Evolution of an Eocene prograding system in the Tromsø Basin, southwestern Barents Sea

Kristine Morsund Karlsen

Master Thesis in Geosciences
Petroleum Geology and Petroleum Geophysics
30 credits

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Faculty of Mathematics and Natural Sciences

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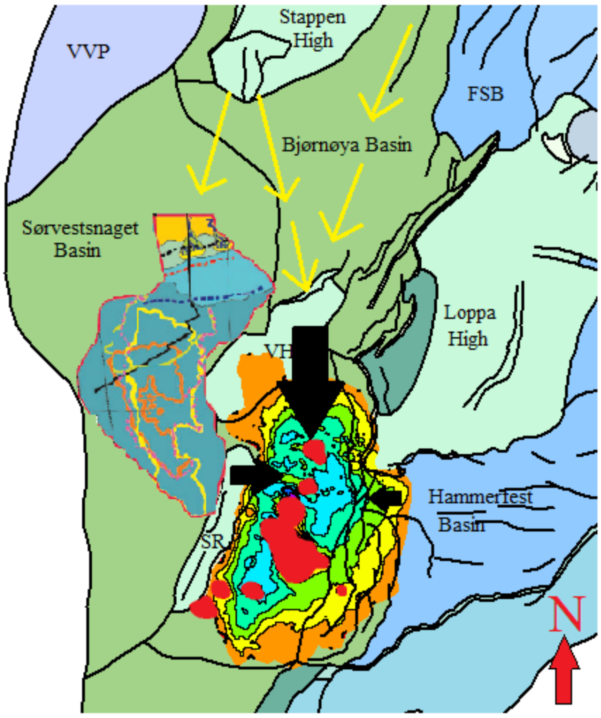

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Abstract

Prinicples of sequence stratigraphy were applied to 2D seismic data to study the evolution of a N-S prograding system that developed in the southwestern Barents Sea during Eocene. Four units were interpreted in the basin, of which two progradational units were studied in detail based on reflection terminations.

The sequence stratigraphic analysis provides evidence for a change in the beginning of Eocene from a bathyal/marine environment to a depositional environment affected by major clastic sediment input from north. The N-S prograding system was complimented by two additional sediment inputs during Eocene, from the northern part of the Senja Ridge and from remains of an ENE-WSW prograding Paleocene system from east.

Several earlier studies have proposed the Loppa High as one of the main source areas of the Eocene succession in the Tromsø Basin, in addition to the Senja Ridge and Stappen High. However, the depositional patterns and geometries observed in this study indicate that the main source area of the Tromsø Basin must have been in the north.

The Stappen High is suggested as one of the northern source areas for the Eocene sediments in the Tromsø Basin, but is most likely assembled by at least one additional source area in the north due to the great volumes of Eocene sediments in both the Sørvestsnaget and Tromsø basins. This could be in the uplifted northern Barents Shelf, and/or in the Western Spitsbergen fold-and-thrust-belt that formed in connection to transform movements during the opening of the Norwegian-Greenland Sea and Eurasia basin during Eocene.

Preface

This master thesis is the result of the two year master program “Petroleum Geology and Petroleum Geophysics” at the University of Oslo, department of Geosciences. This thesis has been supervised by Associate Professor Ivar Midtkandal, Professor Jan Inge Faleide and Professor Emeritus Johan Petter Nystuen.

Acknowledgements

First off all, I would like to give a special thanks to my supervisors; Associate Professor Ivar Midtkandal, Professor Jan Inge Faleide and Professor Emeritus Johan Petter Nystuen. Your encouragement, guidance and discussions through this thesis have been highly appreciated.

I would also like to thank TGS and Fugro for providing the selected 2D lines from their NBR-survey, and TGS for access to filtered gravity data. Special thanks to Senior Engineer Michel Heeremans for preparing the data set used in this thesis. Thanks to Schlumberger for making the Petrel software available.

Thanks to all of my fellow students at the University for discussions and cheerful moments at the University. Finally, a special thanks to my family and friends for encouraging and supporting me during this work.

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1 Introduction

The Barents Sea is a shallow epicontinental sea covering an area of approximately 1.3 million km^2 with water depths ranging from 150-500 meters (Fig. 1.1) (Worsley, 2008; Baig et al., 2016). The area extends from the Svalbard Archipelago and Franz Josef Land in the north to Northern Norway and Russia in the south, and from the Norwegian-Greenland Sea in the west to Novaya Zemlya in the east (Faleide et al., 1993; Worsley, 2008). It is bounded by young passive margins to the west and north that developed in response to the Cenozoic opening of the Norwegain-Greenland Sea and the Eurasia Basin (Faleide et al., 1993).

The structural and stratigraphic development of the Barents Sea is generally well understood, but due to considerable uplift and erosion of the area associated with the Eocene sea-floor spreading and with the late Pliocene-Pleistocene glaciations, are there still several questions about the Cenozoic evolution of the area. Most of the Eocene-Pliocene strata below the upper regional unconformity are missing in the Barents Sea, except for in the western marginal basins such as the Tromsø Basin and Sørvestsnaget Basin (Baig et al., 2016).

The main objective of this study is to establish an understanding of how the southwestern Barents Sea Tromsø Basin was filled by a prograding system in Eocene times. By studying and interpreting 2D seismic data in a sequence stratigraphic manor, first-order information about the basin configuration, infill history, relative sea level changes and development of accommodation can be achieved. The "source to sink" seen in a regional scale is one of the most important goals of the study, where possible sources areas for the Eocene succession in the Tromsø Basin are discussed. Important factors such as the late Cenozoic uplift and erosion, and salt movements within the basin are also discussed.

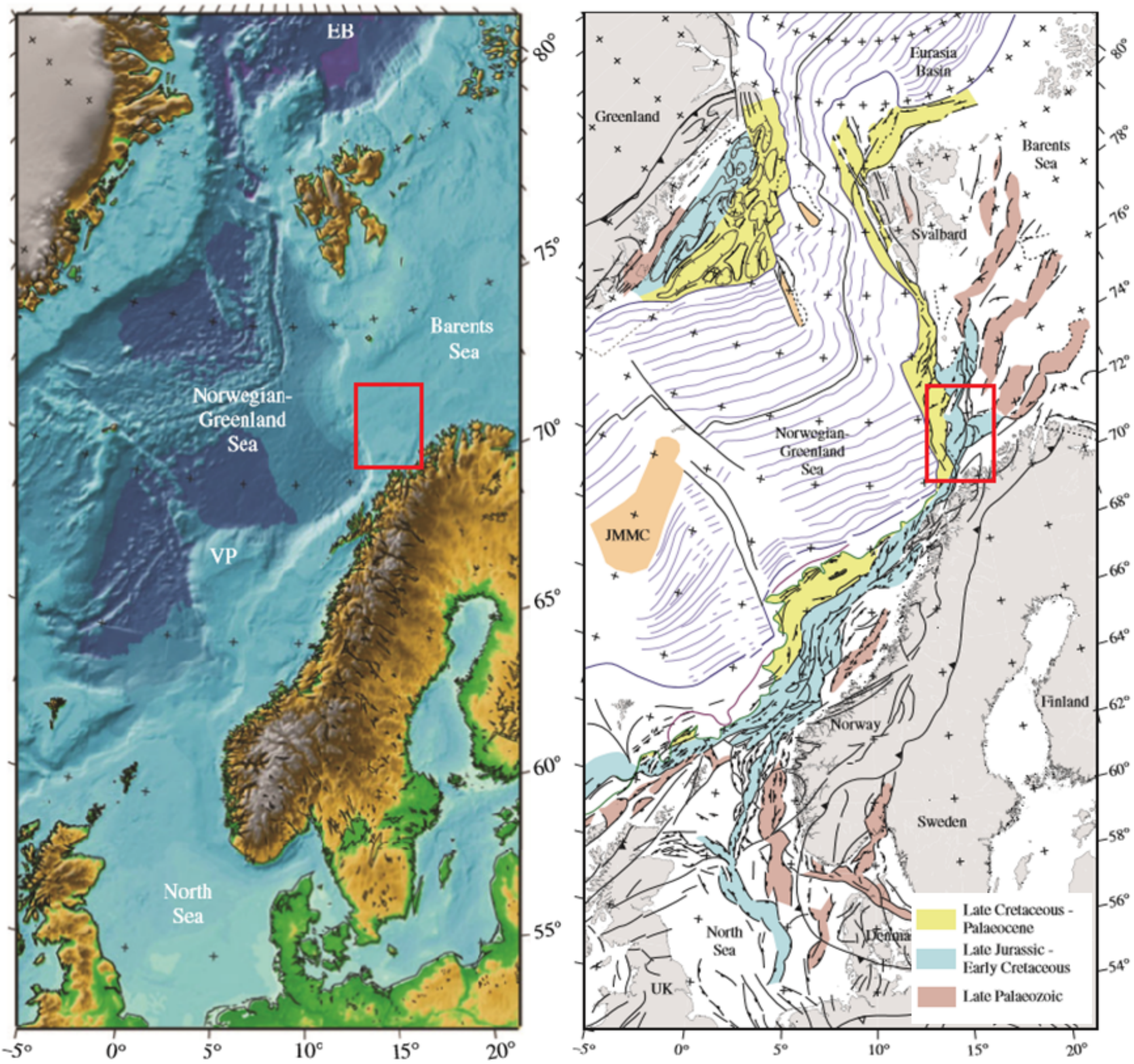


Figure 1.1: Left: Regional settings (bathymetry/topography) of the Norwegian Continental Shelf and adjacent areas. The study area within the southwestern Barents Sea is marked with a red square. **EB**: Eurasia Basin, **VP**: Vøring Plateau. Right: Main structural elements of the Norwegian Continental Shelf and adjacent areas related to different rift phases affecting the NE Atlantic region. **JMCC**: Jan Mayen microcontinent. Both modified from Faleide et al. (2015).

2 Geological framework

2.1 Regional setting

The Barents Sea covers the northwestern corner of the Eurasian continental shelf and overlies an intracratonic area of basins, platforms and highs (Faleide et al., 1993). It is bounded by young passive margins in the north and west that developed during the opening of the Norwegian-Greenland Sea and the Eurasia Basin (Faleide et al., 1993). The area can be divided into two geological provinces: an eastern and a western, where the western part is by far the most complex tectonically (Fig. 2.1) (Faleide et al., 1993). The western Barents Sea represents a different structural style compared to the eastern part, and comprises a Permo-Triassic platform affected by major graben-type basins (Smelror, 2009). A monoclinal structure trending N-S separates the two provinces roughly at the border between Norway and Russia (Worsley, 2008). The sedimentary cover in the Barents Sea exceeds 15 km in some places, and the western part is underlain by large thicknesses of Upper Palaeozoic to Cenozoic strata.

The Western Barents Sea was divided into three distinct regions by Faleide et al. (1993); 1) The Svalbard Platform, 2) a basin province between the Svalbard platform and the Norwegian coast, 3) the continental margin. The Svalbard Platform consists of flat lying successions of upper Palaeozoic and Mesozoic rocks. Several basins and highs build up the basin province where Jurassic-Cretaceous and Palaeocene-Eocene sedimentary strata are preserved. The province has an increased structural relief westwards. The continental margin can be dived into three segments; a southern sheared margin along the Senja fracture Zone, a central rifted complex southwest of Bjørnøya, and a northern sheared and later rifted margin along the Hornsund Fault Zone.

The Barents Sea has experienced several stages of tectonic activity since the Devonian period (Gabrielsen et al. 1990; Faleide et al., 1993; Ryseth et al., 2003). The Post-Caledonian structural history is dominated by three rift phases: in Late Devoninan to Carboniferous, Middle Jurassic to Early Cretaceous and in Early Cenozoic (Faleide et al., 1993). The rift-phases are illustrated in a timescale together with the lithostratigraphy of the western Barents Sea by Glørstad-Clark et al. (2010) in Fig. 2.3.

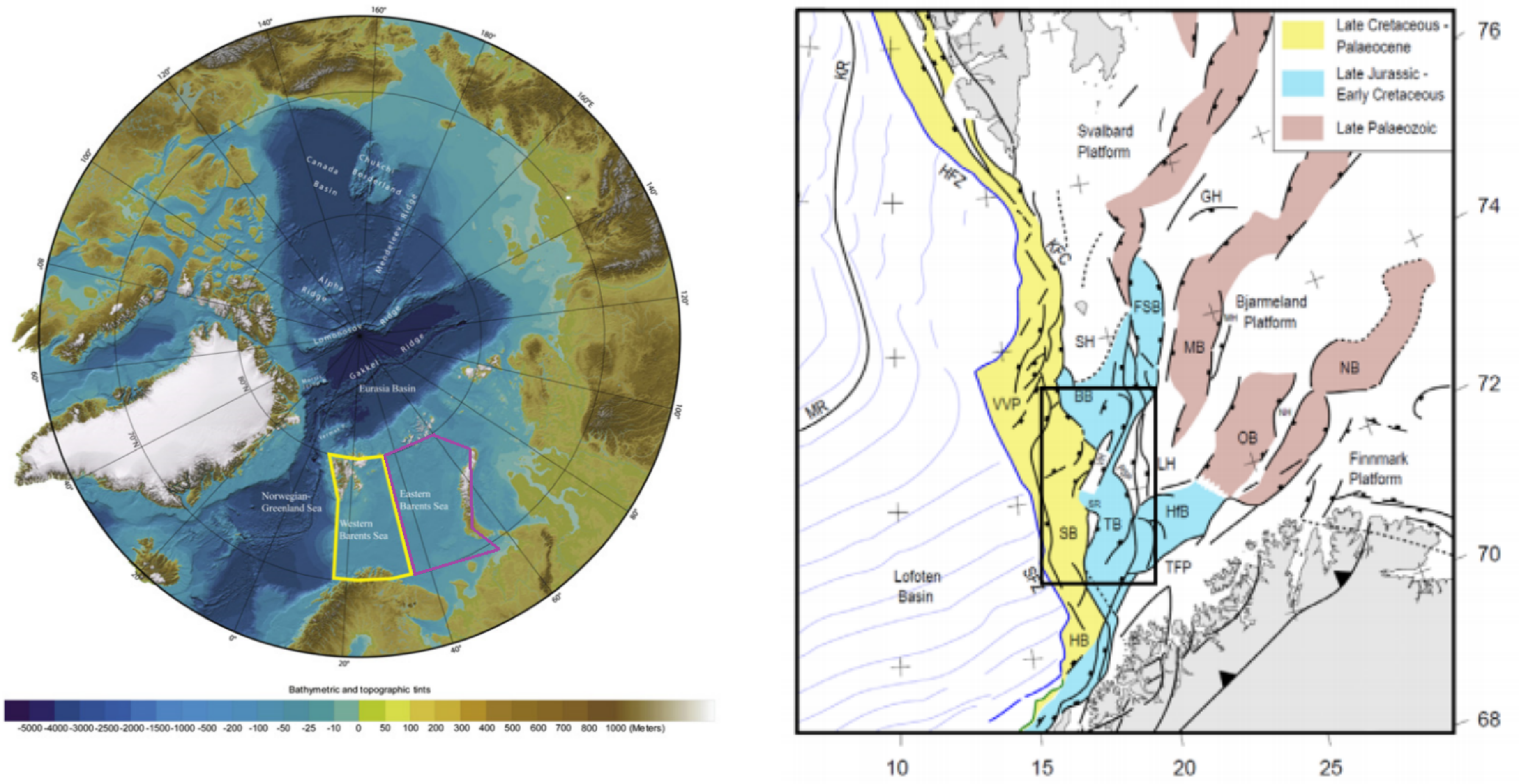


Figure 2.1: *Left:* Regional setting of the Barents Sea. Yellow rectangle marks the Western Barents Sea, Eastern Barents Sea within the red. Bathymetric map modified from Glørstad-Clark et al. (2010). *Right*: Structural elements of the Western Barents Sea. Study area marked within the square. Geological features are marked in the map: **BB**: Bjørnøya Basin, **FSB**: Fingerdjupet Sub-basin, **GH**: Gardarbanken High, **HB**: Harstad Basin, **HfB**: Hammerfest Basin, **HFZ**: Hornsund Fault Zone, **KFC**: Knølegga Fault Complex, **KR**: Knipovich Ridge, **LH**: Loppa High, **MB**: Maud Basin, **MH**: Mercurius High, **MR**: Mohns Ridge, **NB**: Nordkapp Basin, **NH**: Nordsel High, **OB**: Ottar Basin, **PSP**: Polhem Sub-platform, **SB:** Sørvestsnaget Basin, **SFZ**: Senja Fracture Zone, **SH**: Stappen High, **SR**: Senja Ridge, **TB**: Tromsø Basin, **TFP**: Troms-Finnmark Platform, **VH**: Veslemøy High, **VVP**: Vestbakken Volcanic Province. Modified from Faleide et al. (2015).

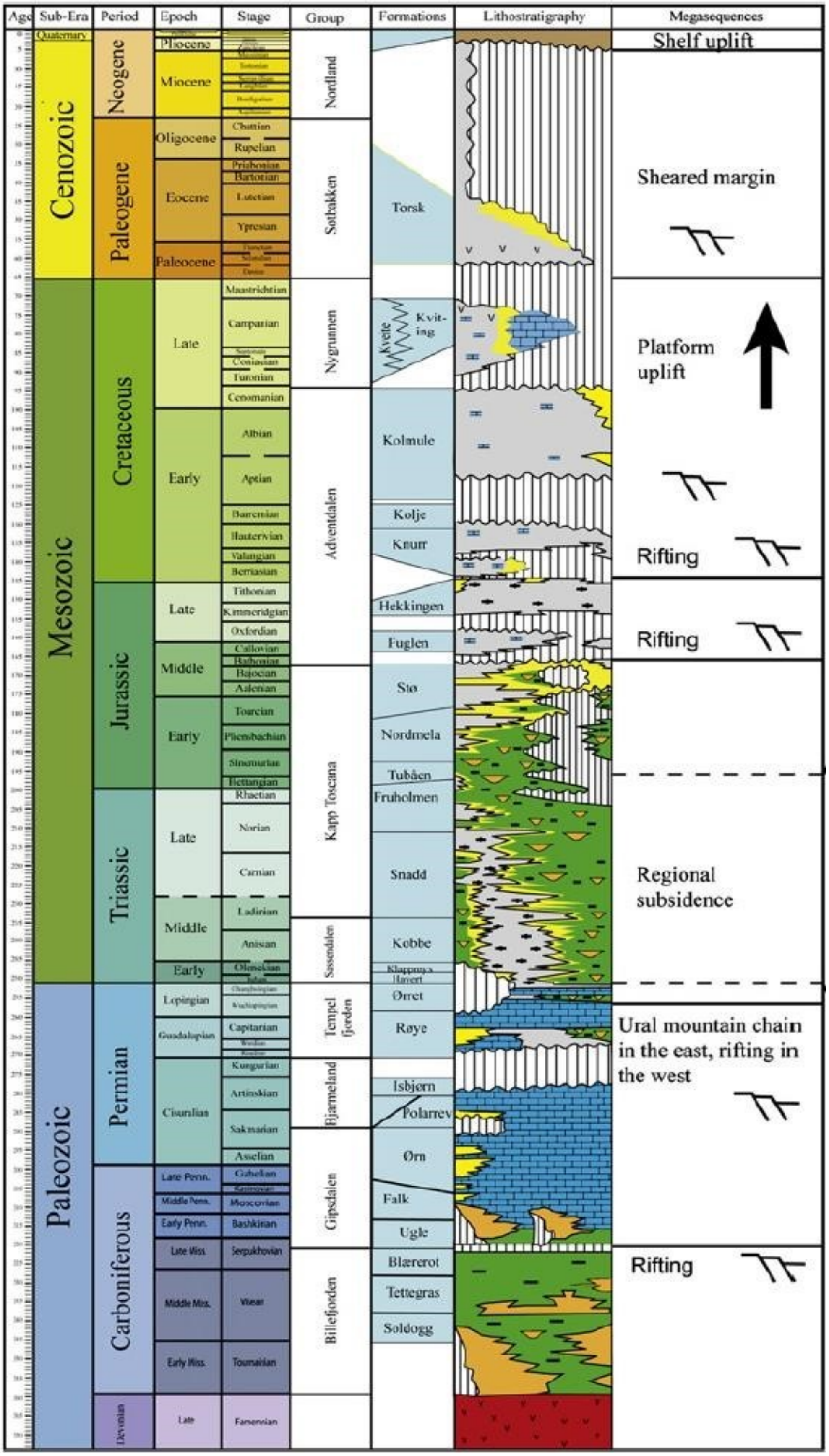


Figure 2.2: Schematic diagram of the lithostratigraphy in the western Barents Sea. The onset of sea floor spreading in Early Eocene times is marked by the sheared margin. From Glørstad-Clark et al. (2010).

2.2 Southwestern Barents Sea

The area of interest is located in the southwestern Barents Sea, within a basin province between the Svalbard platform and the Norwegian coast.

Faleide et al. (1993) divided the southwestern Barents Sea into three geological provinces on the basis of sedimentary fill, tectonic style and crustal structure: 1) The oceanic Lofoten Basin, formed during the Cenozoic opening of the Norwegian-Greenland Sea and the Vestbakken Volcanic Province, 2) The southwestern Barents Sea basin province of deep Cretaceous and early Cenozoic basins (Harstad, Tromsø, Bjørnøya and Sørvestsnaget basins), separated by intrabasinal highs (Senja Ridge, Veslemøy High and Stappen High),
3) Mesozoic basins and highs further east, which have not experienced the pronounced Cretaceous-Cenozoic subsidence (Finnmark Platform, Hammerfest Basin, Loppa High and Fingerdjupet basin)

The study area lies mainly within the Tromsø Basin, but includes parts of the Hammerfest Basin, Loppa High, Veslemøy High and Senja Ridge as well (Fig.2.3).

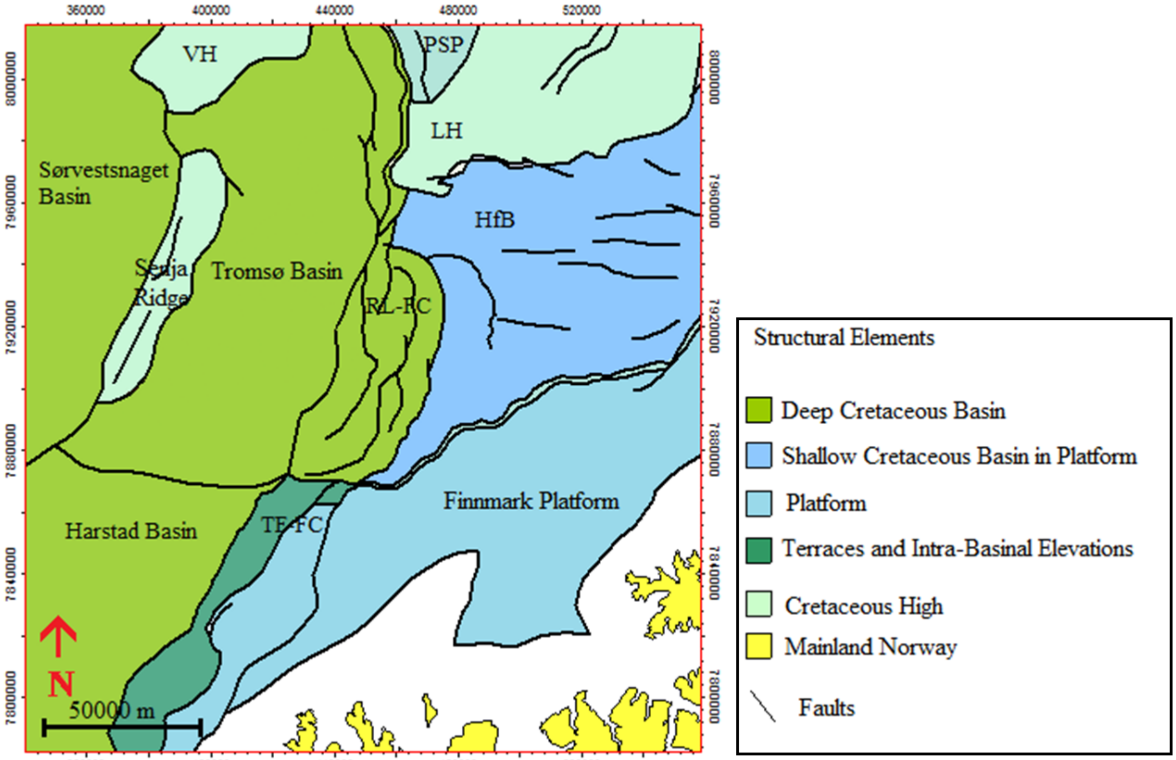


Figure 2.3: Local settings of the study area. Structural elements in the area are marked. **VH:**Veslemøy High, **PSP:** Polhem Sub-platform, **HfB:**Hammerfest Basin, **LH:** Loppa High, **RL-FC**: Ringvassøy-Loppa Fault Complex, **TF-FC:** Troms-Finnmark Fault Complex. Modified from NPD factmaps(2016).

Tromsø basin

The Tromsø Basin is a very deep, NNE-SSW oriented basin located from 71-72 º15 N, and 17º30 to 19 º50 E (Faleide et al., 1984; Gabrielsen et al., 1990). It is bordered by the Senja Ridge in the west and the Ringvassøy-Loppa Fault Complex in the east. In the north it is separated from the Bjørnøya Basin by the Veslemøy High and in the southeast it terminates against the Troms-Finnmark Fault Complex (Fig. 2.3) (Gabrielsen et al., 1990).

The basin was a part of a larger, regional basin in pre-Jurassic times. Clastic deposition occurred during Triassic in a relatively quiet period, characterized by regional subsidence. The development of a separate basin was initiated in Jurassic. During Cretaceous, the sediments were deposited simultaneously with subsidence and salt movements. This led eventually to most of the basin being filled in, and it became a part of the regionally subsiding area in the southwestern Barents Sea in late Cretaceous. In Cenozoic it acted as one of the main depocentres in the southwestern Barents Sea (Gabrielsen et al., 1990).

The Tromsø Basin comprises several salt structures (Faleide et al., 1993). The salts originate from evaporate deposits of late Carboniferous to early Permian age (Smelror, 2009; Faleide et al., 1993). Faleide et al. (1984) mapped the depth of some of these structures to more than 10 km from the sea floor. The salt movements in other basins further east, i.e the Nordkapp Basin, probably started in Early Triassic and have undergone several phases of growth in both Mesozoic and Cenozoic (Smelror, 2009; Henriksen and Vorren, 1996). Faleide et al. (1984) proposed salt movements in the Tromsø Basin during the subsidence in Cretaceous. The age of the last halokinesis in the basin is currently not stated.

Gabrielsen et al. (1990) described the structural elements of the Western Barents Sea region. This description for some of the elements surrounding the Tromsø Basin is summarized below and illustrated in Fig. 2.3.

Hammerfest Basin

The Hammerfest Basin is a relatively shallow Cretaceous basin striking ENE-WSW. It is separated from the Finnmark Platform by the Troms-Finnmark Fault Complex in the south, and from the Loppa High in the north by the Asterias Fault Complex. The western part is divided from the Tromsø Basin by the Ringvassøy-Loppa Fault Complex, while the eastern part borders to the Bjarmeland Platform. Together with the Tromsø Basin it was most likely a part of a larger depositional regime during Triassic to Early Jurassic. It commenced as the basin it is defined as today in Middle-Jurassic, and the major subsidence culminated in Cretaceous.

Loppa High

The Loppa High is located north of the Hammerfest Basin. It has a diamond-shaped outline and includes the Polhem Sub-platform. It is bounded in the south by the Asterias Fault Complex, and by a monocline towards the Hammerfest Basin and the Bjarmeland Platform in the southeast and east respectively. The northern limit of the high is defined by a major salt structure and rim syncline. The Loppa high is associated with positive gravity anomalies caused by shallow metamorphic basement beneath the western part. The high is a result of Late Jurassic to Early Cretaceous and Late Cretaceous –Cenozoic tectonism. The western crest, which incorporates the study area, has been renewed as a high four times since Devonian times. It appeared as an island in Cretaceous, but then covered by Paleogene shales and later eroded by Late Cenozoic uplift.

Senja Ridge

The Senja Ridge is a N-S trending intrabasinal high, which defines the western limit of the Tromsø Basin (Faleide et al., 1993). It is bounded to the west by normal faults and in the east by fewer and smaller faults (Faleide et al., 1993). It was a positive structural element from mid-Cretaceous to Late Pliocene, and has a positive gravity anomaly caused by a core of shallow basement (Gabrielsen et al., 1990; Riis et al., 1986). The relief in the ridge is explained by Late Cretaceous to early Cenozoic normal faulting and salt mobilization in the Tromsø Basin (Faleide et al., 1993).

Veslemøy High

The Veslemøy High was earlier considered to be a northern part of the Senja Ridge, but is now defined as a separate structural element. The high is located north of the Tromsø Basin, and separates it from the Bjørnøya Basin in the north and the Sørvestsnaget Basin in the northwest. A relatively thick Lower Cretaceous sediment package is present within the high, which indicates some continuity between the Tromsø Basin and the Bjørnøya Basin before Late Cretaceous and Tertiarty structuring (Faleide et al., 1993).

Ringvassøy-Loppa Fault Complex

The southern part of this fault complex coincides with the transition zone between the Tromsø Basin and the Hammerfest Basin. The N-S striking trend is defined by the westerly major faults in the complex. Main subsidence initiated in Middle Jurassic and culminated in Early Cretaceous.

2.3 Cenozoic development

The structural and stratigraphic development of the study area during the Cenozoic Era is summarized below. The structural development comprises two major events; the opening of the Norwegian-Greenland Sea and the formation of the western Barents Sea continental margin (Faleide et al., 2015).

In Paleocene the southwestern Barents Sea subsided and continental break up and a sea floor spreading followed (Faleide et al., 2015). This started the complex opening of the Norwegian-Greenland Sea and the Eurasia Basin in early Eocene times. However, the central and eastern parts of the Barents Sea were relatively stable in this period (Martinsen et al., 2013).

The Tromsø Basin was affected by marine conditions during Paleocene (Knutsen et al., 1992; Nagy et al., 1997). The deposits were mainly marine, offshore mudrocks in a widespread bathyal environment (Ryseth et al., 2003; Nøttvedt et al., 1988). Findings of benthic foraminiferal assemblages confirms a middle or upper bathyal environment (Nagy et al., 1997). Subsidence of the Tromsø basin occurred during Paleocene and the area was transgressed (Knutsen et al., 1992). The area reached its highest relative sea level in the end of Palaeocene, followed by a shallowing in the early Eocene (Nagy et al. 1997). Studies of foraminiferal abundance and diversity in the area done by Nagy et al., (1997) suggest an increased clastic sediment input to the basin during Early Eocene times.

The structural development in the Tromsø Basin during Eocene times was affected by seafloor spreading during the opening of the Norwegian-Greenland Sea and the development of the sheared western margin (Faleide et al., 1993). The sea-floor spreading led to elevation of the highs surrounding the Tromsø Basin; Loppa High, Senja Ridge and Veslemøy High (Knutsen et al., 1992). This gave rise to progradational input to the basin area from these highs (Knutsen et al., 1992). The source area of the thick Eocene succession found in the Sørvestsnaget Basin further northwest is suggested by Faleide et al. (1993) to have been the Stappen High. There is an agreement in the literature that the Stappen and Loppa highs were uplifted during Paleogene and acted as major source areas for the Eocene sediments in Sørvestsnaget and Tromsø basins (Knutsen et al., 1992; Faleide et al., 1993). Studies done in the Sørvestsnaget Basin by Ryseth et al. (2003) have suggested a significantly shallowing from early Eocene to Oligocene times.

The Eocene succession in the southwestern Barents Sea is a part of the Paleogene Torsk Fm. of the Sotbakken Group. The Group is defined by Worsley et al. (1988). The erosional unconformity at the base and top of the Torsk Formation corresponds to the Base Cenozoic and the upper regional unconformity, URU, of the area. The Group is dominated by claystones, minor siltstones, tuffaceous and carbonate horizons. The upper part of the Sotbakken group is only persevered in the west due to late Cenozoic uplift and erosion. A time-equivalent group is present on Svalbard, the Van Mijenfjord group, but shows a much more marginal marine development than the deep marine Sotbakken group. The single formation of the Sotbakken groups is the Torsk Fm. (Fig. 2.2).

The western Barents Sea margin started to develop in connection with the opening of the Norwegian- Greenland Sea (Faleide et al., 2015; Nagy et al., 1997). The margin developed as the Atlantic spreading ridge propagated northwards along the sheared Senja Fracture Zone (Ryseth et al., 2003). In early Eocene the boundary was a continent to continent transform, but developed to an ocean-continent transform during Eocene and earliest Oligocene. Oceanic crust developed along the margin between Svalbard and Norway from Oligocene, and subsidence of passive margins followed. This led to deposition of a massive Neogene wedge over and off the western shelf margins, coincided with uplift and erosion of Svalbard and the Barents shelf in the east (Vorren et al., 1991; Faleide et al., 1996; Ryseth et al., 2003;

Worsley, 2008). The relative movement between Norway and Greenland changed from NNW to WNW due to plate tectonic reorganization in early Oligocene (Ryseth et al., 2003).

The present continental margin of the western Barents Sea and Svalbard extends about 1000 km NNW and includes three structural segments: a southern, sheared margin along the Senja Fracture Zone, a central volcanic rift segment called the Vestbakken Volcanic Province, and a northern sheared and rifted margin along the Hornsund Fault zone (Ryseth et al., 2003).

LATE CENOZOIC UPLIFT AND EROSION

The Barents Sea has been greatly influenced by uplift and erosion in the Late Cenozoic. The subject has been discussed by several authors through the years (Riis and Fjeldskaar, 1992; Dore and Jensen, 1995; Dimakis et al., 1998; Ryseth et al., 2003; Cavanagh et al., 2006; Ohm et al., 2008; Henriksen et al., 2011; Baig et al., 2016)

It is difficult to decide the precise timing of uplift and erosion as the Eocene to Pliocene strata below the URU is missing in great parts of the Barents Sea, except in the western margin (Ryseth et al., 2003). However, the uplift and erosion is associated with the opening of the Norwegian-Greenland Sea in the early Eocene and the Late Pliocene-Pleistocene glaciations (Baig et al., 2016).

Baig et al. (2016) compared exhumation estimates from three different studies (Henriksen et al., 2011; Ohm et al., 2008; Riis et al., 1992) with the measured average net exhumation along a transect from the western to the eastern part of the southwestern Barents Sea. The data from two wells located in the western and eastern parts of the Tromsø Basin is of interest in this study. This is illustrated in Fig. 2.4.

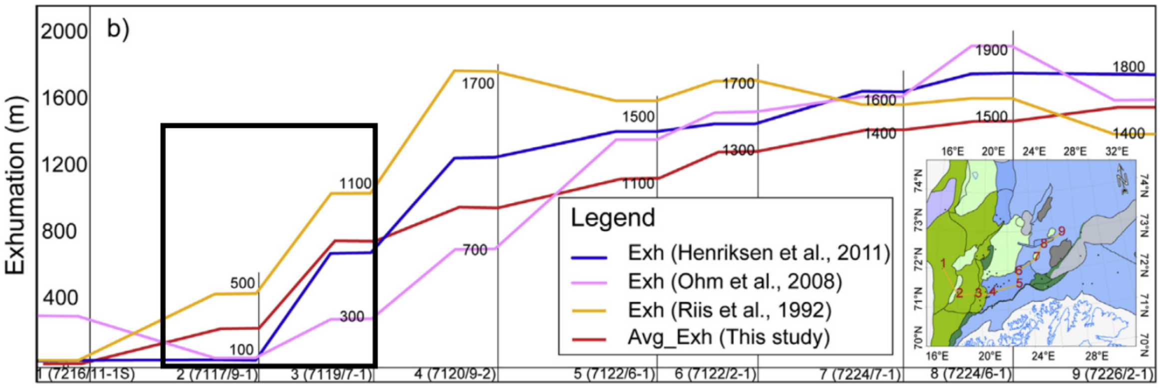


Figure 2.4: Comparison of exhumation estimates from three different data sets (Henriksen et al., 2011; Ohm et al., 2008; Riis et al., 1992), and the average net exhumation estimates along Transect-1from the study by Baig et al., 2016. Exhumation rates are given in meters. Results from well 2 and 3 located respectively in the western and eastern parts of the Tromsø Basin are of interest in this study. Modified from Baig et al. (2016).

The net exhumation in the western Tromsø Basin from the different studies ranges from 100 to 500 meters, with an average of about 300 meters. The net exhumation estimates increase towards the east and northeast. In the eastern part of the Tromsø Basin, in the Ringvassøy-Loppa Fault Complex, the net exhumation rates vary from 300 to 1100 meters, with an average of 700 meters. This means that approximately 500 meters of sediments have been eroded and removed in the Tromsø Basin. Baig et al. (2016) suggested that the present day bathymetry and seafloor morphology may be the result of sub-glacial erosional processes. However, significant erosion also took place prior to the onset of glaciations. The maximum burial in the southwestern Barents Sea probably occurred during the Eocene or Oligocene (Baig et al., 2016).

3 Data and methods

3.1 Data

Both seismic data and well data are used in this thesis.

The 2D seismic data are from the NBR-survey provided by TGS and Fugro. Some additional seismic lines were added in the southwestern corner of the study area to complete the interpretation of the Eocene succession here (Fig. 3.1). The quality of the seismic is generally very good. The density of the lines is high, between 3 and 10 km spacing.

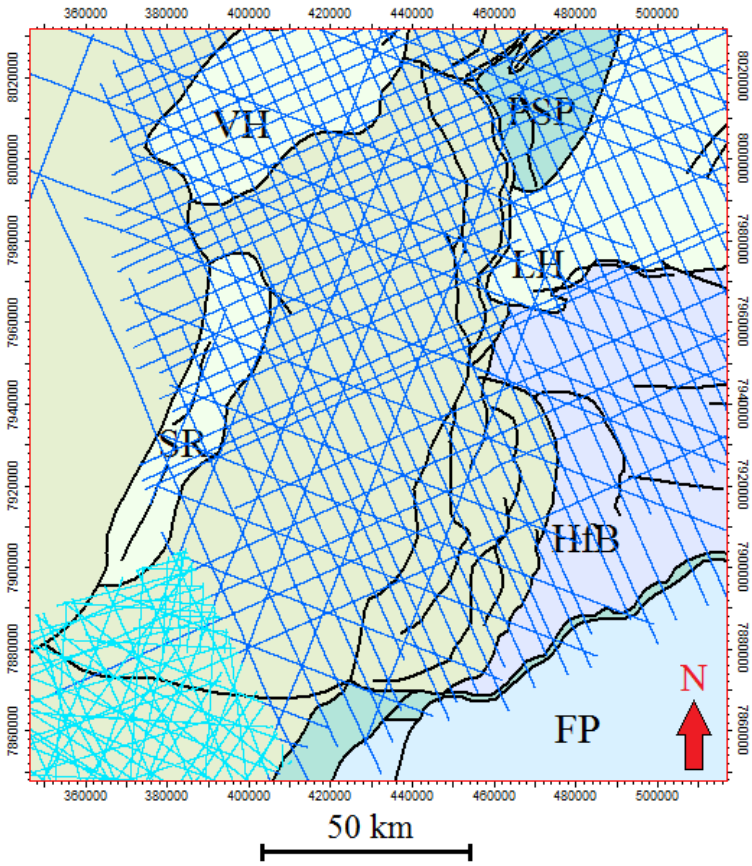


Figure 3.1: Seismic lines used for interpretation of the Eocene succession in Tromsø Basin. The light blue lines are seismic lines added during the interpretation to complete the Eocene succession within the basin. Structural elements are marked: **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform, **LH**: Loppa High, **HfB**: Hammerfest Basin, **FP**: Finnmark Platform.
Modified from NPD factmaps (2016).

There are drilled a total of ten wells in the Tromsø Basin (Fig. 3.2). Most of them are located in the southeastern part of the basin, except for two in the transition from the Senja Ridge to the Tromsø Basin, and one near the Veslemøy High. In addition to these is there one well located on the Veslemøy High.

Well data from the Norwegian Petroleum Directorate are used in the interpretation together with studies of the wells by Nagy et al. (1997, 2000, 2004). The well data are used for correlation of the Torsk Formation. in the area. The Torsk Formation corresponds to the "Base Cenozoic" and URU or base Neogene in the Tromsø Basin. The wells did also provide information about sonic velocities used for depth conversion.

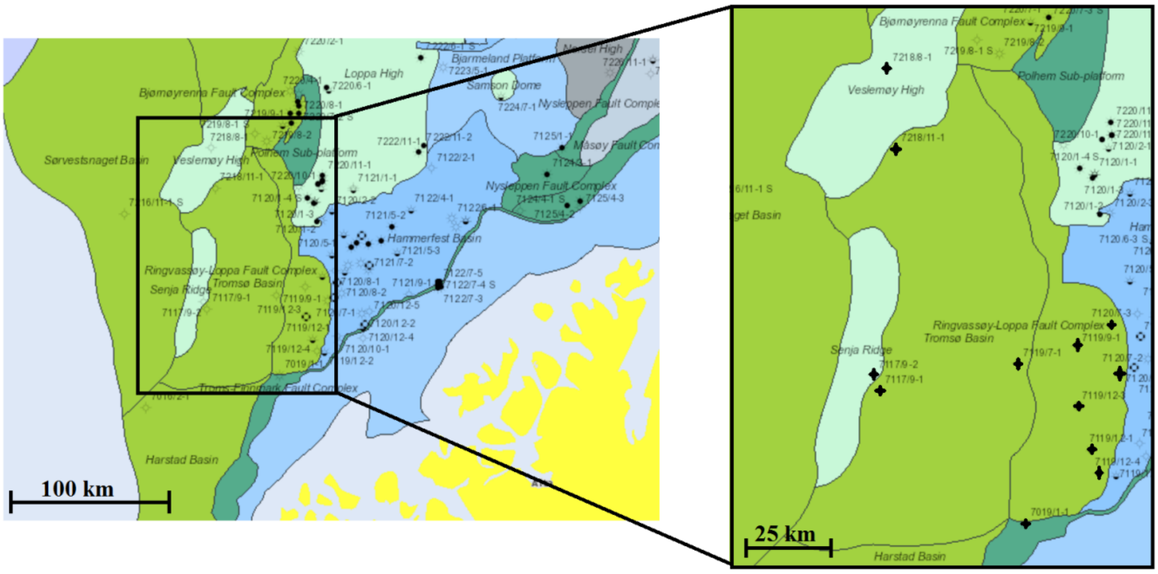


Figure 3.2: Drilled wells in the study area. A total of nine wells are drilled in the Tromsø Basin. In addition one well is drilled on the Senja Ridge and one on the Veslemøy High. Structural elements in the area are marked. Modified from NPD factmaps (2016)

3.2 Methods

2D seismic data were studied with emphasis on the Eocene succession in the Tromsø Basin. The interpretation of the seismic lines was done in the Petrel software, provided by Schlumberger, and by hand on paper. Three surfaces that are bounding the Eocene succession in the Tromsø Basin were interpreted; The near Base Eocene, the Upper Regional Unconformity (URU) and The Base Neogene. The near base Eocene reflector was interpreted by correlation with previous work in the Hammerfest Basin an eastern Tromsø Basin done in a thesis by Prøis et al. (2015). The URU and Base Neogene mark the top of the Torsk Formation in the study area, respectively in the eastern and western part of the basin.

Sonic logs from wells in the Tromsø Basin, available from NPD factpages (2016), were used to calculate an average velocity for the Eocene succession, which corresponds to the upper part of the Torsk Formation. The average velocity for this section is 2150 m/s. This velocity was used to calculate thicknesses and clinoform heights. Even though the Torsk Formation is a relatively uniform formation, it will occur velocity variations within the succession. It is important to emphasize that all of the calculations are approximates.

Detailed analysis of the Eocene succession was done by interpretation of four stratigraphic units within the area. The units are bounded by regionally continuous and lateral extensive surfaces, and studied in a general sequence stratigraphic content.

3.3 Principles of sequence stratigraphy

Sequence stratigraphy is a well-established analytical method of sedimentary succession which can be traced back to the 18th century (Helland-Hansen and Hampson, 2009; Nystuen, 1998). The modern approach is based on work published by the American Association of Petroleum Geologists (AAPG Memoir 26, Payton 1977; i.e Mitcum et al.,1977a+b) and has given improved understanding of how sediments behave and are distributed from source to sink.

The most effective application of sequence stratigraphy is on reflection seismic data as the individual reflections are generated by surfaces separating strata with different acoustic properties (Mitchum et al., 1977b). This approach can be divided into two parts; firstly, a sequence analysis, where the seismic sections are divided into depositional sequences, is done before facies analysis of these sequences gives improved understanding of the depositional environment. In addition to sequence analysis and facies analysis, a trajectory analysis of the platform-edge movement is done.

Sequence analysis

Nystuen (1998) defined a depositional sequence as “the stratigraphic unit that documents a specific and characteristic part of the depositional story of the basin within a scale specified in time and space”. The bounding surfaces that separates younger from older strata can either be erosional- or non-depositional unconformities, or conformities (Mitchum et al., 1977 a).

Reflection terminations are used to separate the seismic sequences from each other, and are characterized by their geometrical relationship to the seismic surface they are terminating against (Bertram and Milton, 1996). Mitchum et al. 1977a+b introduced the terms that are described below. These are illustrated in Fig. 3.3.

Reflection terminations can be either truncations or lapouts. A *lapout* is the lateral termination of a reflector at its depositional limit, while a *truncation* indicates that the reflector originally extended further (Bertram and Milton, 1996).

Baselap is lapout at the lower boundary of a depositional sequence, and can be subdivided into onlaps and downlaps. *Onlap* occurs when horizontal or inclined strata laps out against a surface of higher inclination, and *downlap* when an initially inclined strata terminates downdip against a horizontal or less inclined surface (Mithum et al., 1977b). Onlaps are marine or coastal; where marine is onlap to marine strata, while costal is onlap of non-marine, paralic or marginal marine strata. Downlaps often represent the progradation of basin margins, and their downlap surface generally represent a marine condensed unit (Bertram and Milton, 1996).

Toplap is lapout against the upper boundary of a depositional sequence and an evidence of a non-depositional hiatus (Bertram and Milton, 1996).

Truncations can either be *erosional truncations*, where the reflector is terminated by erosion, or *structural truncations* caused by faulting, gravity sliding, salt flowage or igneous intrusions (Mitchum et al., 1977b). Erosional truncations occur at the upper boundary of a sequence.

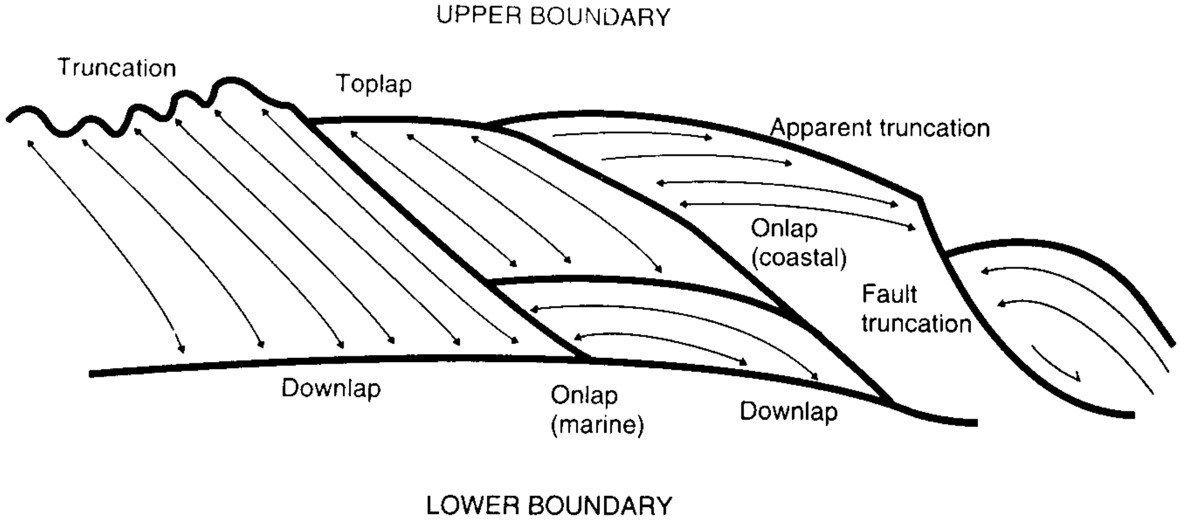


Figure 3.3: Overview of different seismic reflection terminations.
From Bertram and Milton, 1996.

Seismic facies analysis

Seismic reflections can be studied by analyzing the reflection geometry, amplitude, continuity, frequency and internal velocity (Mitchum et al., 1977b; Sangree and Widmier, 1978). The reflections may be continuous, chaotic, divergent, parallel, or prograding, and can express important information concerning the depositional environment, sediment source and geological setting (Mitchum et al., 1977b). Seismic facies analysis may lead to better lithological prediction, i.e. are high continuity of reflections associated with a widespread and uniform depositional environment, while chaotic reflections may represent sediments that have been deposited in a relatively high energy setting or affected by slumps etc. (Sangree and Widmier, 1978; Mitchum et al., 1977a).

Information about deposition and water depth can also be constrained by analyzing the external, geometrical form of prograding clinothems (Mitchum et al., 1977b). It is important to notice the difference between clinothems and clinoforms; Clinothems are the sedimentary successions bounded by clinoforms, while the clinoforms are the surface of the clinothems. There are two main types of clinoform shapes; sigmoidal and oblique.

A sigmoidal clinoform is S-shaped and have low depositional angles, usually lower than 1° (Fig. 3.4) (Mitchum et al., 1977b). This clinoform type has the topsets preserved which indicates continued upbuilding in an low energy environment with low sediment supply, rapid basin subsidence or rapid rise in sea level (Mitchum et al., 1977b; Sangree and Widmier, 1978).

Oblique clinoforms are relatively steep-dipping strata with toplaps against a nearly flat surface and downlaps onto the base. They are characterized by lack of topset and are deposited in a high energy environment (Sangree and Widmier, 1978).

There are other types of clinoform shapes as well, but only the main types are used in this study. Both shapes are illustrated in Fig. 3.4.

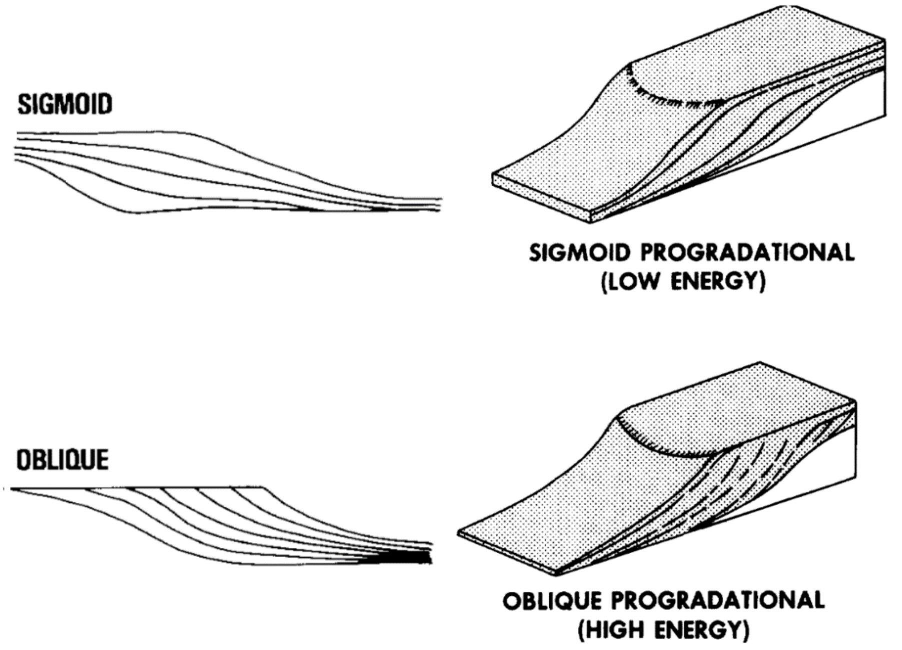


Figure 3.4: The two different clinoform shapes; sigmoidal and oblique clinoforms. Modified from Sangree and Widmier, 1978 and Mitchum et al., 1978.

Trajectory analysis

Trajectory analysis is an analytical method of sequence stratigraphy which gives a dynamic approach to sedimentary successions and provides information about paleogeography, sediment-type, distribution, relative sea-level change and sediment influx rates (Helland-Hansen and Hampson, 2009; Anell et al., 2014).

In trajectory analysis the break-in-slope of clinoforms on the shore-line, platform-edge or shelf-edge are mapped out and analysed. This type of analysis provides a measure of accommodation by discussing the interplay of eustasy, relative sea level and sediment influx. Accommodation is the space available for sediment accumulation, controlled by eustasy and subsidence (Myers and Milton, 1996).

Clinoforms normally occur at two scales; Shoreline clinoforms and shelf-edge or platform clinoforms. The shelf-edge or platform clinoforms have amplitudes of 100-1000 meters, while the shoreline clinoforms normally are less than 100 meters high (Johannessen and Steel, 2005). In this study the platform-edge clinoforms are studied, as the shoreline clinoforms are too small (10's m) to be visible on seismic data.

Clinoforms can roughly be described as the full sigmoidal depositional profile, including the topset, foreset and bottomset (Fig. 3.5) (Helland-Hansen and Hampson, 2009). The topset represents the shallow-water platform where the clinoform are almost flat with a very low gradient. The foreset is the platform-margin that grades down into the deep, whereas the bottomset is the deep-water-toe of the basin-floor (Johannessen and Steel, 2005). The slope of the clinoforms extends from the off-lap break down to the bottomset with an average gradient of less than 6 degrees (Helland-Hansen and Hampson, 2009; Johannessen and Steel, 2005).

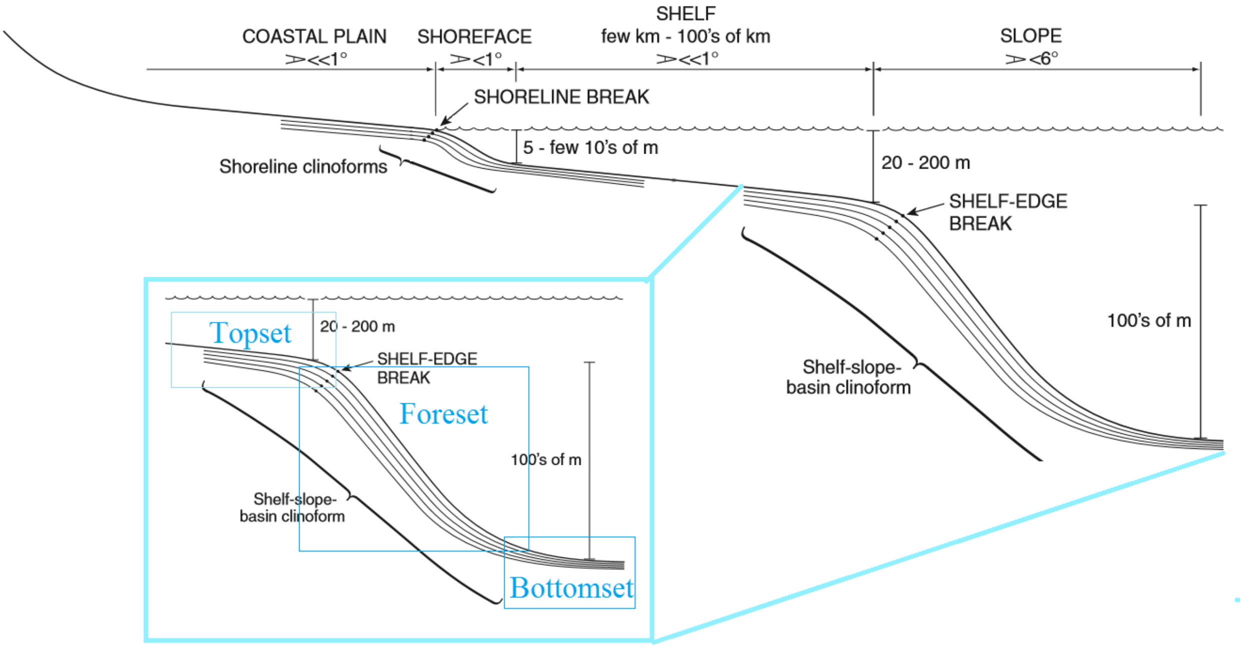


Figure 3.5: Simplified depositional profile with dimensions of both shoreline and shelf-edge clinoforms. In this study are the platform-edge clinoforms analysed, which have the same dimensions as shelf-edge clinoforms in the seismic. The shoreline clinoforms are typically up to a few 10's m, while the shelf-edge/platform-edge clinoforms are several 100's m. Modified from Helland-Hansen and Hampson (2009).

Migration of the platform-edge position, the off-lap break, is suitable for mapping lateral and vertical shifts of depositional systems, and represents a change in depositional processes and products between the platform and the slope. The off-lap break is a distinct break in the depositional profile where the relatively flat topset is separated from the slope (Myers and Milton, 1996). The platform tends to be dominated by prevailing basinal regime, tides and waves, while the slope experiences gravity processes which leads to re-sedimentation, bypass and channelling (Helland-Hansen and Hampson, 2009). The bottomset contains basin-floor deposits and is characterized by deep-water depositional systems (Myers and Milton, 1996).

The platform-edge trajectories can be categorized as flat, descending or ascending (Fig. 3.6) (Helland-Hansen and Hampson, 2009). Flat or descending trajectories are often characterized by oblique clinoforms, while ascending trajectories are sigmoidal in shape (Anell et al., 2014).

The principles and usage of sequence stratigraphy are unlimited. However, the goal of this study is not to implement a detailed sequence stratigraphic analysis of the Tromsø Basin, but to obtain first order information about the infill history of the basin during Eocene.

The methods of sequence stratigraphy were applied to the seismic data provided for this study. As the quality of the data were quite good, several depositional features could be studied and provide information about the Eocene depositional system.

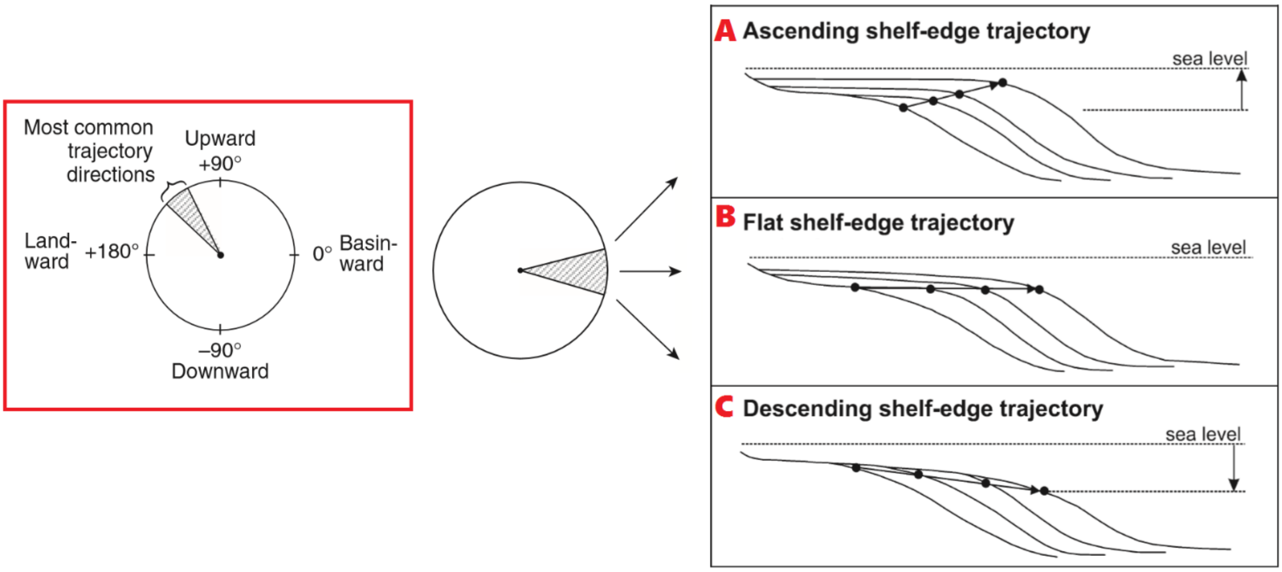


Figure 3.6:. Schematic diagram showing the different shelf-edge trajectories. In this study platform-edge trajectories are studied, trajectory terminations are the same. A) a high-angle ascending trajectory, B) a flat Trajectory, C) a descedning trajectory. Modified from Helland-Hansen and Hampson (2009) and Safronova et al. (2014).

4 Results

4.1 Basin configuration

The study area is mainly located within the Tromsø Basin, surrounded by several geological features such as the Senja Ridge, Veslemøy High, Polhem Sub-Platform, Loppa High, Hammerfest Basin, Finnmark Platform, Harstad Basin, and the two fault zones; Ringvassøy-Loppa Fault Complex and Troms-Finnmark Fault Complex (Fig. 4.1).

In addition to the geological highs, platforms, basins and fault zones surrounding the area, several internal features of different origin are affecting the seismic interpretation of the Eocene development.

Several salt structures occupy parts of the basin and affect the quality of the seismic lines by disturbing the continuity of the reflections. Six independent salt diapirs are mapped out in the northern, south-eastern and south-western parts of the basin. A seventh, massive salt structure occupies the central part of the basin. This structure has a deep core with several smaller salt structures protruding up from it (Fig. 4.2).

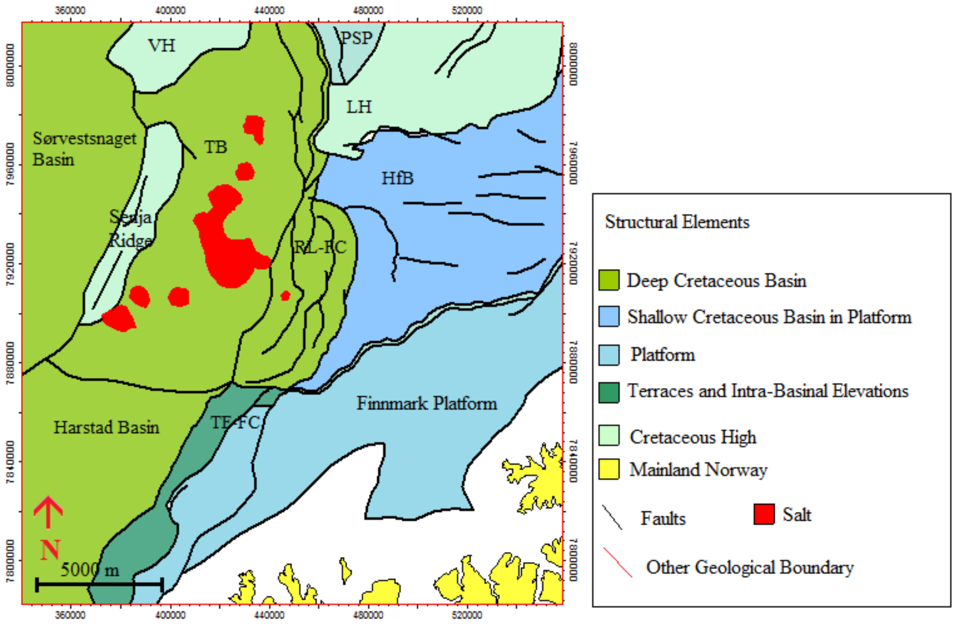
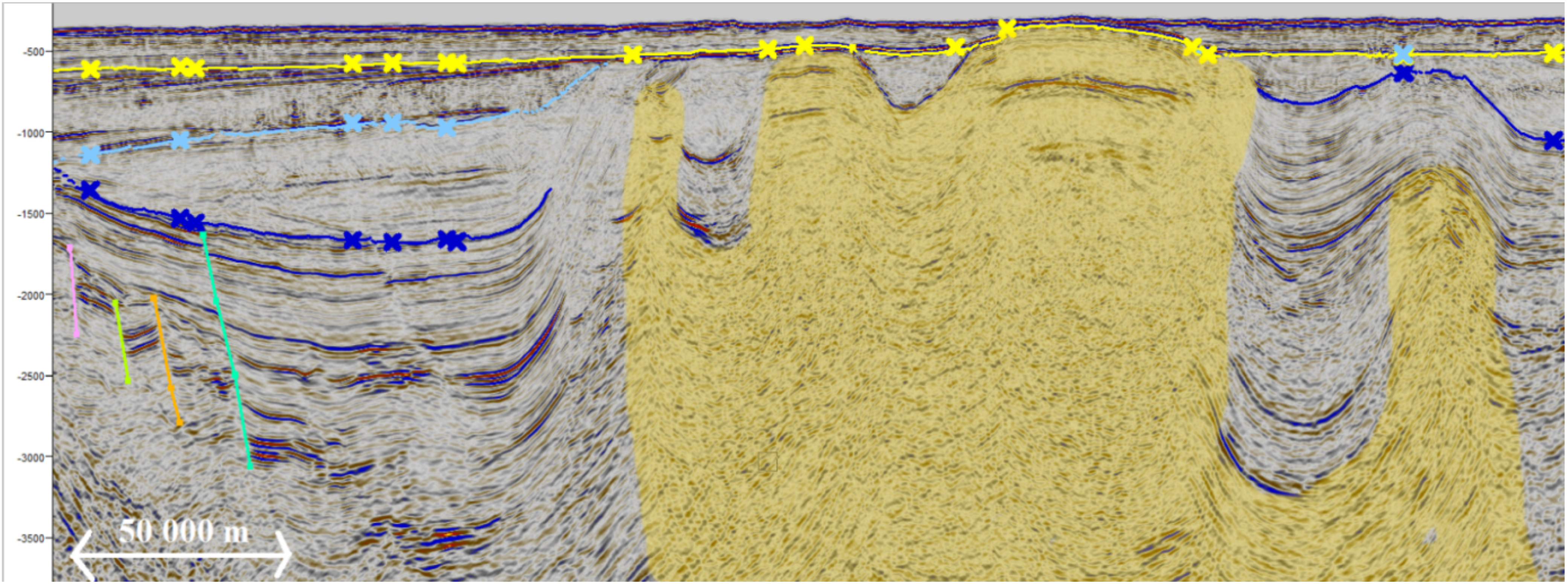


Figure 4.1: Structural map of the study area with the salt structures mapped out in red in the Tromsø Basin (TB). Description of structural elements is attached. **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform, **TF-FC**: Troms-Finnmark Fault Complex, **RL-FC**: Ringvassøy-Loppa Fault Complex. Map modified from NPD factmaps (2016).



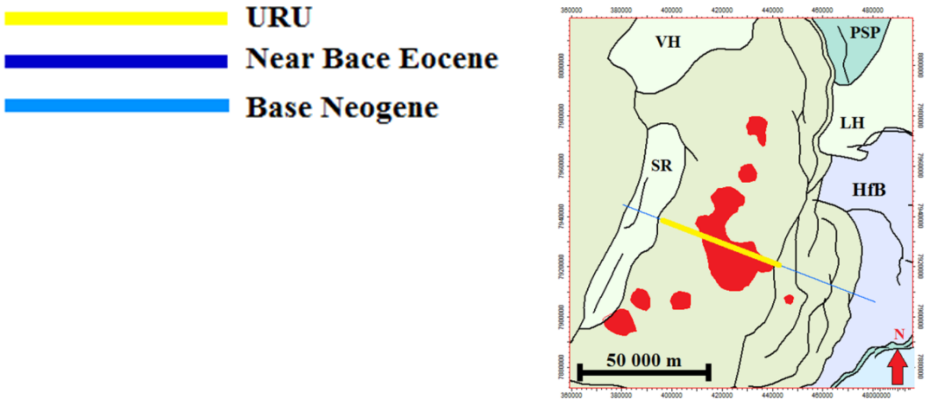


Figure 4.2: Vertical seismic section showing the big salt structure in the central part of the Tromsø Basin. The structure consists of a deep core with several independent protrusions rising up from it. The interpreted surfaces and faults nearby the Senja Ridge are marked. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red color. Map modified from NPD factmaps (2016).

The diapirs are piercing trough the Eocene succession in the Tromsø Basin, and are cut by the URU. There are no visible onlaps onto the salt structures, and the Eocene strata nearby these are deformed by the the salt growth. The interpreted units, mentioned later in this chapter, can be correlated across the salt structures and were not affected by these during deposition.

The interpreted salt structures are combined with a gravity anomaly map for the area in Fig. 4.3. This map shows gravity values measured in the Barents Sea Region. High values correspond to dense material, i.e. heights, while low values correspond to less dense material such as salt diapirs. Basin parts will also show low values. The map was used to enhance the salt interpretation done in Petrel.

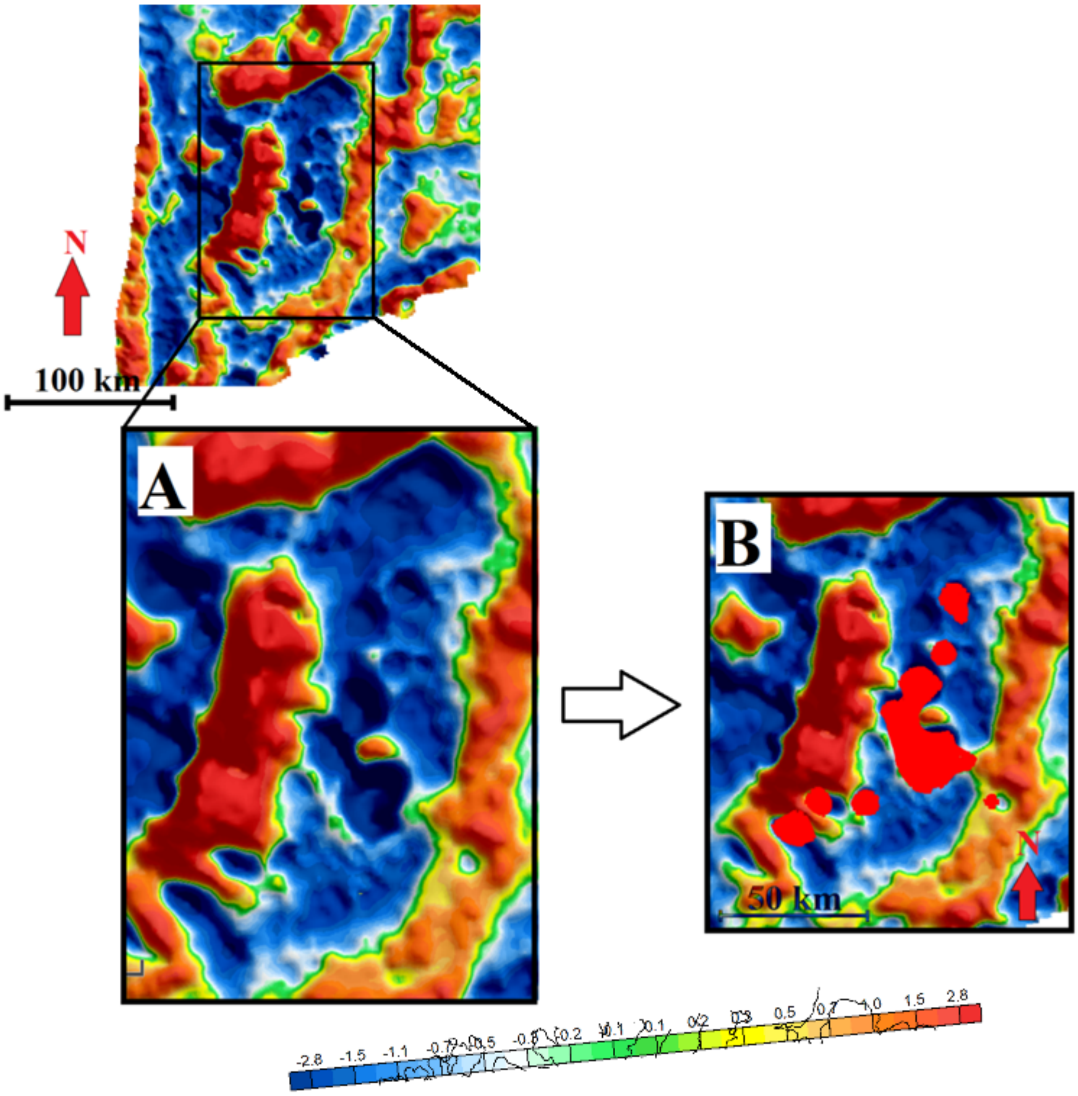


Figure 4.3: Gravity anomaly map of the Barents Sea. Norwegian coastline marked in the southeast with legend showing gravity values where high values corresponds to dense material, i.e. heights, while low values corresponds to less dense material such as salt. Section A shows the study area, while section B shows the interpreted salts combined with the gravity anomaly map. Filtered gravity data courtesy of TGS.

In addition to the disturbances from the salt structures is there a strong seismic reflector visible in the northern part of the basin. It dips towards west, and may be mistaken for a downlap surface. The reflector is interpreted by Riis and Fjeldskaar (1992) as an Opal A to Opal CT transition. This means that it is not a depositional feature, but caused by effects of diagenesis during burial. The transition interfered with the Near Base Eocene in some places in the northern part of the basin (Fig. 4.4 a).

There are several gas chimneys in the area, mainly found in the Ringvassøy-Loppa Fault Complex. These are disturbing the continuity of the reflectors, and can make the interpretation of the seismic sequences a bit more challenging (Fig 4.4 b).

Faults are also found in the area, mainly in the Ringvassøy-Loppa Fault Complex and in the Troms-Finnmark Fault Complex. Some faults are located on the eastern part of the Senja Ridge as well, i.e. in Fig. 4.3.

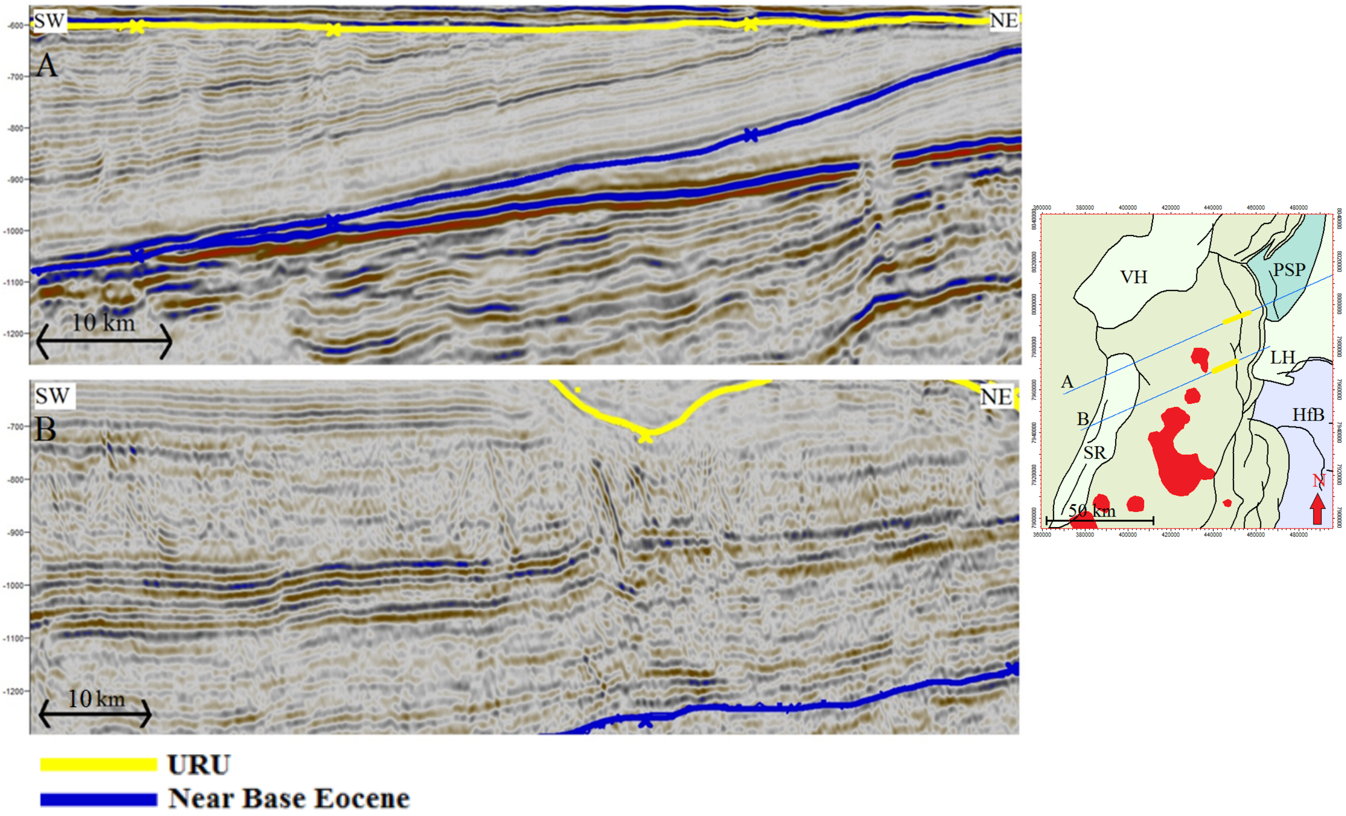
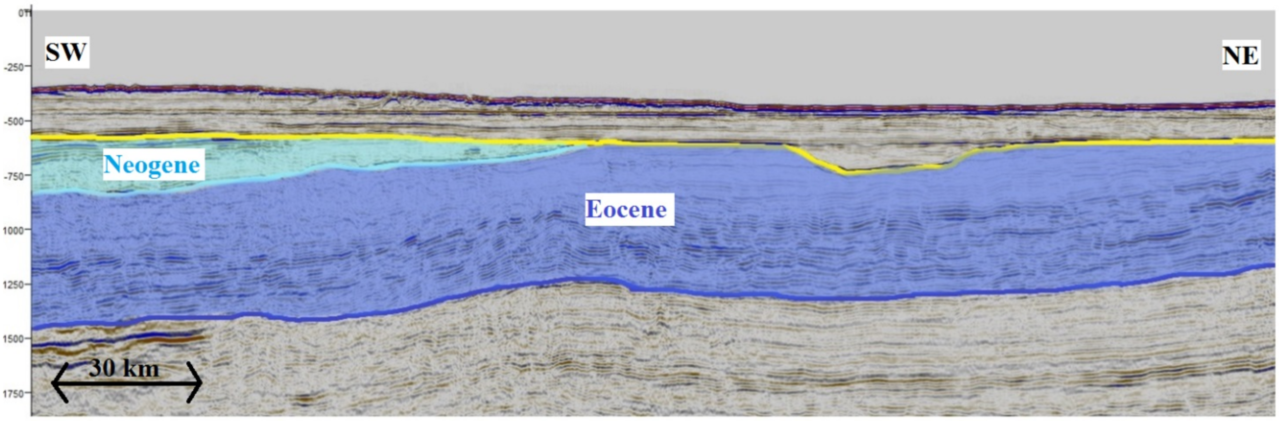


Figure 4.4: Vertical seismic sections showing A: The strong seismic reflector in the northern part of the Tromsø Basin. This reflector is interpreted by Riis and Fjeldskaar (1992) as an diagenetic transition. B: Gas chimneys within the basin disturb the continuity of the seismic reflectors. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

4.2 The eocene succession

The Eocene succession in the Tromsø Basin is bounded by three surfaces; the Near Base Eocene reflector at the base, and the Base Neogene and Upper Regional Unconformity (URU) at the top (Fig. 4.5). In the eastern parts of the Tromsø Basin the URU truncates the Eocene succession, while the Neogene wedge is truncated by the Eocene strata in the western parts of the basin. This is caused by effects of late Cenozoic uplift and erosion.



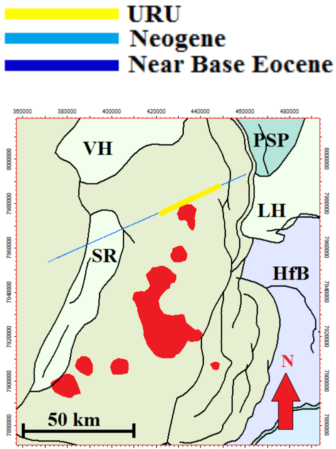


Figure 4.5: Vertical seismic section showing the Eocene succession of the Tromsø Basin bounded by the Near Base Eocene surface (dark blue), the base Neogene surface (light blue) and the Upper Regional Unconformity (yellow). Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-Platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

The Base Neogene surface is a major unconformity with overlying westward dipping and thickening strata. This Neogene wedge was deposited in a marine setting during the subsidence of the passive margin, and the deposits are erosion products of the uplifted Barents shelf to the east (Nøttvedt et al. 1988; Ryseth et al. 2003 ; Faleide et al. 1996). The Neogene wedge is underlain by an erosional unconformity on top of the Eocene strata from the central parts of the Tromsø Basin and westwards (Fig.4.6). The URU and Base Neogene reflectors correspond to the top of the Torsk Formation.

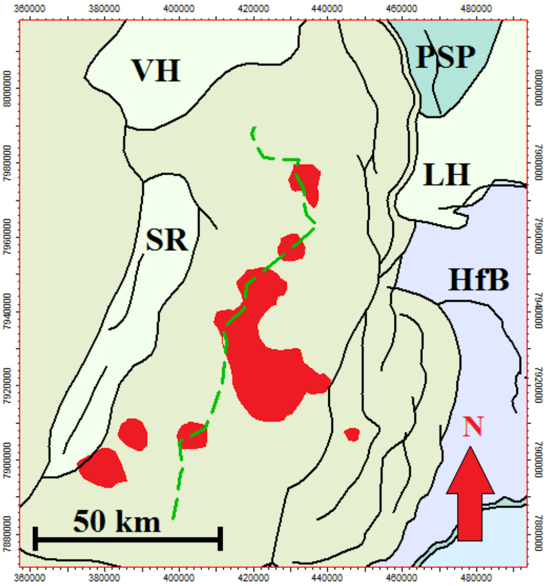


Figure 4.6: Structural map of the study area with a green stippled line which marks where the Eocene strata in the Tromsø Basin is truncating the Base Neogene or the URU. The strata west of the green line is truncating the Base Neogene reflector, while the strata east of the green line is truncating the URU. Geological features are marked in the map: **LH**: Loppa High**,** **HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Structural map modified from NPD factmaps (2016).

The Near Base Eocene reflector is found within most of the Tromsø Basin. It is overlain by the URU in the eastern parts of the basin at the transition from the Tromsø Basin to the Hammerfest Basin, Loppa High and the Polhem Sub-platform. The reflector is eroded on the Senja Ridge and overlain by the Neogene wedge, but is preserved in the central parts of the Veslemøy High (Fig. 4.7).

The Near Base Eocene reflector is recognized by baselaps onto the surface, i.e. from west in the Hammerfest Basin (Fig. 4.8). The surface has an average depth of 1100-1200 ms in the eastern parts of the basin, but has been mapped as deep as 1900 ms TWT in the western part. The reflector is disturbed by salt movements in the basin, but has been traced around these structures and mapped out in the whole basin.

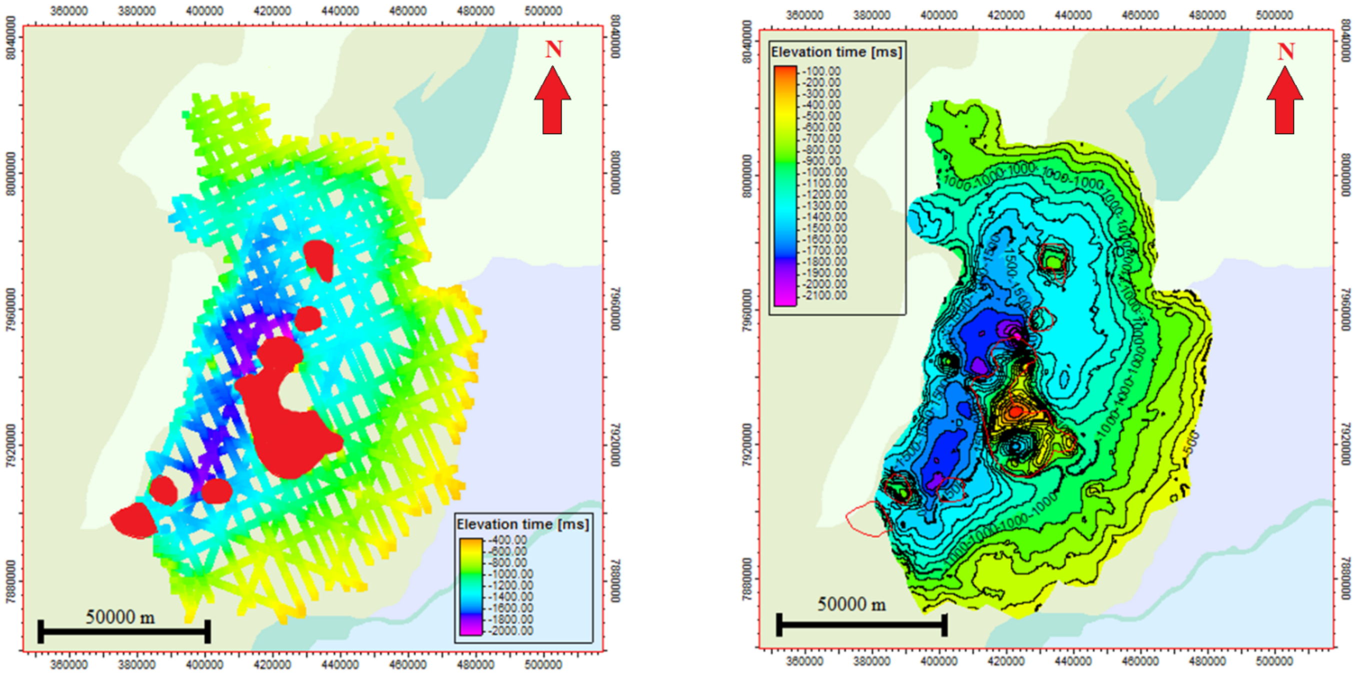
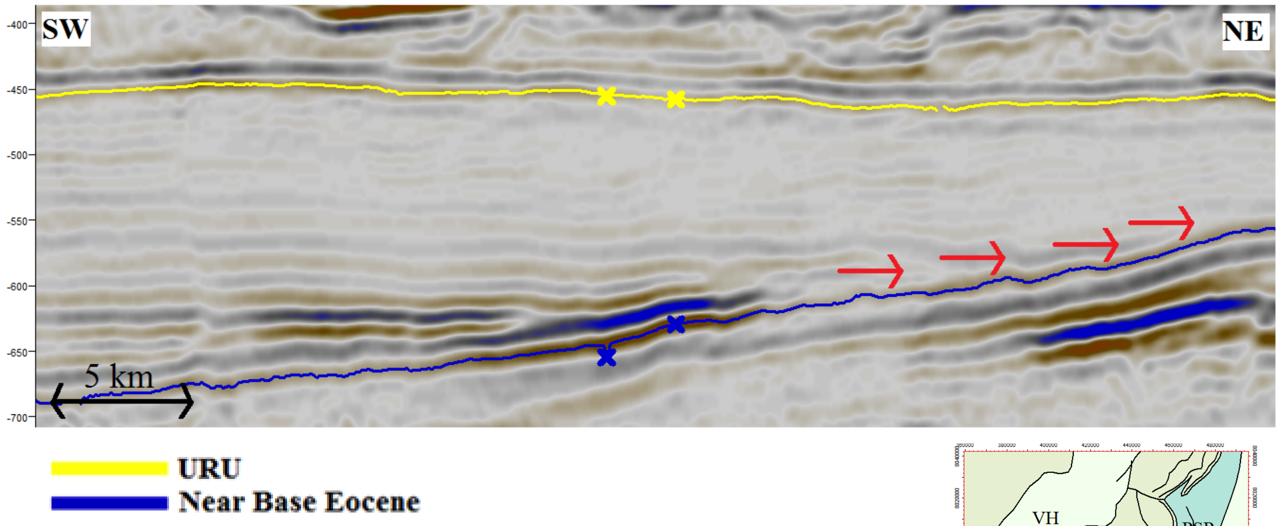


Figure 4.7: The seismic interpretation of Near Base Eocene to the left and the Near Base Eocene surface to the right. The salt structures are marked with red.



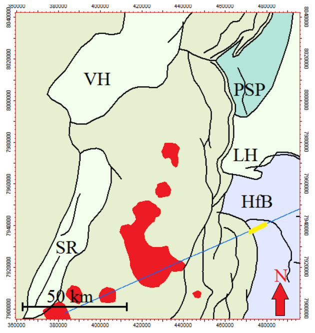


Figure 4.8: Vertical seismic section showing the Eocene succession of the Tromsø Basin bounded by the Near Base Eocene surface (dark blue and the Upper Regional Unconformity (yellow). The reflection terminations are marked in red, onlapping the Near Base Eocene surface. Depth in TWT, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-Platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

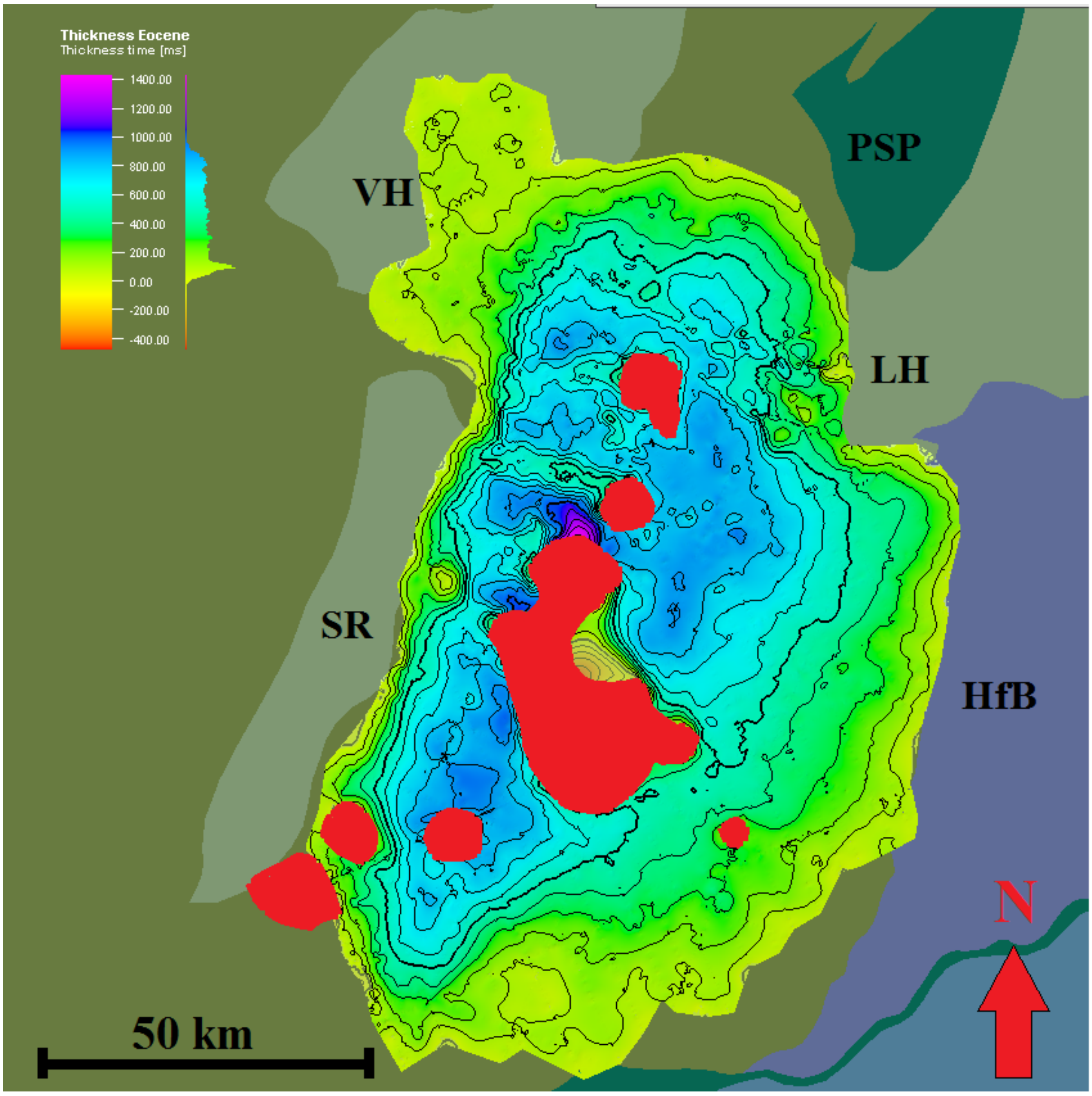


Figure 4.9: Time-thickness map for the Eocene succession in the Tromsø Basin. Geological features are marked in the map: **LH**: Loppa High**, SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red.

4.3 Unit 1

The lowermost unit of the Eocene succession in the Tromsø Basin is the aggradational Unit 1. This unit is located in the northern part of the basin, and represents the part of the Eocene strata that is not removed by uplift and erosion on the Veslemøy High.

Unit 1 is bounded by the Near Base Eocene surface at its base, and separated from the overlying Unit 2 by the surface onto which Unit 2 downlaps onto, termed the Unit 2 downlap surface (Fig 4.10). The areal extent of the unit is about 1800 km^2, and it has a full thickness between 160 and 240 meters. The original thickness is only preserved in the central parts as it thins out in the western part of the basin due to erosion. The unit generally dips westward and has a greater thickness in the western part compared to the eastern (fig.4.11).

The internal seismic reflections in this unit vary from clearly visible parallel reflections to weaker and less continuous compared to the younger Eocene units. Chaotic patterns are observed in several parts of the unit. The amplitude reflectivity is generally low.

Interpretation

Unit 1 is bounded by the Near Base Eocene surface at its base and a maximum flooding surface (MFS) (Unit 2 downlap surface) at the top. The chaotic patterns observed in the sequence may represent a period of less continuous deposition, possibly in a basin floor environment affected by gravity flows and similar depositional mechanisms. The unit is only present in the northern part of the Tromsø basin. It is possible that there are volumes of the unit present in other parts of the basin, but with thicknesses below seismic resolution.

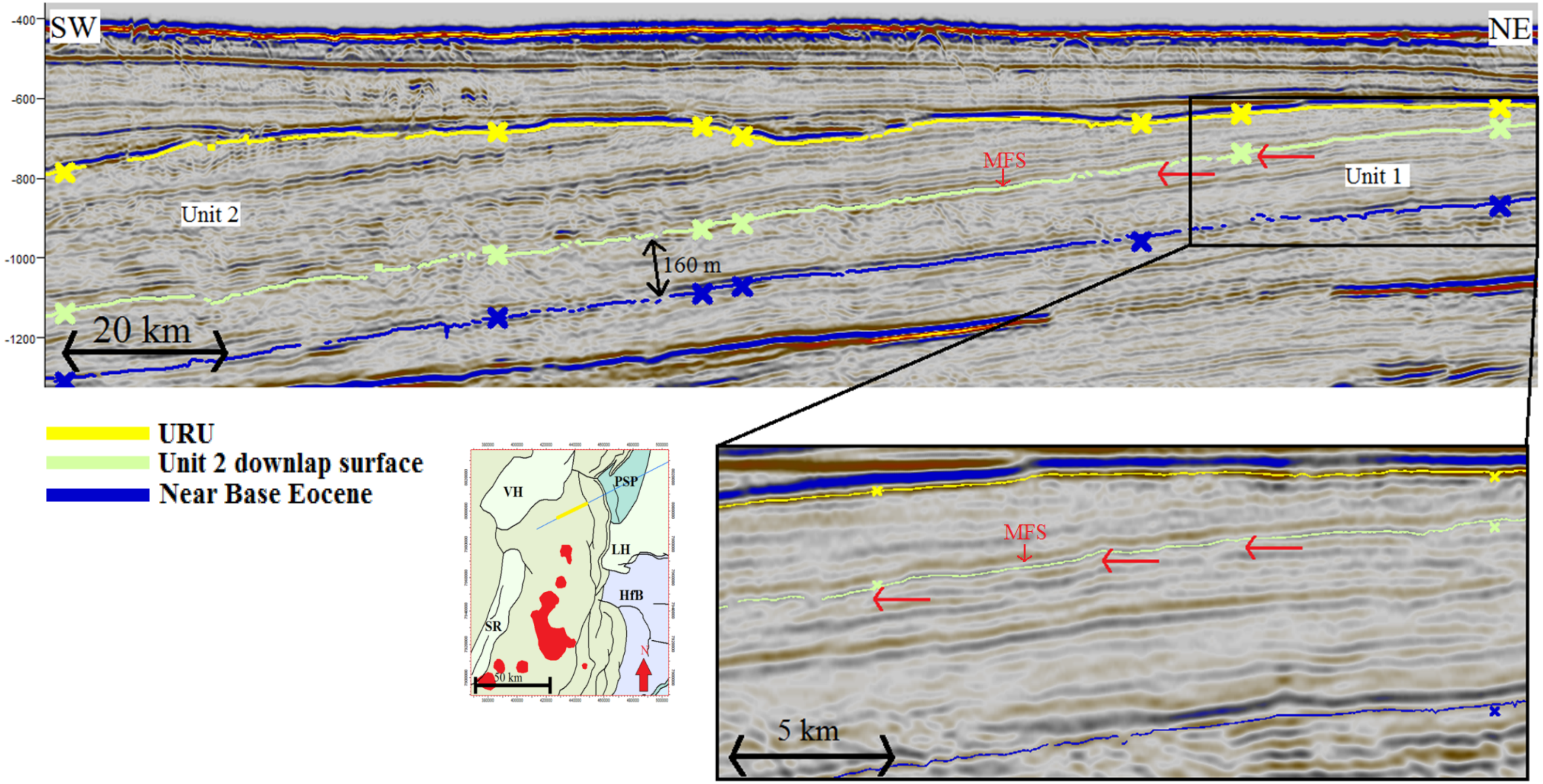


Figure 4.10: Vertical seismic section showing Unit 1 with its surrounding units and surfaces. Unit 1 is bounded at its base by the Near Base Eocene surface, and bounded at the top by a maximum flooding (MFS) surface onto which Unit 2 clinoforms onlaps, or by the URU or Base Neogene. The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

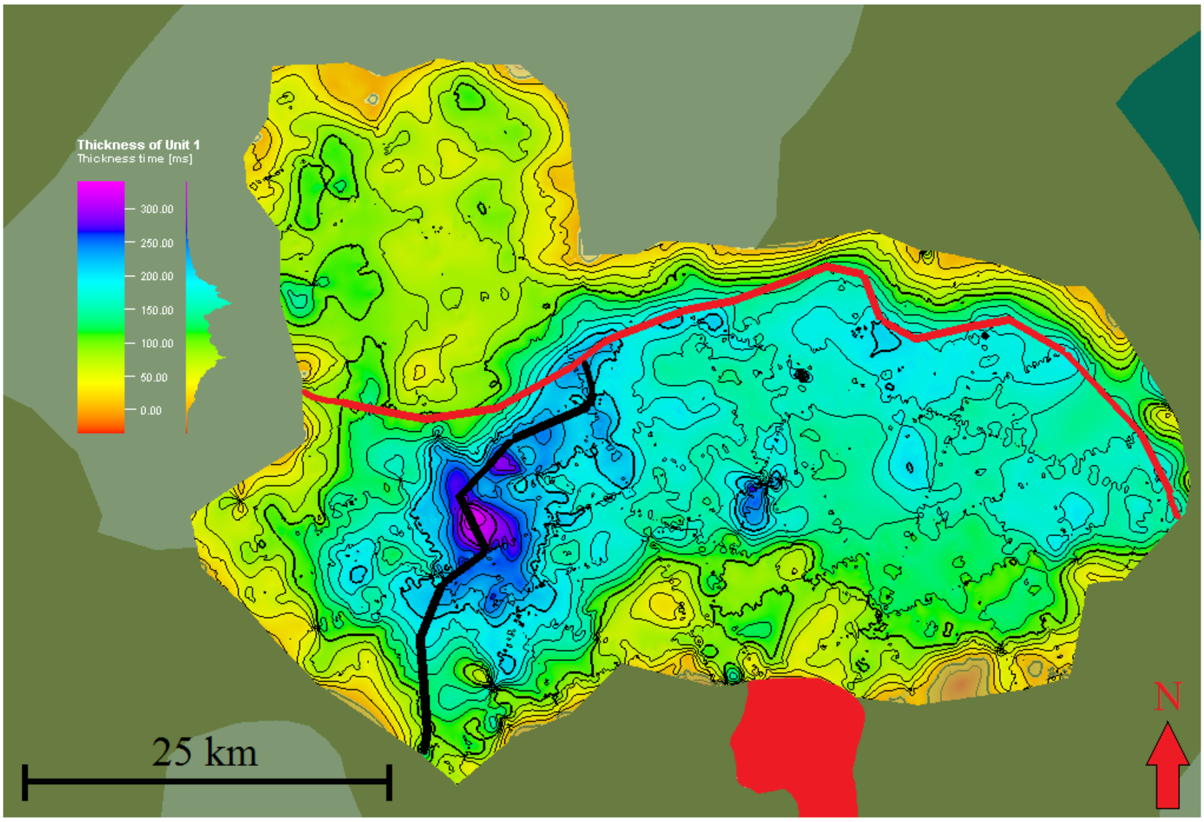


Figure 4.11: Time-thickness map for Unit 1. Black and red lines represent the erosional limits of the unut. Red line marks where the unit is truncated by the URU (north of this line), while the black line marks where the unit is truncated by the Neogene Wedge (west of this line). The full thicknesses of the unit are preserved in the area south and east of the black and red lines. Geological features are marked in the map: **LH**: Loppa High**, SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structure is marked with red.

4.4 Unit 2

The second unit of the Eocene succession in the Tromsø Basin is prograding from north to south. This is the lowermost of two prograding units, and is bounded at the base by the Unit 2 downlap surface in the northern parts of the basin, and the Near Base Eocene surface elsewhere. The top of the unit is limited by Unit 3, URU and the Base Neogene surface.

The unit extends over about 6000 km^2 and covers most of the northern and central parts of the Tromsø Basin (Fig. 4.12). It reaches its progradational limit in the south-eastern part. The unit is truncated by the Neogene wedge on the Senja Ridge and in the south-western part of the basin, while in the north and northeastern parts it is truncated by the URU, i.e. in Fig. 4.14 and Fig. 4.15.

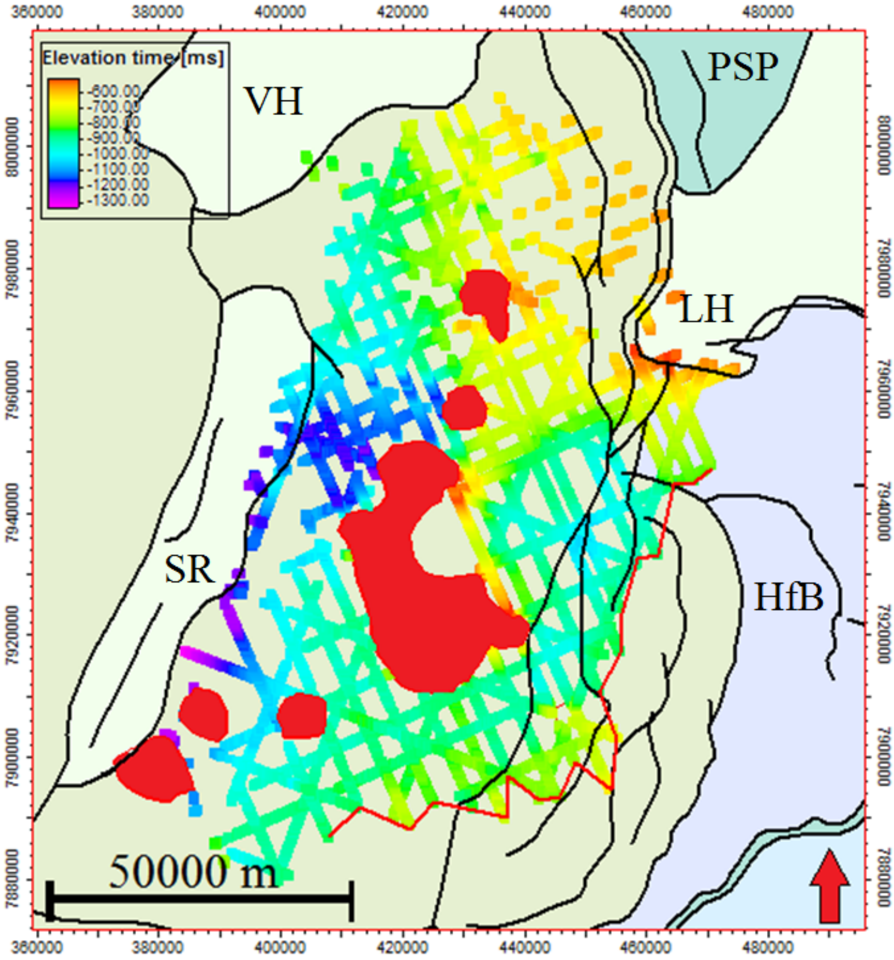


Figure 4.12: Areal extent of Unit 2 in the Tromsø Basin. Red line represents the progradational limit of the unit. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red.
Map modified from NPD factmaps (2016)

The original thickness of the unit is preserved where the top is defined by the Unit 3 downlap surface, from the central parts of the basin to the progradational limit in the south-southeast, i.e. in Fig. 4.14. However, erosion in post-Eocene times has rendered the unit incomplete in the rest of the basin. The average original thickness of the unit is between 540 and 700 meters. The thickness is greatest in the northern, western and southwestern part of the unit, especially east of the Senja Ridge. Thickness map of the unit is illustrated in Fig. 4.13 with progradational and erosional limits.

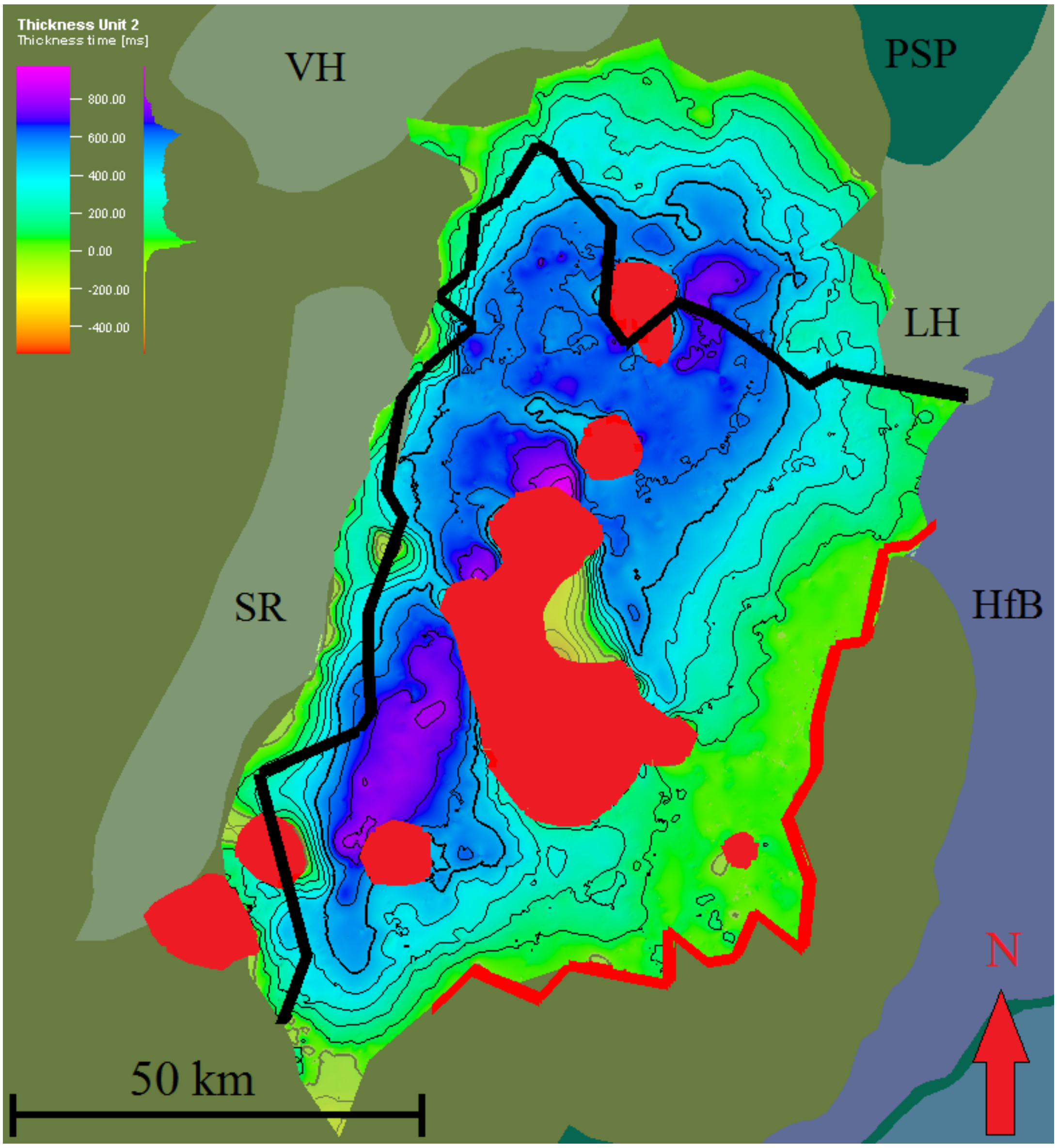


Figure 4.13: Time-thickness map for Unit 2. The thickness is greatest in the northern and western parts of the basin. The thinning in the eastern part is caused by clinothem geometries as they are thinning out towards the progradational limit (red line). Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red.

The main progradational direction of the unit is from N to S with visible clinothems on seismic lines in both NW to SE and NE to SW directions (Fig. 4.14 and Fig. 4.15). The system prograded southward, and reached its progradational limit in south-southeast. The progradational limit is not visible in the south-western part of the basin due to erosion.

Prograding clinothems are also observed out from the northern part of the Senja Ridge (Fig. 4.16 and 4.17). These are prograding in northeast, east and southeast directions. No depositional patterns into the Tromsø Basin from the central and southern parts of the Senja Ridge are observed. However, thickening of the unit is observed out from the central Senja Ridge into the basin (Fig 4.18). No prograding clinothems are observed out from the southern part of the Senja Ridge, but the Eocene succession onlaps towards the ridge (Fig. 4.19).

The infill of Unit 2 in the Tromsø Basin is complex and has more than one sediment input. In addition to the sediment input from the north and the northern Senja Ridge, a small input to the unit from East is observed in the eastern part of the basin (Fig. 4.20). A small thickening of the unit is observed westwards out from the Loppa High, but there are no distinct clinoform geometries observed here.

Unit 2 can further be divided into three sub-units based on seismic facies, clinothem geometry and trajectory analysis (Fig. 4.21).

Subunit 2.1 is the lowermost subunit of Unit 2, and downlaps onto Unit 1 and the Near Base Eocene surface. The lowermost strata in sub-unit 2.1 show only slope sediments, while their proximal counterpart to the north is not contained in the seismic dataset. It consists of high amplitude reflections with good continuity in both topset and slope near the upper part of sub-unit 2.1. This suggests that the deposition was continuous and of great extent in the area. The clinothem geometries are well-developed, but the erosion below has removed some of the topsets in the northern and north-eastern parts of the basin. The slopes are well preserved, and the offlap-breaks can be traced and analyzed to infer first-order information regarding the depositional environment and movement of the platform-edge. The platform-edge of subunit 2.1 is prograding southwards, but is descending and does not build in height. The clinoforms are oblique and have heights of about 400 meters.

The following sub-unit 2.2 is separated from sub-unit 2.1 by the change in the shape of clinoforms. The clinoforms are oblique, but the depositional angle is less steep compared to sub-unit 2.1. The heights of the clinoforms are lower than in subunit 2.1, about 270 to 300 meters, and the shelf-edge trajectory is flat. Subunit 2.2 prograded further south than the previous subunit (Fig. 4.22). This subunit has also high amplitude reflections with good continuity.

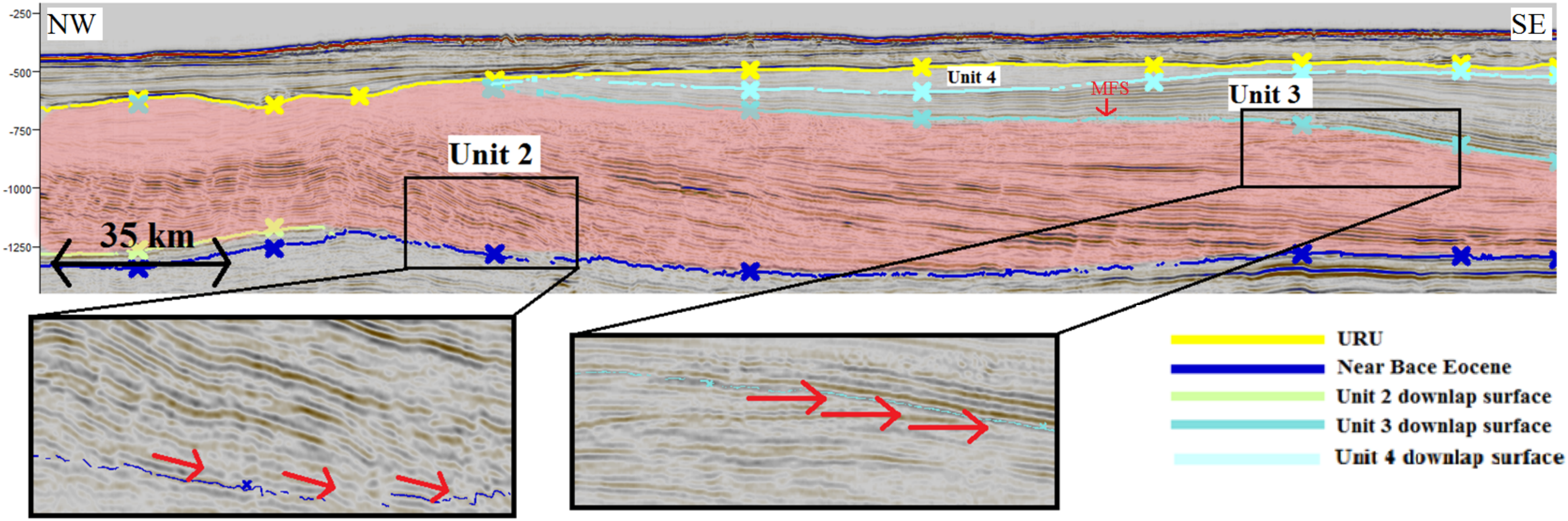
The last subunit 2.3 is less continuous and has lower amplitude reflections than the two lower subunits. It is separated from subunit 2.2 by a clear, horizontal reflection which may be a diagenetic front (Riis and Fjeldskaar, 1992). In this subunit it is difficult to find visible clinoforms and geometries to analyze.

Interpretation

Unit 2 is separated by two maximum flooding surfaces at its top and base (Unit 2 downlap surface and Unit 3 downlap surface). The thickness decreases towards south-southeast as an effect of the clinoform geometry, as the bottomsets are thinner than the topsets and foresets. The decrease in thickness in the southwest is a combined effect of the differential uplift and erosion and the clinoform geometry. The unit has three sediment inputs; one from north-northeast, the second out from the northern Senja Ridge to the west, and a third from the Hammerfest Basin to the east. The input from the northern part of the Senja Ridge delivered sediments eastward that interfered with the prograding system from north. The thickening of the unit out from the central part of the Senja Ridge may be explained by depositonal geometries from the main prograding system from the north. The thickening out from the Loppa High may be explained by the same effect. The sediment input from the east is very small compared to the great prograding depositional system from the north.

The platform-edge was descending during the deposition of the upper subunit 2.1 (the lower 2.1 does not allow for any platform edge analysis), which indicates a fall in rate of relative sea level rise, possibly explained by basin subsidence. The sediment influx was probably high, as the clinothems are progressively building out in the basin with an oblique surface geometry. The oblique clinoforms and a relatively steep depositional angle give an indication of a relatively higher energy environment than the succeeding sub-units. As the clinoforms of subunit 2.2 are lower than in subunit 2.1, the relative sea level appears to have been lower during this time. However, the shelf-edge trajectory of subunit 2.2 is flat to flat-descending, which gives an indication of a stable relative sea level with little or no subsidence. The clinoforms within sub-unit 2.2 are oblique, which may indicate a high energy environment

(Myers and Milton, 1996). Sub-unit 2.3 is hard to analyse as it is very diffuse with low amplitude reflections, but may represent a rise in the relative sea level associated with deeper water deposition, or a reduction on sediment influx to the area.



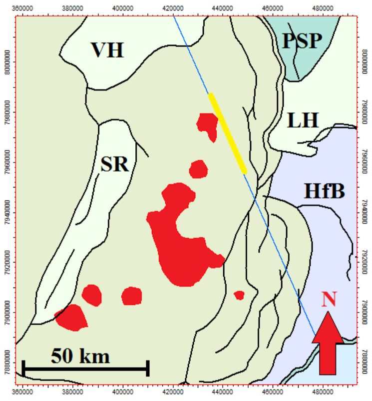
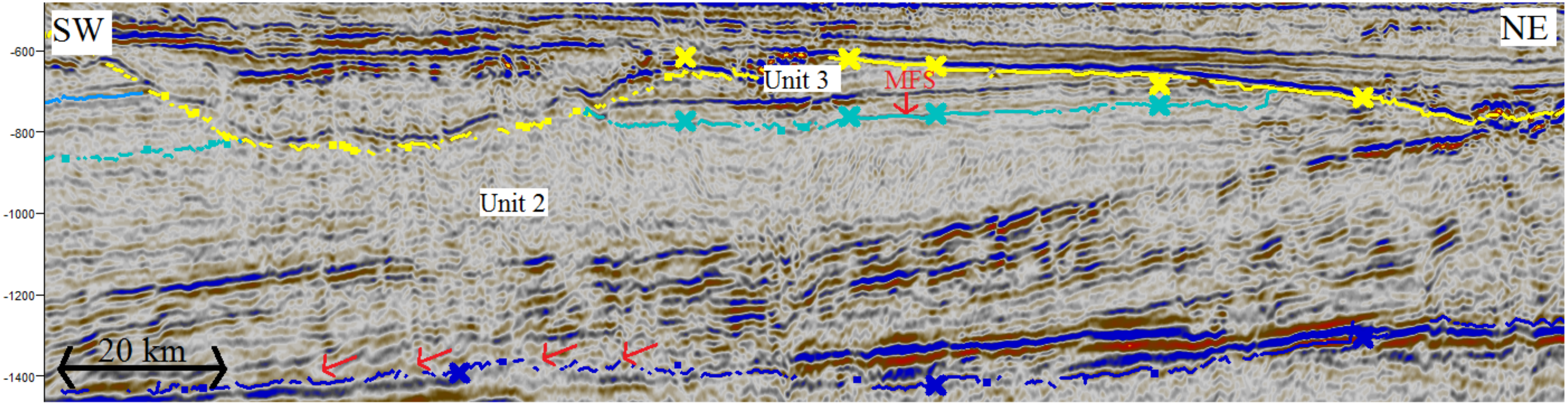


Figure 4.14: Vertical seismic section showing Unit 2 with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).



▬ **URU**

▬ **Near Bace Eocene**

▬ **Unit 2 downlap surface**

▬ **Unit 3 downlap surface**

▬ **Base Neogene**

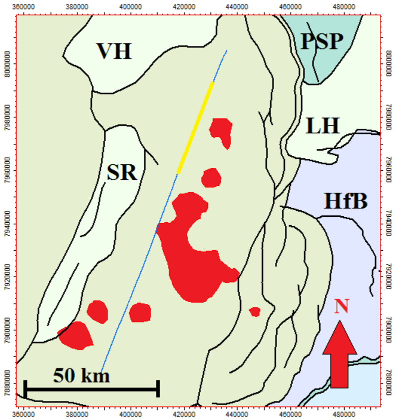
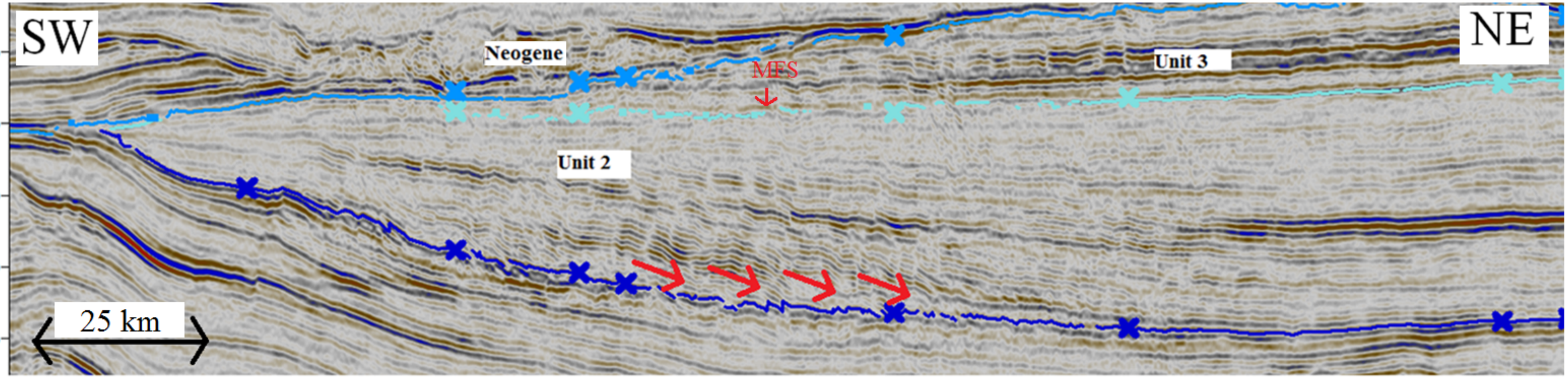


Figure 4.15: Vertical seismic section showing Unit 2 with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).



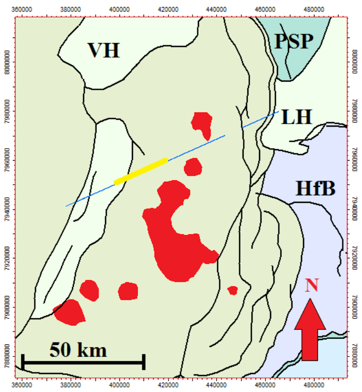
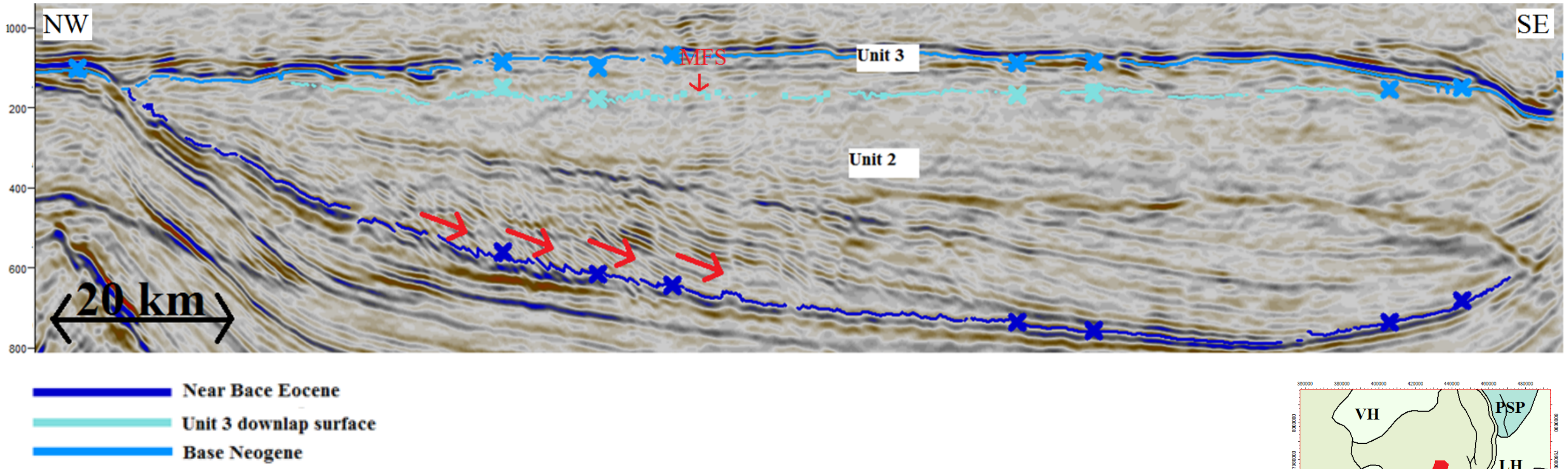


Figure 4.16: Two vertical seismic sections from showing Unit 2 near the Senja Ridge with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). Both sections show downlaps of Unit 2 onto the Near Base Eocene reflector. The sections show a prograding depostional system building out from the northern Senja Ridge into the Tromsø Basin. The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).



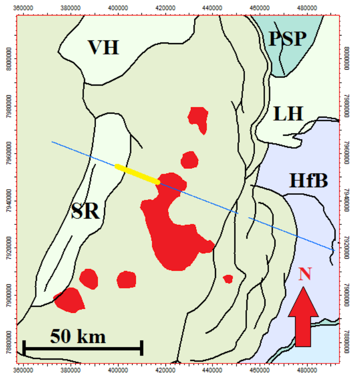
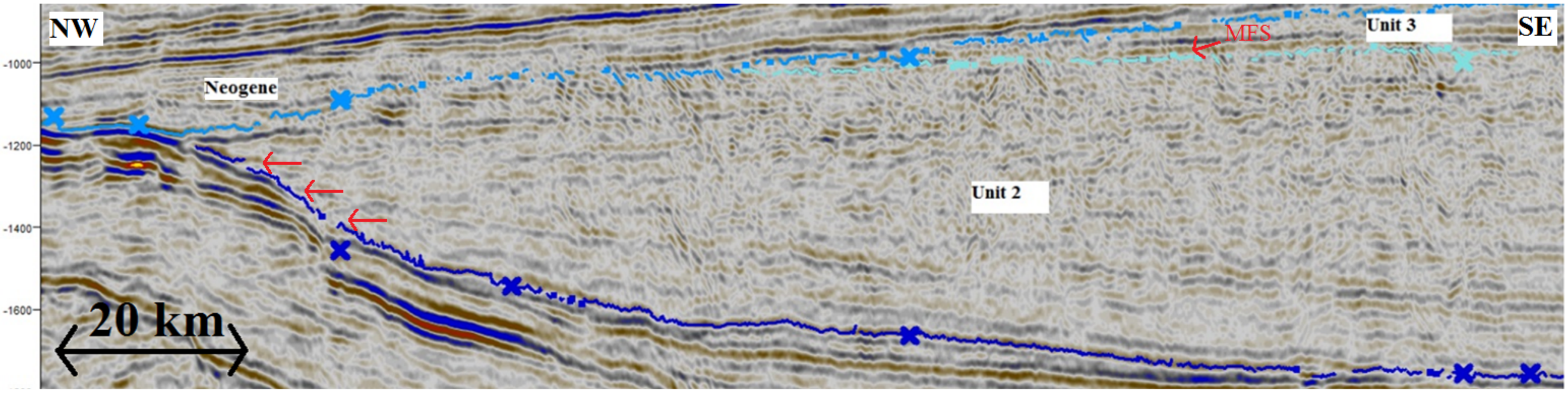


Figure 4.17: Vertical seismic section near the Senja Ridge showing Unit 2 with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).



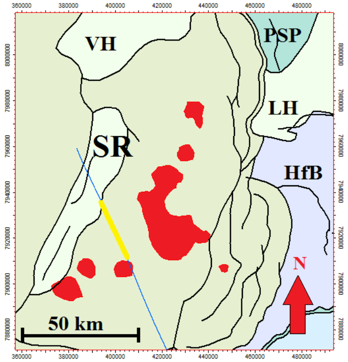
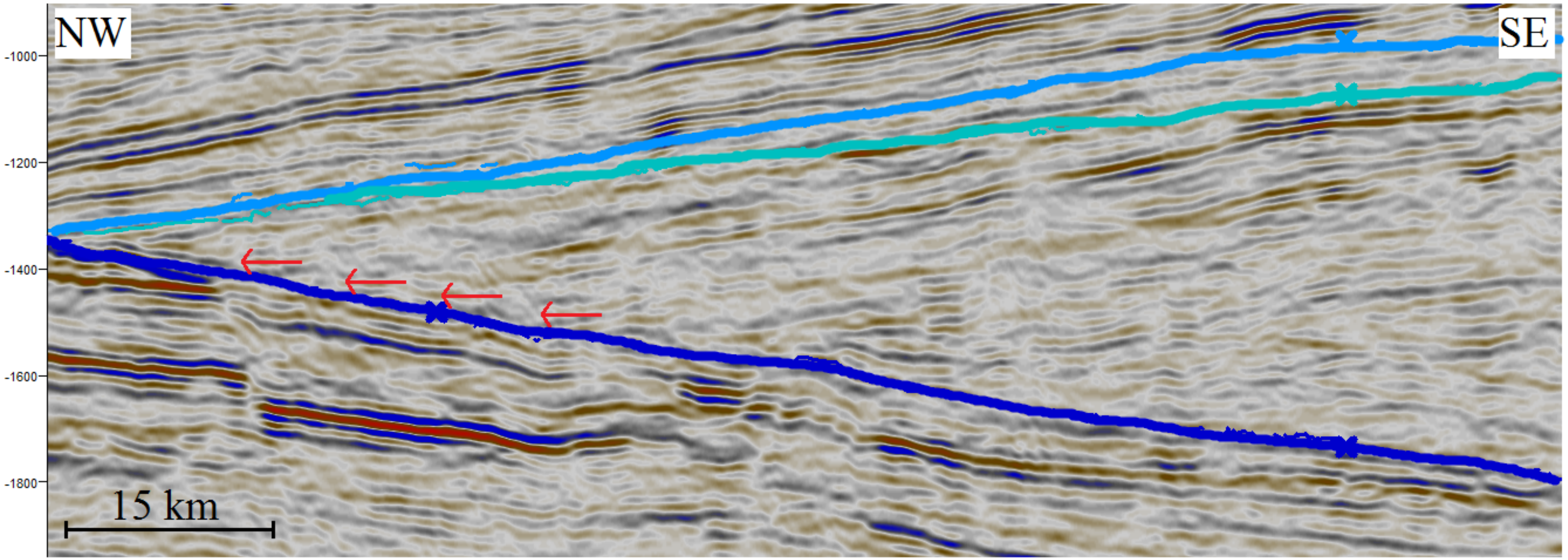


Figure 4.18: Vertical seismic section near the Senja Ridge showing Unit 2 with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). The unit is thickening out from the ridge. The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform.
Salt structures are marked with red. Map modified from NPD factmaps (2016).



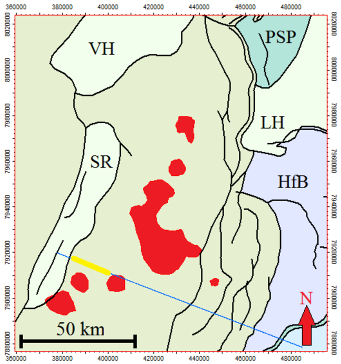


Figure 4.19: Vertical seismic section near the southern Senja Ridge showing Unit 2 with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). No depositional patterns and no thickening of the unit observed. The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

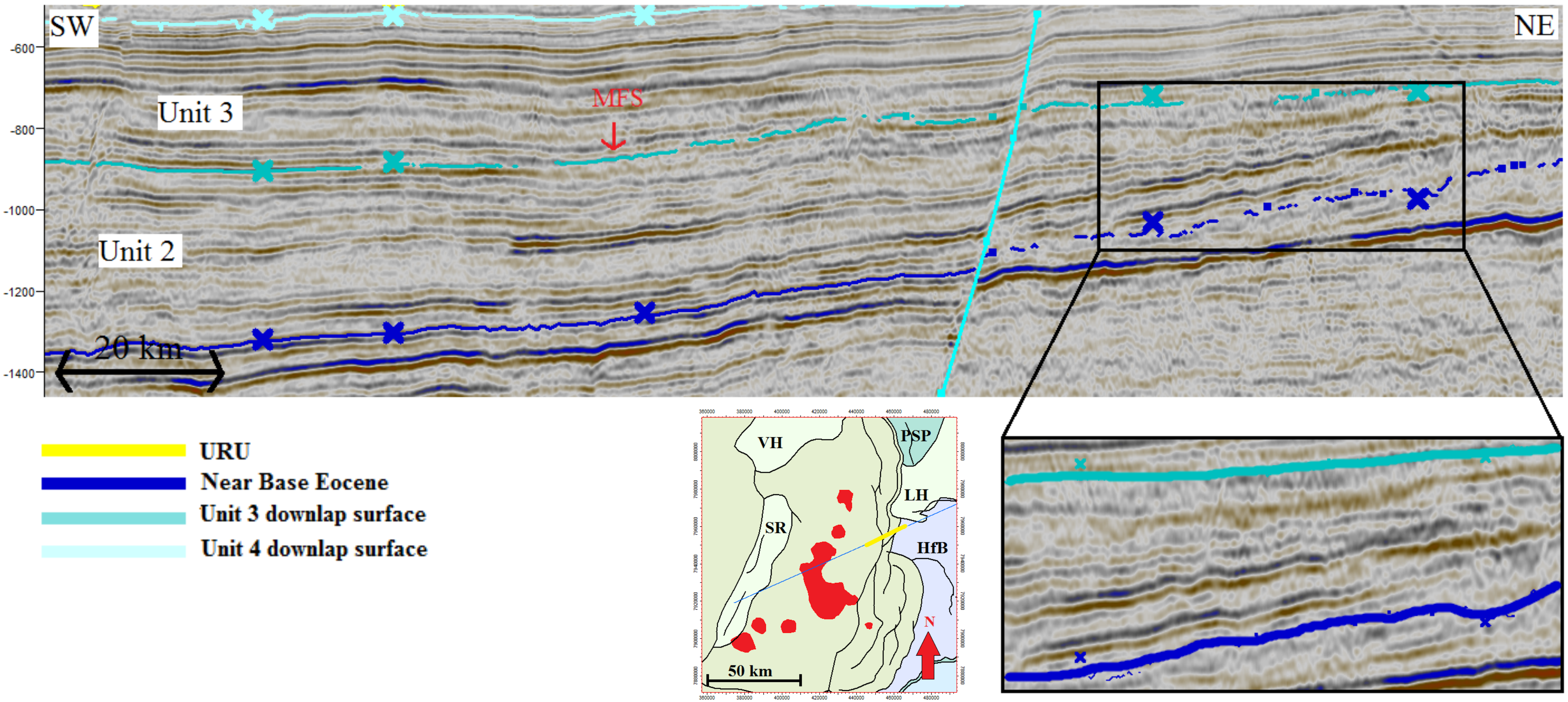


Figure 4.20: Vertical seismic profile from showing Unit 2 near the Hammerfest Basin with its surrounding units and surfaces. Unit 2 is bounded at its base and top by maximum flooding surfaces (Unit 2 downlap surface and Unit 3 downlap surface). The reflection terminations are marked with red arrows, fault marked with light blue. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

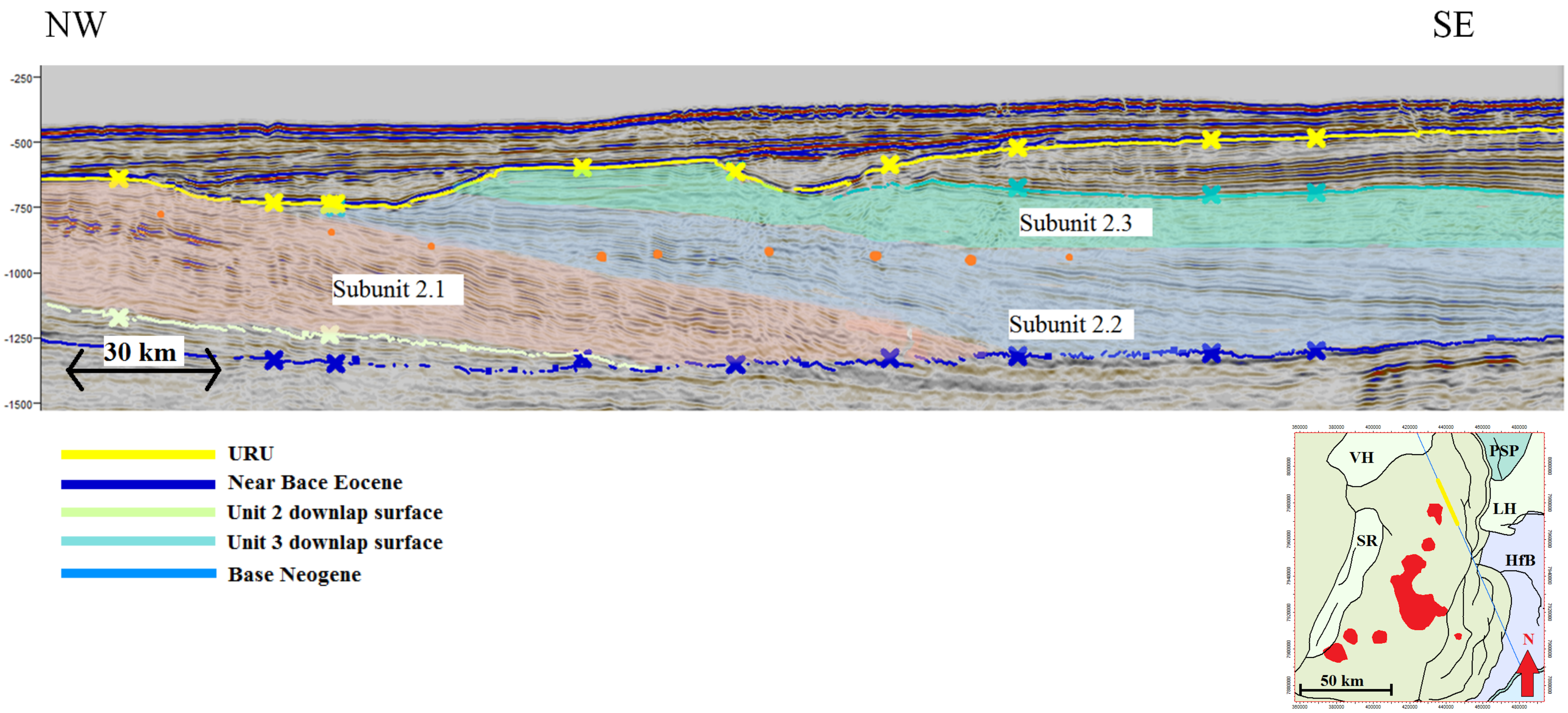


Figure 4.21: Vertical seismic profile from showing the subunits of Unit 2. Subunit 2.1 is marked with light red color, subunit 2.2 with light blue color and subunit 2.3 with light green color. The positions of the offlap-breaks are marked with orange dots. The shelf-edge trajectory is descending within in subunit 2.1 and the slope is steeper than in subunit 2.2. The shelf-edge trajectory in subunit 2.2 is flat to descending. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Subplatform.
Salt structures are marked with red. Map modified from NPD factmaps (2016).

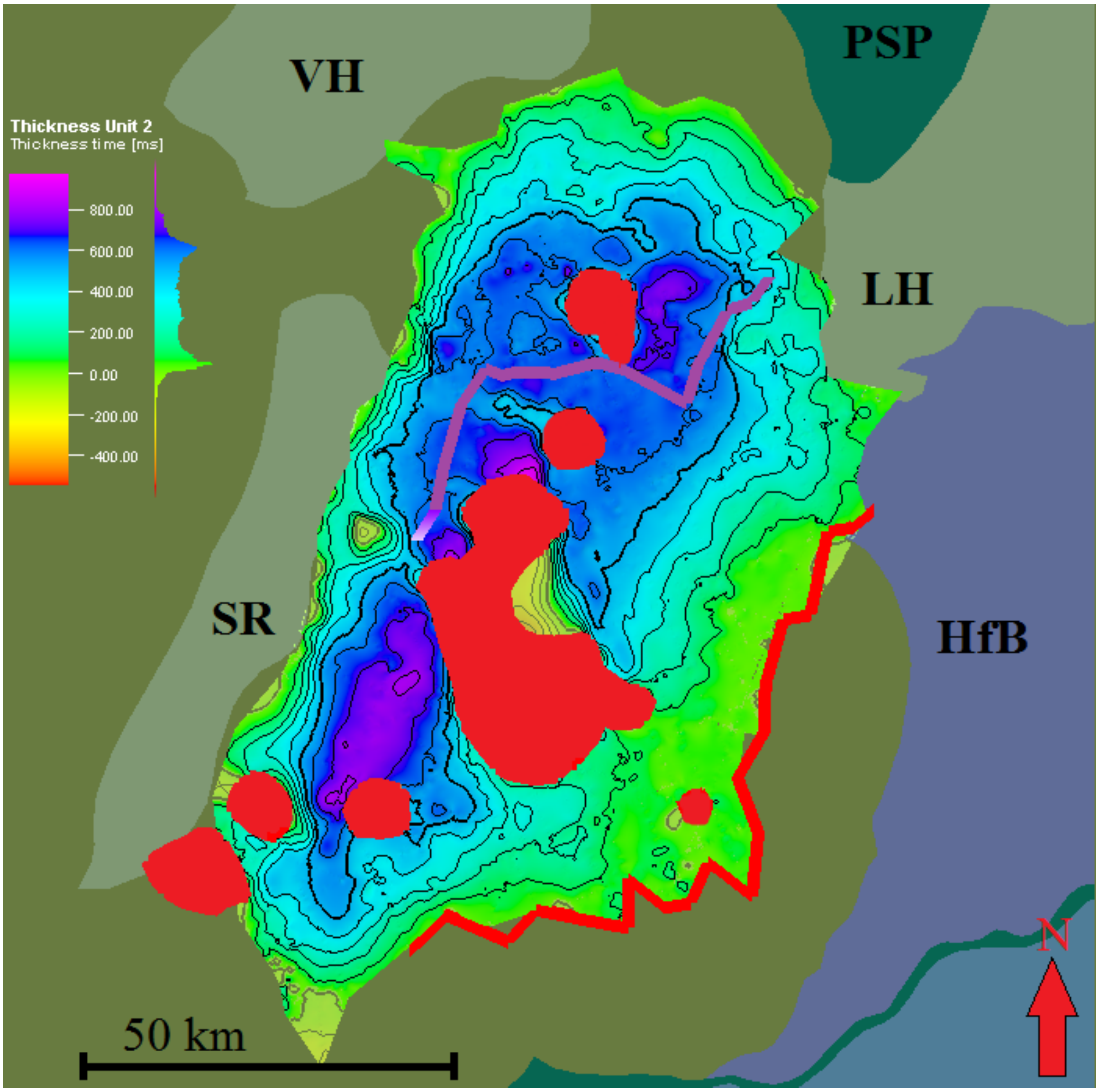


Figure 4.22: Time-thickness map for Unit 2 with progradational limits of sub-unit 2.1 (red line) and 2.2 (purple line). Sub-unit 2.2 progrades further south than sub-unit 2.1. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red.

4.5 Unit 3

The third sequence of the Eocene system in the Tromsø Basin is Unit 3. The areal extent of the unit is about 4800 km^2 (Fig. 4.23). The unit is mostly bounded at the base by Unit 3 downlap surface, and by the Near Base Eocene surface in the eastern parts nearby the Hammerfest Basin. The surface is separated by onlaps onto Unit 4 and truncates the Base Neogene surface or URU elsewhere (Fig. 4.24). The unit prograded in the same direction as Unit 2, from north to south. It extends further east and south-east than Unit 2, but not as far south and south-west. The western parts of the unit are preserved in greater depths than the eastern, even though these are eroded prior to the deposition of the Neogene wedge, and are less preserved than the eastern. The eastern parts of the unit are preserved in shallower depths than the western parts (Fig. 4.23).

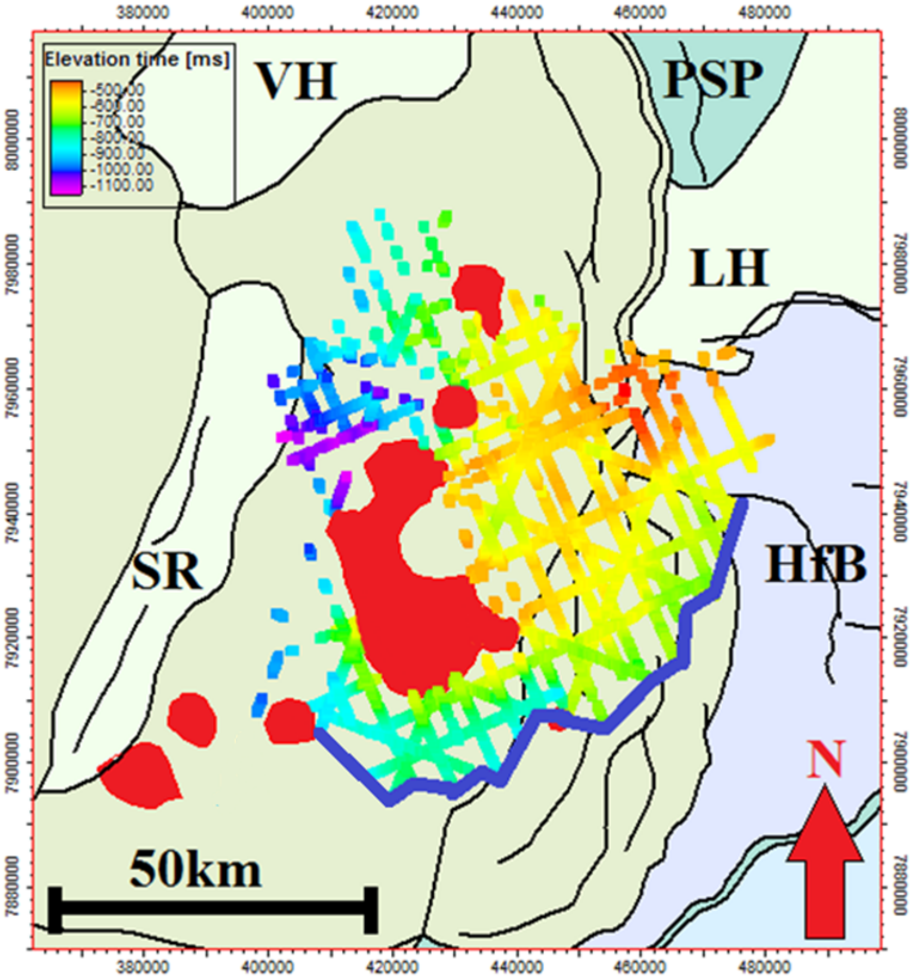
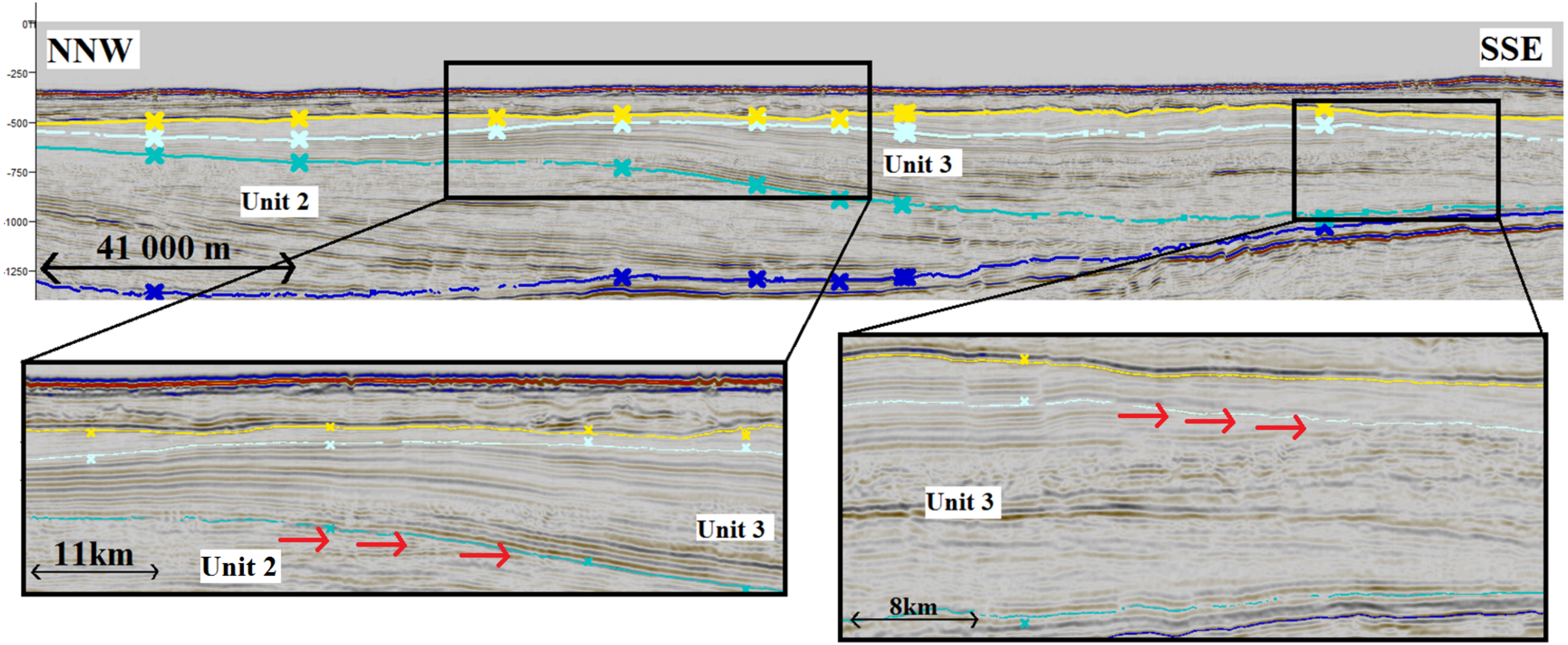


Figure 4.23: Extent of Unit 3 in the Tromsø Basin. Blue line represents the progradational limit of the unit. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red color. Map modified from NPD factmaps (2016).



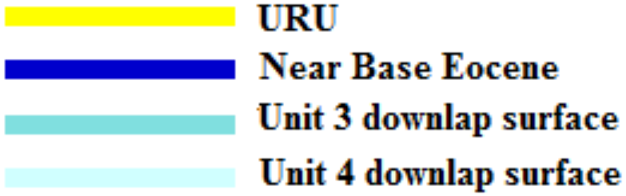
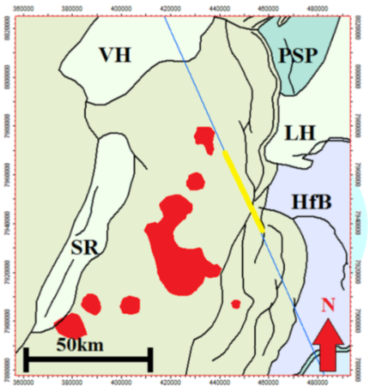


Figure 4.24: Vertical seismic profile showing Unit 3 with its surrounding units and surfaces. Unit 3 is bounded at its base by a maximum flooding surface (Unit 3 downlap surface). The underlying Unit 2 onlaps onto this surface, while Unit 3 onlaps onto Unit 4. The reflection terminations are marked with red arrows. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).



The unit is truncated by the URU in the north-eastern parts and by the Base Neogene in the western and north-western parts of the basin. The full thickness of the unit is preserved in the central and eastern parts of the basin, north and east of the big salt structure (Fig. 4.25 and 4.26). The thickness decreases close to the salt structures. The full thickness varies from about 130 to 150 meters in the northern part to more than 400 meters in the eastern part. A thickness map of the unit is shown in Fig. 4.25. In contrast to Unit 2 are almost no thicknesses of the unit preserved in the south-western parts of the basin. Additionally, there are no visible depositional structures from the Senja Ridge into the Tromsø Basin within this (Fig. 4.27).

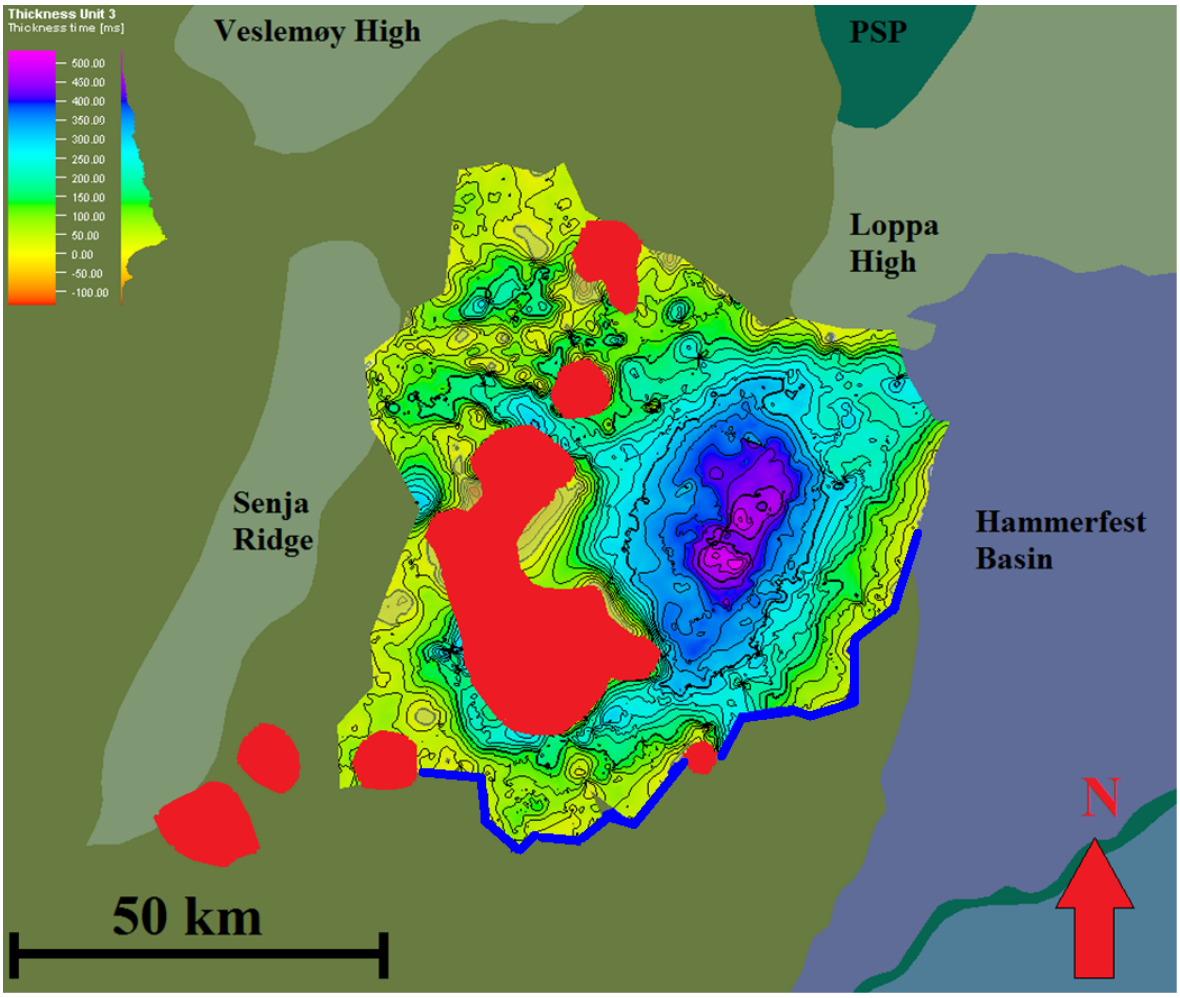


Figure 4.25: Time-thickness map for Unit 3. The thickness is greatest in the eastern part of the unit. The progradational limit is marked with a blue line. Geological features are marked in the map. Salt structures are marked with red color.

There are only found visible clinoform geometries of unit 3 in the eastern part of the basin, east of the big salt structure. The effects of salt movements and erosion have probably removed deposits with internal clinoform profiles in the central parts of the basin.

The seismic reflections are clear and have high amplitude from the topset and through the foreset down the slope. The bottomset reflections are less visible and more chaotic, which are typical for basin floor sediments. The clinoforms are sigmoidal in shape and have heights between 70 and 100 meters.

There are no distinct platform-breaks visible in the seismic, but a trajectory analysis was done by tracing the apparent off-lap breaks (Fig. 4.28). The trajectory shows an ascending shelf-edge; a shelf-edge that is building out in a basin with a rising relative sea level. As the bottomset sediments are relatively thick compared to the topsets, major volumes of sediments are inferred to havebypassed on the platform.

Interpretation

Unit 3 represents a sequence separated by a maximum flooding surface at its base (Unit 3 downlap surface). The unit is smaller than unit 2 in both thickness and extent, and shows a NNE to SSW prograding trend.

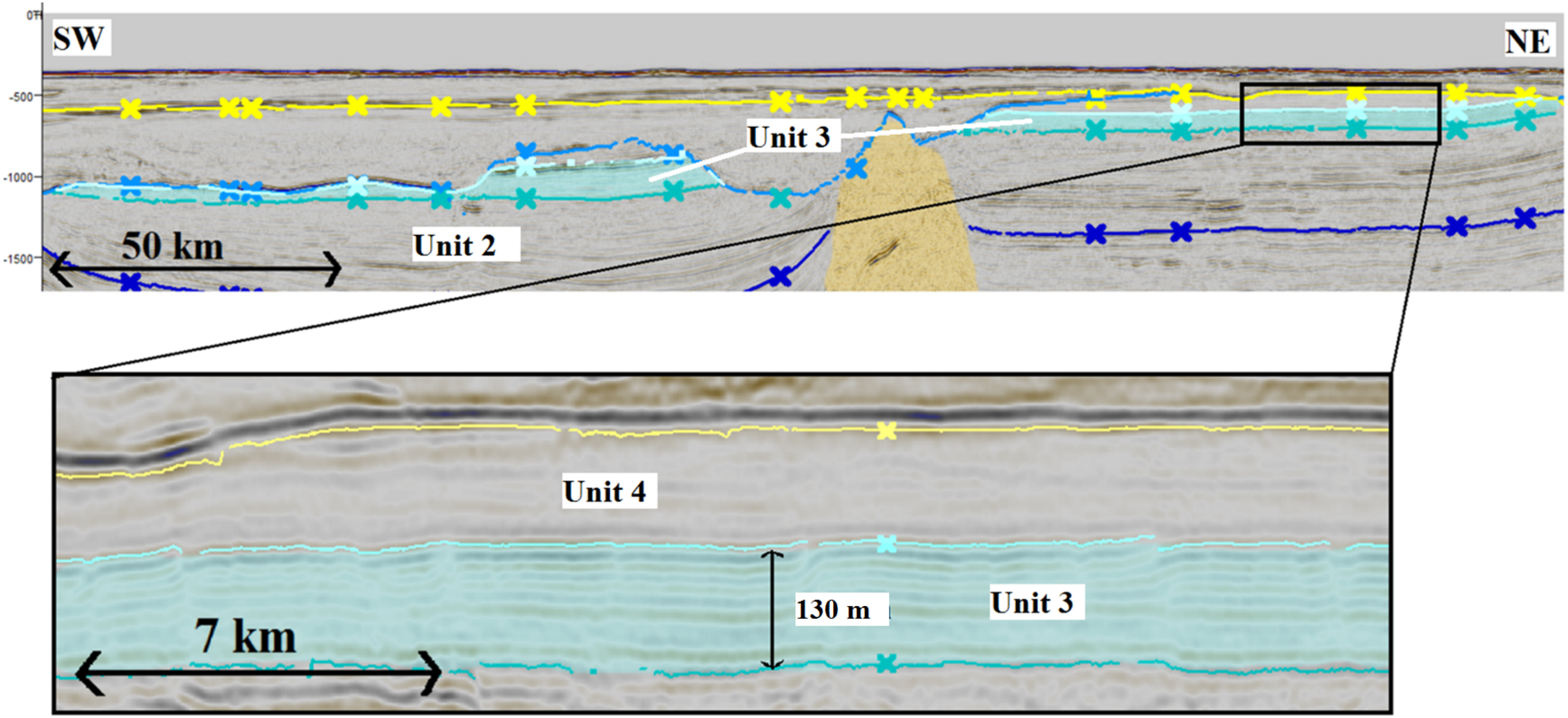
The direction of progradation was decided with emphasis on the development of the clinoforms and their geometry in the eastern part of the unit. As there only was one seismic line crossing this area from NE to SW, and the rest from WNW to ESE or NE to SW, the direction was fully decided upon the clinoforms found in the WNW-ESE oriented profiles. However, as Unit 2 prograded from North to South, it is fair to assume that Unit 3 is a following sequence of the same depositional system.

The ascending shelf-edge trajectory indicates that the sediment supply was high and kept pace with a rising relative sea level. The thick bottomset of the clinothems indicates a high sediment input, while the thin topset gives an indication of less accommodation on the platform and bypass of sediments here.

The lack of sediments of Unit 3 in the southwestern part of the basin is mainly due to erosion prior to deposition of the Neogene wedge, but the absence can probably also be explained by thinning of the unit in this direction and presence of sedimentary strata of the Unit 3 here but in thicknesses below seismic resolution. If so, the main deposition of the unit took place in the central and eastern parts. The variation of thickness from north to south is caused by differences in depositional environment and clinothem geometries. The topsets are thin and parallel, while the platform-edge and slope deposits are thickening out towards south-southeast. This matches the thickness map in Fig. 4.26 which indicates that most of the sediment volumes of the unit are found in the east. The thickness of Unit 3 was probably greater in the central parts of the basin, but has later been affected by the salt movements. The thickness decreases near the salt structures because of the deformation of the strata that occurred when the salt ascended towards the surface.

It is difficult to discuss the western part of the unit as is it truncated by the Neogene wedge. The sediment input from the Senja Ridge could possibly be continuing, but the seismic profiles from this area show no depositional geometries. There are no full thicknesses of the unit preserved nearby the northern Senja Ridge, where most of the sediment input from this high in Unit 2 came from. Hence, it is fair to assume that the depositional input from the Senja Ridge died out after the deposition of Unit 2. However, some of these geometries can have been removed by the later erosion at the base of the Neogene Wedge.

The eastern parts of Unit 3 are preserved on shallower depths than the western. This is an effect of the late Cenozoic uplift and erosion, where the western part was more affected than the eastern part.



🟨 URU

🟦 Near Base Eocene

🟦 Unit 3 downlap surface

🟦 Unit 4 downlap surface

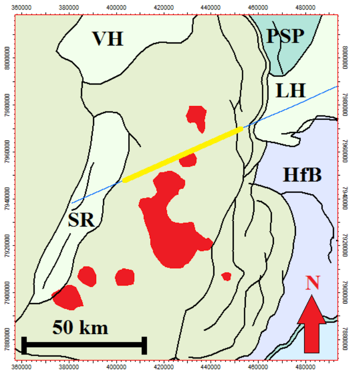


Figure 4.26: Vertical seismic profile showing Unit 3 in the northern part of its extension. The full thickness of the unit is about 130 meters in this part of the basin, representing platform sediments. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

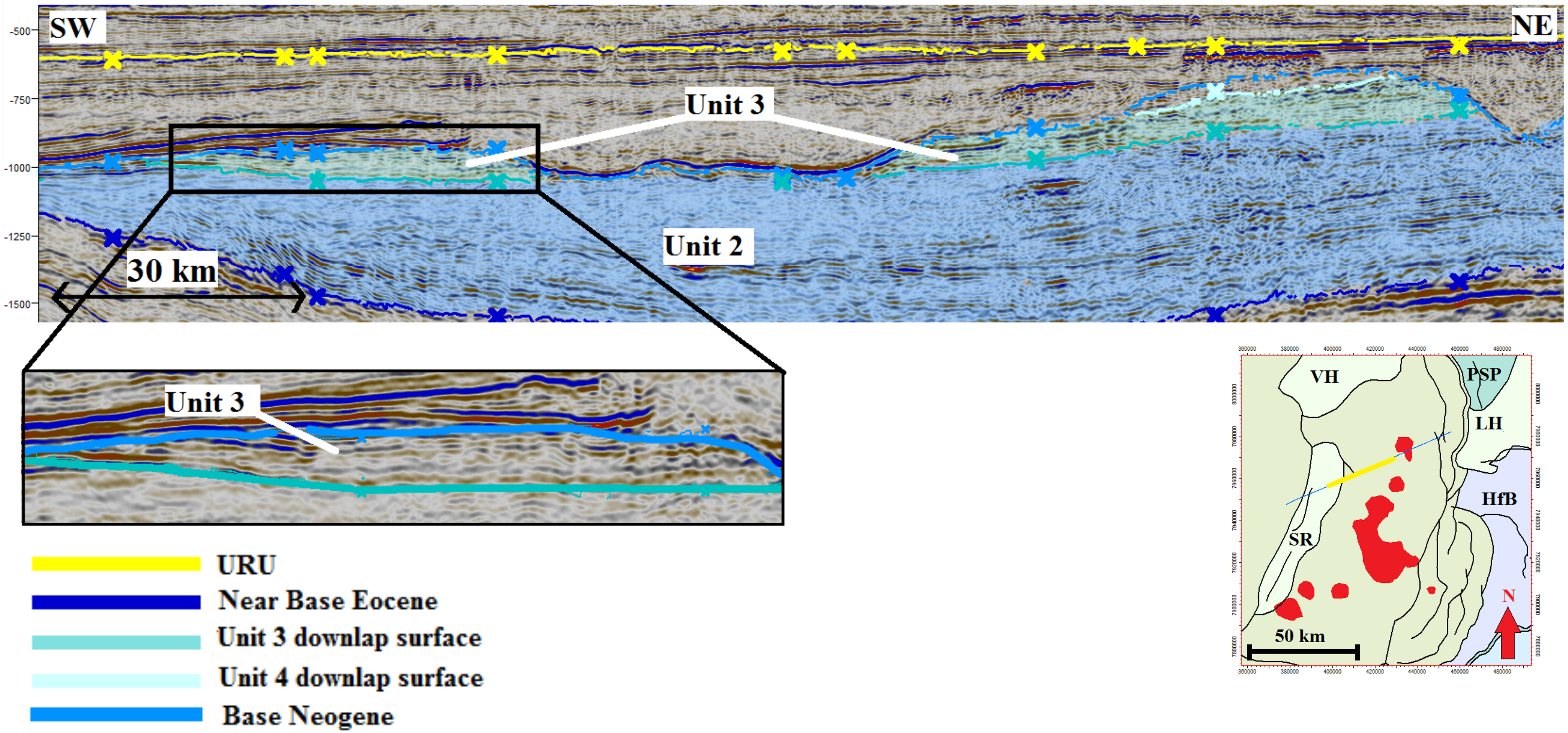
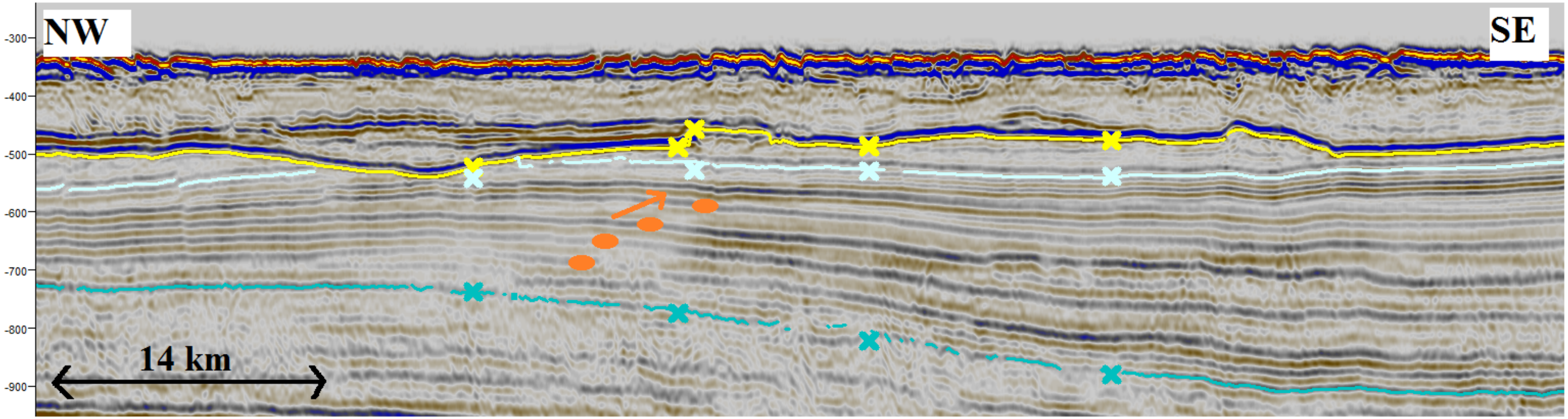


Figure 4.27: Vertical seismic profile showing Unit 3 near the Senja Ridge. No distinct depositional geometries are found. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).



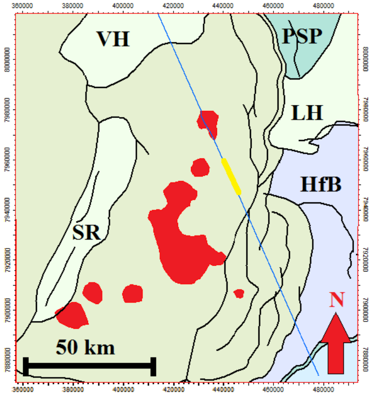


Figure 4.28: Vertical seismic profile showing Unit 3 near the Senja Ridge. No distinct depositional geometries are found. Depth in TWT, color description of lines is attached, see small map of location of the seismic line within the study area. Geological features are marked in the map: **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform. Salt structures are marked with red. Map modified from NPD factmaps (2016).

4.6 Unit 4

The uppermost unit of the Eocene succession present in the Tromsø Basin is greatly affected by the late Cenozoic erosion. The unit is bounded at its base by the Unit 4 downlap surface, onto which Unit 3 onlaps to. It is difficult to find preserved depositional patterns within this unit, i.e. in Fig.4.14 and 4.26, and it has not been analyzed. The Unit is probably filling the remaining accommodation available in the southern part of the basin.

5 Discussion

5.1 Basin infill

The lowermost Eocene succession found in the Tromsø Basin is the aggradational Unit 1. It extends over the northern part of the basin, and some parts of the Veslemøy High, as shown in Fig. 4.11. No progradational deposition patterns are observed within this unit. The reflections are chaotic overall and less continuous compared to the overlying units (Fig. 4.10). The unit is interpreted to have formed as basin floor deposits, probably in a bathyal environment, and consisting of clay and mud-rich sediments (Worsley, 2008; Nagy et al., 1997). It is possible that the unit is also present in other parts of the basin, but with thicknesses below seismic resolution.

Ryseth et al. (2003) proposed a low-energy marine environment for the lowermost Eocene succession found in the adjacent Sørvestsnaget Basin. Microfaunal evidence gave indications of a poorly oxygenated deep marine shelf or bathyal environment, which was further supported by facies seen in a core section. Nagy et al. (1997) proposed a deepening of the Tromsø Basin in the end of Paleocene. In addition, the Unit 2 downlap surface is interpreted as a maximum flooding surface in this study, which further supports a bathyal setting as likely for this time interval.

The aggradational Unit 1 is covered by at least two progradational units, Unit 2 and Unit 3. The basin infill changed from aggradational to progradational across the maximum flooding surface that forms the downlap surface of Unit 2 (Fig. 4.10). This surface demarcates a change in depositional environment from deep marine/bathyal to an environment affected by clastic sediment input from the north.

The second Eocene unit, Unit 2, in the Tromsø Basin exhibits sediment input from three different directions; one from the north, the second out from the northern Senja Ridge, and a third from the nearby Hammerfest Basin in the east. The input from the north is by far the greatest, shown by the significant progradational geometries in the seismic lines trending NW-SE and NE-SW, i.e. in Fig. 4.14 and 4.15. The input from the northern part of the Senja Ridge delivered sediments to the east that interferred with the system prograding from north to south and added additional volumes of sediments into the basin. Progradational patterns from the ridge into the Basin in both northeastern and southeastern directions are observed on seismic lines; Fig. 4.16 and 4.17 respectively. The sediment input from east was relatively small compared to the major input from the north, and the depositional geometries are not as significant as from the north or the Senja Ridge (Fig. 4.20). This eastern input may be a part of the Paleocene depositional system prograding from the east described in an MSc thesis by Prøis (2015), mentioned later in chapter 5.4.

The first depositional sub-unit of Unit 2, progradational sub-unit 2.1, comprises high amplitude reflectors that are inferred to represent widespread and continuous deposits of outer neritic to upper bathyal clays (Nagy et al., 1997; 2000). The clinothems display progradational architecture from the north, with oblique surface geometries, illustrated in Fig. 4.21. The depositional angles are relatively steep compared to the following sub-unit 2.2, which may indicate a relatively higher energy environment (Sangree and Widmier, 1978). The trajectory analysis of the sub-unit, illustrated in Fig. 4.21, shows a descending platform-edge where visible, representing a stage of regression and/or subsidence of the basin. The lowermost strata of sub-unit 2.1 do not allow for trajectory analysis due to the NW (proximal) cut-off of the seismic profile.

Clinoforms of the succeeding sub-unit 2.2 are thinner than those of sub-unit 2.1 (Fig. 4.21). The reflectors are continuous and have high-amplitudes, indicating a widespread deposition of clays in the basin (Sangree and Widmier, 1978; Nagy et al., 2000). The sediment supply was probably high as the gradient of the clinoforms is low and the clinothems are laterally extensive. The accommodation-to-sediment supply ratio could have been low as the topsets of this sub-unit are relatively thin compared to sub-unit 2.2, illustrated in Fig. 2.1 (Anell et al., 2014). If the sediment supply was greater than the accommodation during deposition of this sub-unit, the platform would be dominated by bypass of sediments into the basin (Anell et al., 2014). The change from thick to thin topsets may represent a change from high A/S ratio during depositon of sub-unit 2.1, to low A/S during deposition of sub-unit 2.2. This is further discussed in chapter 5.3.

Progradational patterns of sub-units 2.1 and 2.2 in the Tromsø Basin are illustrated in Fig. 5.1. Sub-unit 2.2 prograded further south than the preceding sub-unit 2.1.

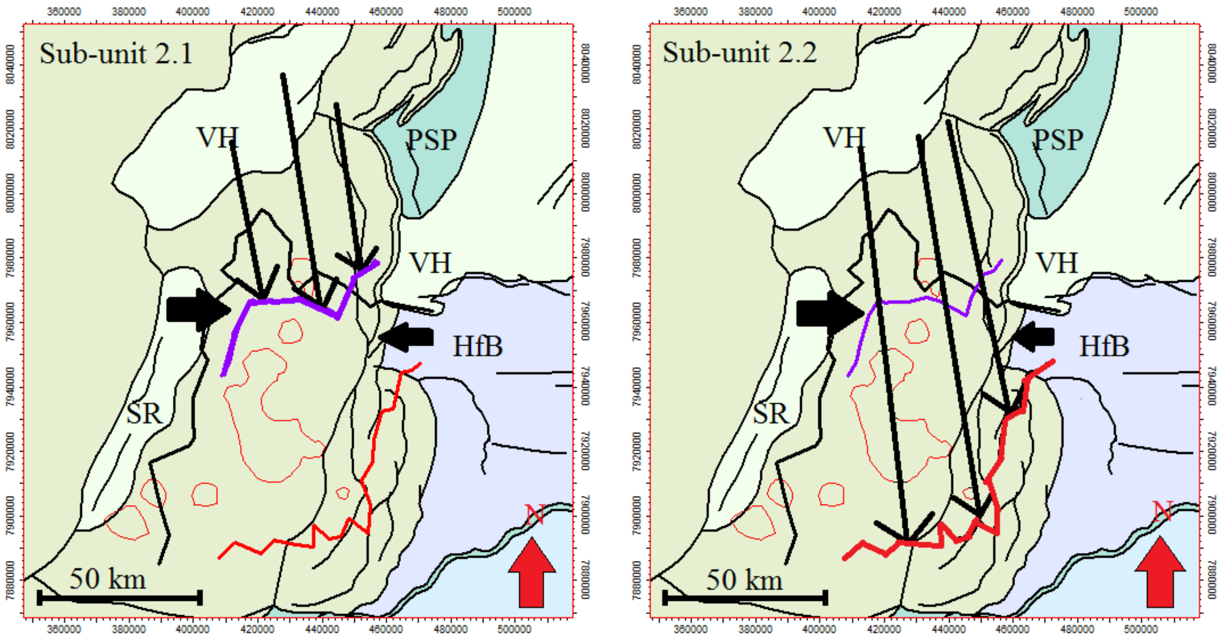


Figure 5.1: Progradational patterns of sub-unit 2.1 (left) and sub-unit 2.2 (right) in the Tromsø Basin. Black line represents the erosional limit of Unit 2, purple line marks the progradational limit of sub-unit 2.1, red line marks the progradational limit of sub-unit 2.2, thin black arrows indicate the progradational direction of the respective units, and thick black arrows indicate the additional sediment inputs into the Tromsø basin. Geological features are marked. **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform Salt structures are marked with red outline. Modified from NPD factmaps (2016).

The sedimentary infill of the Tromsø Basin in Eocene times is discussed by several authors. Knutsen et al. (1992) suggested progradation from Loppa High from early Eocene and additional sediment supply southward and eastward from middle Eocene. Vorren et al. (1991) observed early Eocene clinoforms prograding from the Loppa High into the Hammerfest Basin in a south-southwestward direction. In this study the observed prograding system from north is bypassing Loppa High and reaches its progradational limit in the Hammerfest Basin south of Loppa High. The clinoforms from the Loppa High into the Hammerfest Basin observed by Vorren et al. (1991) may be a part of a major depositional system from the north. Studies of benthic foraminiferal abundance pattern in well 7119/9-1, located in the transition between Tromsø Basin and Hammerfest Basin illustrated in Fig. 1.1, by Nagy et al. (1997) suggested cycles of increase in rate of sediment input into the basin. However, changes in sediment texture are not apparent from the gamma log (Nagy et al., 1997).

Unit 3 also shows progradation in from north to south, but with less significant clinoform geometries than observed in unit 2, i.e. in Fig. 4.24. By tracing apparent offlap-breaks in Fig. 4.28, an ascending trajectory is interpreted with sigmoidal clinoforms. The thick bottomset of the clinothems indicate a high sediment input, while the thin topset gives an indication of less accommodation on the platform and bypass of sediments here (Anell et al., 2014). The relatively low thickness in the southwestern part of the basin is mainly due to erosion by the Neogene wedge, but this can also be explained by thinning of the unit in this direction. If so, the main deposition of the unit took place in the central and eastern part.

There appears to have been no additional sediment input to Unit 3 from adjacent highs, in contrast to Unit 2. No depositional geometries are evident in the western part of the Tromsø Basin near the Senja Ridge within Unit 3, illustrated in Fig. 4.26 and 4.27. There are no full thicknesses of Unit 3 preserved nearby the northern Senja Ridge, i.e. in Fig. 4.26 and 2.27. Hence, it is here assumed that the depositional input from the Senja Ridge waned out after the deposition of Unit 2. However, it cannot be excluded that sediments were sourced from erosion of the Senja Ridge and deposited in the upper part of Unit 3, but that these sediments then may have been removed by later erosion at the unconformity beneath the Neogene Wedge

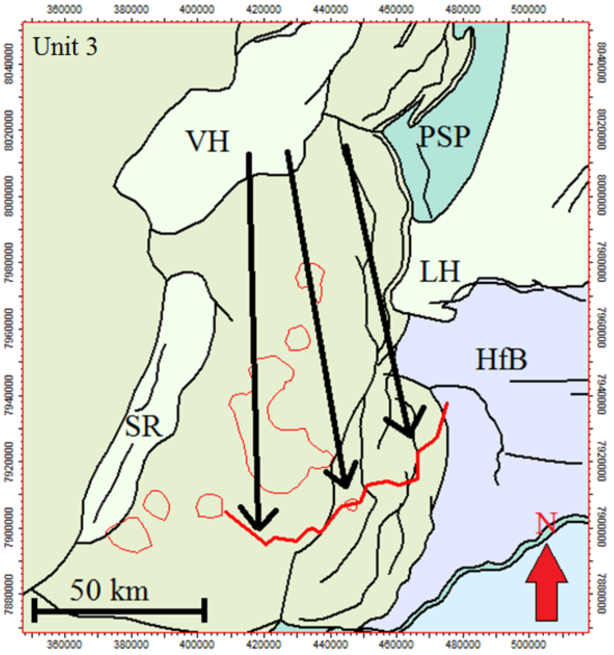


Figure 5.2: Progradational patterns of Unit 3 in the Tromsø Basin. Red line indicates the progradational limit of Unit 3. The black arrows show the N-S progradation direction. Geological features are marked. **LH**: Loppa High**, HfB**: Hammerfest Basin, **SR**: Senja Ridge, **VH**: Veslemøy High, **PSP**: Polhem Sub-platform Salt structures are marked with red. Modified from NPD factmaps (2016).

Unit 2 and Unit 3 are probably parts of the same, major depositional system that prograded from north to south

A direction of sediment infill from the north to the south in the Tromsø Basin during Eocene is supported by the observed clinothems building out in the basin on seismic lines trending NW-SE and NE-SW, i.e. in Fig. 4.14, 4.15, 4.24 and 4.28. None of the lines are in the same direction as the proposed direction of the sediment infill (N-S). This must be taken in consideration as the N-S progradational direction is only an approximate.

The uppermost unit of the Eocene succession in the Tromsø Basin has not been interpreted due to lack of preserved sediments caused by late Cenozoic uplift and erosion (i.e. Baig et al., 2016). However, Ryseth et al. (2003) studied late Eocene deposits found in the adjacent Sørvestsnaget Basin and proposed a marine shallowing in the Eocene to Oligocene transition

5.2 Relative sea level

The relative sea level is measured between the sea-surface and a local moving datum (basement or surface within a sediment pile) (Myers and Milton, 1996). The relative sea level rises due to subsidence, compaction and/or eustatic sea-level rise, and falls due to tectonic uplift and/or eustatic sea-level fall (Myers and Milton, 1996). The eustatic sea-level is the same as global sea-level. An outline of the depositional system in the southwestern Barents Sea during Eocene by Martinsen et al. (2013) is illustrated in Fig. 5.3. This sketch gives an impression of the sea levels during the deposition of the prograding sequences in the Tromsø Basin.

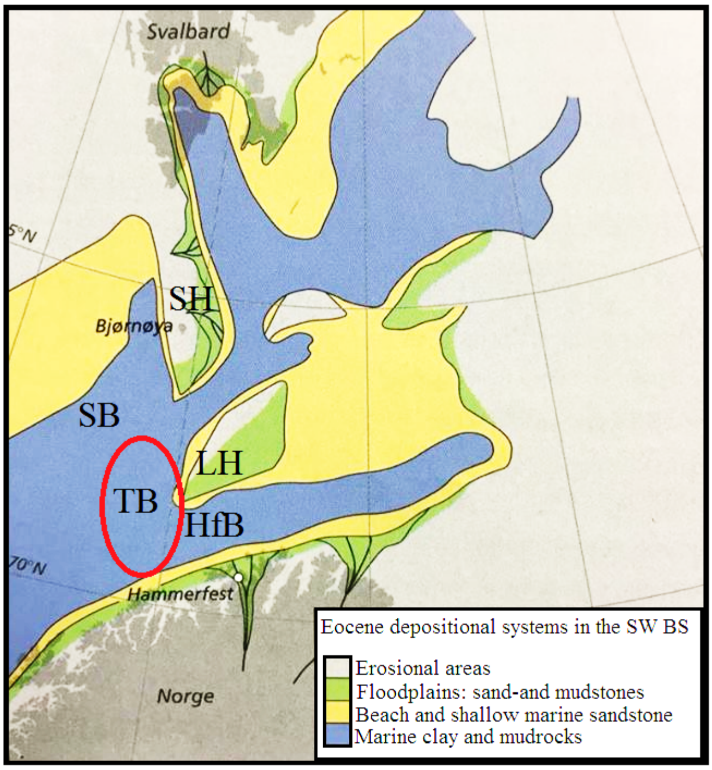


Figure 5.3: Depositional systems in the southwestern Barents Sea during Eocene times. The Tromsø Basin is marked by a red circle. Geological structures are marked. SH: Stappen High, LH: Loppa High, SB: Sørvestsnaget Basin, HfB: Hammerfest Basin, TB: Tromsø Basin. Modified from Martinsen et al. (2013).

The first depositions of the Eocene succession in the Tromsø basin are interpreted to have been deposited in a deep marine, bathyal, basin-floor environment due to the chaotic patterns observed in i.e. Fig. 4.10. This sequence was probably deposited during the high relative sea level in Paleocene-Eocene times (Nagy et al., 1997). The composition of benthic foraminiferal assemblages indicates a Paleocene transgression that reached its maximum some time during the beginning of Eocene (Nagy et al. 1997).

The normal faulting along the Ringvassøy-Loppa Fault Complex and in the eastern Senja Ridge Fault System, illustrated in Fig. 4.2, indicates subsidence of the Tromsø Basin during Paleocene (Knutsen et al., 1992). These faults do not penetrate the Eocene succession in the eastern Senja Ridge Fault system, but the subsidence in Paleocene led to high relative sea levels in early Eocene. The Paleocene transgression led to deposition of marine sediments in the basins and on the adjacent structural highs such as Loppa High, Senja Ridge and

Veslemøy High (Knutsen et al., 1992). Studies by Ryseth et al. (2003) in the Sørvestsnaget Basin suggested a subsequent transgression and subsidence during late Paleocene until early Eocene.

It is thus concluded here that Unit 1 was deposited during high relative sea level in the beginning of Eocene, and that this high sea level probably was caused mainly by tectonic subsidence.

Unit 2 of the Eocene succession in the Tromsø Basin shows, as discussed in chapter 5.1, progradation from north to south. The oblique clinoforms and the descending platform trajectory of the first sub-unit, illustrated in Fig. 4.21, may represent a period of increased subsidence of the Tromsø Basin, or fall in relative sea-level due to fall in eustatic sea-level. A combination of these two factors is considered most likely during the deposition of sub-unit 2.1.

The succeeding sub-unit 2.2 shows a flat and stable trajectory where the clinothems were progressively building out into the basin. This implies stable or falling relative sea level during that time (Helland-Hansen and Martinsen, 1996; Anell et al., 2014). The last sub-unit of Unit 2 is interpreted to be represent a transgression of the basin area and a flooding of the platforms deposited within sub-unit 2.1 and 2.2, due to the less continuous and low amplitude reflections.

Vorren et al. (1991) proposed that the occurrence of neritic diatoms of early Eocene age in northern Finland and Sweden indicates a transgression in the southwestern Barents Sea in early Eocene times. Knutsen et al. (1992) also proposed that the Paleocene transgression continued during deposition of the Eocene succession. As a prograding sequence with descending platform-trajectories is observed in this study, Fig. 4.21, it is assumed that the depositional area was most likely affected by a shallowing during the deposition of the first prograding unit. The shallowing of the basin may be caused by basin uplift (basin inversion), fall in eustatic sea-level (forced regression) or/and increased sediment influx.

Nagy et al. (1997) described a shallowing of the Tromsø Basin from early Eocene, which was explained by high terrigenous influx related to increased sediment supply from north. This confirms the suggestion of a shallowing Tromsø Basin from early Eocene. Studies of Sørvestsnaget Basin also propose a significant shallowing during the beginning of Eocene (Ryseth et al., 2003). It is therefore assumed that the relative sea-level during the deposition of sub-units 2.1 and 2.2 fell due to an increased sediment influx into the basin, before the basin subsided during deposition of sub-unit 2.3 and was transgressed.

Unit 3 in the Tromsø Basin shows progradation in the same direction as Unit 2, illustrated in Fig. 5.2. The ascending platform-edge trajectory and the sigmoidal clinoforms interpreted in Fig. 4.28 indicate that the relative sea level was rising, due to subsidence of the basin or rise in eustatic sea-level (Myers and Milton, 1996).

5.3 Development of accommodation

The amount of space available for sediment accumulation, termed as accommodation, is controlled by eustasy (global sea level) and rate of subsidence (Myers and Milton, 1996). The prograding system from the north indicates increased sediment supply into a basin with an overall increasing accommodation due to subsidence, though relative sea level and water depth changed trough time, as discussed in chapter 5.2.

After deposition of the Paleocene succession by the ENE-WSW prograding system, described by Prøis (2015), the area was transgressed and the platform-edge was most likely flooded. When the Eocene depositional system prograded from north in the Eocene, the platform-edge from the Paleocene system was trending in an N-S direction, and acted as a barrier leading the sediments into the Tromsø Basin. At the same time the Senja Ridge and Veslemøy Highs were uplifted from the beginning of Eocene and made up the western and northwestern barrier of the basin (Faleide et al., 1988).

The thicknesses of the prograding units illustrated in Fig.4.22 and 4.25 can give important information about how the accommodation was distributed in the basin during Eocene. Unit 2 was deposited from the northern to the southern part of the basin, with maximum thickness in the northern and western parts of the basin. The great thickness in west is caused by the additional sediment input from the Senja Ridge, which interfered with the progradation from north. However, the great thickness in this area also implies large accommodation that may have been brought about by a rather high rate of basin subsidence along the eastern flank of the Senja Ridge. During deposition of Unit 3 much less was deposited in the western part compared to Unit 2, while the thickness in the eastern part is much greater compared to Unit 2. This is probably caused due to the available accommodation during deposition of Unit 3. If the western part of the basin was rapidly filled by the sediment influx from both the Senja

Ridge and the north, the sediments prograding in Unit 3 would have found a way to where there was accommodation available, i.e. in the eastern part of the basin where Unit 2 is thin. This change in depositional pattern and preserved thickness of the Eocene in the Tromsø Basin may imply changes in position or/and rate of basin subsidence during Eocene.

As discussed in chapter 5.1, the topsets changed from thick to thin from sub-unit 2.1 to 2.2 (Fig. 4.21). This may indicate a change in the accommodation-to-sediment supply ratio (Anell et al. 2014). When the sediment supply is greater than the accommodation (low A/S ratio), the topsets will appear thin because of bypass of sediments on the platform (Anell et al., 2014). This means that the A/S ratio during deposition of sub-unit 2.1 and 2.2 changed from high to low. Hence, the accommodation decreased in pace with the sediment input.

Additionally, clinoform heights, which are calculated from the average velocity in the upper Torsk Formation, can provide information about the accommodation during deposition of the prograding units in the Tromsø Basin. The oblique clinoforms observed in sub-unit 2.1 (Fig. 4.21) are ~400 meters high, but decreases to 270-300 meters in sub-unit 2.2. This indicates a shallowing of the basin, and less accommodation available for the sediments prograding from the north. The clinoforms within Unit 3 have heights of 70-100 meters, which reflects a rather shallow basin during the time of deposition. The trajectory analysis of Unit 3 shows an ascending platform-edge, which is indicating that the accommodation increased during deposition of this unit.

Early Eocene represents the time of the breakup of the Norwegian-Greenland Sea and the Eurasia Basin (Faleide et al., 1993). The onset of sea-floor spreading was preceded by rifting and transform movements, which affected the Cenozoic deposition in the basins of the southwestern Barents Sea (Faleide et al., 1993). The transtentional and transpressional components led to uplift and erosion of the Stappen High, which acted as a source for sediments deposited in the Sørvestsnaget and Tromsø Basins during this time (Faleide et al., 1993). The rifting in early Eocene resulted in a rearrangement of basins and highs along the western Barents Sea margin (Glørstad-Clark et al., 2011). The western Barents Sea Margin developed as a shear margin, illustrated in Fig. 5.4.

The area where the Tromsø Basin is located was affected by the opening of the Norwegian-Greenland Sea and Eurasia Basin by the transform movements. Additional accommodation was created due to subsidence related to the tectonics in Eocene, and great amounts of sediments could accumulate in the western basins (Glørstad-Clark et al., 2011).

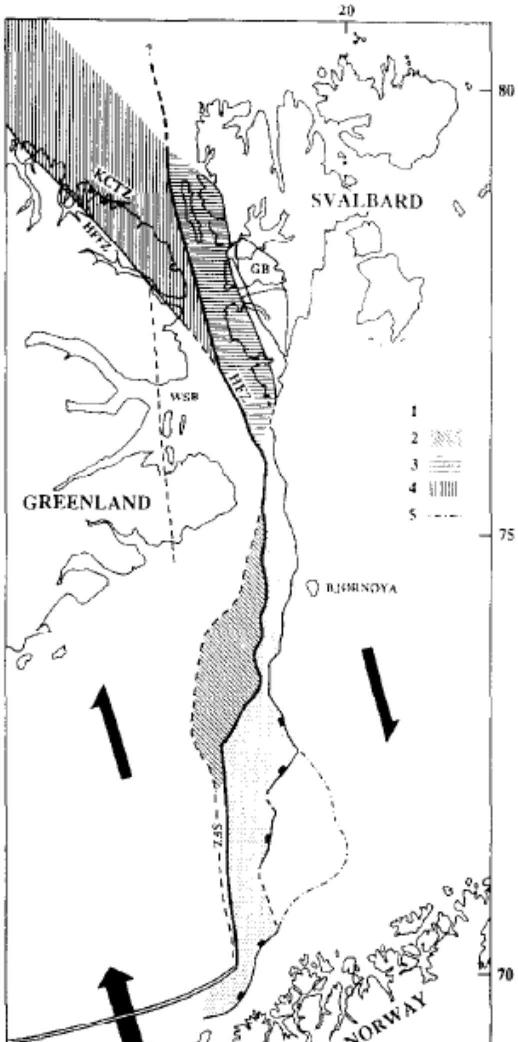


Figure 5.4: Structural configuration of the western Barents Sea in the Paleocene-Eocene transition (the time of break-up between Greenland and Barents Sea/Svalbard. Areas affected by the Eocene opening of the Norwegian-Greenland Sea are marked. 1= Transtension in a marginal basin, 2= Vestbakken Volcanic Province, 3= Transpression in the Spitsbergen fold and thrust belt, 4= Eurekan deofmration, 5= eastern limit of Eocene sediments. Modified from Faleide et al. (1993).

5.4 From source to sink

Previous studies of the Tromsø Basin operate with the Loppa High as the major contributor of Eocene sediments into the Tromsø Basin (Vorren et al., 1991; Knutsen et al., 1992; Faleide 1993). This was proposed as westward progradational geometries were observed out from the Loppa High. Knutsen et al. (1992) described a shift in middle Eocene where the progradation no longer is merely from east to west, but contributed by a southward and an eastward component from Veslemøy High and Senja Ridge.

The results from this study indicates a major input of sediments into the Tromsø Basin in Eocene from the north, contributed by minor inputs from the Senja Ridge and Hammerfest Basin during deposition of Unit 2. There are no clinoform geometries observed out from the Loppa High in any other direction than southwards, which is assumed to be a part of the major depositional system from north. The deposition from the northern part of the Senja Ridge contributed with small sediment volumes compared to the prograding system from north. In addition, a study by Nagy et al. (1997) on foraminiferal abundance and diversity in well 7119/9-1 in the transition zone between Tromsø Basin and Hammerfest Basin suggested an increased sediment supply with high terrigenous influx from north during Eocene.

The small eastern input to the Basin may be a part of the remains of a westward prograding depositional system described by Prøis (2015). In this study of the Paleocene sediments in the Hammerfest and Tromsø Basins an ENE-WSW prograding system was observed (Prøis, 2015). The source area of these sediments was assumed to be located on the northern Barents shelf, as there is lack of evidence for a source area in the east (Prøis, 2015). Unfortunately, the late Ceonozoic uplift and erosion of the Barents Shelf has removed indicators that could have contributed with important information about the Paleogene.

There is an agreement in the literature that the Stappen High was uplifted during Paleogene, and acted as a sediment source for the Eocene deposits in the Sørvestsnaget Basin (Rønnevik and Jacobsen, 1984; Knutsen and Vorren, 1991; Faleide et al., 1993; Ryseth et al., 2003; Safronova et al., 2014). Faleide et al. (1993) also noted that the Stappen High acted as source for the thick Eocene succession in Vestbakken Volcanic province. The Stappen High was uplifted in the Cenozoic due to shearing along the Hornsund Fault Complex, and eroded between 1-3 km due to early Eocene tectonism and volcanism (Rønnevik and Jacobsen, 1984; Faleide et al., 1993; Gabrielsen et al. 1990).

Rasmussen et al. (1995) noted continuous and westward progradational shorelines from the Stappen High during middle and late Eocene. The Middle Eocene fan deposits in the Sørvestsnaget Basin and in the Vestbakken Volcanic Province were most likely eroded and re-deposited locally from Jurassic sandstones on the uplifted Stappen High (Ryseth et al., 2003). Safronova et al (2014) described a gradual middle Eocene basin infilling of the Sørvestsnaget Basin generated by southward prograding shelf-margin clinoforms.

Hence, the Stappen High is a wise suggestion as a northern source area for the N-S prograding succession in the Tromsø Basin. The complex sediment input into the Basin from the Stappen High in the north, the Senja Ridge in the west and the Hammerfest Basin in the east is illustrated in Fig. 5.5.

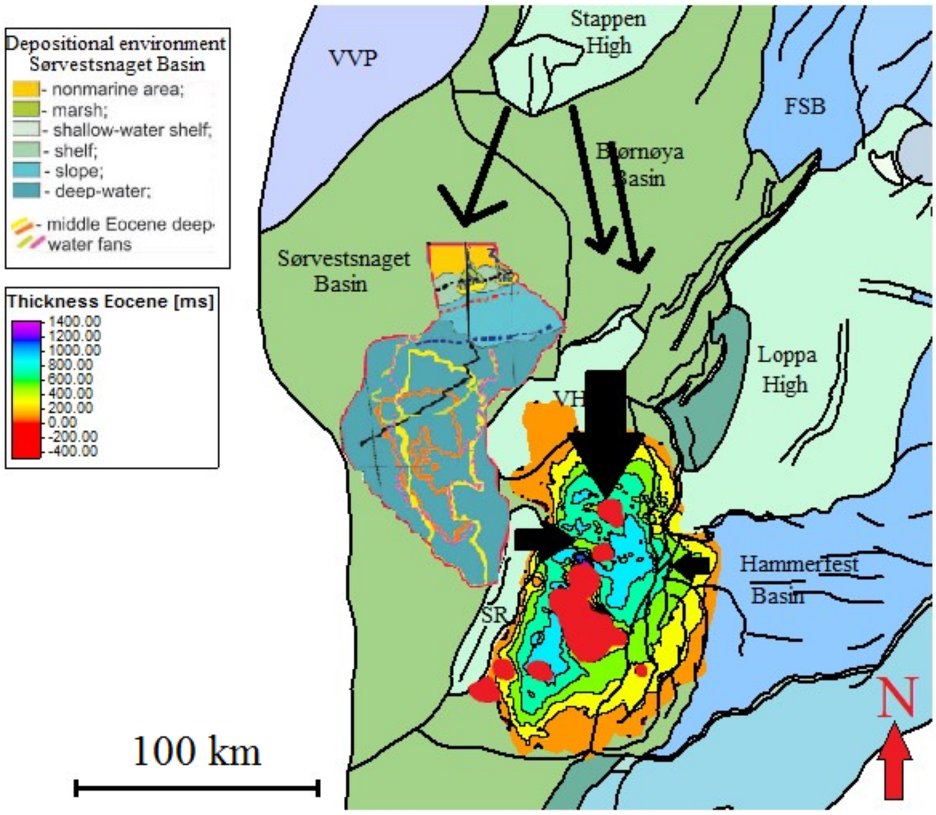


Figure 5.5: Sediment inputs of the Eocene succession in the Sørvestsnaget Basin and Tromsø basin, with the Stappen High as the norhern source area. The sediment inputs from north, east and west in the Tromsø Basin are marked with thick black arrows. The routes for the sediments prograding from the Stappen High in the north are marked with thin black lines. The Stappen High serves as a source area for both of the basins in Eocene. VVP: Vestbakken Volcanic Province, FSB: Fingerdjupet Sub-basin.
Modified from NPD factmaps (2016) and Safronova et al. (2014).

Even though the Stappen High is a likely source area of the Eocene succession in the Tromsø Basin, it cannot have delivered all of the sediment volumes of Eocene within the basin. The Stappen High is assumed to have delivered major volumes of sediments into the Vestbakken Volcanic Province and the Sørvestsnaget Basin as well. The Eocene succession found in the Sørvestsnaget Basin is about 1000 meters thick. Hence, the total sediment volume of the Eocene succession within the Vestbakken Volcanic Province, Sørvestsnaget Basin and Tromsø Basin appears to be greater than what could have been eroded and deposited from the high. This suggests that there must have been a contributor to the sediment input in the Tromsø Basin from the north in addition to the input from the erosion of the Stappen High

Prøis (2015) suggested a northern provenance of the Paleocene sediments found in the Hammerfest and Tromsø Basins. This was based on evidences of a major hiatus found in a borehole (ACEX- Arctic Coring Expedition) on the Lomonosov Ridge, which was a part of the northern Barents Shelf prior to the opening of the oceanic Eurasia Basin. The Eocene prograding system in the Tromsø Basin may be a continuation of this system, but with a rendered depositional pattern from ENE-WSW to N-S. This could be caused by changes in relative sea-level caused by uplift of adjacent highs and ridges which gave rise to new drainage patterns for the sediments from the north.

However, the hiatus in the ACEX well is dated from 65,5-56,2 Ma, which means it was uplifted and eroded during this time until the beginning of the Eocene (Backman and Moran, 2009). The opening of the Norwegian-Greenland Sea and Eurasia Basin in early Eocene led to separation between the ridge and the Barents Shelf, and later subsidence followed by marine deposition above the hiatus (Faleide et al., 1993; Backman and Moran, 2009). The remaining part of the northern Barents Shelf, located on the southern flank of the Eurasia Basin, may still have been uplifted and eroded after the onset of the sea-floor spreading. This could have caused a continuation of the northern provenance for the Eocene sediments in the Tromsø basin and other places in the southwestern Barents Sea.

Evidences for Cenozoic depositional environments on the northern Barents Shelf are hard to restrain due to the great exhumation of the area in the end of Cenozoic (Baig et al., 2016). A northern provenance of the Eocene succession in the Tromsø Basin could be connected to the formation of the Western Spitsbergen fold and thrust belt, 65-40 Ma, associated with strike-slip movements during the opening of the Norwegian-Greenland Sea and the Eurasia Basin (Martinsen et al., 2013). The area was uplifted because of the initiation of the fold and thrust belt, and Paleocene-Eocene deposits are found in the Central Basin on Spitsbergen (Steel et al., 1985; Vorren et al., 1991). The uplifted area could have delivered sediments to the south, which may have been transported in a passage east of the Stappen High, and eventually merged together with the sediments from the Stappen High before they were deposited in the Tromsø Basin.

It is difficult to suggest an accurate source area in the north for the Eocene prograding system in the Tromsø Basin. The sediment input from the north is most likely complex with several different provenances. The northern provenance could be a mix of the Stappen High, the uplifted fold and thrust belt on Svalbard, and the probably uplifted areas on the northern Barents Shelf. This suggestion is illustrated in Fig. 5.6 and 5.7.

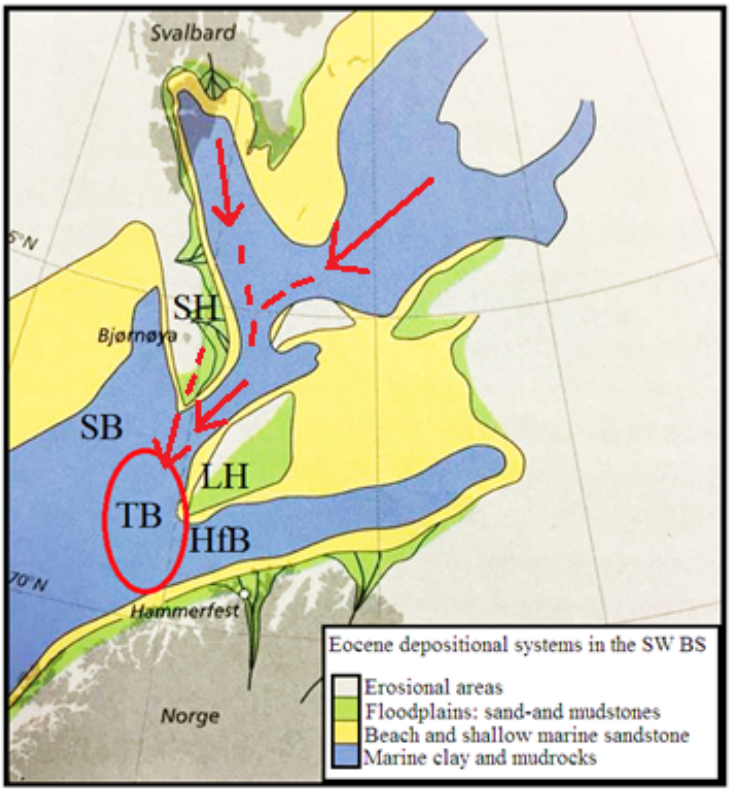


Figure 5.6: The suggested depositional system of the complex northern provenances for the Eocene succession in the Tromsø Basin Sea during Eocene (red circle). The northern provenance may have been a combination of the Stappen High, the folded-thrust belt on Svalbard and the uplifted northern Barents Shelf. The suggested depositional patterns are marked with red arrows. Geological structures are marked. SH: Stappen High, LH: Loppa High, SB: Sørvestsnaget Basin, HfB: Hammerfest Basin, TB: Tromsø Basin. Modified from Martinsen et al. (2013).

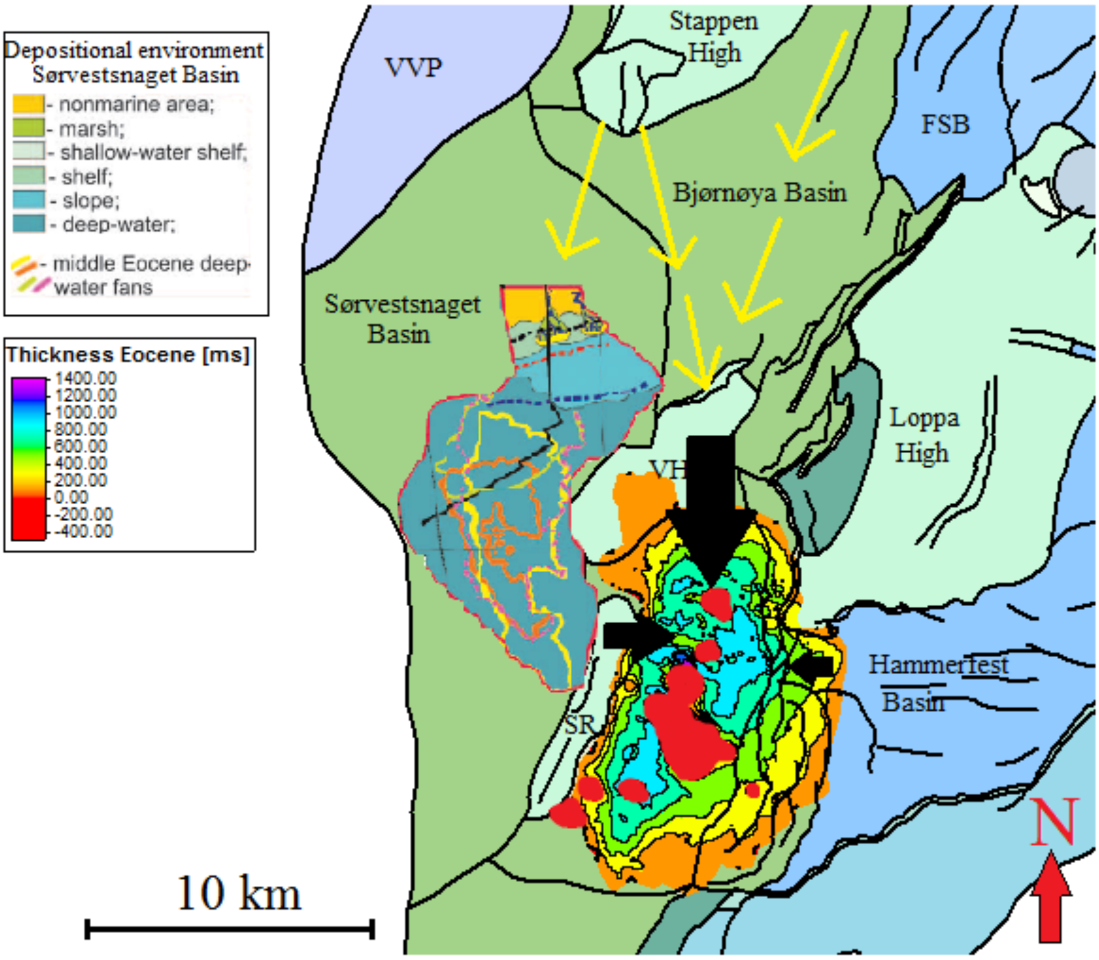


Figure 5.7: Sediment inputs of the Eocene succession in the Sørvestsnaget Basin and Tromsø basin, with a complex source area in the north consisting of the Stappen High, the folded-thrust belt on Svalbard and the uplifted northern Barents Shelf. The sediment inputs from north, east and west in the Tromsø Basin are marked with thick black arrows. The routes for the sediments prograding from the Stappen High and the other northern provenances are marked with thin yellow lines. VVP: Vestbakken Volcanic Province, FSB: Fingerdjupet Sub-basin. Modified from NPD factmaps (2016) and Safronova et al. (2014).

5.5 Veslemøy High, Senja Ridge and Loppa High

The Loppa High, Veslemøy High and Senja Ridge are bounding the Tromsø Basin in east, north and west, respectively.

The Veslemøy High was uplifted during Late Cretaceous and early Cenozoic, and formed a contemporary bathymetric high in Paleocene (Knutsen and Larsen, 1997; Ryseth et al., 2003). Small thicknesses of the Eocene succession are found on parts of the Veslemøy High in this study, which may indicate that the high was transgressed in early Eocene. The high was most likely a bathymetric high that later was uplifted and eroded. Unit 1 represents the part of the Eocene succession that is preserved on the Veslemøy High. Its thickness here is only ~50 meters. Knutsen et al. (1992) did also observe the Base Eocene reflector on the Veselmøy High. It is assumed that the high was transgressed after the uplift in Late Cretaceous, during the deepening of the Tromsø Basin in Paleocene. This led to deposition of Paleocene and Eocene sediments on the high, which later was uplifted in Eocene due to effects of the opening of the Norwegian-Greenland Sea and Eurasia Basin. Hence, the Veslemøy High is suggested to have appeared as a bathymetric during Eocene that guided the sediments from north into the basin.

The Senja Ridge probably appeared as a positive structure during the deposition of the first sub-unit of Unit 2. Prograding clinothems are observed out from the northern part of the ridge in an eastward direction, in Fig. 4.17 and 4.18. No depositional patterns are observed out from the southern part of the ridge, which may indicate that this stayed as a bathymetric high during Eocene. This interpretation is supported by onlaps onto this southern part of the ridge, illustrated in Fig. 4.19). The progradation into the Tromsø Basin from the northern Senja Ridge most likely stopped before deposition of Unit 3. There are no depositional geometries from the ridge observed in Unit 3 (Fig. 4.26 and 4.27). Parts of this unit are probably removed by erosion. However, Unit 3 is overlain by Unit 4 some places nearby the ridge, which means that the original thickness is preserved here.

The northern Senja Ridge was probably still uplifted during deposition of Unit 3 in the Tromsø Basin, but the deposition must have been concentrated merely to the west into the Sørvestnaget Basin. The uplift and erosion of Senja Ridge is associated with the Paleogene breakup of the Norwegian-Greenland Sea uplift along the Senja Fracture Zone (Nagy et al., 1997).

The Loppa High may have been a bathymetric high during Eocene, as the prograding units from the north are onlapping the structure. The lowermost deposits are deposited on the western flank of the Loppa high. Vorren et al. (1991) and Knutsen et al. (1992) suggested that the Loppa High was uplifted from Paleocene and delivered sediments into the Tromsø Basin. The high may have been uplifted, but as no depositional patterns are observed into the Tromsø Basin from the Loppa High in the Eocene succession, the drainage area may have been merely to the east. There is possible that the Loppa High contributed with sediments into the Tromsø Basin in late Eocene-Oligocene, but due to uplift and erosion of the Barents Shelf are there no evidences of this left in the area. The Loppa High was located further away from the continental break up zone compared to i.e. Stappen High during Eocene, and did not experience the same margin uplift as the western parts (Glørstad-Clark et al., 2011) This may suggest that the Loppa High appeared as a bathymetric high in Eocene, and later uplifted and eroded during the shallowing of the area in late Eocene-Oligocene (Nagy et al., 1997).

5.6 Effects of uplift and erosion

The Barents Shelf has experienced considerable uplift and erosion associated with the Eocene opening of the Norwegian-Greenland Sea and with the late Pliocene-Pleistocene glaciations (Dimakis et al., 1998; Baig et al., 2016). The exact timing of the uplift and erosion is difficult to decide, as the Eocene to Pliocene strata below the URU are missing on the shelf, except for in the western marginal basins such as the Tromsø Basin and Sørvestsnaget Basin (Baig et al., 2016). Fig. 5.8 shows net exhumation rates constrained from a study by Baig et al. (2016). The uplift and erosion is increasing towards east and northeast, and have been supported by several other studies, i.e. by Riis et al. (1992), Ohm et al. (2008) and Henriksen et al. (2011). The uplift and erosion of the Barents Shelf have affected the present day Eocene succession found in the Tromsø Basin. As the eastern part may have been exposed to uplift and erosion of up to 1000 meters, parts of the Eocene strata are assumed to have been eroded here. The western part of the Tromsø Basin is assumed to have been exposed to about 500 meters of exhumation. However, the time thickness map of the Eocene succession in the Tromsø Basin shows no increased thickness in the eastern part. This may indicate that the Eocene succession has been equally exposed for exhumation in all parts of the basin.

Most likely were the Eocene sediments deposited across greater areas than what is evident in the southwestern part. As there are estimated uplift and erosion up to 1000 meters in areas where the Eocene sediments are present, i.e. in the transition zone between Tromsø Basin and Hammerfest Basin illustrated in Fig.5.8, there must have been great thicknesses of younger sediments deposited here. Additionally, the time of maximum burial occurred in the end of Eocene-Oligocene (Baig et al., 2016). This may indicate that much of the uplifted and eroded strata must have been of Eocene age, and that the Eocene succession may have been quite extensive across other parts of the Barents Shelf, not only in the Tromsø and Sørvestsnaget basins.

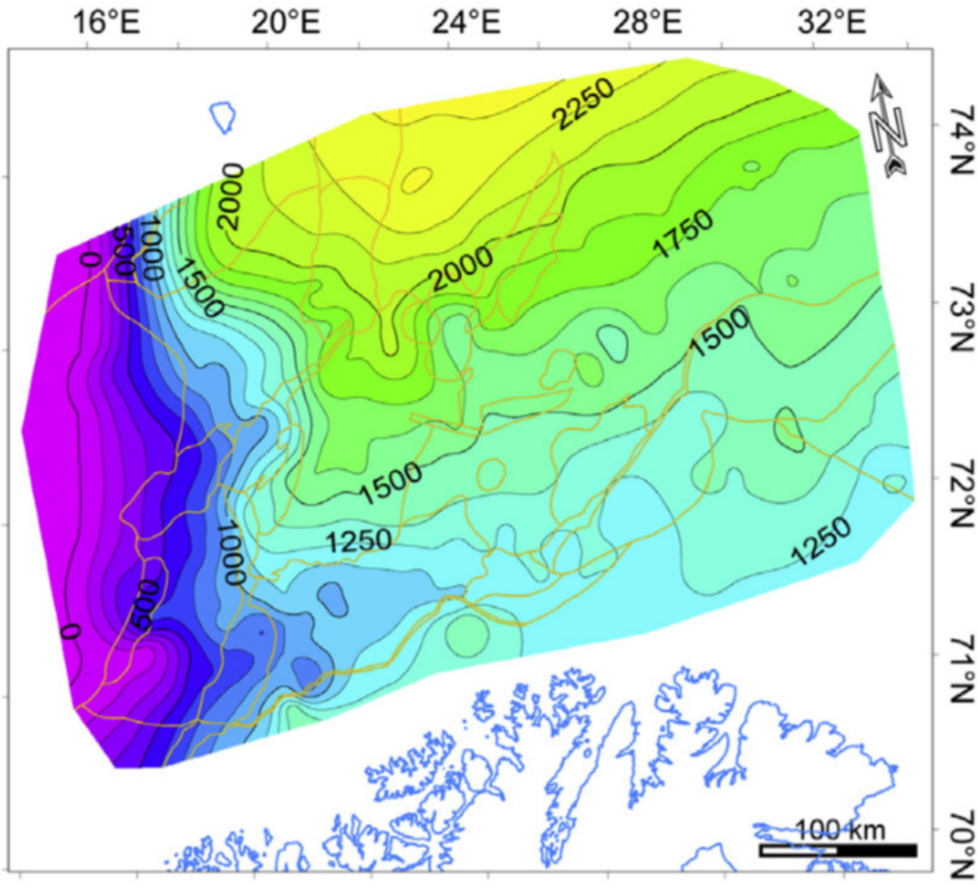


Figure 5.5: Arthimetic average net exhumation map from the SW Barents Sea. The northeastern and eastern parts of the Barents Sea are by far more affected by uplift and eroision than the western part. Modified from Baig et al. (2016).

5.7 Salts in the Tromsø Basin

The Tromsø Basin contains several salt structures. The latest movements of these may have taken place in late- or post Eocene times as there are not observed any onlaps onto the salt by the Eocene strata. Furthermore, the Eocene sequences that prograded from north and west can be traced and followed on the opposite side of the salt structures, which indicate that they were deposited before the salt structures occurred. The Eocene succession close to the buoyant salt is affected by the growth of the structures in the same way as the underlying units, by being pulled up and deformed. Additionally, as both the Upper Regional Unconformity and the Neogene wedge is preserved in the area and unaffected by the salt structures, the salt movement must have taken place prior to Neogene, see Fig. 4.2.

Jackson and Vendeville (1994) proposed that thin skinned extension may provoke the growth of salt structures. Salts behave differently from other rocks during strain. If salt beds are buried deep, the average density of the overburden will exceed the salt and it will become buoyant and gravitationally unstable (Jenyon, 1986). As the area was exposed to tectonic movements in an extensional regime in Early Eocene, it is fair to assume that the salt growth in the Tromsø Basin was triggered by the opening of the Norwegian-Greenland Sea. This is also suggested for the salt structures found in the Sørvestsnaget Basin further northwest of the Tromsø Basin (Knutsen and Larsen, 1997). These are considered to be related to the extensional faulting and subsidence during the early spreading phase of the Norwegian-Greenland Sea (Knutsen and Larsen, 1997). When comparing the salt structures of these two basin, it must be taken in consideration that the Sørvestsnaget Basin has been exposed to more intense tectonic movements than the areas further east (Knutsen and Larsen, 1997).

Knutsen and Larsen (1997) suggested that the Cenozoic movement of the salt structures found in the Sørvestsnaget Basin, northwest of the Tromsø Basin, took place in middle-late Eocene. This suggestion was made upon the age of the thickening of the middle and upper Paleogene sequence in the synclines surrounding the salt structures. In addition, there are preserved upper Paleogene sediments above the salt structures here (Knutsen and Larsen 1997). In the Tromsø Basin there is only observed thickening of the Eocene strata west of the great salt structure, i.e. in thickness map illustrated in Fig. 4.9. This thickening is probably not caused by the growth of the intrabasinal salt structures, but to the infilling pattern of the basin.

6 Summary and conclusions

The Tromsø Basin is studied in a seismic sequence stratigraphic manner to retrieve first-order information about the depositional system and infill pattern during Eocene. Four units were analysed, of which two progradational units were studied in detail. The progradational direction was mainly from north to south, with minor inputs from east and west.

The first depositional unit, Unit 1, found in the Eocene succession of the Tromsø Basin is aggradational and deposited in the northern part of the basin, inclusive parts of the Veslemøy High. Unit 1 probably formed as basin floor deposits in a bathyal environment dominated by mud- and clay-rich sediments in early Eocene. It was deposited during high relative sea level caused by tectonic subsidence related to the onset of the opening of the Norwegian-Greenland Sea and the Eurasia Basin in early Eocene. The unit may have been deposited in other parts of the basin as well, but in thicknesses below seismic resolution.

A maximum flooding surface at the end of deposition of Unit 1 marks the change from a bathyal/deep marine environment to an environment affected by a major clastic sediment input from the north, and minor inputs from the Senja Ridge and Hammerfest Basin, forming Unit 2. The first sub-unit of Unit 2, sub-unit 2.1, reflects a fall in rate of relative sea level rise, before it stabilized during deposition of sub-unit 2.2. A change in A/S ratio is recorded from the first to the second sub-unit indicating a lowering of accommodation during this time. Unit 2 is most likely affected by both falling eustatic sea level and increased subsidence. The unit was probably transgressed during deposition of the last sub-unit, and the platforms were flooded.

The third unit, Unit 3, in the Eocene succession in the Tromsø Basin shows progradation exclusively from north to south, with no additional inputs from east or west. The unit represents a period of high sediment input and platform bypass due to decreased accommodation here. The last unit preserved in the Tromsø Basin, Unit 4, is not analysed in detail due to lack of preserved thicknesses and depositional geometries.

The Senja Ridge, which is bounding the basin in the west, probably appeared as a positive structure during the deposition of Unit 2 as Eocene depositional geometries are observed from the northern flank into the basin. The southern part may have been a bathymetric high during this time, as there are only observed onlaps onto the structure and no depositional patterns out from it.

The Veslemøy High was uplifted during Late Cretaceous, and formed a contemporary bathymetric high that was flooded during the deepening of the Tromsø Basin in Paleocene. This led to deposition of Paleocene and Eocene sediments on the high, prior to uplift and erosion.

The Loppa High may have appeared as a bathymetric high in Eocene as onlaps are observed along the structure margin in NW-SE profiles. It did not deliver any sediments into the Tromsø Basin during the time span of the Eocene sediments preserved in the Tromsø Basin, but may have been uplifted, eroded and supplied the basin with sediments from late Eocene. These would later be removed due to late Cenozoic uplift and erosion.

A northern provenance for the Eocene succession in the Tromsø Basin is proposed with basis of the progradational patterns observed in a north to south direction. This source of sediments was most likely a complex system, with input from the Stappen High, the uplifted northern Barents Shelf and possibly the Western Spitsbergen fold-and-thrust-belt that formed in early Eocene in connection to transform movements during the sea-floor spreading in the northeastern part of the Norwegian-Greenland Sea.

The last halokinesis of the salt structures found within the Tromsø Basin are assumed to have taken place post- or late Eocene. Hence, the deposition of the prograding sequences in Eocene was unaffected by salt growth, and the Tromsø Basin comprised accommodation across the whole basin.

Uplift and erosion of the Barents Shelf associated with the sea-floor spreading and late Pliocene-Pleistocene glaciations have removed significant volumes of Cenozoic sediments. As the Tromsø Basin has experienced exhumation up to 1000 meters in the eastern part, it is fair to assume that considerable volumes of Eocene strata have been removed here. Most likely the Eocene deposits were widespread and more extensive than what is evident in the southwestern part of the Barents Sea today. Unfortunately it is hard to constrain required information to infer the depositional environment during Eocene in other parts of the Barents Sea.

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