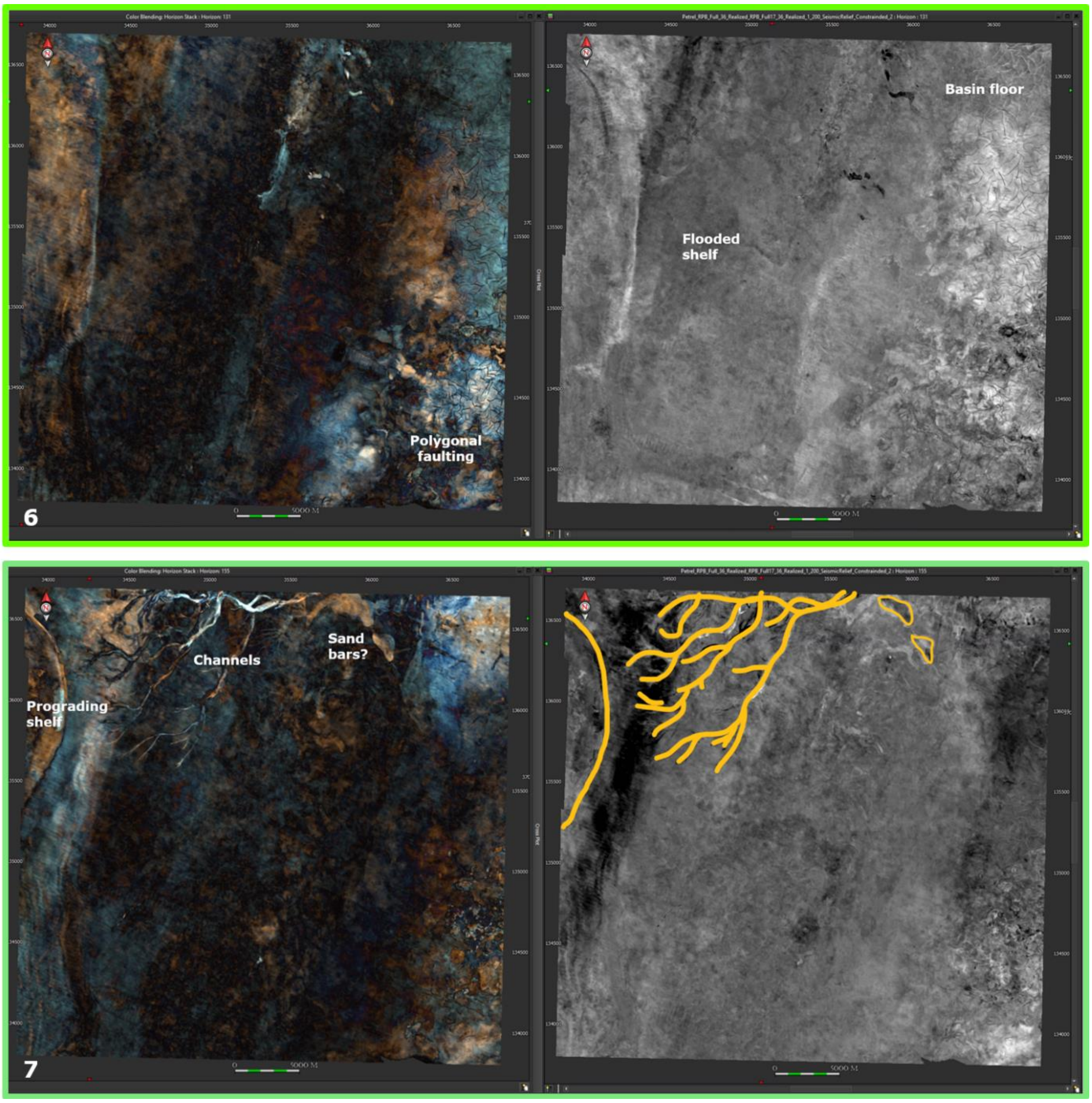


Figure 6-4: Spectral decomposition blend and seismic relief attribute maps of PaleoScan surfaces 6 and 7. Proposed depositional elements are annotated on the map.

The integrated interpretations visualised in the chronostratigraphic chart show a varying depositional environment from deeper marine in unit 1 transitioning to shallow marine in unit 2, possibly initiated by a forced regression and the deposit of a sand body eastward of the later mapped coastline. The first sand deposit is then flooded before a sand-rich shallow marine system prograding west to east over the first deposited sand. The unit is again followed by a regional flooding event as the area settles back to a deeper marine environment in unit 3a before a new gradual shallowing of the basin. A gross depositional environment map has been created of the interpreted shallow marine environment in unit 2. Figure 6-5 compares the attribute maps of PaleoScan surface 3 and the interpreted GDE map from this time.

Figure 6-5: PaleoScan surface 3 attribute maps and interpreted GDE

Several analogues have been studied on Google Earth, and Figure 6-6 shows an overview map of the main one used for comparison (Google Earth, 4/17/2003). The analogue is from a tidally influenced river on the east coast of Africa, in Mozambique. Similarities between the analogue and the interpreted GDE is shown in Figure 6-6. The GDE has been flipped to match the western direction of the prograding shelf in the analogue opposite of the northern progradation in the studied sand attribute maps. The morphology of the interpreted feeder channel is similar to the tidally influenced river mouth shown in this and also studied in several other tidally influenced river analogues. From this, one can infer that modern-day analogues of shallow marine tidal systems strengthen the interpretation from seismic in the study area of a variation from deeper marine to shallow marine systems through time and space.

Figure 6-6: Location of analogue in Mozambique from Google Earth (Google Earth, 4/17/2003).

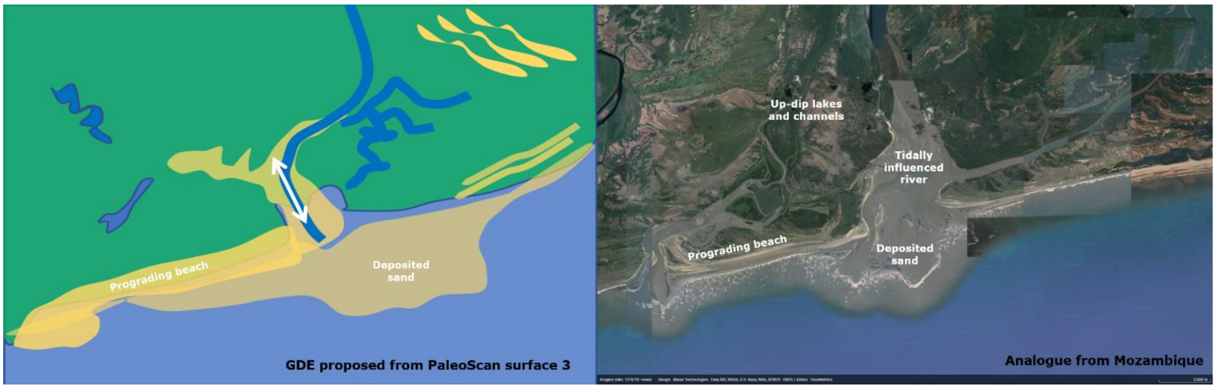


Figure 6-7: Comparison of interpreted GDE and analogue in Mozambique (Google Earth, 4/17/2003).

The extensive erosion and deposition of the studied sand bodies in unit 2 may be interpreted as a response to a sea level fall during this time. Deposits related to a sea level drop in early Chattian time (mid Oligocene) have been recorded by studies in other areas of the North Sea (Sørenson, et al., 1992); (Danielsen, et al., 1997). Sørensen et al., (1992) observed Chattian sands in the southeast Norwegian North Sea area that they proposed had been deposited in response to an uplift of the Fennoscandian Shield. A study in the Danish North Sea sector identified two types of low-stand prograding deposits within the Oligocene sequence stratigraphy and concluded that there was an overall southward progradation of the shoreline during the Oligocene, with minor interruptions of shoreline retreats (Danielsen, et al., 1997); (Bleivik, 2019). The findings from this study in the Northern North Sea Viking Graben area show similarities to these studies with a prograding sandy system in unit 2.

Whether this potential sea level drop causing the deposition in unit 2 was initiated during mid or late Oligocene time is difficult to determine as the wells within this area need more data for age determination. The top of unit 3 is thought to be the transition from the Oligocene to the Miocene time. This surface has been correlated to the previously mapped

Top Oligocene sequence of the semi-regional study. The interpretations from the semi-regional study have been tied to wells investigated by the regional NPD study, where ages have been confirmed with biostratigraphic data. The detailed study interpretations are compared to the semi-regional and age-correlated interpretations in Figure 5-4.

The semi-regional interpretations divided the Oligocene sequence into two main units. Figure 6-8 is from the Specialisation project fall 2022 and illustrates how the previous sub-regional study was correlated and compared to the regional NPD study interpretations. The sub-regional study attempted to divide the Oligocene into an upper sand section and a lower mudstone section to reflect the NPD interpretations. However, it is evident from the figure that several problems and questions were posed to this interpretation. The three units in the current detailed Oligocene study are data-driven and show more detail from seismic facies analysis that points towards a more geologically dynamic Oligocene sequence. The detailed study does not extend as far north as the interpreted cross section shown in Figure 6-8, but similarities can be compared.

One of the findings from this detailed study is that the Ull formation may not be the only sand sourced from the East Shetland Platform present in the Oligocene sequence in this area. The Ull formation is described to be of turbiditic origin and is interpreted to have been deposited in bathyal conditions (Rundberg & Eidvin, 2005); (Eidvin, et al., 2022). This formation has mainly been studied in the Northern Viking Graben, Tampen area, which is located North of the PGS16M01 survey. Eidvin et al., (2022) mention that Chattian deposits have also been recorded below the Skade formation in the Frigg field area. These deposits are drawn in as a conceptual model in several NPD study figures but have yet to be described in detail. The interpreted seismic section shown in Figure 6-8 shows that these sands have been interpreted as the Ull formation. The sands interpreted in this detailed study do not match the description of the Ull formation, as they are proposed to have been deposited in a shallow marine environment. Eidvin et al., (2022) say that deep marine bathyal conditions prevailed in the basinal areas until the late Miocene. The interpretations from this detailed study propose that the basinal area has been changing through the Oligocene time and that a period of low-stand may have sourced the deposition of possibly forced regression local sand deposits in the area. These new interpretations may explain the challenges posed in the previous overburden interpretations of the area shown in Figure 1-4. Here the sand sourced from the east may have been misinterpreted as the Ull Formation.

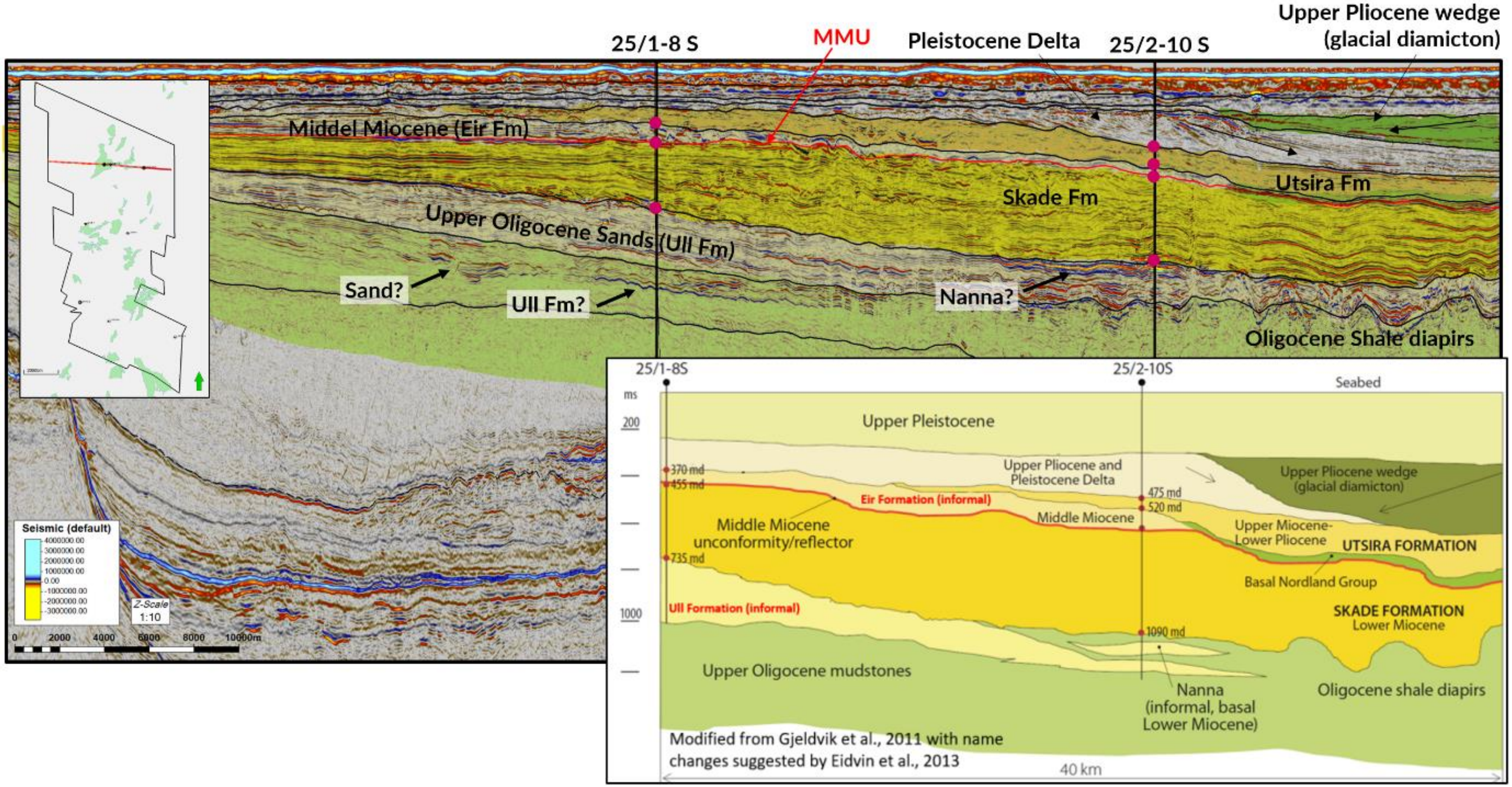


Figure 6-8: Initial interpretations from the sub-regional study covering the full PGS16M01 survey compared to the interpreted geo-section by the NPD study. Modified figure from (Helland-Hansen, 2022).

6.2 Data Limitations

One of the limitations to the current understanding is the limited data quality and availability in the overburden sequences. The data is usually focused for deeper prospective stratigraphy of higher economic value to oil and gas companies. Detailed well logs are not collected in the overburden, and the seismic data is processed and optimized for a broader scope. Therefore, one of this master project's goals has been to improve the data quality.

The seismic data has been analysed, and a post-processing conditioning workflow has been applied to remove noise. The main challenge through the noise removal process was to not remove geological signal and important frequency information. This can be challenging as there is so much noise present in the overburden that to remove it, some geological information may follow. It is therefore important to remember the goal and main purpose of the resulting seismic throughout the processing procedure. The conditioning was conducted and optimized for the main Oligocene sand body, and the signal of deeper or shallower geological features has not been considered. Figure 4-5 shows an example from the first denoise filter applied. When applying this filter, a maximum dip value is assigned and all steeper dipping features will be interpreted as noise. The figure shows that more data has been removed from the lower half of the window. Most of this removed data is believed to be noise, but there is reason to believe that part of this is signal removed from the steeper dipping injectite sands that we know are present below the region of interest. These trade-offs where removing noise in one area will affect the signal in other areas are essential to be aware of when using the resulting seismic for later interpretations.

The difference between the original and conditioned seismic data is most evident when comparing the seismic attribute maps (Figure 5-3). The results show that the conditioned data attribute map is smoother and less noisy than the original seismic. It is still important to remember that the two surfaces that the attribute maps have been displayed on have been created using separate geo models, and their time consistency may not be the same in all areas of the volume. Time consistency of the continuous PaleoScan surfaces is important to keep in mind when interpreting. This is also why manual interpretations in Petrel are conducted before using the PaleoScan software and further used to guide the model. The same interpretations have been used to guide the original and conditioned seismic data model, and one can assume that the main differences are due to the difference in the seismic data.

The well-log data has also been analysed in more detail. Various methods, including rock physics analysis and a machine learning algorithm, have been applied to quality check the available well logs and estimate new well logs. To account for missing data, synthetic Density logs, and ACS data have been created based on the present logs. As discussed in the specialisation project estimating new logs, such as synthetic Density curves from the measured Sonic log, will not create any new information, and the synthetic density curve will correlate directly to the measured sonic curve (Helland-Hansen, 2022). In addition, the sonic log quality is questionable as there are several areas where poor measurements lead to significant kicks in the sonic log (Helland-Hansen, 2022). The sonic log and density curve are necessary when creating a seismic-to-well tie. Poor quality logs will therefore directly affect the resulting synthetic seismic (Helland-Hansen, 2022) The well ties were conducted on the conditioned data and compared to the original seismic well ties. The correlation factor improved by only 0.1 and was still very poor. The poor data quality and availability of overburden logs make it challenging to create reliable well ties, and removing noise in the seismic data itself did not improve the correlation results significantly. Even though the well ties do not show significant correlation, the interpreted sand body correlates well with the tied Gamma ray and predicted lithology log. The lithology log has been created using Aker BP's internal Machine learning (ML) model. The model takes in all present and predicted well-log curves and uses these to predict the present lithology. Even though the model utilizes more data to predict the lithology curves, it will still be limited by the low quality of the present well logs. Another limitation is that the resulting ML Lithology curve can only differentiate between sand and shale. The present geology is interpreted to be more complex and varied than this, and in the Chronostratigraphic chart, there are also sections interpreted to be silty.

Finally, the findings of this study are limited by the lack of biostratigraphic data in the detailed study wells. Precise age determination of the studied sand is therefore challenging and has been based on the correlation of interpretations with the sub-regional surfaces. These previously interpreted sub-regional surfaces were tied to two re-dated NPD wells further North in the PGS16M01 study area.

7 Conclusion

An integrated approach, including geological and geophysical analysis, has been used to study the Northern North Sea's local depositional systems of the Oligocene time. The method consists of three main steps: seismic mapping, well calibration, and predictive seismic stratigraphy. One of the main limitations is the quality and availability of data in the overburden sequences. The study has therefore conducted a post-processing conditioning workflow to optimize the seismic data quality and remove noise. The conditioned data has further been used for seismic mapping and well calibration. The resulting mapped horizons, seismic facies descriptions, attribute maps, and well data have been integrated, and the interpretations have been synthesised in a Chronostratigraphic chart. The results from the detailed study have been discussed in relation to previous work and published literature.

The conditioning workflow applied has significantly improved the quality of the seismic data. The resulting seismic is smoother, less noisy, and detailed geological features are more prominent. The results have demonstrated the value of conditioning the seismic data before conducting a detailed interpretation study.

An improved seismic-lithostratigraphic subdivision of the Oligocene strata has been proposed for the Greater Alvheim area in the Northern North Sea. The sequence has been subdivided into three main units separated by two regionally confirmative surfaces. The previously interpreted Ull Fm in this area has been re-evaluated, and based on the findings from this detailed study, it has been proposed that the deposits originate from a shallow marine environment rather than purely marine and bathyal conditions of the Ull Fm. It is therefore suggested that the Ull Fm is not the only sand sourced from the East Shetland Platform during the Oligocene time, and this new formation has been deposited during a potential low-stand before the basin was flooded again.

The new understanding that the geology is more varied in the late Oligocene with relatively quick temporal and lateral changes from marine to shallow marine depositional environment means that this stratigraphic interval warrants a better interpretation over a larger regional area. The detailed study findings impact not only correlation efforts, but there are likely to be similar non-mapped, potentially isolated, and sealed-off sand units present in the region. These sands can be prospective for shallow oil and gas, CO_2 storage sites, and potential drilling hazards if over-pressured.

More work is needed to fully understand and map out the extent of these shallow marine observations. One of the main limitations is the need for Biostratigraphic and detailed well logs for correlation. It would therefore be interesting to analyse the re-dated NPD wells in more detail to see if more evidence can be found. Conducting a geophysical inversion would be beneficial to map out the extent of other potential shallow marine sands within the Oligocene. Prior to an inversion, it is necessary to expand the conditioned volume area. However, the same workflow and parameters used in this study can be applied as these are optimized for sand at this depth interval.

The study highlights the importance of studying shallow stratigraphy in more detail to understand the geological history of these recent geological times fully. Local depositional systems and their source-to-sink relationship can reveal details that regional studies may have overlooked.

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