University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Petroleum Geosciences Engineering	Spring, 2016 Open
Writer: Victoria Christin Fløystad Pettersen	 ____________________ (Writer's signature)
Faculty supervisor: Sylvia Nordfjord External supervisor(s):	
Title of thesis: Tectono-stratigraphic development of the Cenozoic sedimentary succession of the shallow water Norwegian Sea	
Credits (ECTS): 30	
Keywords: Sequence Stratigraphy Norwegian Sea Cenozoic period 3D seismic interpretation Regional study	Pages: 79 +enclosure: CD Stavanger, 15.06.2016

TECTONO-STRATIGRAPHIC DEVELOPMENT OF THE CENOZOIC SEDIMENTARY SUCCESSION OF THE SHALLOW WATER NORWEGIAN SEA

By

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MASTER THESIS

Presented to the Faculty of Science and Technology

The University of Stavanger

THE UNIVERSITY OF STAVANGER

JUNE 2016

Acknowledgements

This study was conducted at the Department of Petroleum Engineering at the University of Stavanger, as a part of my master degree in petroleum geoscience engineering. I would like to acknowledge several people that have been important for me and my research project and master program. First, I would like to thank my supervisor, Dr. Sylvia Nordfjord for the helpful discussions, guidance and constructive comments and feedbacks throughout this process. Her persistence, dedication and support has been crucial for the end-result, and has been a big inspiration. I also wish to thank Statoil ASA for providing the dataset that made this thesis possible.

I also wish to thank Dr. Alejandro Escalona for the support throughout the master program. He gave me many challenges and opportunities to grow personally and professionally, and for this, I am truly grateful.

Lastly, I wish to express my appreciation to everyone that supported and entertained me throughout the master program. However, I am sorry that this thesis has created such chaos for the family I was given, and the family I have chosen. I dedicate this thesis to all of you.

Victoria C. F. Pettersen
Stavanger, 15.06.16

Abstract

TECTONO-STRATIGRAPHIC DEVELOPMENT OF THE CENOZOIC SEDIMENTARY SUCCESSION OF THE SHALLOW WATER NORWEGIAN SEA

Victoria Christin Fløystad Pettersen, M.Sc.

The University of Stavanger, 2016

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The understanding of Cenozoic sedimentary succession in the Norwegian Sea (62°N-69°N) has proven to be important in petroleum exploration endeavors in the Norwegian Sea. The purpose of this study was to improve the understanding of the dynamics of the Cenozoic depositional and sedimentary system of the mid-Norwegian Continental Shelf. This study includes a seismic stratigraphic and seismic facies analysis on a mega-regional 3D seismic survey and seventeen exploration wells on quadrants 6507, 6508, 6607 and 6608.

The Cenozoic succession formed as a response to a complex interplay between a set of diverse controlling factors, such as tectonics, climate, sediment supply and accommodation space. Seven seismic sequences and six seismic facies were identified and mapped based on reflector terminations and internal reflector configuration. The bounding surfaces between these sequences include Regional Downlap Surface (RDS), Unconformity Clinoform Surface (UCS) and Upper Regional Unconformity (URU).

Sedimentation rates changed through time, mostly depending on glacial activity and relative sea level changes. A model for the tectono-stratigraphic development for the Norwegian Sea is proposed, incorporating major bounding surfaces, tectonics, eustacy and climatic changes.

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1.0 INTRODUCTION

The Cenozoic sedimentary successions on the passive continental margin of the Norwegian Sea display great variations in facies and depositional environments. These deposits are of central importance in petroleum exploration as they have a big influence on reservoir configuration and top seals (Henriksen et al., 2005). Offshore Mid-Norway, most of the commercial hydrocarbon discoveries are located at the Halten Terrace and surrounding areas (Figure 1).

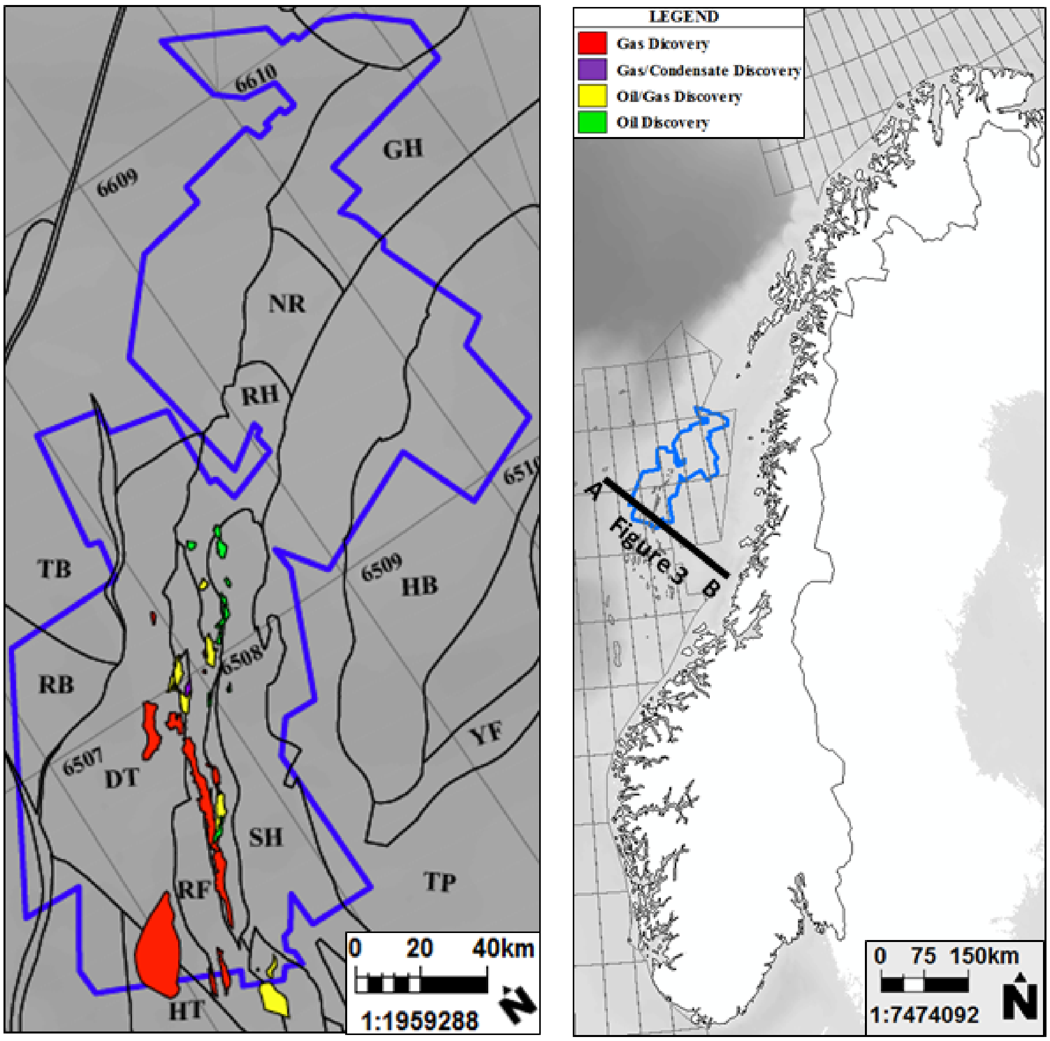

Figure 1. The geographic location of the study area situated in the Norwegian Sea in relation to mainland Norway (GEBCO, 2009). Structural elements and discoveries have been defined by the Norwegian Petroleum Directorate (NPD), and the study area for this thesis is located within the blue polygon. DT: Dønna Terrace, GH: Grønøy High, HB: Helgeland Basin, HT: Halten Terrace, NR: Nordland Ridge, RB: Rås Basin, RF: Revfallet Fault Complex, RH: Rødøy High, SH: Sør High,, TP: Trøndelag Platform, VB: Vøring Basin

The early stage of exploration in the Norwegian Sea was restricted mainly to Jurassic targets in the Halten Terrace, Dønna Terrace and Nordland Ridge areas (Henriksen et al., 2005). Reservoir sandstones of Cenozoic age are uncommon and this play was consequently not considered very prolific in this region. However, the reservoir rock potential and trapping mechanisms of the Cenozoic succession is well documented in the North Sea and by the Ormen Lange gas field in the southern Norwegian Sea.

In geological history, the mid-Norwegian Continental Shelf (NCS) has experienced several phases of rifting, uplift and erosion, but its present shape was formed during Neogene with the development of a thick prograding shelf succession. This was due to a complex interplay between a set of diverse controlling factors, such as tectonics and tilting (due to uplift and subsidence), climate, sediment supply from a variety of sources, and sediment transport mechanisms (Rise et al., 2010, Rise et al., 2005, Ottesen et al., 2009). The Plio-Pleistocene sedimentary succession is considered to be glacially driven prograding wedges formed by westwards transportation of glacial and glacio-fluvial sediments derived from mainland Norway. This area is particularly suited for studies of the interaction between climate and tectonics.

1.1 Objectives

The primary objective of this study is to provide a broad tectono-stratigraphic framework of the Cenozoic deposits in the Norwegian Sea by interpretation of 3D seismic data and seventeen wells from quadrants 6507, 6508, 6607 and 6608 of the NCS (Figure 1). This will be one of the first studies where the Cenozoic deposits in the Norwegian Sea have been interpreted on 3D seismic reflection data on a regional scale. The 3D seismic data allows for a sequence stratigraphic analysis temporally and spatially of the entire Cenozoic section over an extensive area, and aids to constrain the timing of events. It also enables high-resolution attribute analysis and visualizing of paleogeography based on thickness and attribute maps. The wells will contribute to obtain a improved age control and hence, reduce uncertainty in the interpretation.

Additionally, this project also aims to map out the sequence stratigraphic boundaries and the relationship between accommodation space and sediment supply throughout the Cenozoic succession. The 3D seismic stratigraphy and the well interpretation lead to a shoreline trajectory and facies analysis, along with chronostratigraphic charts for the study area. In terms of hydrocarbon potential, the Cenozoic interval are considered targets in the Norwegian Sea area, consequently, a study of these deposits might reveal undiscovered plays (e.g. intervals containing reservoir, seal rocks and trapping mechanisms).

1.2 Previous studies

The last major shaping of the shelf topography occurred during the Late Weichselian glaciation, and several types of moranic ridges and glacial lineations demonstrate the dynamic nature of the Scandinavian palaeo-ice sheet (Ottesen et al., 2009). Rise et al. (2005) and Rise et al. (2010) have previously mapped the depositional pattern of the last three glaciations on the outer shelf. This has revealed very dynamic nature of the ice sheets with changing depocenters from glaciation period to glaciation period.

The sedimentary regime when large volumes of sediments in the Pleistocene were deposited, and especially the lower parts, has been an ongoing topic of discussion (Rokoengen et al., 1995, Henriksen and Vorren, 1996, Rise et al., 2005, Ottesen et al., 2009). These thick deposits were most likely caused by the onset of glaciations in Scandinavia, which led to major erosion of the mainland (Ottesen et al., 2009). This is why the sedimentary succession is considered to be prograding wedges formed by westward transportation of glacial and glacio-fluvial sediments from the mainland Norwegian Shelf.

The Cenozoic Era was in general a period of regional uplift, the exact timing and mechanisms are however highly debated, but can generally be associated with the opening of the Norwegian Sea (Stuevold and Eldholm, 1996). There is evidence of atleast two separate uplift events during the Cenozoic, where the first represents a plate-boundary syn-rift uplift associated with the continental breakup. The second is an intraplate flexural deformation linked to heating from the Icelandic plume, characterized by a two-stage uplift (Stuevold and Eldholm, 1996).

Previously, several sequence stratigraphic studies have been conducted on the Cenozoic deposits on a regional scale in the Norwegian Sea and North Sea (Figure 2). Most of these studies are however focused on the Pleistocene deposits, and there has not been a clear focus on the sedimentary outbuilding on the narrow Dønna Terrace. In addition, these studies were performed on regional 2D lines over significant distances, without sufficient well control. Consequently, the age control of some of these sequences might be inadequate.

Rise et al. (2010) divided the Naust Formation into 5 units; N, A, U, S and T, while other studies, such as Talat (2012) identified 32 sequences in the same interval (Figure 2). However, most of the studies concur regarding some of the bounding surfaces.

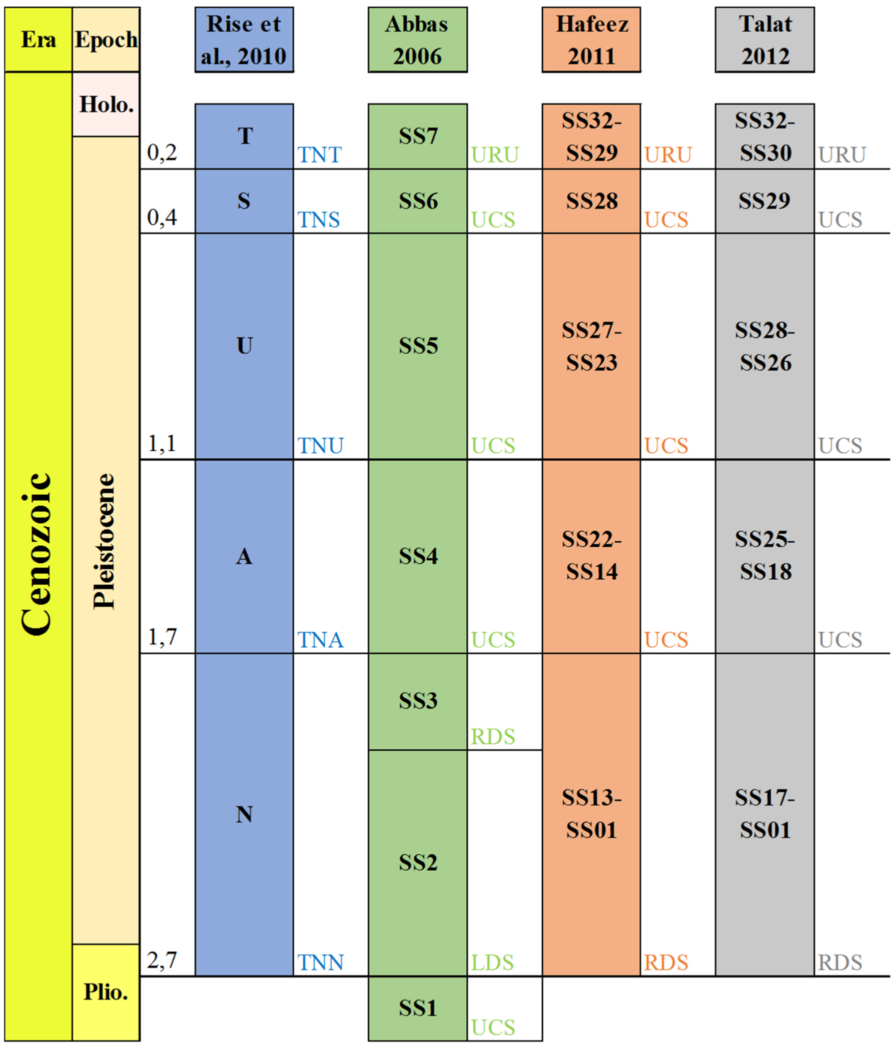

Figure 2. Summary of previously defined sequences and horizons in the Plio-Pleistocene prograding wedge in the Norwegian Sea. Based on Rise et al. (2010), Abbas (2006), Hafeez (2011) and Talat (2012). URU: Upper Regional Unconformity, LDS: Local Downlap Surface, RDS: Regional Downlap Surface, UCS: Unconformity Clinoform Surface,

2.0 GEOLOGICAL SETTING

The Norwegian Sea is a part of the Atlantic Ocean located offshore Mid-Norway, and covers most of the passive continental margin between approximately 62^0 and 71^0N. This margin developed in an area impacted by sequential episodes of regional lithospheric extension, followed by subsidence, leading to the development of several sedimentary basins. The Caledonian basement underlies most of the mid-Norwegian margin. Weak zones inherited from the Caledonian orogeny played a major role in later evolution of the continental margin off mid-Norway with formation of sub-basins, structural highs and lineaments (Brekke et al., 2001). Figure 3 illustrates an example of the configuration of the strata offshore Mid Norway.

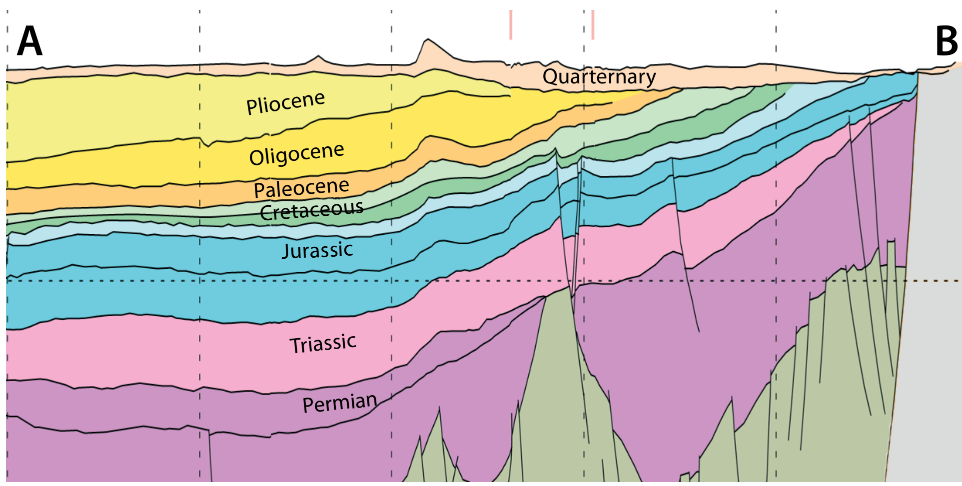

Figure 3. Subcroping strata under the Quaternary offshore Mid Norway, modified after Sigmond et al. (2002). Location of geoseismic line is shown in figure 1.

According to Blystad (1995), the tectonic history of the Norwegian Sea can be divided into three major episodes:

1. The final closure of the Iapetus Ocean during the Caledonian Orogeny during Late Devonian
2. The Late Devonian to Paleocene epoch was dominated by a series of mainly extensional deformation episodes, culminating with the continental separation of Greenland and Eurasia
3. Active seafloor spreading in the North Atlantic between Eurasia and Greenland during earliest Eocene to Present (Figure 4)

All rift phases and subsequent post-rift thermal cooling phases were characterized by subsidence and deposition of sediments, mostly marine sandstones and mudstones, but also continental facies. Basin inversions also took place along rotated fault blocks and structural highs.

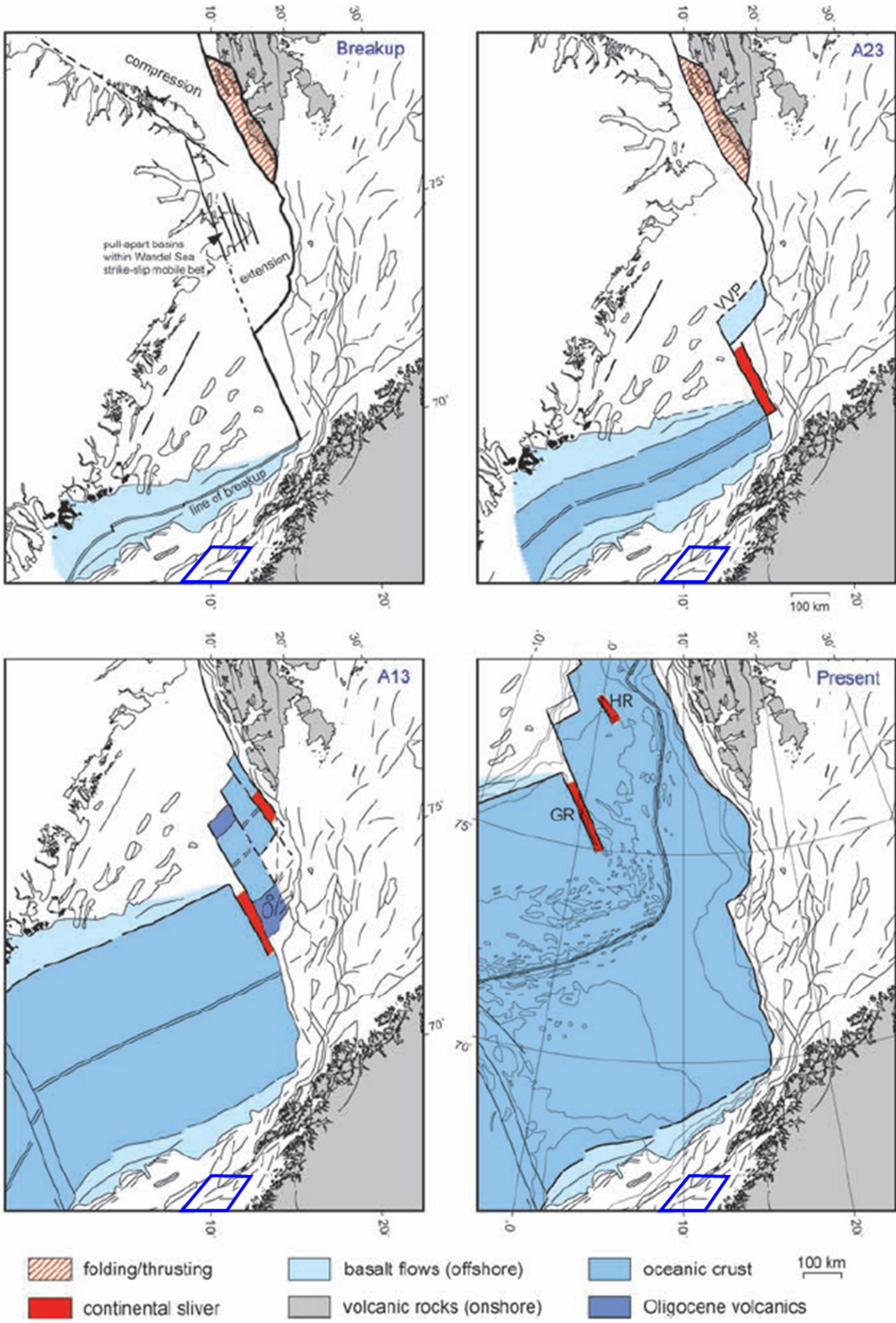

Figure 4. Cenozoic plate tectonic evolution of the Norwegian-Greenland Sea. GR: Greenland Ridge, HR: Hovgård Ridge, VVP: Vestbakken Volcanic Basin (Faleide et al., 2008). The study area is marked with a blue box, and extends towards the south.

2.1 Structural elements

The present geomorphology of the NCS developed on a passive continental margin that was formed during early Eocene (Blystad, 1995). In the shallow Norwegian Sea, seafloor depths range between 100-200 meters on the shallow bank areas to the deep transverse glacial troughs, and the shelf break is located at depths between 280 and 410 meters (Dahlgren et al., 2002). Several troughs and depressions separate the shallower bank areas on the platforms and highs (Figure 1). Many of these troughs have been important for the margin development, as they represent paths for enhanced glacial transport by palaeo ice-streams during the Late Quaternary (Ottesen et al., 2001).

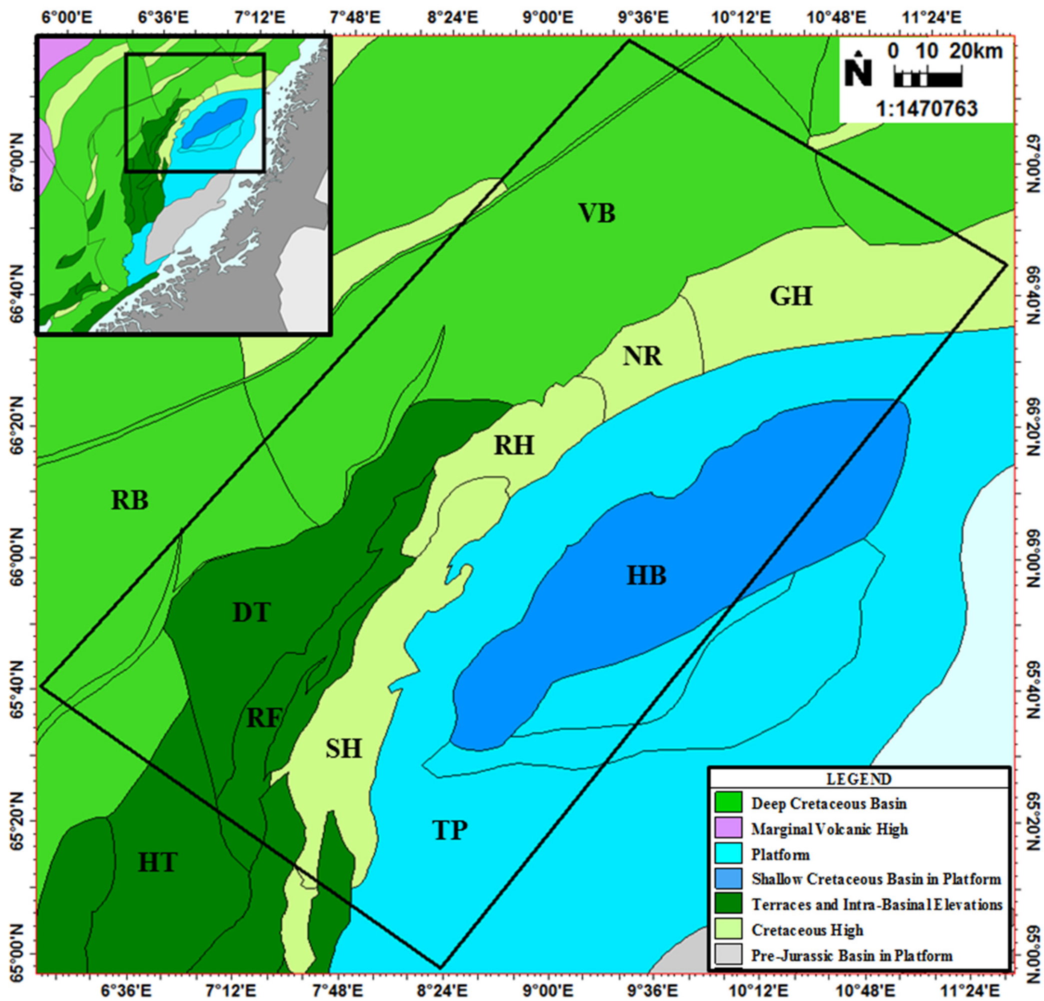

Figure 5. Regional map of the Norwegian Sea with structural elements (defined by NPD), focus area is within the black box. DT: Dønna Terrace, GH: Grønøy High, HB: Helgeland Basin, HT: Halten Terrace, NR: Nordland Ridge, RB: Rås Basin, RF: Revfallet Fault Complex, RH: Rødøy High, SH: Sør High,, TP: Trøndelag Platform, VB: Vøring Basin

2.1.1 Dønna Terrace

The Dønna Terrace (DT) is a structural element of the Meso-Cenozoic mid-Norwegian margin. It is bounded by the Revfallet Fault Complex against the Nordland Ridge to the east-southeast, and the Ytreholmen Fault Zone to the west-northwest (Figure 5). The terrace dies out north-west of the Rødøy High in the north, while in the south the Dønna Terrace becomes somewhat wider and less well-defined as is approaches the northern part of the Halten Terrace (Blystad, 1995). The Dønna Terrace is highly faulted, with tectonically induced basins with major faults trending N-S to NNE-SSW, and minor fault trending NNW-SSE, which created horsts, grabens and rotated fault blocks (Hollander, 1984). This structural development is related to crustal stretching in the Jurassic and further down-faulting relative to the Nordland Ridge in the Late Cretaceous.

2.1.2 Revfallet Fault Complex

The Revfallet Fault Complex (RF) is composed of westerly-dipping, left-stepping, en echelon normal faults oriented NNE-SSW (Figure 5). The most pronounced single fault in the Revfallet Fault Complex is in the southwest where displacements of more than 2000 m are recorded (Blystad, 1995). The RF defines the western boundaries of the Nordland Ridge and Trøndelag Platform and separates these from the Dønna Terrace (in the south) and the Træna Basin.

2.1.3 Trøndelag Platform

The Trøndelag Platform (TP) covers an area of more than 50,000 km^2 (Figure 5). This has been a large stable area since the Jurassic and the platform is covered by relatively flatlying and mostly parallel-bedded strata, which usually dip gently northwestwards (Blystad, 1995). The Trøndelag Platform is one of the major structural elements off central Norway and includes several subsidiary elements like the Nordland Ridge and Helgeland Basin. In the north and west, the platform is bounded by the Revfallet Fault Complex, which runs along the Nordland Ridge separating it from the Vestfjorden and Træna Basins in the north and the Dønna Terrace in the south.

2.1.4 Helgeland Basin

The Helgeland Basin (HB) is bound by Nordland Ridge and the crestal part of the Trøndelag Platform in the west. The HB is mainly a Cretaceous feature, although signs of subsidence relative to the Nordland Ridge may be traced from mid Jurassic time (Blystad, 1995). It is intimately connected with the development of the Nordland Ridge, and is a depocenter on the lower part of the southeasterly tilted platform.

2.1.5 Nordland Ridge

The Nordland Ridge (NR) is an elongated structural high situated between 65°15'N - 66°50'N and 7°30'E -12°30'E (Figure 5). It is delimited to the northwest by the Revfallet Fault Complex and to the east and southeast by the Helgeland Basin (Blystad, 1995). Along the extension of the Nordland Ridge, its orientation changes from NNE-SSW to NE-SW. The ridge is transected by deep faults, and three individual highs have been described from south to north: the Sør High, Rødøy High and Grønøy High.

Structuring of the Nordland Ridge area started in Late Carboniferous-Early Permian time, and continued activity in the Triassic and Jurassic culminated in an increase in faulting in the late Middle Jurassic-Early Cretaceous (Blystad, 1995). The Nordland Ridge is defined relative to an unconformity representing a major hiatus.

2.1.6 Vøring Basin

The Vøring Basin (VB) is a large sedimentary basin province off central Norway comprising grabens, basins and structural highs of various ages. Numerous, generally strata-parallel, strong reflectors throughout the basin provinces are interpreted as igneous sills and dykes. Unlike the volcanics of the adjacent Vøring Marginal High, the sediment record of the Vøring Basin documents the history of the passive margin before, during and after rifting.

2.2 Cenozoic Development

During the Cenozoic Era the collision of India with Asia, and Africa with Europe continued, creating one long mountain chain from the Pyrenees and the Alps in the west, to the Himalayans in the east (Martinsen and Dreyer, 2001). This had a significant impact on the ocean currents, the wind systems and ultimately the climate.

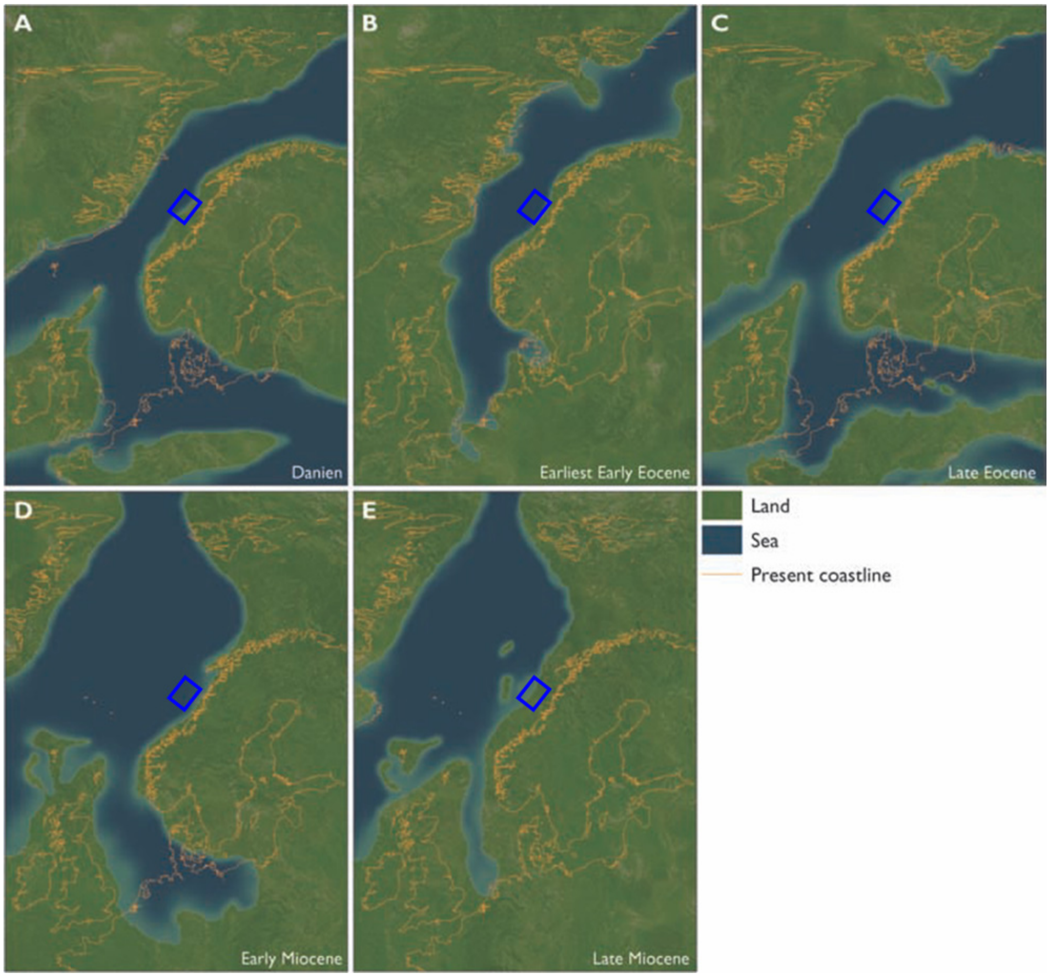

Figure 6. Paleogeographic reconstruction of the NE Atlantic Sea during the A) Danian, B) Earliest Early Eocene, C) Late Eocene, D) Early Miocene, E) Late Miocene. The study area is shown as a blue box. (Modified after Rasmussen et al. (2008))

In the Norwegian Sea, Cenozoic deposits reveals great variations in thickness, facies, and depositional styles, depending on regional and local structural elements and other controlling factors on the depositional and sedimentary systems. The sedimentary environment was a response to the Paleogene transition from the continental rift setting to a drift and passive continental margin setting, and the subsequent climatic change (Brekke et al., 2001, Eidvin et al., 1998). Additionally, Scandinavia was exposed to tectonic uplifts in the late Cenozoic due to glaciation. Consequently, the NCS successions contains a prominent record of combined effects of climate in glacial periods and tectonics (Ottesen et al., 2009).

During Paleocene, the NCS experienced a regional uplift and subaerial exposure of the mainland (Figure 6), resulting in increased sediment transport (Eidvin et al., 2007). The erosion of the mainland transported large amounts of sediment out into the basin, through old fault complexes along the coast. Most of the sediments came from the eastern coast, but some of might have originated from East Greenland. Towards the beginning of the seafloor spreading, the area experienced an increase in volcanism caused by the commencing of the rift.

During the Eocene, the continental crust was split in half between Norway and Greenland due to extensive rifting. This resulted in the formation of oceanic crust along the newly established oceanic ridge. As the two continents continued to drift apart, the newly formed seafloor cooled down and subsided. After the regional uplift in Paleocene, the area experienced subsidence followed by the Ypresian transgression (Figure 7) of the Norwegian shelf and the mainland (Figure 6) (Eidvin et al., 2007). Eocene was also a period of global warming, possibly connected to the volcanism of the continental breakup (Figure 7).

Oligocene was a period with tectonic activity, which resulted in compression and regional uplift (Eidvin et al., 2007). The seafloor spreading continued and the ocean between the continents expanded, and the thermal cooling of newly formed seafloor caused the basin to subside further and the water depth continued to increase (Figure 6). With the greater water depths, less sediment was transported into the basin. The transition from Eocene to Oligocene also represents the shift from predominantly warm climate, to a colder and less tropical climate. And the changes in the $\delta^{18}O$ isotope trend (Figure 7) indicate a drop in sea level temperature, from approximately 12 to 4.5 °C (Rasmussen et al., 2008).

The interval between Lower Eocene and Middle Miocene is defined by a hiatus known as the Mid-Miocene Unconformity, defined as a period of non-deposition, and not as a period of erosion (Eidvin et al., 2007). Polar ice caps were rebuilt in Antarctica, causing a major sea level fall (Figure 7). Middle to Late Miocene was the second compressional phase recorded after the initiation of the seafloor spreading. Uplift of the mainland caused a major regression, moving the coastline 50-150 km westward of present day coastline (Figure 6). Deltas were built out into the basins, transporting sediments from the Fennoscandinavian mainland (Henriksen et al., 2005, Rasmussen et al., 2008).

Following these events, the area experienced climate cooling and consequently an onset of glaciation. The first glaciations advanced in Late Pliocene, around 2.8 Ma. Before 1.5 Ma, the glaciers did not extend beyond the mainland. Between 1.5 Ma and 0.5 Ma the glaciers advanced onto the shelf and after 0.5 Ma the glaciers covered the shelf in three glacial periods until the glaciers retreated in Holocene (Eidvin et al., 2007).

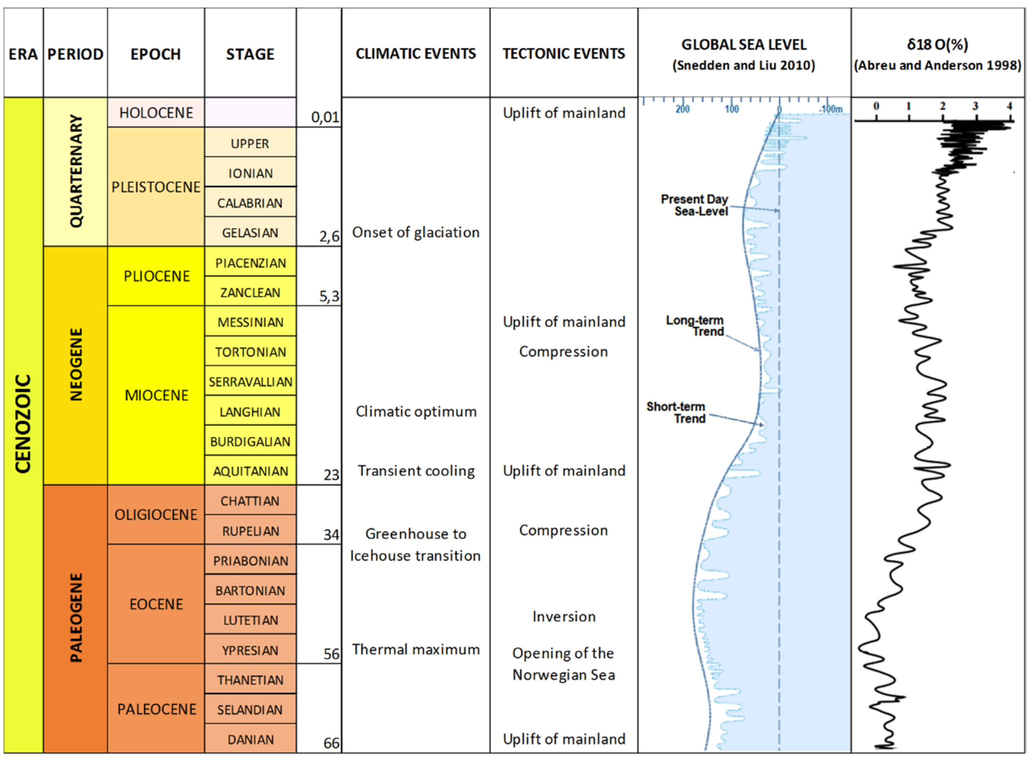

Figure 7. Main tectonic and climatic events during the Cenozoic era in the Norwegian Sea. Ages, tectonics and climatic events are based on: Reemst et al. (1994), Stuevold and Eldholm (1996), Abreu and Anderson (1998), Henriksen et al. (2005), Eidvin et al. (2007), International Commission on Stratigraphy (2009) and Snedden and Liu (2010).

2.3 Lithostratigraphy

The Paleocene to Lower Eocene Rogaland Group (Figure 8) consists of argillaceous marine sediments with clastic sand wedges mainly in the east. In the Paleocene, uplift and subaerial exposure of the Norwegian mainland resulted in progradation of clastic sediments from the mainland into the Norwegian Sea. The sediments consists of a combination of sand, silt and clay, the latter being dominant. Most of the sediments came from the eastern coast, but some of might have originated from East Greenland before the seafloor spreading commenced. In early Paleocene, the clay-dominated formation known as the Tang Formation was deposited (Figure 9). Towards the beginning of the seafloor spreading, the area experienced an increase in volcanism caused by the commencing of the rift. The youngest formation in Paleocene, known as the Tare Formation (Figure 9), has a high content of volcanic constitutes mixed in with the clay-dominated lithology.

After the regional uplift in Paleocene, the area experienced subsidence followed by the Ypresian transgression of the Norwegian shelf and the mainland (Eidvin et al., 2007). Subsequently, the sediment influx from mainland Norway decreased and only a thin clay dominated formation was deposited in the basin, known as the Brygge Formation of the Eocene to Oligocene Hordaland Group. Eocene was also a period of global warming, possibly connected to the volcanism of the continental breakup. The sediments from this period consists of extensive marine mud deposit (Dalland et al., 1988), and include smectitic clays formed from volcanic ash that was spread from subaerial eruptions. The separation between Greenland and Eurasia and the onset of seafloor spreading started in the Earliest Eocene. In Oligocene, the water depth kept on increasing, and subsequently, less sediment was transported into the basin.

The Middle Miocene to recent Nordland Group (Figure 8) overlies a hiatus known as the Mid-Miocene Unconformity, which is defined as a period of non-deposition, and not as a period of erosion (Eidvin et al., 2007). The syn-tectonic Kai Formation was deposited in depressions and synclines related to the compressional structures, such as inversion domes and reactivated reverse faults. Due to the regression, the Kai Formation is the most basinward of the Cenozoic formations and consists of shallow to deep marine deposits, mainly shale (Dalland et al., 1988). The Kai Formation and the proximal equivalent Molo Formation can be found above the unconformity (Figure 9), where the deltaic Molo Formation consist of good developed sands.

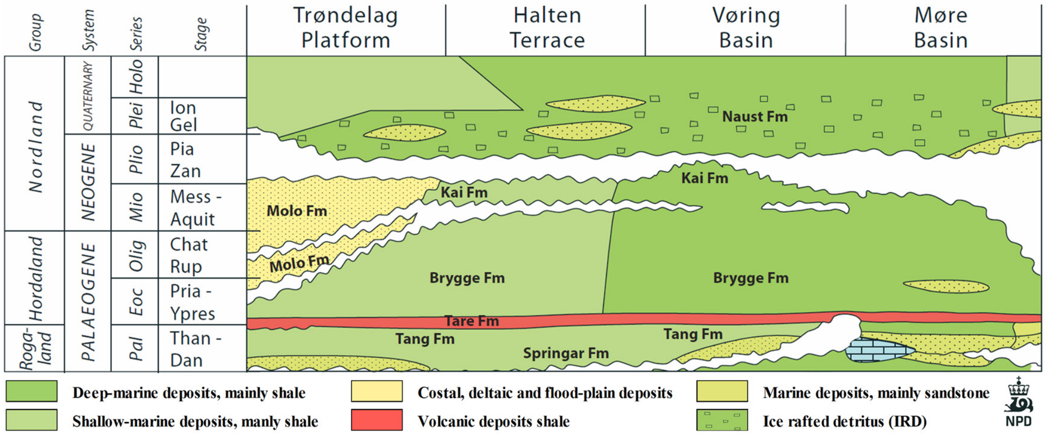

Figure 8. Lithostratigraphic chart of the Cenozoic deposits in the Norwegian Sea modified after Halland et al. (2013)

In the Pliocene and Pleistocene, new uplift and glaciations caused erosion and deposition of thick sedimentary wedges onto the mid-Norwegian shelf (Halland et al., 2013). The Naust Formation is the youngest and shallowest formation in this study and was deposited in the glacio-marine environment, therefore, it consist of shallow marine deposits and ice rafted detritus (Figure 8).

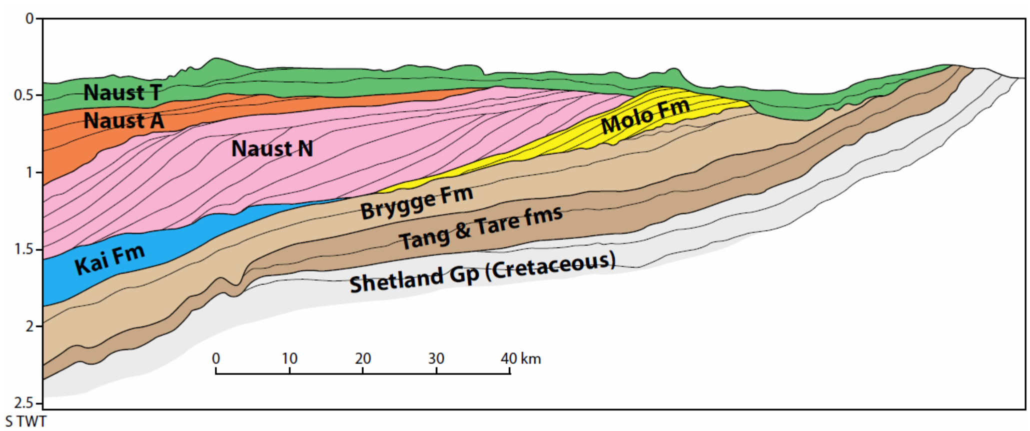

Figure 9. Overview of the Cenozoic succession and formations on the Halten Terrace, based on geoseismic data (Eidvin et al., 2007)

3.0 SEQUENCE STRATIGRAPHY

Sequence stratigraphy is an advanced, well-established tool for investigation of rock successions. The technique focuses on analyzing changes in facies and geometric character of strata, along with identification of key surfaces to determine the chronological order of basin filling and erosional events (Catuneanu et al., 2009). This framework ties changes in stratal stacking patterns to the responses in varying accommodation and sediment supply through time. The technique provides a more effective method for evaluating and predicting reservoir system continuity and directions, source rocks and sealing facies (Van Wagoner et al., 1988).

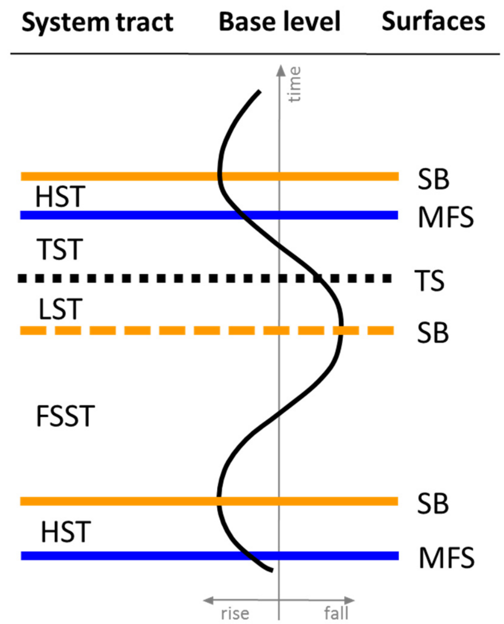

Figure 10. Timing of sequence boundaries and systems tracts in relation to time and base level changes. Modified after (Catuneanu et al., 2011). HST: Highstand system tract, TST: Transgressive system tract, LST: Lowstand System Tract, FSST: Falling sea level stage system tract, SB: Sequence boundary, MFS: Maximum flooding surface, TS: Transgressive surface.

This study follows Depositional Sequence IV (Catuneanu et al., 2011) as a sequence model when defining surface boundaries and systems tracts.

3.1 Seismic stratigraphy

Seismic stratigraphy is a very beneficial tool for continuous subsurface interpretation of structural trends, lapout relationships, depositional features, stratal stacking patterns, geomorphology and stratal geometries (Catuneanu et al., 2009). Systems tracts are identified by geometrically bounding seismic reflectors, as different genetic system tracts refer to different positions of relative sea level during deposition (Catuneanu, 2002).

3.1.1 Key stratigraphic surfaces

It is important to recognize and identify key stratigraphic contacts such as the sequence boundary, maximum flooding surface and unconformity (Figure 10). This is because they indicate times when facies belts shifted position and sediments was eroded from the shelf areas, before being redeposited into the basin. Additionally, they have significant impact on field architecture and modeling of regional reservoir distribution.

Sequence boundaries (SB) are identified as significant erosional unconformities and their correlative conformities. These boundaries are the product of a relative fall in sea level, leading to subaerially exposure, followed by erosion of the sediment surface of the earlier sequence or sequences (Figure 10). These boundaries are diachronous, capping the previous highstand systems tract and eroding the surface of the downstepping sediments deposited during accompanying forced regression associated with the base level fall (Catuneanu, 2002).

The maximum flooding surface (MFS) is a stratigraphic surface that marks a change in stratal stacking patterns from transgression to highstand normal regression (Figure 10). The MFS can be defined as the paleo-seafloor at the end of a transgression, and its correlative surface within the non-marine setting (Van Wagoner et al., 1988). This is often expressed as a downlap surface in seismic stratigraphic terms, as it is typically downlapped by the overlying highstand clinoforms which record progradation.

The transgressive surface (TS) is a marine flooding surface that forms the first major flooding surface in a sequence (Figure 10), and marks the onset of the period when the accommodation space is greater than the rate of sediment supply (Mitchum Jr et al., 1977). It forms the base of the retrogradational stacking patterns. However, if the rate of sediment supply is low over the transgressive surface, this may merge with the MFS.

3.1.2 System tracts

System tracts are defined as contemporaneously linked depositional systems defined by stratal geometries at bounding surfaces, position within the sequence and internal parasequences stacking patterns (Van Wagoner et al., 1988). In this thesis the falling stage systems tract (FSST), lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST) are utilized (Figure 10).

3.1.3 Stacking patterns

Truncation patterns can be used to identify depositional trends (progradation, aggradation and retrogradation) and genetic types of deposits (transgressive, normal regressive and forced regressive) (Catuneanu et al., 2011).

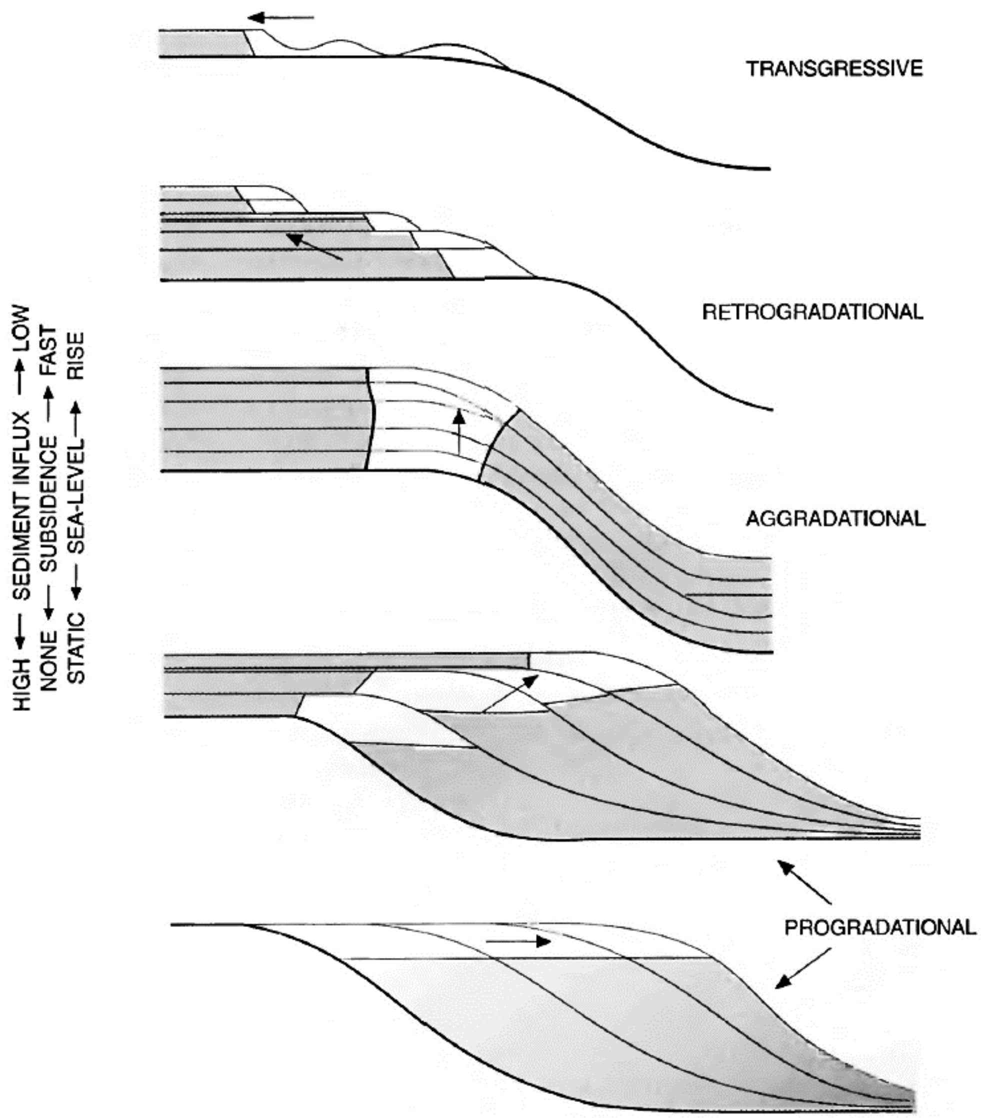

Figure 11. Depositional architectures as a function of accommodation space and sediment supply (Emery and Myers, 2009)

In a retrogradational system, younger sequences are deposited successively landward in a backstepping pattern, because the sediment supply is limited and cannot fill the available accommodation space (Figure 11). This is most common during periods of transgressions or due to extremely low sediment supply.

In a progradational system, younger parasequences are deposited successively basinward because the sediment supply exceeds the accommodation space (Figure 11). This is most common during periods of regressions or extremely high sediment input.

In an aggradational system, younger parasequences are deposited above one another with no significant lateral shifts when the rate of accommodation approximates the rate of deposition (Figure 11).

3.1.4 Parasequences

Parasequences are defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces. In addition to these defining characteristics, most parasequences are asymmetrical shallowing-upward sedimentary cycles (Catuneanu, 2002).

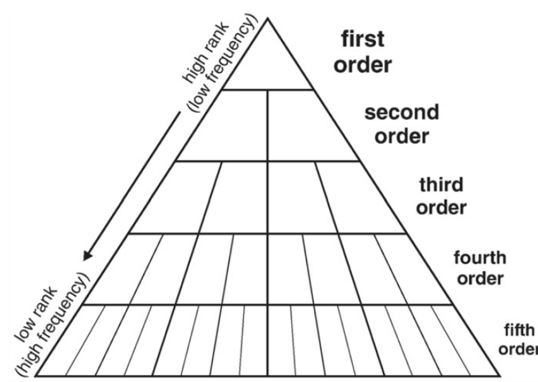

Figure 12. Diagrammatic representation of the concept of hierarchy (Catuneanu, 2002)

The events leading to the formation of the most important sequences and bounding surfaces (first order) occurs less often through the geological time relative to the events leading to the formation of lower order sequence boundaries, shown in Figure 12 (Catuneanu, 2002). Parasequences are usually too thin to discern on seismic data, but when added together, they form sets called parasequence sets that are visible on seismic data. In this dataset, only third order sequences are visible in the seismic.

3.1.5 Clinoforms

Clinoforms are identified through break-in-slope and their migration patterns (Figure 11), and are an integral part of continental shelves as they develop on varying scales, and are influenced by the complex interaction of a multitude of different factors. The term clinoform is used for depositional profile with the complete sigmoidal topset-foreset-bottomset (Emery and Myers, 2009). There is significant interest and economic implications related to understanding how clinoforms develop and what controls their geometry and sediment distribution, as this can contribute to predictions of facies distribution (Anell and Midtkandal, 2015).

3.1.6 Stratal terminations

Stratal terminations (Figure 13) are a result of the interaction between sediment supply and accommodation space, and reveal depositional trends associated with stratal stacking patterns. The stacking patterns are a result of the interaction between variations in sedimentation and base level (Catuneanu, 2002). Toplap truncations and onlaps define events of a fall in relative sea level, whereas downlap seismic surfaces generally imply a rise in relative sea level. The identification of these changes is of major significance when identifying the controlling factors on sedimentary facies and architectural style, including tectonics, climate and eustacy.

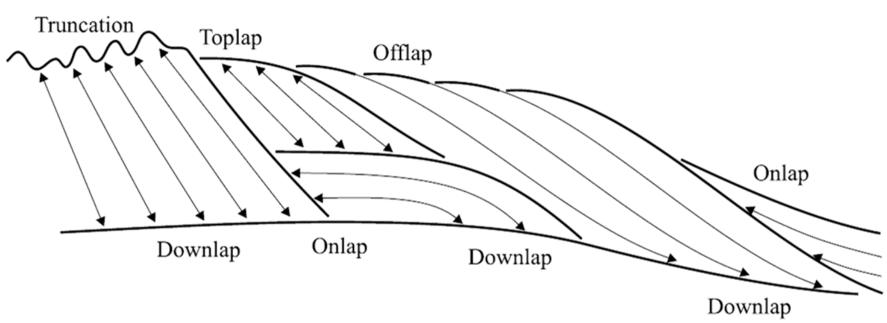

Figure 13. Types of seismic stratigraphic reflection termination (Catuneanu, 2002).

3.2 Shoreline trajectory analysis

A shoreline or shelf margin trajectory is the path taken by the shoreline or shallow shelf margin facies as they change position when a sedimentary basin fills (Helland-Hansen and Martinsen, 1996). The shoreline trajectory concept is used in conjunction with high quality 3D seismic data to determine the existence of a relationship between varying rates and directions of shelf-edge progradation, depositional elements encountered in the costal-plain/shelf environment, and the character and geometry of slope/basin-floor deposits. Shelf transit times influence the supply of sediment to the edge of the shelf, and therefore affect the shelf-edge trajectory. Essentially these trajectories are responsible for the retrogradational, progradational and aggradational stacking patterns. This analysis provide an improved understanding of the relationship between specific facies associations and various shelf-edge trajectories. This may have important implications for the exploration of petroleum reservoirs, and provide an improved understanding of proven petroleum plays.

3.3 Chronostratigraphy

Sequence stratigraphy are used mainly for establishing a notional chronostratigraphic framework as some sequence stratigraphic surfaces can serve as useful time-markers. A Wheeler diagram (or stratigraphic summary chart) plots geologic time as the vertical scale, and distance across the area of interest as the horizontal scale. They also display the horizontal distribution of the contemporaneous component sediment layers of a sequence and significant hiatuses in sedimentation (Wheeler, 1958). These diagrams are commonly built from seismic and may be used to identify trends in potential hydrocarbon reservoir, seal and/or source rock facies. Based on this, sedimentary layers and system tracts of sequences can be considered in terms of their relationship to base level, hiatuses, timing and geographic location (Mitchum Jr et al., 1977).

3.4 Seismic facies analysis

Seismic facies analysis is the interpretation of the environment and lithologies from seismic reflection data (Mitchum Jr et al., 1977). It involves the delineation and interpretation of reflection parameters, as well as the external and three-dimensional associations of groups of reflection patterns; produced by reflection geometry, continuity, amplitude, frequency and interval velocity (Figure 14). By integrating these data, the facies units can be interpreted with environmental setting, depositional setting, depositional processes, and estimates of lithology. Both vertical and horizontal aspects of seismic resolution are a function of acoustic pulse frequency, pulse wavelength and layer velocity.

The concept of facies trajectory coupled with stacking patterns represents an important tool to the interpretation of shoreline and shelf systems. It aids in the determination of the depositional setting of the component system tracts and enables the prediction of the lateral and vertical extent and character of these sedimentary bodies.

However, there is no single characteristic seismic reflection property that provides a unique guide to the recognition of individual facies. Therefore, this kind of analysis is heavily reliant on well control to calibrate the geological models. Each facies should be studied in relation to the neighboring units, and paleo-topography should therefore be considered to ensure that the most probable interpretation of seismic data is made.

SEISMIC FACIES PARAMETERS	GEOLOGIC INTERPRETATION
Reflection configuration	Bedding patterns Depositional processes Erosional processes Fluid contacts
Reflection continuity	Bedding continuity Depositional processes
Reflection amplitude	Velocity-density contrast Bed spacing Fluid content
Reflection frequency	Bed thickness Fluid content
Interval velocity	Estimation of lithology Estimation of porosity Fluid content
External form & areal association of seismic facies units	Gross depositional environment Sediment source Geologic setting

Figure 14. Seismic reflection parameters used in seismic stratigraphy and their geologic significance. Modified after (Mitchum Jr, Vail et al. 1977)

4.0 DATA AND METHODS

This study is based on a dataset consisting of 3D seismic, seventeen exploratory wells, well log sets and lithostratigraphic and chronostratigraphic well tops, that was provided by Statoil ASA. The interpretation of the seismic reflection data and well in Petrel E&P 2014 and OpendTect 5.0, and the analyzed data will aid in understanding the evolution of the Cenozoic deposits in the northern Norwegian Sea.

4.1 Seismic data

The 3D seismic dataset used in this study is a fullstack merge of 18 surveys (Figure 15), and is covering a total area of approximately 17 500 km^2. This mega-merge provides context for regional interpretation work, and allows for a regional sequence stratigraphic analysis. These surveys have different acquisitions, such as spread lengths, source/receiver depths, inline/crossline sampling and shooting directions.

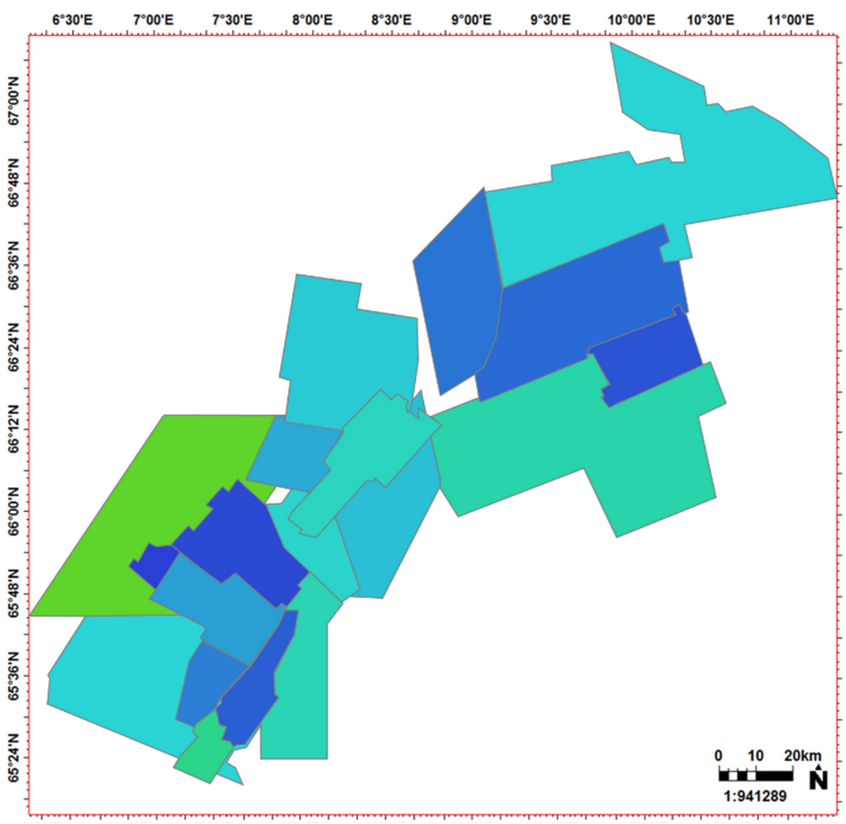

Figure 15. Illustration of all the seismic surveys in the mega-merge seismic cube that are utilized in this study

3D seismic data allows for a relatively high-resolution sequence stratigraphic analysis of the entire Cenozoic section over a large area and helps constrains the timing of events. It also enables high-resolution attribute analysis and visualizing of paleogeography based on thickness and attribute maps.

In this study, the main emphasis has been interpretation down to 3 seconds two way travel time (TWT). A summary table for the full merge is shown in Table 1.

Seismic survey information table	
Geodetic datum	ED50
Projection	UTM 32N
Total area	17500 km^2
Merged surveys	18
Sample interval	4
Number of inlines	10062
Number of X-lines	7399
Inline direction	-66.38°
Grid size	25x25
Polarity	Normal
Dominant frequency	25-30 Hz
Wavelength	128 ms
Wavelet phase	0 degrees
Vertical resolution	23 meter

Table 1. Information table with details regarding the seismic cube

4.2 Well data

Seventeen exploration wells that have penetrated the Cenozoic deposits in the study area are utilized in this study (Figure 16 and Table 2). These wells provide an age control of the sediments, along with detailed information regarding sedimentation rates, unconformities and lithology. The well data consists of conventional well logs, among which gamma ray, sonic, density and resistivity logs were used for this study. The wells with complete sets of sonic and density logs for the Cenozoic interval were used for well ties (red points in Figure 16).

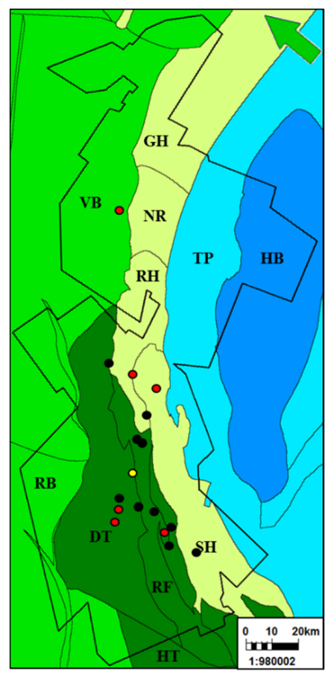

Figure 16. Location of wells utilized in this study is marked as black points, red points mark wells tied to the seismic. The yellow point displays well 6507/3-1 displayed in the well-to-seismic tie below.

The well control in the southern part of the study area is considerable higher than in the north, as illustrated by Figure 16. This is one of the sources of uncertainty in the interpretation and correlation of the seismic sequences and bounding surfaces in this study.

Well bore name	Structural element	Year	Thickness of Naust Fm	Thickness of Kai Fm	Thickness of Brygge Fm	Thickness Tare Fm	Thickness of Tang Fm	Thickness of Cenozoic
6609/5-1	TB	1985	1252 m	177 m	86 m	101 m	202 m	1818 m
6608/8-2	DT	2007	1132 m	114 m	158 m	55 m	32 m	1491m
6507/3-1	DT	1990	912 m	305 m	277 m	36 m	61 m	1591 m
6507/2-2	DT	1992	990 m	283 m	170 m	91 m	46 m	1580 m
6507/2-1	DT	1986	-	255 m	155 m	118 m	44 m	572 m
6507/2-4	DT	2008	-	425 m	52 m	112 m	-	589 m
6507/2-3	DT	1994	997 m	460 m	113 m	57 m	47 m	1674 m
6608/11-3	SH	2002	842 m	57 m	66 m	66 m	15 m	1046 m
6608/10-2	RF	1992	955 m	213 m	292 m	56 m	38 m	1554 m
6608/10-3	RF	1993	966 m	224 m	266 m	57 m	36 m	1549 m
6507/6-2	RH	1991	1062 m	423 m	163 m	58 m	53 m	1759 m
6507/5-2	RF	1990	1030 m	436m	188 m	55 m	33 m	1742 m
6507/5-1	RF	2000	1034m	421 m	185 m	45 m	44 m	1729 m
6507/5-5	RF	2002	1001 m	495 m	133 m	41 m	44 m	1714 m
6507/3-7	RF	2009	697 m	342 m	258 m	54 m	26 m	1377 m
6608/11-4	RH	2004	1012 m	44 m	93 m	-	-	1149 m
6507/6-1	SH	1986	568 m	-	-	-	-	568 m

Table 2. Showing details about the thickness of the Cenozoic deposits in the seventeen exploration wells utilized in this study (based on well tops from NPD)

4.3 Seismic-to-well tie

This step was performed to provide a time-depth relationship between the well and seismic data, and to identify important reflectors. The interval of interest was defined based on formation information provided by Statoil ASA, as well as interpretation of the well logs. A statistical extraction was applied for all wells to construct wavelets for the well-tie process (Figure 17). The wavelet is calculated to have a wavelength of 128 ms, and a sample interval of 4 ms, it is zero phased and has not been modified. In addition, has a normal polarity resulting in hard acoustic impedances being displayed as red peaks. The power spectrum reveals that the highest seismic frequencies are located around 25-30 Hz (Figure 17). The objective of generating a synthetic seismogram is to tie seismic reflectors to geologic units by ensuring that the borehole seismic and the surface seismic at the borehole trajectory look as similar as possible (Figure 17). This connects the surfaces identified in seismic to events in the borehole and subsequently correlate and evaluate properties between wells. In this study, the seismic data near each well were fitted by convolving the density and sonic logs with an extracted statistical wavelet, to produce the synthetic predicted traces. Synthetic seismograms were produced for six wells by extracting wavelets from the relevant windows of the seismic, and when necessary, minor time-shifts were applied to tie the seismic and the wells together.

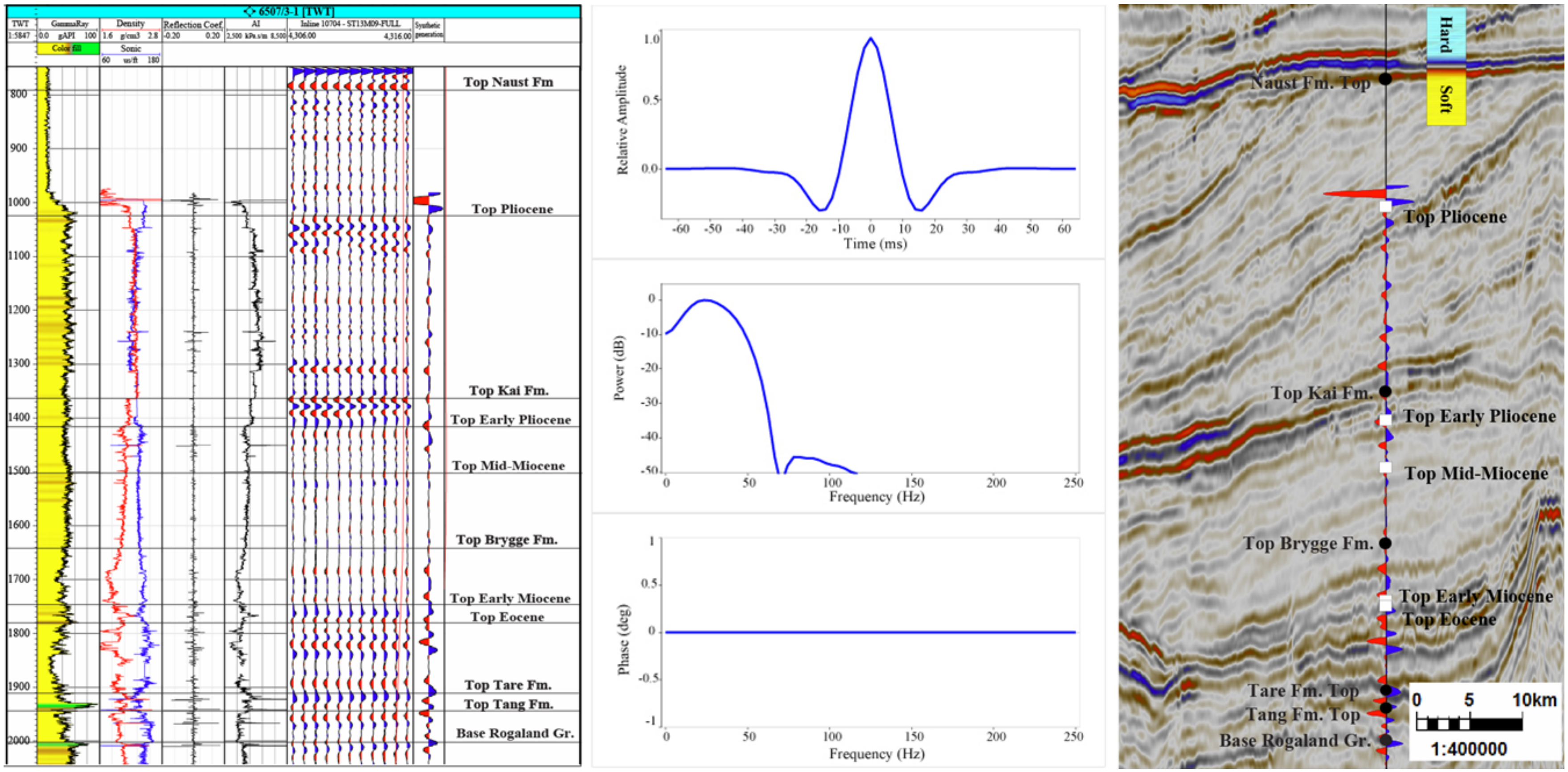

Figure 17. Seismic-to-well tie for the type well 6507/3-1 on the Dønna Terrace in the Norwegian Sea, illustrating the different interpreted formation tops in the Cenozoic succession based on gamma ray log, sonic log, density log and acoustic impedance. The figure also shows the synthetic seismogram, seismic section, wavelet, power spectrum and phase spectrum. Peaks are shown as red, while troughs are shown as blue. Location of the well is shown in Figure 16.

4.4 Interpretation strategy

To establish a stratigraphic framework in the basin two major sequence stratigraphic surfaces were identified

1. The erosional unconformity, and
2. The downlap surface

Both surfaces acts as disconformities in the seismic section, but they are created in significantly different ways. The erosional unconformity represents the time of exposure and erosion of sediments during a relative sea level fall. It represents a sequence boundary and transport of sediments in a basinward direction. The downlap surface represents a starvation surface produced during the time of transgression, and subsequently forms a surface on which prograding clinoforms downlap.

The tectono-stratigraphic sequences of Cenozoic age was interpreted based on sequence stratigraphic observations of the seismic. Seismic interpretation work was focused on interpretation of various unconformities and sediment wedges. The products, such as the TWT-structure, total stratigraphic thickness and seismic attribute maps were used as basic tools to interpret and analyze the sedimentary succession of the study area.

The seismic volume and well logs were cropped in the depth domain as the study mainly focuses on the Cenozoic deposits, which allowed for a more efficient interpretation. The seismic horizons of this study have been interpreted with an interval of 100 traces with guided autotracking, expect for the seafloor, which were interpreted using 3D autotrack. The vertical exaggeration was kept at 15.

4.5 Seismic attributes

Seismic attributes are useful when certain seismic characteristics are of interest. They can be used to map out specific geometries or physical parameters, and may therefore increase the geological understanding of the study area. In this study, the generation of attribute maps relies upon the calculation of amplitude values for a given seismic interval around a pre-determined seismic horizon.

In this study, variance and RMS amplitude attributes have been used to enhance structural features in the seismic. .

5.0 OBSERVATIONS AND RESULTS

The results presented in this chapter are based on observations from a mega-regional 3D seismic reflection survey and seventeen exploration wells.

5.1 Seismic stratigraphy

The seismic stratigraphy of the Cenozoic deposits in the study area has been correlated using chrono- and lithostratigraphic well tops from NPD and Statoil ASA, throughout the dataset. Seismo-stratigraphic units were identified based on amplitude and continuity of the bounding reflectors, nature of the bonding surfaces, geometries and extension. Based on this, the Cenozoic package along the mid-Norwegian continental margin has been divided into seven seismic sequences (Figure 18).

Era	Period	Epoch		Sequences and boundaries		Seismic pattern (Hjelstuen et al., 2004)
CENOZOIC	Quaternary	Holocene	0,01	SS-7	URU	High amplitude reflectors separating sub-sequences of non-strucutrally, weakly layered and chaotic seismic facies
		Pleistocene		SS-6	UCS	
				SS-5	UCS	
				SS-4	UCS	
			2,6	SS-3	RDS	
	Neogene	Pliocene	5,3	SS-2		Parallel medium amplitude reflectors
		Miocene	23		RDS	
	Paleogene	Oligocene	34	SS-1		Parallel, non-faulted, high amplitude reflectors in the upper part. Non-strucutral acoustic pattern in the lower part
		Eocene	56			
		Paleocene	66			

Figure 18. The 7 identified seismic sequences and their bounding surfaces. RDS: Regional Downlap Surface, URU: Upper Regional Unconformity, UCS: Unconformity Clinoform Surface

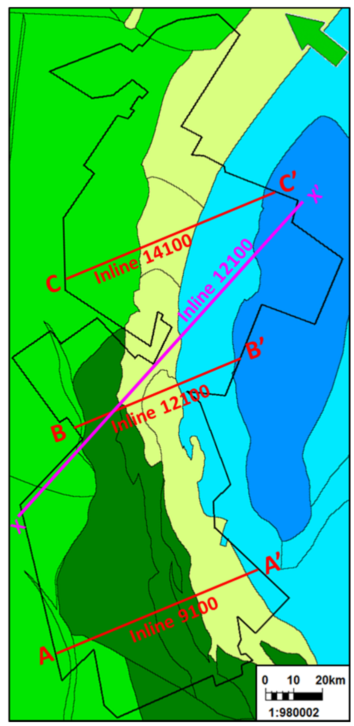

Figure 19. Map showing the location of seismic lines shown in Figures 20, 21, 22 and 23.

Each of the Cenozoic seismic sequences has been named seismic sequence from SS-1 to SS-7. Bounding surfaces are named Regional Downlap Surface (RDS), Unconformity Clinoform Surface (UCS) and Upper Regional Unconformity (URU) (Figure 18).

The Paleogene Unconformity at the base of Cenozoic is extensively developed and is usually a very good lithostratigraphical marker. However, the unconformity is diachronous in many areas and can hence not be used as a high-resolution chronostratigraphic marker.

A Regional Downlap Surface (RDS) of mid-Miocene age (Figure 18) is ubiquitous in the dataset. It is characterized by regional scale downlapping onto it, high amplitude and high acoustic impedance contrast, but show local changes from south to north.

A Regional Downlap Surface (RDS) of Pliocene age (Figure 18) is ubiquitous in the provided dataset. It is characterized by regional scale downlapping clinoforms onto it, high amplitude and high acoustic impedance contrast. The seismic velocities drop dramatically due to the transition from glacio-marine sediments to Miocene strata, giving a high acoustic impedance contrast.

Unconformity Clinoform Surfaces (UCS) are found in the upper seismic sequences (Figure 18) and represent minor hiatuses of non-deposition or erosion. These surfaces are characterized by low amplitude and low acoustic impedance contrast. The age control on these sequences are limited, but have been defined as Pleistocene based on well data.

The Upper Regional Unconformity (URU) of Pleistocene age (Figure 18) is an angular unconformity abundant in the provided dataset. It is characterized by high amplitude and that the underlying depositional surfaces are truncated by it. Resulting in that the majority of the clinoform topsets and rollover points in some of the seismic sequences below URU are not preserved. This surface displays various fluvial incisions into the underlying sequences eroding into various levels, which infers an erosional surface.

The purpose of mapping out these bounding surfaces and seismic sequences is to establish a semi-chronostratigraphic framework for the Cenozoic deposits in the Norwegian Sea. Bounding surfaces and seismic sequences changes throughout the study area, and Figure 20 shows the complete Cenozoic succession, while Figure 21, Figure 22, and Figure 23 show type sections for the various seismic sequences.

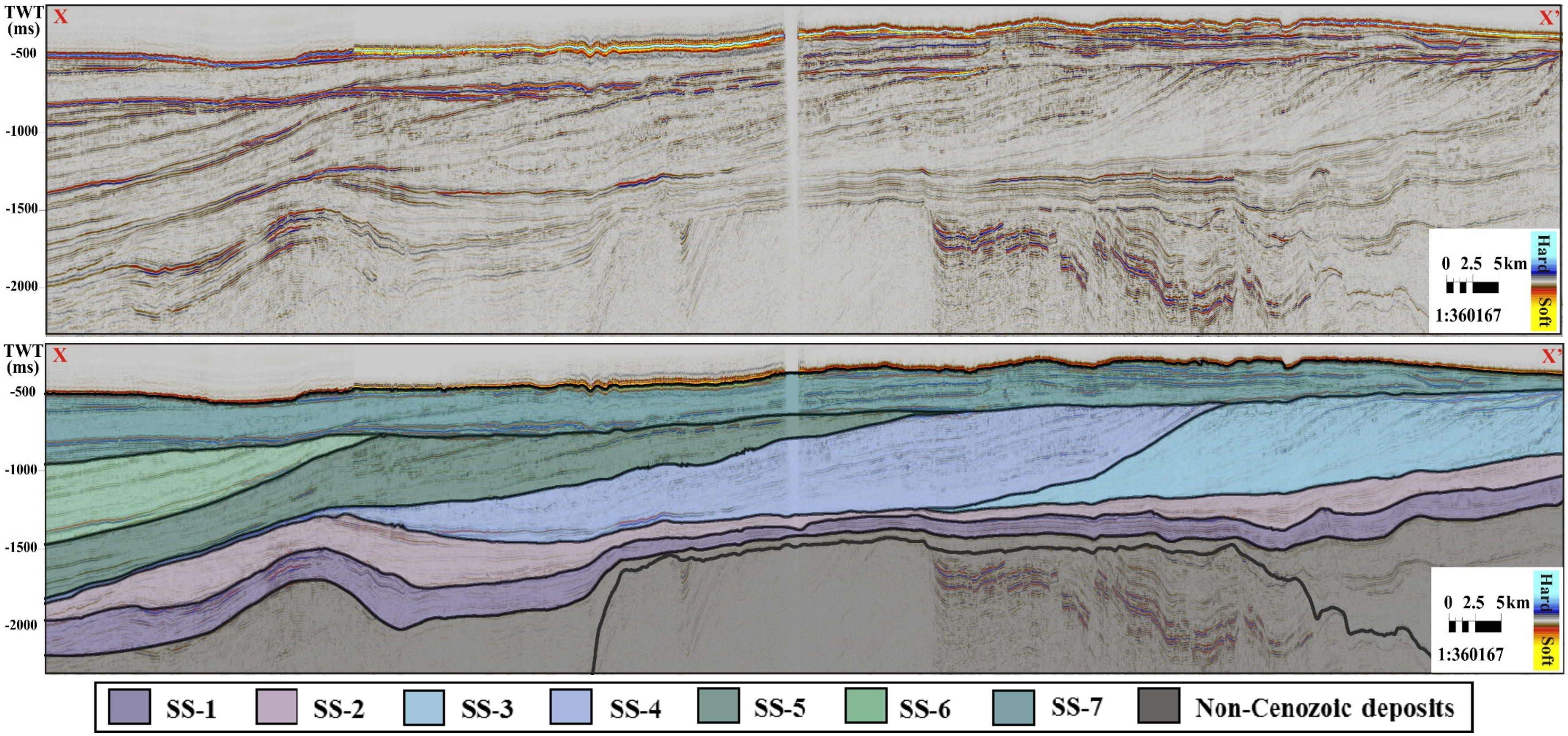

Figure 20. Un-interpreted and interpreted arbitrary seismic line (location shown in Figure 19) with all the interpreted seismic sequences defined in this study, extending from Rås Basin, through Dønna Terrace and Rødøy High to Trøndelag Platform and Helgeland Basin. All the seismic sequences and bounding surfaces are present, and displays their thickness, geometry and relation to each other.

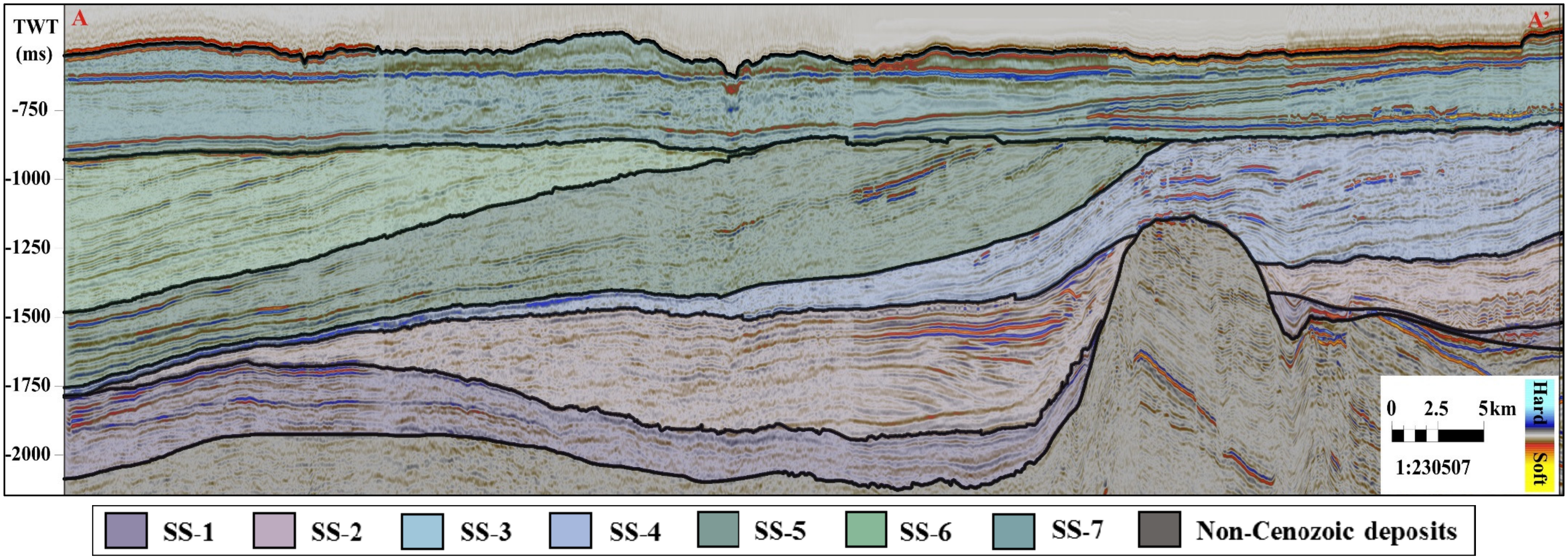

Figure 21. Inline 9100 (location shown in Figure 19) with some of the interpreted seismic sequences defined in this study lies in the southern part of the study area, and extends from Rås Basin, through Dønna Terrace and Revfallet Fault Complex to Sør High. This seismic section displays the seismic sequences presence, thickness, geometry and their relation to each other in the southern part of the study. This line is a type section for the seismic sequences SS-6 and SS-7. SS-6 displays variable erosion of the topsets and rollover points of the clinoform units, but is interpreted to have a prograding stacking pattern and a descending trajectory. SS-7 still displays major erosion of the topsets and rollover points of the clinoform units, but is interpreted to have a prograding stacking pattern and a descending trajectory.

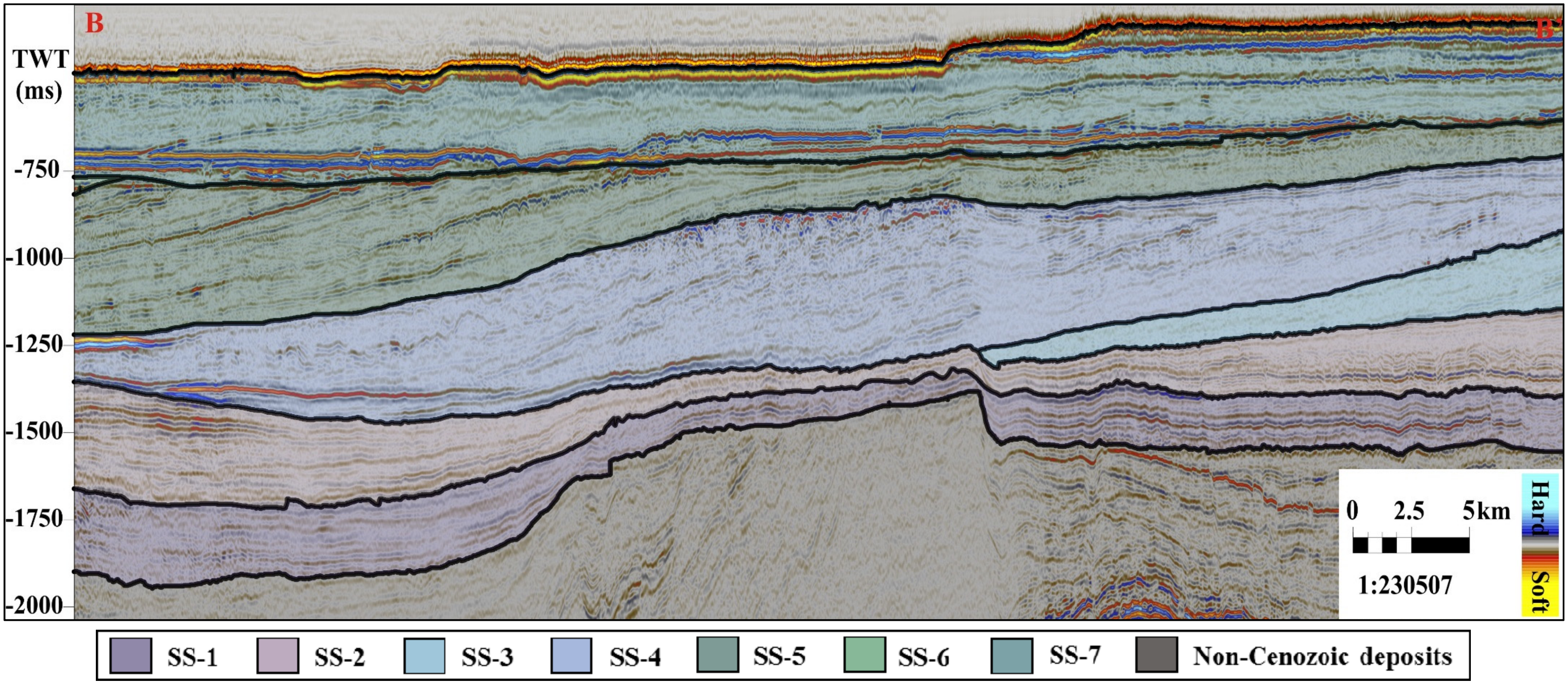

Figure 22. Inline 12100 (location shown in Figure 19) with some of the interpreted seismic sequences defined in this study, lies in the southern part of the study area, and extends from Vøring Basin, through Dønna Terrace, Rødøy High and Sør High to Trøndelag Platform and Helgeland Basin. This seismic section displays the seismic sequences presence, thickness, geometry and their relation to each other in the central part of the study area. This line is a type section for the seismic sequences SS-4 an SS-5 as most of the unit geometries are preserved within the sequences. SS-4 displays variable erosion of the topsets and rollover points of the clinoform units, but is interpreted to have a prograding stacking pattern and a descending trajectory. SS-5 still displays major erosion of the topsets and rollover points of the clinoform units, but is interpreted to have a prograding stacking pattern and a descending trajectory. SS-1 and SS-2 shows polygonal faulting in the eastern part of this section.

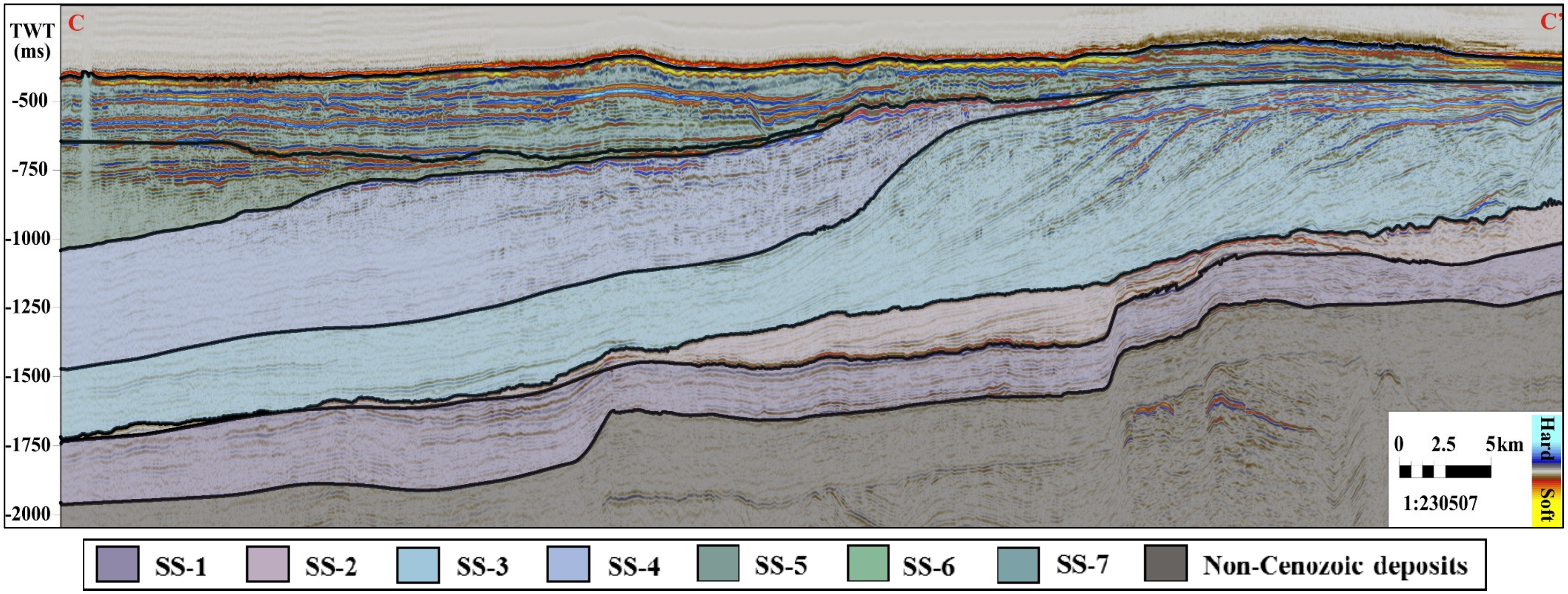

Figure 23. Inline 14100 (location shown in Figure 19) with some of the interpreted seismic sequences defined in this study, lies in the southern part of the study area, and extends from Vøring Basin, through Nordland Ridge to Trøndelag Platform and Helgeland Basin. This seismic section displays the seismic sequences presence, thickness, geometry and their relation to each other in the northern part of the study area. This line is a type section for the seismic sequences SS-3 as most of the unit geometries are preserved within the sequences. SS-3 displays minor erosion of the topsets of the clinoform units, and is interpreted to have a prograding stacking pattern and a descending trajectory.

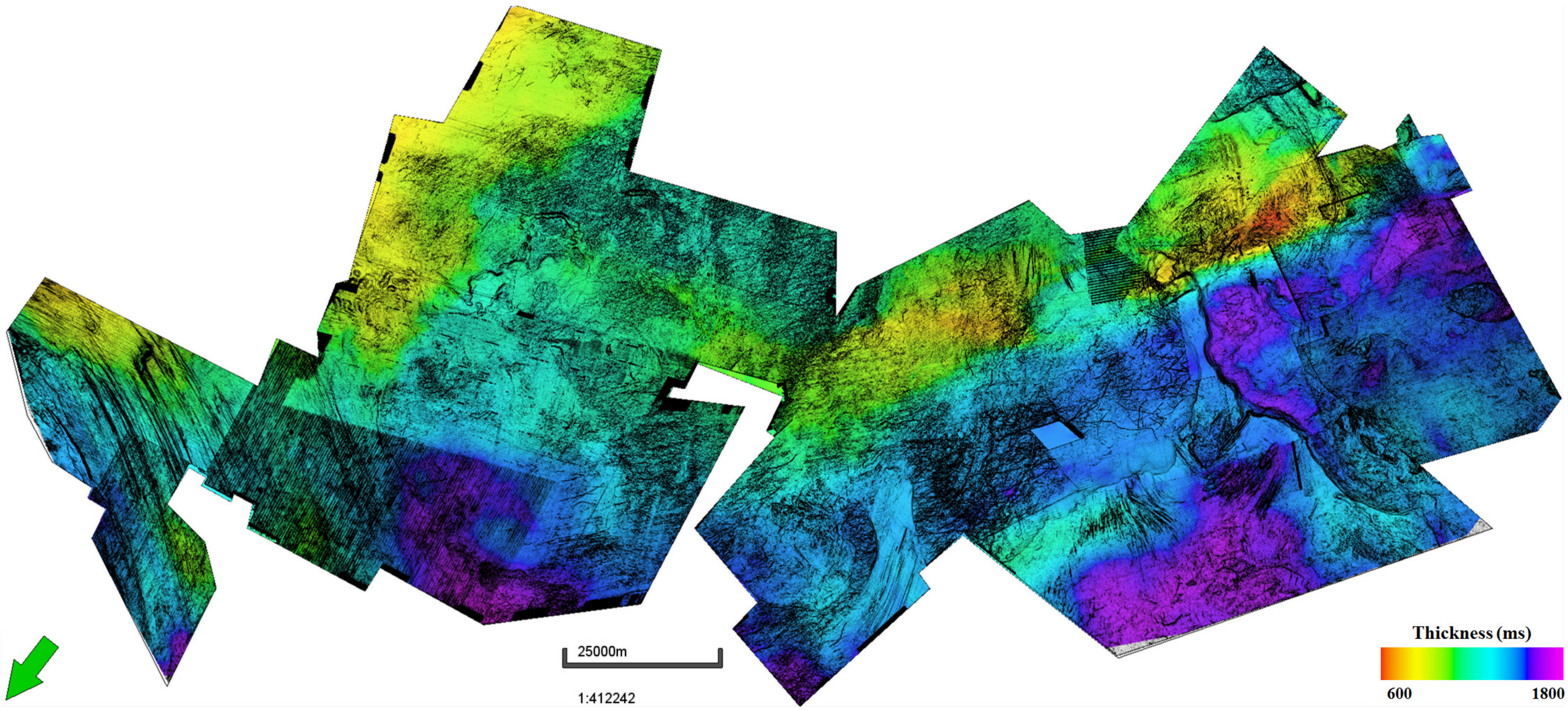

Figure 24. Time thickness map (TWT) of the entire Cenozoic succession, with a variance map of the seafloor superimposed. The thickness for the succession varies between 600 and 1800 ms, with an average of 1200 ms. Depocenters are located west of the Nordland Ridge (Sør, Rødøy and Grønøy High) along the Revfallet Fault Complex, Dønna Terrace, Rås Basin and Vøring basin. The superimposed variance map displays some of the quality of the seismic dataset and seismic artifacts that can be observed on the seafloor.

5.1.1 Seismic sequence 1 (SS-1)

Top SS-1 can be recognized by an increase in acoustic impedance, which results in a hard seismic impedance contrast (red peak). SS-1 is bounded by the base Cenozoic below and a Regional Downlap Surface (RDS) of mid-Miocene age at the top (Figures 19, 20, 21 and 22). This sequence is ubiquitous in most of the study area, but truncates towards the Rødøy High in the central, and towards the Sør High in the south (Figures 25 and 27). SS-1 sequence consist of parallel-laminated semi-continuous reflections units. Sedimentary packages within the sequence are semi-continuous and varies in thickness. In general, the thickness increases towards the north (Figure 27) and depocenters are located in the Vøring Basin and the Dønna Terrace.

The bounding surface at the top of SS1, RDS of mid-Miocene age, is a prominent seismic marker that varies locally in character, and have younger seismic sequences downlapping onto it. However, the amount of sedimentary packages downlapping onto it decreases towards the north.

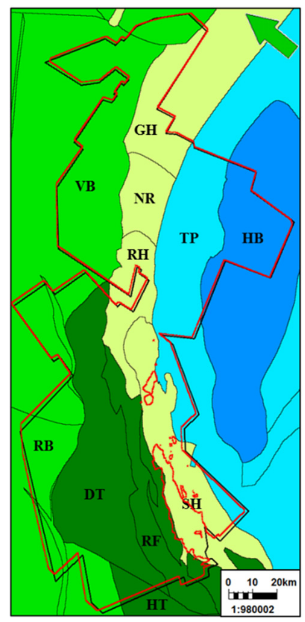

Figure 25. Location of SS-1 in the study area, marked in red

SS-1 comprises several areas containing polygonal faulting, which is small-offset faults that show a lack of dominant strike direction (Figure 22 and 26). They are widespread in at least one layer in the uppermost part of the sequence and their upper and lower terminations do not necessarily occur at the same stratigraphic level. Generally, the fault throw is highest close to the lower termination, and the height of the fault depends on the thickness of the hosting layer.

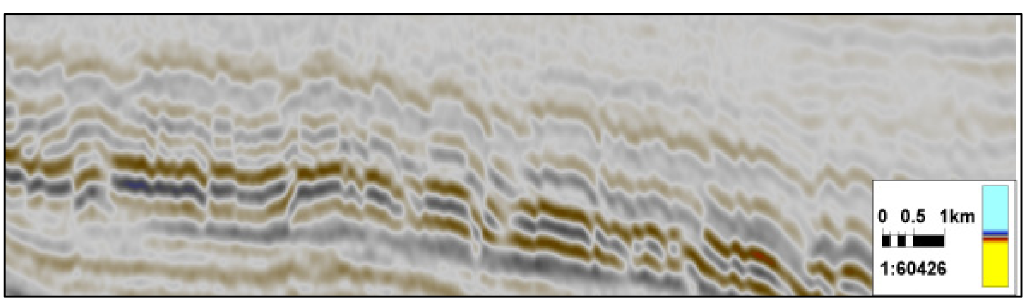

Figure 26. Example of polygonal faulting in SS-1 in seismic. Figure 27 also displays polygonal faulting on the superimposed variance map of the RDS of mid-Miocene age. The fault system is mainly located on the Dønna Terrace and Trøndelag Platform in the central part of the study area.

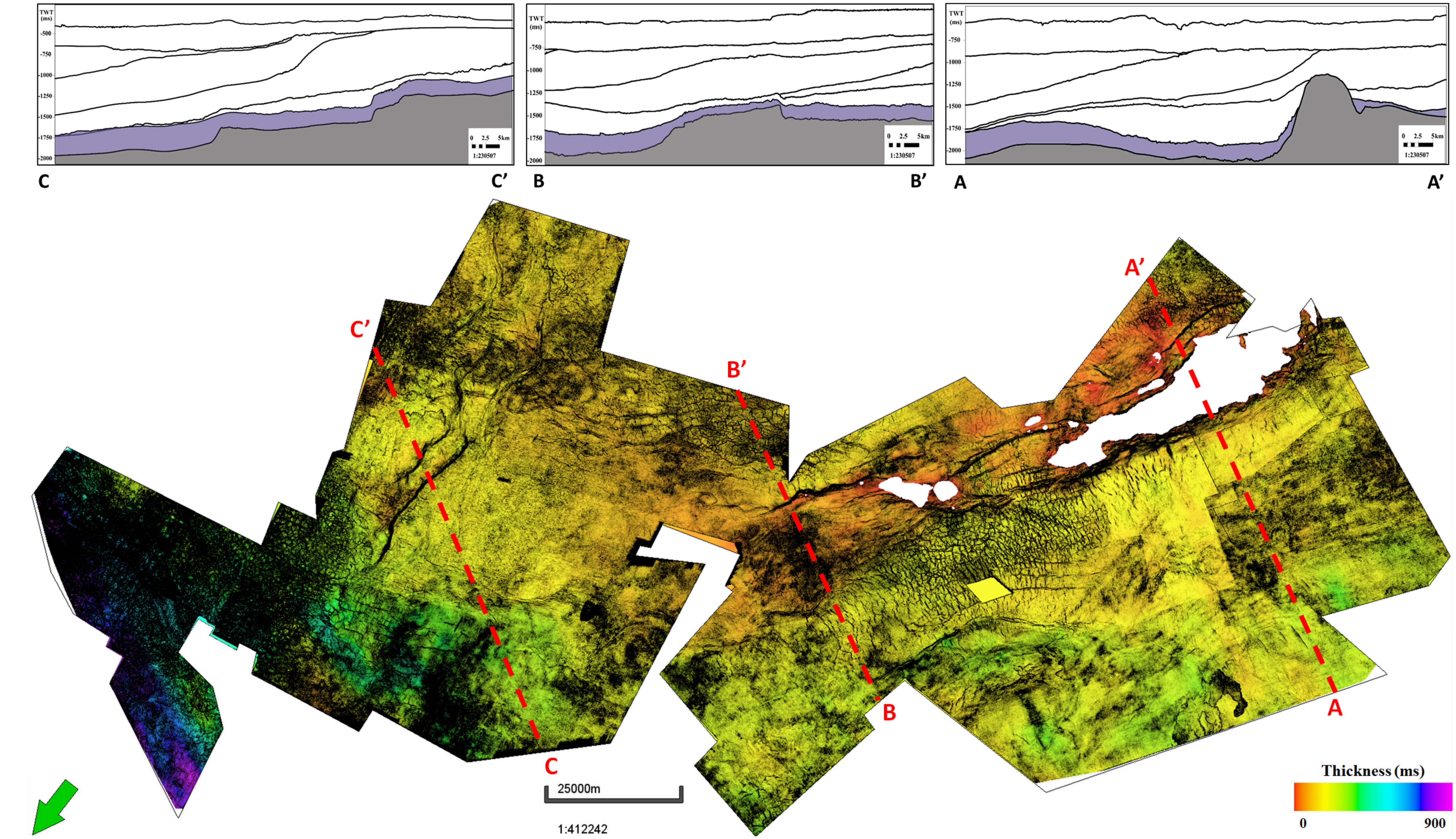

Figure 27. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-1 throughout the study area. The time thickness map (TWT) of SS-1, shows thicknesses varying between 0 and 900 ms, with an average of 230 ms. The white areas illustrates areas where the sequence onlaps onto the Nordland Ridge. Depocenters are located in the Vøring Basin and Dønna Terrace. A variance map of the RDS of mid-Miocene age is superimposed to illustrate discontinuities and features observed at the top of SS-1, e.g. a polygonal fault system can be observed on the Revfallet Fault Complex and Dønna Terrace in the central part of the study area..

5.1.2 Seismic sequence 2 (SS-2)

Top SS-2 can be recognized by an increase in acoustic impedance, which results in a hard seismic impedance contrast (red peak). SS-2 is bounded by a Regional Downlap Surface (RDS) of mid-Miocene age at the base, and a Regional Downlap Surface (RDS) of Pliocene age at the top (Figures 19, 20, 21 and 22). The seismic sequence consists of parallel-laminated semi-continuous reflections units, which onlap onto structural highs (Figures 28 and 30). Within the sequence, there are local downlap and onlap surfaces. In general, the thickness increases towards the north (Figure 30), but depocenters are located in the Vøring Basin and the southern part of the Dønna Terrace.

Sedimentary packages within the sequence thins and onlaps onto the Nordland Ridge in the south, and downlaps onto the RDS of Pliocene age in localized areas in the NE, NW and SW (Figures 28 and 30). The units are semi-continuous and varies in thickness (Figure 30).

The bounding surface at the top of SS-2, RDS of Pliocene age, is a prominent seismic marker, which varies locally in character.

SS-2 contains the same polygonal fault system (Figure 22) as described in SS-1, and the oldest observation of iceberg plough marks and glacial deposits in the study area (Figure 29).

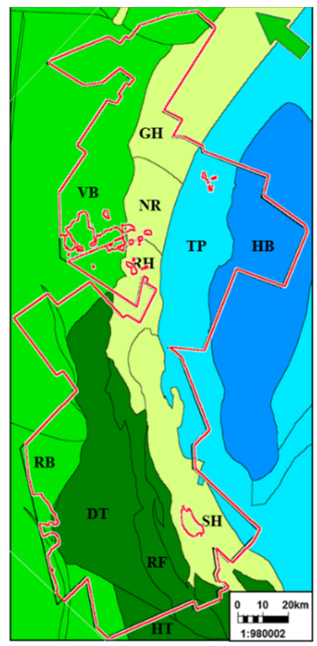

Figure 28. Location of SS-2 in the study area, marked in red

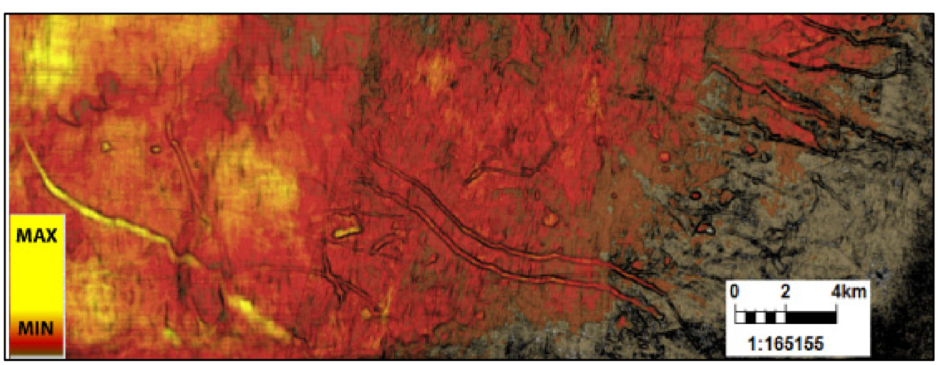

Figure 29. Iceberg plough marks and other glacial features within SS-2, shown on a RMS map of near-RDS of Pliocene age with a variance map superimposed

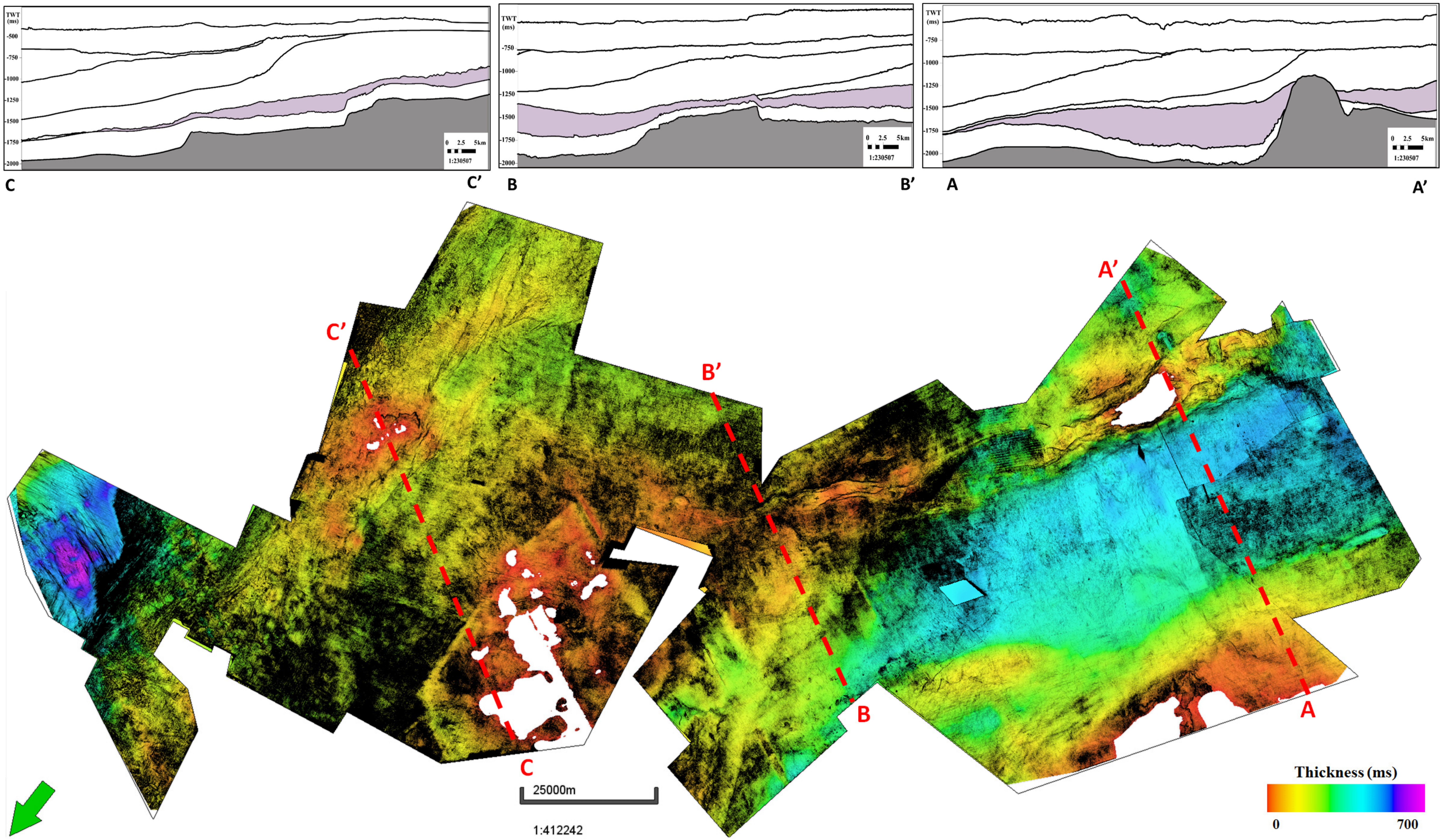

Figure 30. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-2 throughout the study area. The time thickness map (TWT) of SS-2, shows thicknesses varying between 0 and 700 ms, with an average of 200 ms. The white areas illustrates areas where the sequence downlaps onto the RDS of mid-Miocene age. Depocenters are located in the Vøring Basin and southern Dønna Terrace. A variance map of the RDS of Pliocene age is superimposed to illustrate discontinuities and features observed at the top of SS-2.

5.1.3 Seismic sequence 3 (SS-3)

Top SS-3 is recognized by a decrease in acoustic impedance, which results in a soft seismic response (blue through). SS-3 is bounded by a Regional Downlap Surface (RDS) of Pliocene age at the base and an Unconformity Clinoform Surface (UCS) of Pleistocene age at the top (Figures 19, 20, 21 and 22). The seismic sequence consists of numerous low-angle parallel to sub-parallel, wedge-shaped westerly prograding clinothem units (Figure 19, 20, 21 and 22). Several angular unconformities occur within the sequence, indicating severe erosion during the glacial-interglacial cycles (Figure 31 and 32). In general, the thickness increases towards the north (Figure 33) and depocenters are located on the Trøndelag Platform, Vøring Basin and Grønøy High.

Clinoform units within the sequence downlap onto the RDS of Pliocene age, and the whole sequence pinches out in the central part of the study area (Figures 31 and 33). URU has eroded the topsets and rollover points of the clinoform units of varying degree. In the northern areas, the seismic sequence shows more erosion compared to the southern areas. Several of the units are thick, and becomes narrower down-slope and pinch-out onto the middle-lower slope (Figures 20, 21 and 22).

The bounding surface at the top of the SS-3 is a prominent seismic marker, but it varies locally in character, as the surface changes from a local downlap surface to a local onlap surface towards the north.

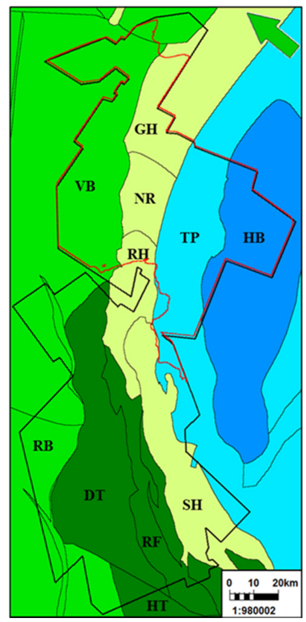

Figure 31. Location of SS-3 in the study area, marked in red

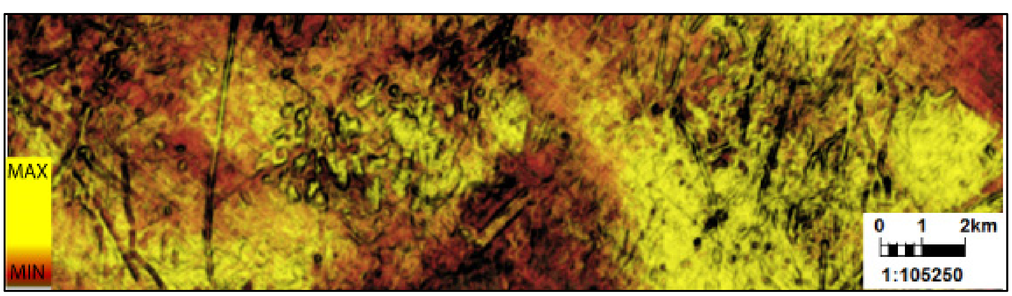

Figure 32. Iceberg plough marks and other glacial features within SS-3, shown on a RMS map of near-RDS of Pliocene age with a variance map superimposed

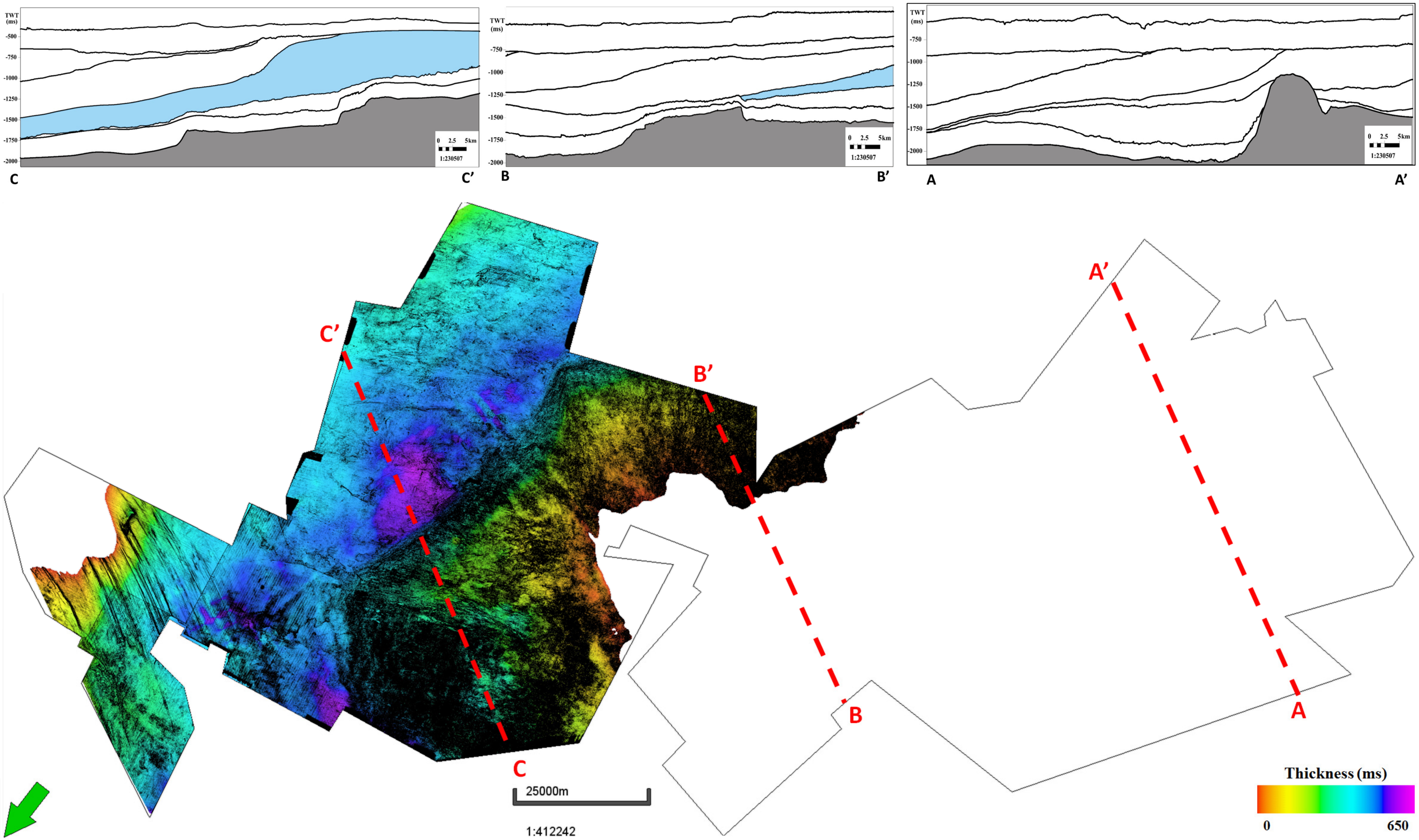

Figure 33. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-3 throughout the study area. The time thickness map (TWT) of SS-3, shows thicknesses varying between 0 and 650 ms, with an average of 380 ms. The white areas illustrates areas where the sequence is truncated by URU and downlaps onto the RDS of Pliocene age. Depocenters are located in the Vøring Basin, Trøndelag Platform and Grønøy High. A variance map of the UCS of Pleistocene age is superimposed to illustrate discontinuities and features observed at the top of SS-3.

5.1.4 Seismic sequence 4 (SS-4)

Top SS-4 is recognized by a decrease in acoustic impedance, which results in a soft seismic response (blue through). SS-4 is bounded by an Unconformity Clinoform Surface (UCS) of Pleistocene age at the base and an Unconformity Clinoform Surface (UCS) of Pleistocene age at the top (Figures 19, 20, 21 and 22). The seismic sequence consists of several low-angle, parallel to sub-parallel wedge-shaped westerly prograding clinothem units (Figures 19, 20, 21 and 22). Several angular unconformities occur within the sequence, indicating erosion during the glacial-interglacial cycles (Figure 34 and 35). In general, the thickness is highest in the center of the study area (Figure 36) and depocenters are located on the Rødøy High, Vøring Basin and Sør High.

Clinoform units within the sequence downlap onto the UCS of Pleistocene age, and the whole sequence pinches out against the underlying seismic sequences in the southern part of the study area (Figures 30 and 31). URU has eroded the topsets and rollover points of the clinoform units in varying degree, the northern and southern areas shows more erosion compared to the central.

The bounding surface at the top of SS-4 is a good seismic marker, but varies locally in character, and the surface changes from a local downlap surface to a local onlap surface towards the north.

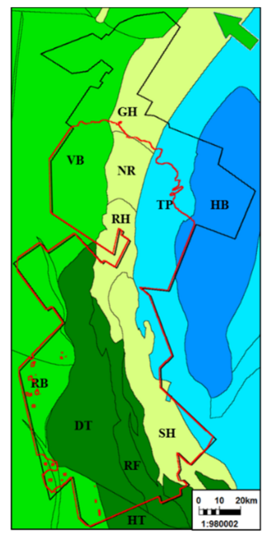

Figure 34. Location of SS-4 in the study area, marked in red

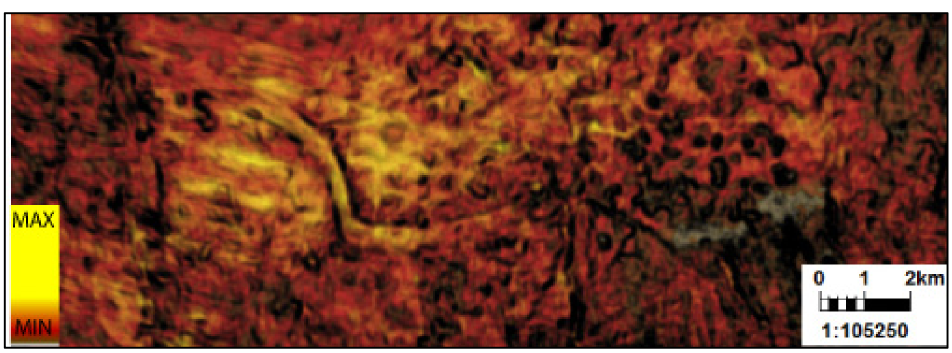

Figure 35. Iceberg plough marks and other glacial features within SS-4, shown on a RMS map of the UCS of Pliocene age at the top of the sequence, with a variance map superimposed

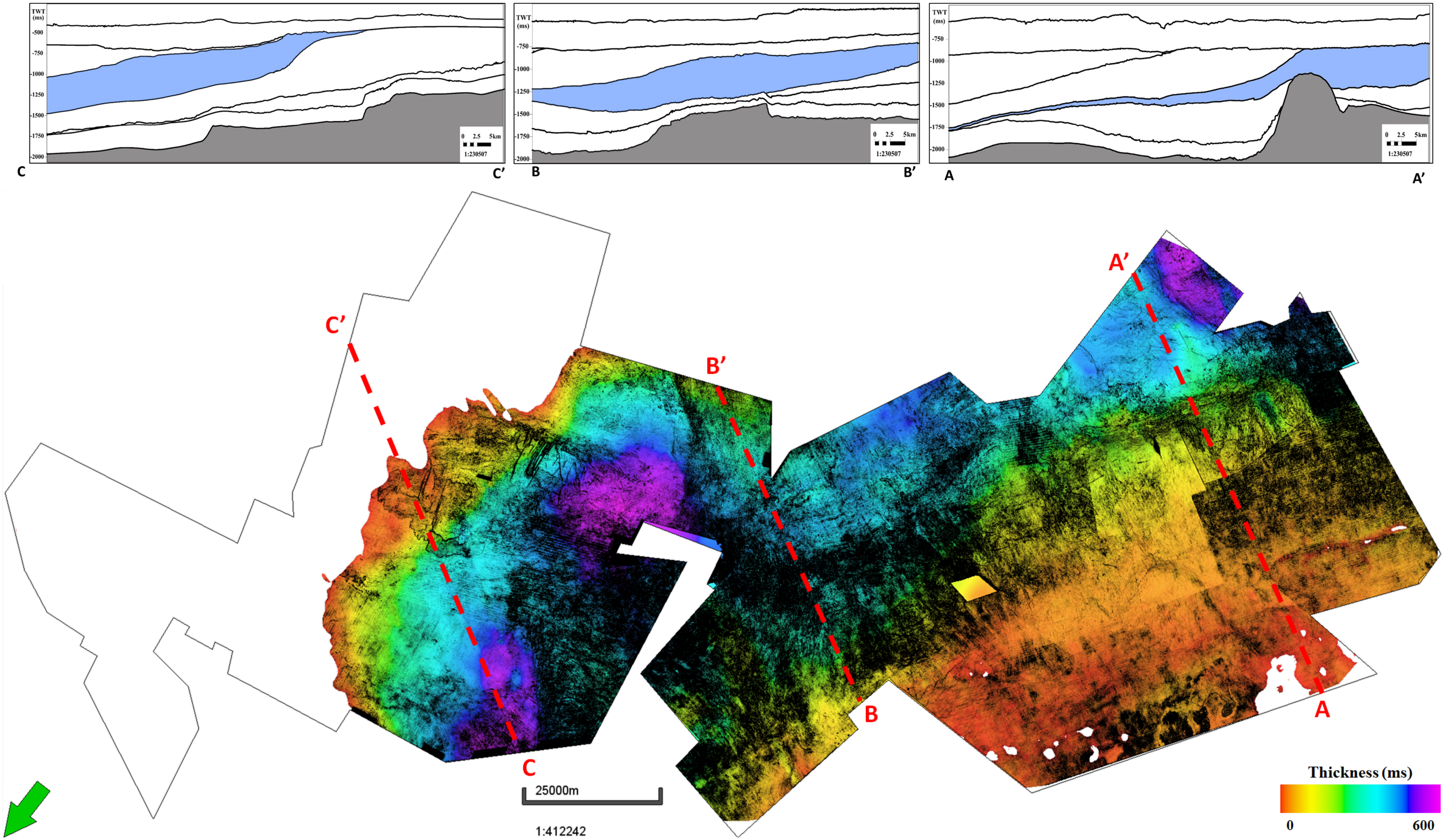

Figure 36. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-4 throughout the study area. The time thickness map (TWT) of SS-4, shows thicknesses varying between 0 and 600 ms, with an average of 220 ms. The white areas illustrates areas where the sequence is truncated by URU and downlaps onto the UCS of Pleistocene age. Depocenters are located in the Vøring Basin, Rødøy High and Sør High. A variance map of the top of SS-4, UCS of Pleistocene age, is superimposed to illustrate discontinuities and features observed at the top of SS-4.

5.1.5 Seismic sequence 5 (SS-5)

Top SS-5 is recognized by a decrease in acoustic impedance, which results in a soft seismic response (blue through). SS-5 is bounded by an Unconformity Clinoform Surface (UCS) of Pleistocene age at the base and an Unconformity Clinoform Surface (UCS) of Pleistocene age above (Figures 19, 20, 21 and 22). SS-5 consists of several low-angle, parallel to sub-parallel wedge-shaped westerly prograding clinothem units (Figures 19, 20, 21 and 22). Several angular unconformities occur within the sequence, indicating severe erosion during the glacial-interglacial cycles (Figures 37 and 38). In general, the thickness is highest west of the Nordland Ridge (Figure 39) and depocenters are located on the Revfallet Fault Complex, Dønna Terrace and Rås Basin.

Clinoform units within the sequence downlap onto the UCS of Pliocene age, and the topsets and rollover points of the units have been eroded by URU in a varying degree (Figure 39). The topsets of the seismic sequence are not preserved in the northern areas, and the units are relatively thin a spatially distributed. Topsets in the south are better preserved, and the units are thicker than in the north, but less spatially distributed (Figure 39).

The bounding surface of top SS-5 is a good seismic marker, but varies locally in character, and the surface changes from a local downlap surface to a local onlap surface towards the north.

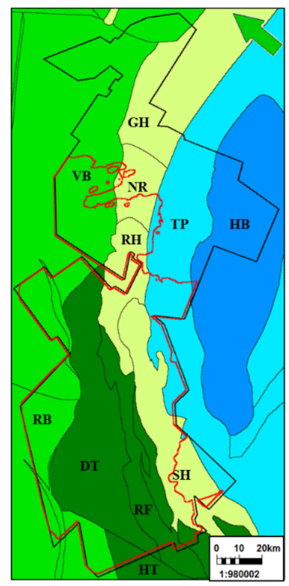

Figure 37. Location of SS-5 in the study area, marked in red

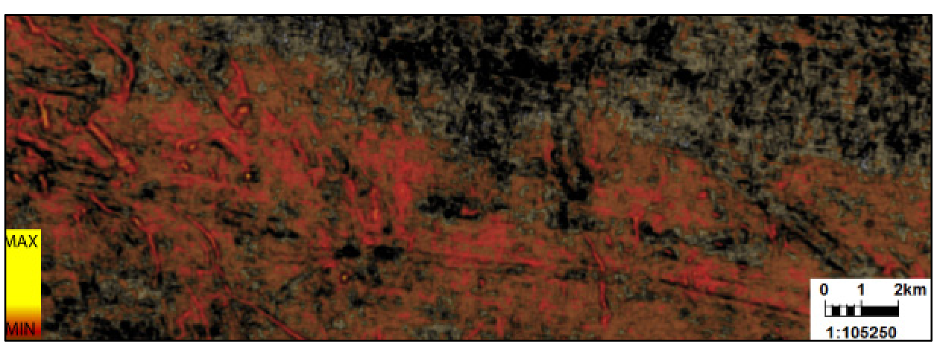

Figure 38. Iceberg plough marks and other glacial features within SS-5, shown on a RMS map of the UCS of Pliocene age at the top of the sequence, with a variance map superimposed

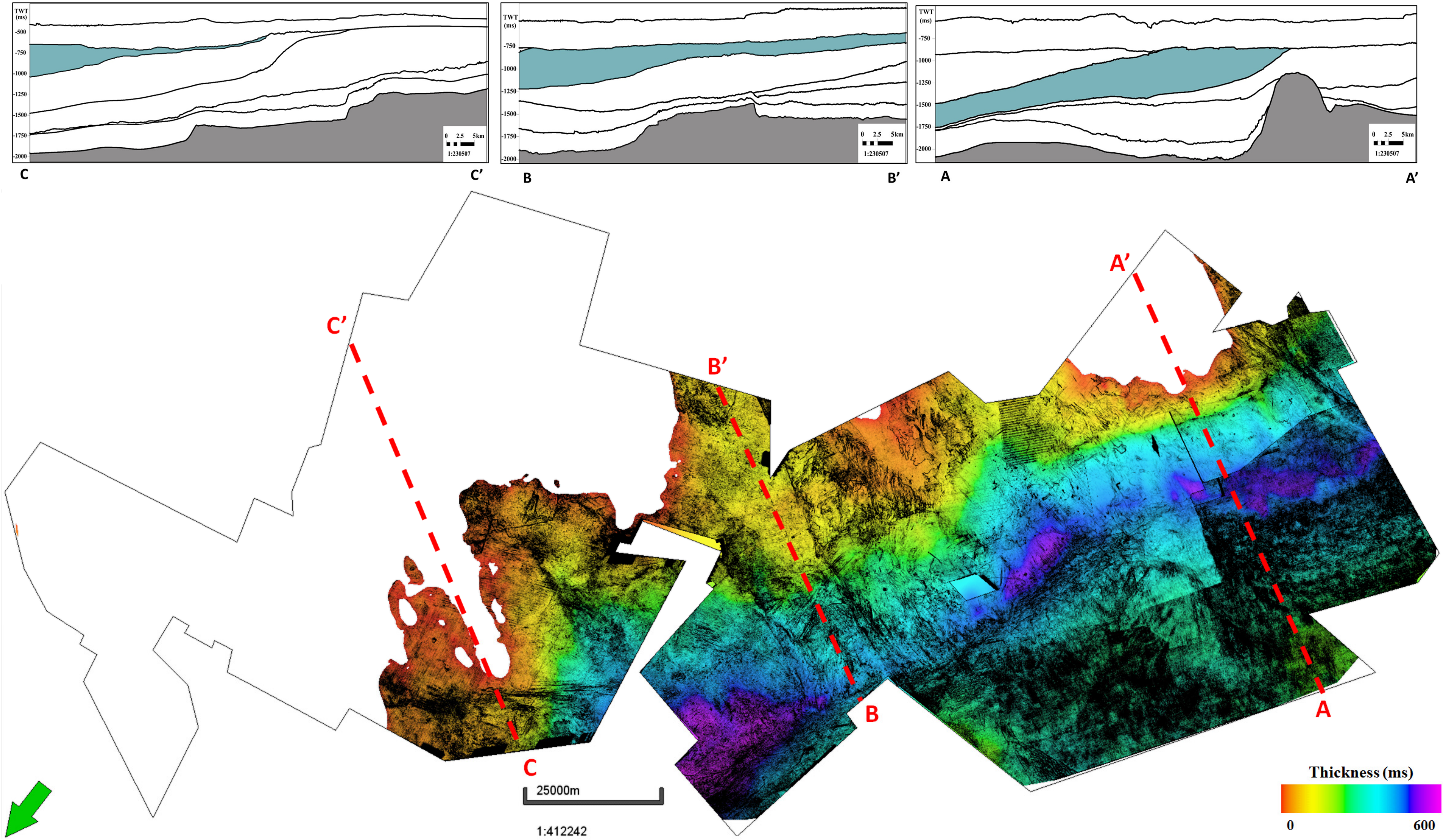

Figure 39. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-5 throughout the study area. The time thickness map (TWT) of SS-5, shows thicknesses varying between 0 and 600 ms, with an average of 290 ms. The white areas illustrates areas where the sequence is truncated by URU and downlaps onto the UCS of Pleistocene age (Top SS-4). Depocenters are located in the Revfallet Fault Complex, Dønna Terrace and Rås Basin. A variance map of the top of SS-5, UCS of Pleistocene age, is superimposed to illustrate discontinuities and features observed at the top of SS-5.

5.1.6 Seismic sequence 6 (SS-6)

Top SS-6 is recognized by a decrease in acoustic impedance, which results in a soft seismic response (blue through). SS-6 is bounded by an Unconformity Clinoform Surface (UCS) of Pleistocene age at the base and the Upper Regional Unconformity (URU) of Pleistocene age above (Figures 19, 20, 21 and 22). SS-2 is present in the SW part of the study area (Figure 40 and 42), and consists of several low-angle, parallel to sub-parallel wedge-shaped westerly prograding clinothem units. In general, the thickness is highest on the western edge of this dataset, in the Rås Basin (Figure 42).

Clinoform units within the sequence downlap onto the UCS of Pleistocene age, and the whole sequence pinches out and the topsets and rollover points of the units have been eroded by URU in a varying degree (Figure 39). This seismic sequence is the thinnest and least preserved in this study. However, the units display a prograding stacking pattern towards the west of the study area.

The bounding surface at the top of SS-6 is a good seismic marker and is characterized by high amplitude and that the underlying depositional surfaces is truncated by it. This surface demonstrates various fluvial incisions and glacial features (Figure 41) into the underlying sequences at various levels, and represents an erosional surface.

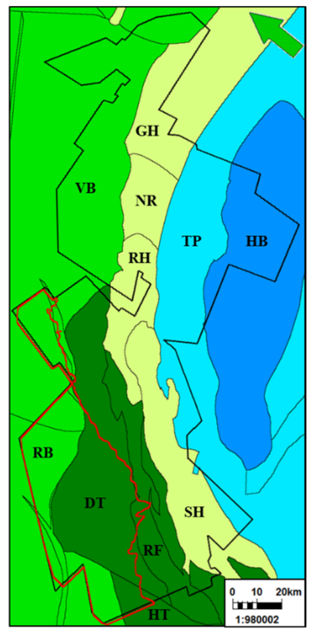

Figure 40. Location of SS-6 in the study area, marked in red

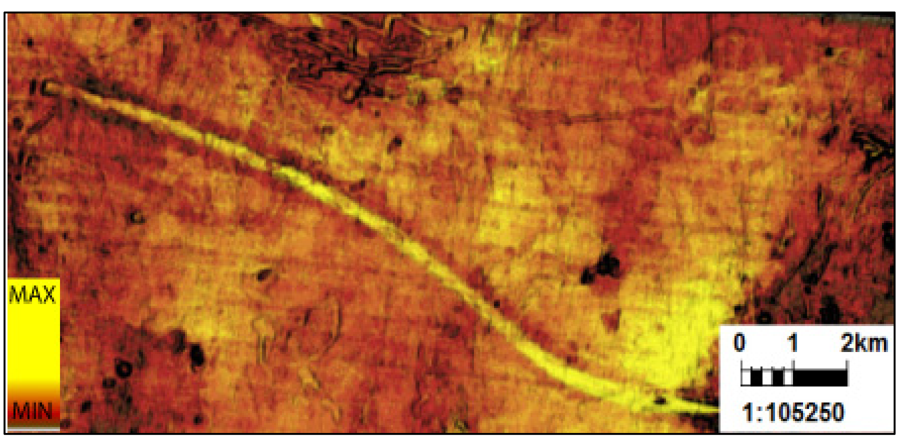

Figure 41. Iceberg plough marks and other glacial features within SS-6, shown on a RMS map of URU with a variance map superimposed

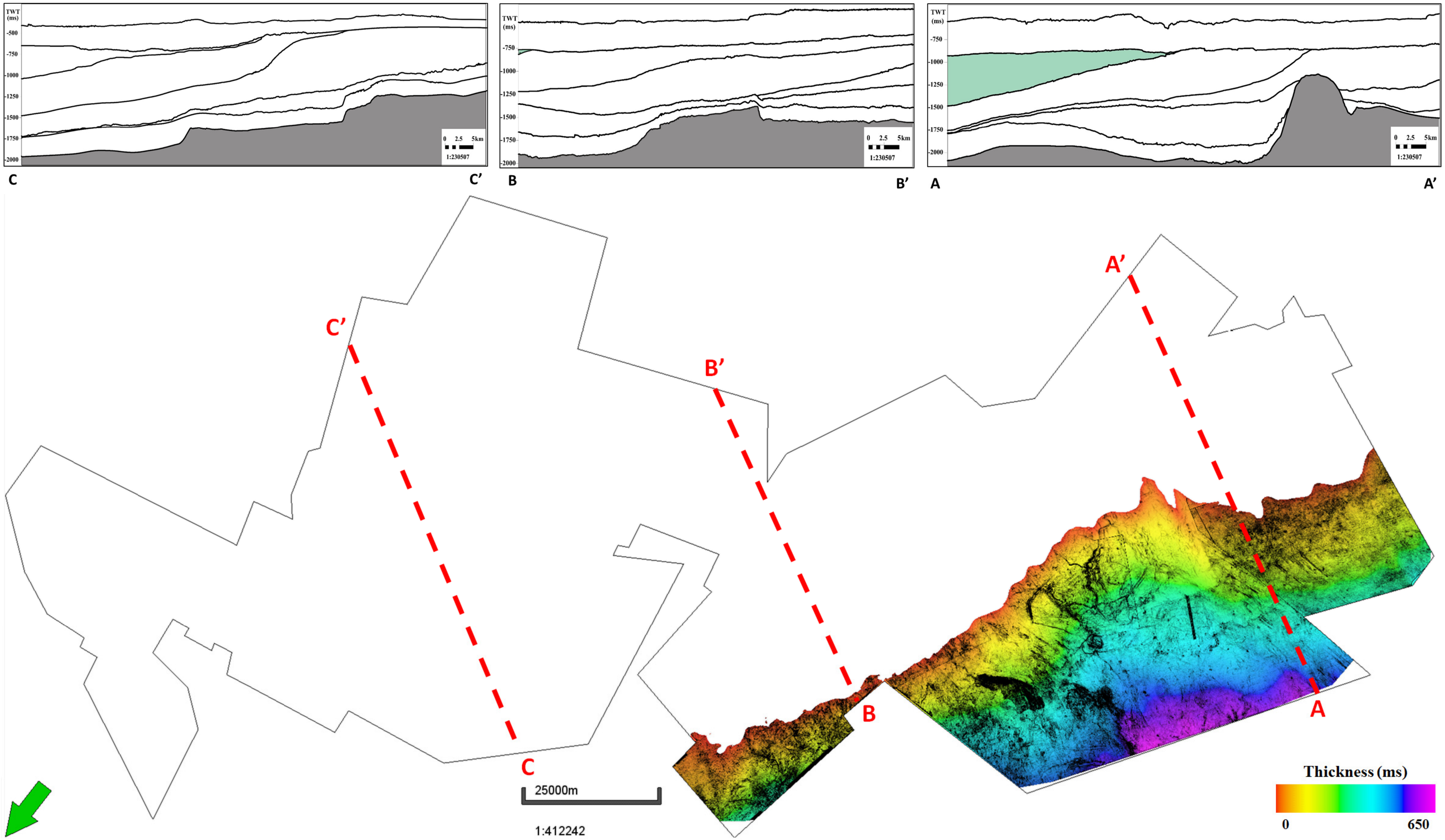

Figure 42. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-6 throughout the study area. The time thickness map (TWT) of SS-6, shows thicknesses varying between 0 and 650 ms, with an average of 280 ms. The white areas illustrates areas where the sequence is truncated by URU. Depocenters are located in the western edge of the Rås Basin. A variance map of URU is superimposed to illustrate discontinuities and features observed at the top of SS-6.

5.1.7 Seismic sequence 7 (SS-7)

Top SS-7 is marked as a decrease in acoustic impedance, which results a soft seismic response (blue through). SS-7 is bounded by the Upper Regional Unconformity (URU) of Pleistocene age at the base and the seafloor at above (Figures 19, 20, 21 and 22), and is ubiquitous in the study area. The seismic sequence consists of several low-angle, parallel to sub-parallel wedge shaped westerly prograding clinothem units with an aggradational outbuilding pattern (Figures 19, 20, 21 and 22). Within the sequence, angular unconformities occur, showing erosion during the glacial-interglacial cycles (Figure 43 and 44). In general, the thickness is highest in the south and central, with depocenters Dønna Terrace, Rås Basin, Trøndelag Platform and Vøring Basin.

Units within the sequence downlap onto the URU, which separates the upper aggrading depositional units from the underlying prograding units (Figure 45). The aggradation is very prominent in the southern part of the study area, but the pattern is still the dominant style throughout the sequence.

URU contains erosional structural depressions that may represent scours or channels formed by glacial erosion (Figure 44). Prograding or onlapping sediments have subsequently filled these erosional depressions.

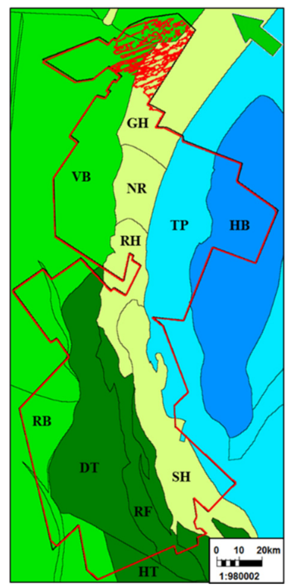

Figure 43. Location of SS-7 in the study area, marked in red

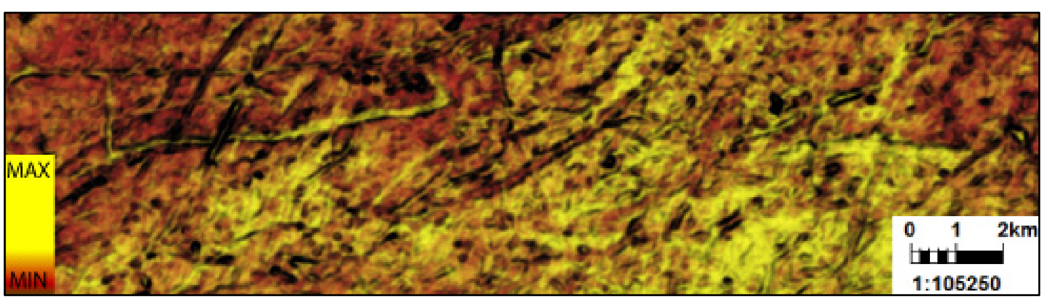

Figure 44. Iceberg plough marks and other glacial features within SS-7, shown on a RMS map of URU with a variance map superimposed

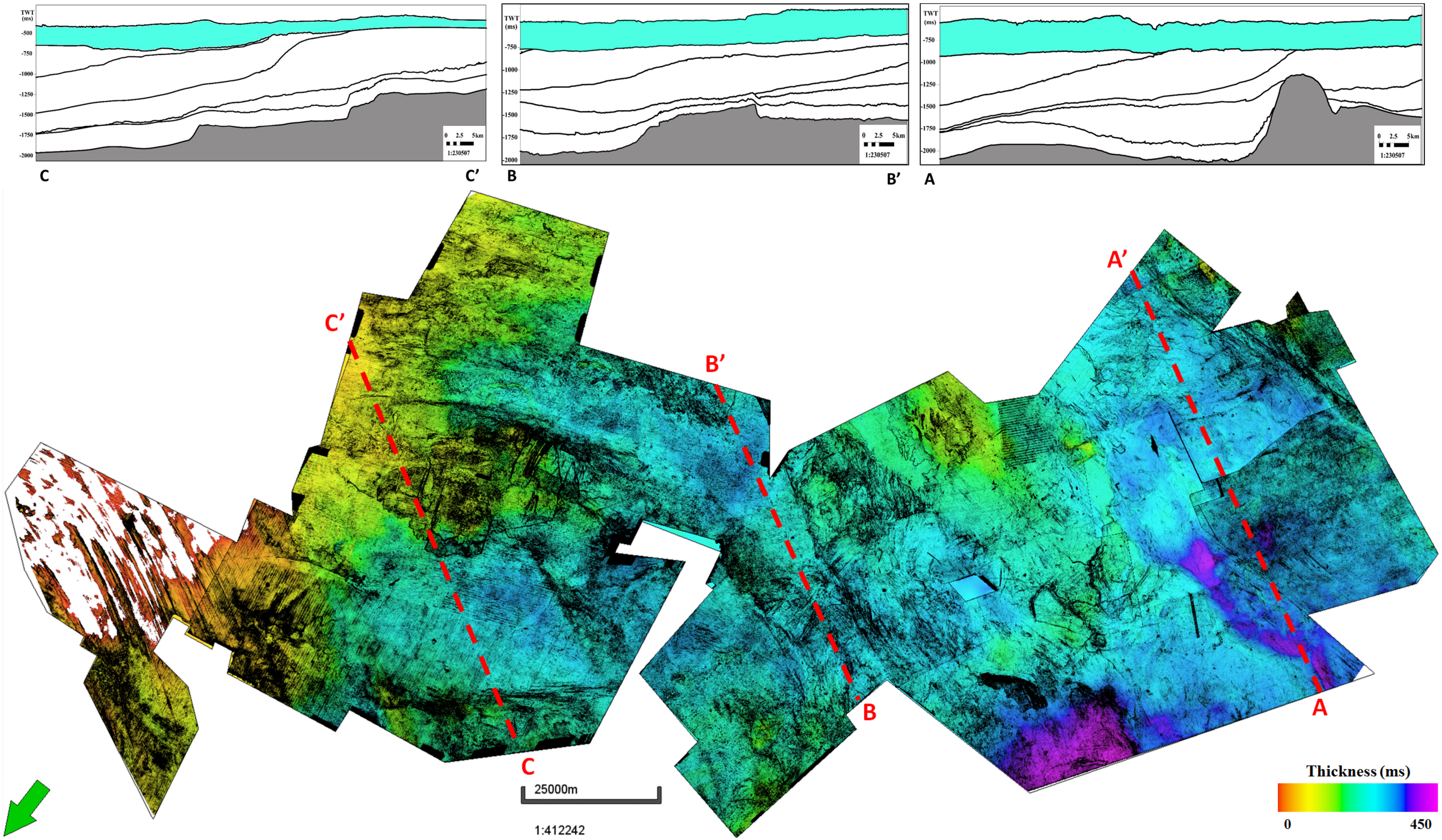

Figure 45. Three cross sections located in the southern (A-A'), central (B-B') and northern (C-C') part of the study area demonstrates the relative position and outbuilding pattern of SS-7 throughout the study area. The time thickness map (TWT) of SS-7, shows thicknesses varying between 0 and 450 ms, with an average of 200 ms. The white areas illustrates areas where the sequence is truncated by the seafloor. Depocenters are located on the Dønna Terrace, Rås Basin, Trøndelag Platform and Vøring Basin. A variance map of the seafloor is superimposed to illustrate discontinuities and features observed at the top of SS-7.

5.2 Facies analysis

Five seismic facies categories have been identified within the study area and the seismic facies have been classified based on internal reflector configuration, external geometry of the surface bounded seismic facies, seismic reflectivity and continuity. The classification (Table 3) is created to define the seismic character variations caused by geological changes. Horizontal and vertical seismic resolution constrains the sizes of recognizable depositional geometries in the seismic data. Both vertical and horizontal aspects of seismic resolution are a function of acoustic pulse frequency, pulse wavelength and layer velocity.

Seismic facies	Depositional facies	Internal configurations	Amplitude	Continuity	Sedimentary facies interpretation	Seismic Sequences
SF-A	Parallel to sub-parallel facies	Parallel to sub-parallel	High	Continuous	Shelf to shelf margin and prograding slope	SS-3, SS-4, SS-5, SS-6
SF-B	Sub-parallel to convergent reflectors	Sub-parallel to convergent	Low	Semicontinuous	Prograding slope	SS-5, SS-6, SS-7
SF-C	Prograding clinoforms	Sub-parallel to convergent to oblique	Moderate	Semicontinuous	Shelf margin and prograding slope	SS-3, SS-4, SS-5
SF-D	Chaotic facies	Wavy to chaotic	Variable	Discontinuous	Platform interior and gravitational collapsed	SS-1, SS-2, SS-7
SF-E	Onlapping-fill seismic facies	Sub-parallel, onlapping	Variable	Semicontinuous	Basin slope and basin floor	SS-2, SS-3, SS-7
SF-F	Polygonal fault system	Small offset faults	Moderate	Semicontinuous	Dewatering and compaction of host sediments	SS-1, SS-2

Table 3. The 5 different seismic facies identified in the study area. Four seismic reflection attributes were used to classify the facies types: internal geometry, amplitude strength, external geometry and continuity. External geometry is observed from a 3D view of the package. (modified after Mitchum Jr et al. (1977))

5.2.1 Seismic facies category A; parallel to sub-parallel facies

Seismic facies category A (SF-A) consists of high reflectivity, continuous parallel to sub-parallel reflectors (Table 3). This seismic facies category ranges in some areas from thin, single seismic wavelets to more complex waveforms expressed as doublets or broad, complex, high amplitude sets or troughs and peaks (Figure 46).

The category is interpreted to represent fine clastic sub-marine fan/sheet deposits with interbedded pelagic to hemiplegic clay, and this combination is probably responsible for the high amplitude of these seismic facies.

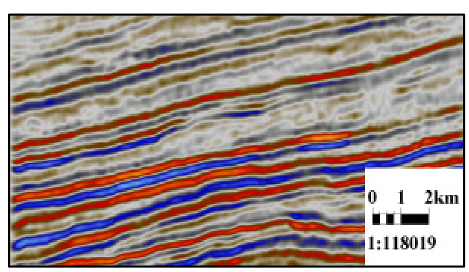

Figure 46. Seismic section displaying SF-A, parallel to sub-parallel facies

5.2.2 Seismic facies category B; sub-parallel to convergent facies

Seismic facies category B (SF-B) consists of low reflectivity, generally continuous sub-parallel to convergent reflectors (Table 3).

This seismic facies category occurs in close association with SF-A, and is interpreted to be related to interbedded sediments within stratigraphic units otherwise characterized by SF-A. The category is interpreted to represent hemipelagic and mud rich deposits between sub-marine lobe/fan deposits characterized by SF-A.

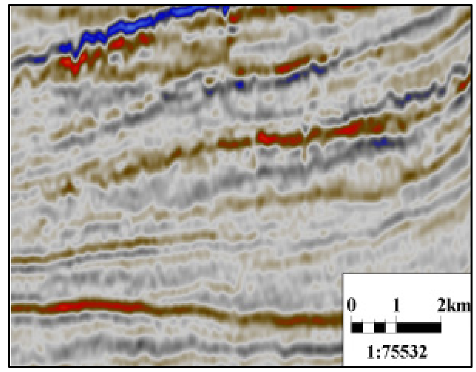

Figure 47. Seismic section displaying SF-B, sub-parallel to convergent facies

5.2.3 Seismic facies category C; prograding clinoforms

Seismic facies category C (SF-C) consists of sigmoid to sigmoid-oblique clinothem units (Table 3) when viewed parallel with the depositional dip.

Internal reflectors are terminated by toplap at or near the upper surface, and by downlap at the base (Figure 48). The downlapping reflector terminations represent outbuilding of sediments from relatively shallow into relatively deep waters.

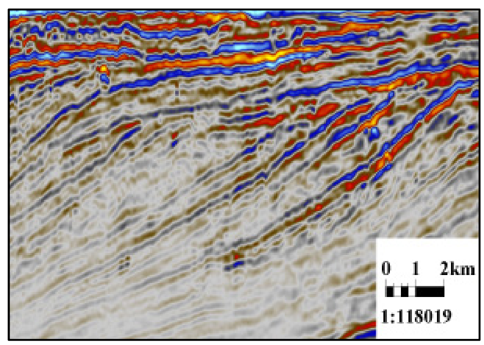

Figure 48. Seismic section displaying SF-C, prograding clinoforms

5.2.4 Seismic facies category D; chaotic facies

Seismic facies category D (SF-D) consists of low reflectivity, low amplitude, poor reflection continuity and almost no internal reflection configuration (Table 3 and Figure 49).

This reflect the extent of homogenization in mass transport types of these chaotic units. However, it could also be a result of either variable sand content in dominantly muddy sections, or rafted blocks within debris flow deposits.

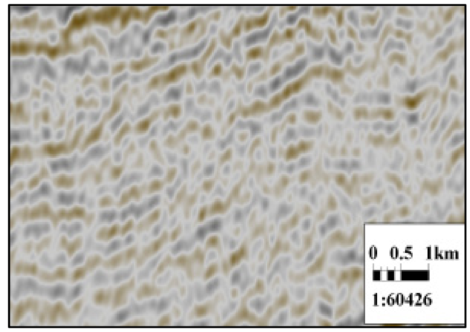

Figure 49.Seismic section displaying SF-D, chaotic facies

5.2.5 Seismic facies category E; onlapping-fill facies

Seismic facies category E (SF-E) consist of uniform, parallel to gently divergent reflectors patterns with high continuity and high to variable amplitude (Table 3 and Figure 50).

This indicates deposits formed by relatively low velocity turbidity currents interbedded with hemiplegic and pelagic deposits. On a broader scale, the onlapping-fill seismic facies can be interpreted to represent a basin slope and basin floor depositional environment.

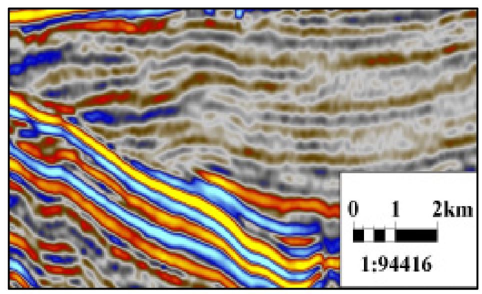

Figure 50.Seismic section displaying SF-E, onlapping fill facies

5.2.6 Seismic Facies Category F; polygonal fault system

Seismic facies category F (SF-F) consists of layer of small-offset faults that show a lack of dominant strike direction.

Their upper and lower terminations do not necessarily occur at the same stratigraphic level. Generally, the fault throw is highest close to the lower termination, and the height of the fault depends on the thickness of the hosting layer.

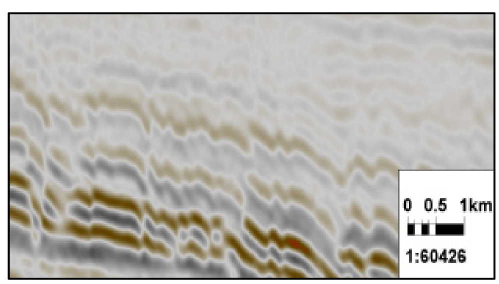

Figure 51. Seismic section displaying SF-F, polygonal fault system

5.3 Chronostratigraphic charts

The chronostratigraphic chart was constructed to obtain better insight into the time relationships of the depositional systems, and their relationships to surfaces of non-deposition, condensation and erosion. Seismic reflectors that are considered to represent time lines have been plotted in order of age, with an equal time increment given to each horizon.

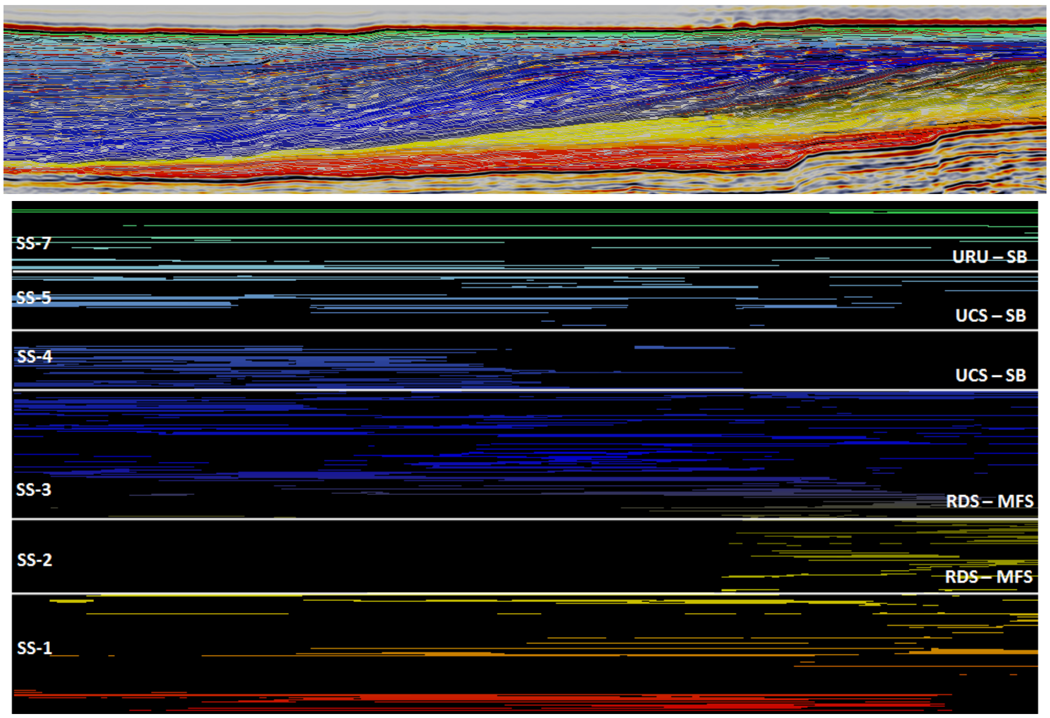

Figure 52. Chronostratigraphic diagram for Inline 14100 covering the Cenozoic deposits of mid-Norway, showing the relative age and distribution of the sequences

SS-1 and SS-2 represents periods of relatively warm climate, deep oceans and thin deposits, and are genetically related to one other. SS-3 to SS-5 represents glacio-marine deposits, and contains several smaller periods of inter-glaciations, but because of the lack of time, the prominent ones have been mapped out and shown. SS-3 to SS-5 is genetically related to each other, but SS-7 is not related to other sequences. SS-7 marks the end of glacial advancement and marks the end of regional tilting.

Blank areas represents areas of non-deposition, erosion or condensed sections. The condensed sections have thickness below seismic resolution and appear to die out. Note that SS-6 is not available in inline 14100.

6.0 DISCUSSION

This study has divided the Cenozoic succession into seven seismic stratigraphic sequences and this chapter discusses the ages of the defined seismic sequences, the controlling factors on deposition and petroleum significance of this analysis.

6.1 Ages of the sequences

The ages of regional seismic surfaces like RDS, URU, UCS, and other seismic horizons have been extrapolated from well tops and compared with the proposed ages from previous studies (Rise et al., 2005, Abbas, 2006, Eidvin et al., 2007, Rise et al., 2010, Hafeez, 2011, Talat, 2012).

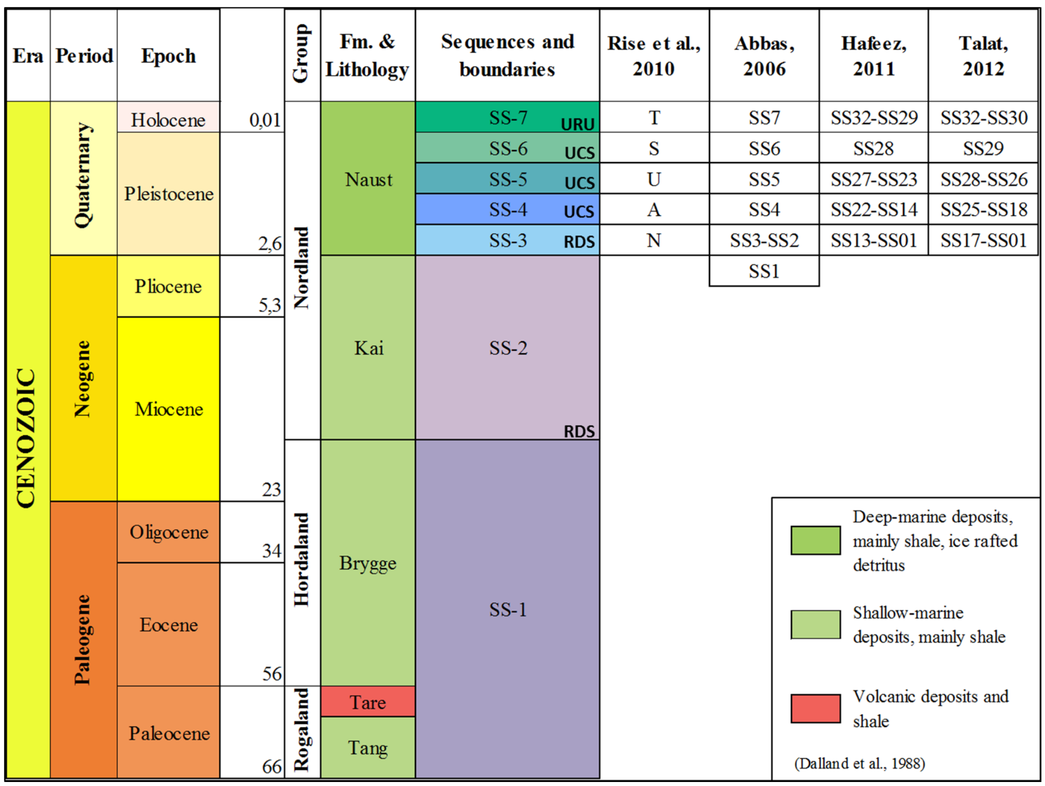

Figure 53. Summary showing the identified seismic sequences, bounding surfaces, formations, lithology and comparison with seismic sequences defined previous studies.

The age, number and boundary surfaces of the seismic stratigraphic sequences defined in this study correlates with some of the seismic stratigraphic sequences and boundaries interpreted in previous studies (Figure 53). However, this study is focused on the complete Cenozoic succession, not only Quaternary deposits. The seismic sequences defined in the Naust Formation coincide with the depositional subdivisions defined by

Rise et al. (2010). In addition, the age control on the various boundaries, especially the Unconformity Clinoform Surfaces, were improved when comparing sequences defined in this study with previous work. Hafeez (2011) and Talat (2012) have interpreted more than 25 sequences within the Quaternary (Figure 53), and are believed to be detailed studies of the parasequences within the defined seismic sequences of this study.

SS-1 was deposited in the timespan 18-55 Ma, and have an average thickness of 230 ms. It consists of Tare, Tang and lower Brygge formations (Figure 53). The seismic character of the unit indicates inactive depositional system, and indicates low sedimentation rates and clay-dominated lithology. There was a transgression during the deposition of SS-1, inferring restricted sediment supply.

SS-2 was deposited in the timespan 4-15 Ma, and have an average thickness of 210 ms. It consists of upper of Brygge Formation (Figure 53). The seismic character of the unit indicates varying depositional systems and water depths, representing a general decrease in water depth throughout the sequence. In addition, this sequence illustrates a higher sedimentation rate than in SS-1. Within the sequence, there are local downlap and onlap surfaces, indicating potential local conditions of subsidence, sediment supply and eustacy.

SS-3 of Pliocene age was deposited in the timespan 1.5-1.8 Ma., and have an average thickness of 390 ms. It comprises what is defined as Naust N by Rise et al. (2010) (Figure 53). The bounding surface at the top of the SS-3 is a prominent seismic marker, however, it varies locally in character, as the surface changes from a local downlap surface to a local onlap surface towards the north. This surface demonstrates various fluvial incisions and glacial features into the underlying sequences at various levels, and represents an erosional surface.

SS-4 of Pliocene age was deposited in the timespan 0.8-1.5 Ma., and have an average thickness of 260 ms. It comprises what is defined as Naust A by Rise et al. (2010) (Figure 53). The bounding surface at the top of SS-4 is a good seismic marker, but varies locally in character, and the surface changes from a local downlap surface to a local onlap surface towards the north, which might indicate a rise of relative sea level.

SS-5 of Pliocene age was deposited in the timespan 0.4-0.8 Ma, and have an average thickness of 290 ms. It comprises what is defined as Naust U by Rise et al. (2010) (Figure 53). The bounding surface of top SS-5 is a prominent seismic marker, but varies locally in character, and the surface changes from a local downlap surface to a local onlap surface towards the north. This may have been caused by an increase in accommodation space and sedimentation rate during the rise of relative sea level.

SS-6 of Pliocene age was deposited in the timespan 0.2-0.4 Ma, and average thickness of 280 ms. It comprises what is defined as Naust S by Rise et al. (2010) (Figure 53). The bounding surface at the top of SS-6 is a good seismic marker and is characterized by high amplitude and that the underlying depositional surfaces is truncated by it. The bounding surface at the top of SS-6 is a good seismic marker and is characterized by high amplitude and that the underlying depositional surfaces is truncated by it. This surface demonstrates various fluvial incisions and glacial features into the underlying sequences at various levels, and represents an erosional surface.

SS-7 of Holocene age was deposited in the timespan 0-0.2 Ma, and average thickness of 230 ms. It comprises the lowermost and youngest seismic stratigraphic sequence of the Naust Formation and is defined as Naust T by Rise et al. (2010) (Figure 53). Naust T was deposited on the shelf and uppermost slope during the two glacial-interglacial cycles. Units within the sequence downlap onto the URU, which separates the upper aggrading depositional units from the underlying prograding units. This pattern change indicates limited sediment input from land areas or a decrease in accommodation space. The aggradation is very prominent in the southern part of the study area, but the pattern is still the dominant style throughout the sequence.

The seismic stratigraphic analysis method is based on interpretation of the stratigraphic record and is therefore subjective, and contains uncertainties of the age constraints of sequences and tectonics events identified in this study. There are also limitations in this study related to possible over-or-under representation of certain traits or shapes based on the resolution of the seismic.

6.2 Controlling factors

Several factors have influenced the rate of sediment delivery throughout the successive glacial cycles during the Cenozoic era, such as climate, tide, waves, tectonics and basin geometry (Emery and Myers, 2009). By subdividing and linking sedimentary deposits into unconformity-bounded units, the stratigraphic units can be explained in terms of variations in sediment supply and rate of change in accommodation space.

The Cenozoic sediment outbuilding in the mid-NCS reveals important information regarding how and when accommodation space was created or destroyed through time and space. However, these variations in accommodation space cannot only be explained by eustatic sea level changes. Tectonics have played a significant role in the varying rate of accommodation space during the Cenozoic in the Norwegian Sea. Significant uplift of the mainland Norway in Late Eocene to Early Oligocene were accompanied by a lowered eustatic sea level and subsidence of the basin floor (Faleide et al., 2008). This, combined with the onset of glacial erosion in mountainous areas lead to a large increase in sediment supply.

The wide and gently dipping Trøndelag Platform, along with the variable basin physiography have exerted major control on the sequence development throughout the Cenozoic period. Presuming that the sedimentation rates were constant during the deposition of Kai, Brygge, Tang and Tare formations, this is largely a question about accommodation. However, some of the depocenters might have developed due to increased subsidence or previous underfilling. The time thickness maps (Figures 27, 30, 33, 36, 39, 42 and 45) of sedimentary deposits in the Cenozoic reveal that the depositional pattern changed significantly from SS-2 to SS-3 and again from SS-6 to SS-7. Sedimentary depocenters changed from the southern part of the study area to the west before switching to the south again. The evolution of the sediments indicate that the sediments were mainly sourced from the continental shelf and the Norwegian mainland. The change from dominantly along-slope to dominantly down-slope sedimentary processes is related both to the uplift of Fennoscandia (Stuevold and Eldholm, 1996) and the climatic cooling which started at ca. 2.5 Ma by the onset of the Northern Hemisphere Glaciations (Hjelstuen et al., 2004).

SS-1 and SS-2 are both bounded by a Regional Downlap Surface, indicating two separate events of transgressions during the period of deposition of these seismic sequences. They also contain localized downlap and onlap surfaces, indicating local conditions for subsidence, sediment supply and eustacy.

SS-3 marks the onset of the Late Cenozoic uplift and associated subsidence, and the erosional surfaces on top SS-3 and SS-4 was created by tectonic uplift and erosion from advancing ice sheets. Rise et al. (2005) suggests that the topsets of SS-5 and SS-6 were eroded by recent glacial advancements, and are consequently not associated with tilt-related erosion. SS-7 marks the ending of this tectonic tilting, hence, the accommodation space is suggested to be the complex interplay between eustatic sea-level changes and glacial erosion. The regional extent of the eroded topsets, rollover points and topsets of the clinoform units within SS-3 to SS-6 illustrates that the hinge line of the shelf-hinterland tilting, was approximately parallel to the present day coastline. Tectonic uplift of the eastern hinterland of this study area caused destruction of accommodation space in this area, along with erosion. Additionally, tectonic subsidence west of the hinge line formed accommodation space and deposition of sediments. However, since the amount of tectonic uplift and subsidence have altered, it is difficult to identify the position of the hinge line exactly through time.

SS-3 to SS-6 are interpreted to contain westerly prograding clinoform units with a progradational stacking pattern, but because URU has eroded the topsets and rollover points, there are uncertainties to whether the offlap break trajectories are showing a positive, flat or negative trajectory. SS-3 are the seismic sequence with the best-preserved topsets, and show a general change from a flat to a negative offlap trajectory. This suggests a change from high rates of creation of accommodation space to a situation where accommodation space and sediment supply were more or less equal.

The pronounced erosional surface URU at the base of SS-7 was caused by glacial advancements onto the basin. Rise et al. (2005) suggests that the advancements of ice sheets was the possible mechanism for the erosion of topsets of the clinothemes in SS-3 to SS-6. This indicates that the ice sheets had the necessary thickness to be grounded and hence, cause erosion of the underlying seismic sequences. The ice sheets capacity to advance onto the continental shelf also indicates that the sea level was lowered glacio-eustatically. However, the relative sea level may have risen in areas where the rate of tectonic subsidence is higher than the rate of fall in eustacy.

Sediment load of the outbuilding sediments throughout the Cenozoic period have played a significant role in the subsidence of the basin, predominantly when the uplift-related tilting was waning. A rise in the relative sea level might have been triggered by sediment load driven subsidence, which might explain the local differences in sediment deposition and depocenters.

The almost complete absence of onshore Mesozoic and Cenozoic sedimentary rocks, together with the existence of large volumes of Cenozoic sediments deposited along most of the Norwegian margin are considered to be the result of several phases of regional uplift and erosion of Scandinavia (Henriksen and Vorren, 1996). A tectonically induced increase in elevation will under, most conditions, increase the sediment yield into the bordering basins. However, it is difficult to separate the tectonic pulses from increased erosion caused by a eustatic sea level change or by a change in climate. Stratigraphic mapping does not constrain the location of the sediment source on its own, as sediment influx can overprint the eustatic record, e.g. high sediment yield can lead to a regression of the shoreline, even during a rise in eustatic sea level. This leads to uncertainties in the stratigraphic interpretation.

The basinward tilting of the Upper Regional Unconformity (URU) and over-deepened buried paleo-shelf breaks are uncommon features of glacial shelves, which suggests that the outer mid-NCS has been affected by subsidence. This indicates that the shelf has been prone to tectonic tilting after the deposition took place (Dahlgren et al., 2002).

Naust sequence (Fig. 1B)	Age (Ma)	Time interval (k.y.)	Sediment volume (km^3)	Average sediment delivery rate (m $k.y.^{-1}$)	Bedrock volume (20% compaction) (km^3)	Bedrock erosion (m)	Average bedrock erosion rate (m $k.y.^{-1}$)
T	0–0.2	200	16,300	0.50	13,000	81	0.41
S	0.2–0.4	200	12,500	0.38	10,000	63	0.31
U	0.4–0.6	200	17,100	0.52	13,700	86	0.43
A	0.6–1.5	900	24,400	0.17	19,500	122	0.14
N	1.5–2.7	1200	34,400	0.18	27,500	172	0.14
Total	0–2.7	2700	104,700	0.24	83,700	524	0.19

Table 4. Sediment volumes and ages, together with rates of sediment delivery and catchment erosion, for the five sequences of the Naust Formation on the mid-Norwegian margin (Dowdeswell et al., 2010)

If the ages suggested by this study and previous work is correct, the sediment supply to the shelf areas was extremely high during the deposition of Naust Formation. Table 4 shows that there is a link to the combination of thicker and faster flowing ice and longer periods of full-glacial ice extent on the continental shelf over the past few hundred thousand years. Regional uplift has probably also influenced ice-sheet growth (Riis 1996). The amount of ice-rafted debris in the Norwegian Sea, together with oxygen isotope measurements and terrestrial geological evidence indicates that the intensity of iceberg production from the western Fennoscandinavian Ice Sheet was higher during the late Cenozoic period (Dowdeswell et al., 2010). By looking at the late Cenozoic ice age on the mid-Norwegian shelf as a whole, the sedimentation rate has increased through the present ice age. The main control on sediment delivery through this period is therefore not the removal of pre-glacial weather products and fluvial sediments, but rather the intensity of glaciations.

6.3 Petroleum significance

Seismic sequence stratigraphy has become an important tool to predict facies distribution and depositional environments, and it is commonly used to predict the formation and infill patterns of sedimentary basins. This generally reflect basin morphology and physiography, and is therefore a powerful tool in studying the basin formation and configuration.

Modern seismic interpretation aims to obtain as much geological information as possible from seismic reflection data. Combining this with sequence stratigraphic analysis, more geology can be extracted from the seismic. By creating Wheeler transformed domains, sedimentary rocks can be classified, correlated and mapped using time-stratigraphic units. This assists in increasing the understanding of the depositional history of sedimentary packages, improved seismic facies and litho-facies predictions, and provided more accurate targeting of reservoir rocks, source rocks and seal potential away from well control.

In this study, the regional seismic sequences that were interpreted revealed information regarding the Cenozoic deposits, especially their outbuilding pattern and seismic facies. The seismic sequences, sedimentary packages and systems tracts mapped out in this study provides a method of predicting lithology and infill patterns in the basin. This study provides the necessary information to identify the most promising areas in a petroleum setting, but a more detailed study of each sequence is needed to identify individual units of continuous reservoir rock and trapping mechanisms.

The sedimentary environments and patterns during the Cenozoic period have additionally major implications for installation of hydrocarbon-producing equipment on or above the seafloor, and thus the importance of understanding the Quaternary development cannot be underestimated (Martinsen and Dreyer, 2001).

7.0 CONCLUSION

The formerly glaciated mid-Norwegian passive continental margin has received considerable attention during the last decades in terms of reservoir rock prospectivity. Cenozoic reservoirs are primary targets, and this is due to the overall thickness of the sedimentary pile, but the structuring is also of interest as a trapping mechanism. The present shape of the mid-NCS developed during last 2.8m.y.

The almost total absence of Cenozoic sediments on the adjacent Norwegian mainland points to several phases of uplift and erosion. Sedimentation rates changed through time, mostly depending on glacial activity and relative sea level changes. The importance of glaciations in the study area increased through the Pleistocene period.

Seismic sequence stratigraphic analysis assisted to understand the source-to-sink relationship, tectonics and climate changes for the Cenozoic outbuilding of the mid-Norwegian continental margin. The Cenozoic succession formed as a response to a complex interplay between a set of diverse controlling factors, such as tectonics, climate, sediment supply and accommodation space.

The sequence stratigraphic evolution of the Cenozoic outbuilding the Norwegian Sea took place by the formation of seven seismic sequences, bounded by Regional Downlap Surfaces (RDS), Unconformity Clinoform Surfaces (UCS) and the Upper Regional Unconformity (URU). Age control of the seismic sequences are based on well information and previous studies.

Glacioeustacy and differential subsidence resulted in falls and rises in relative sea level occurred repetitively throughout the Cenozoic succession, resulting in several downlap surfaces in the Brygge and Kai formations, and erosional surfaces within the westerly prograding clinoforms in the Naust Formation.

Preserved rollover points reflect the relative sea level fluctuations and thickness of ice sheet. In the northern part of the study area, the positive offlap break trajectories reflect thin ice sheet fronts, which were not eroding the shelf. After the development of URU a marked shift in stacking pattern from progradation to aggradation occurred. This shift indicates the end of tilting and accommodation space was mainly created by the subsidence due to the sediment loading.

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