Cretaceous and Cenozoic tectono-stratigraphic evolution of the southern Lofoten and northern Vøring margins, offshore northern Norway

Amra Kalač

Master Thesis in Geosciences
Petroleum Geology and Petroleum Geophysics
30 credits

Department of Geosciences
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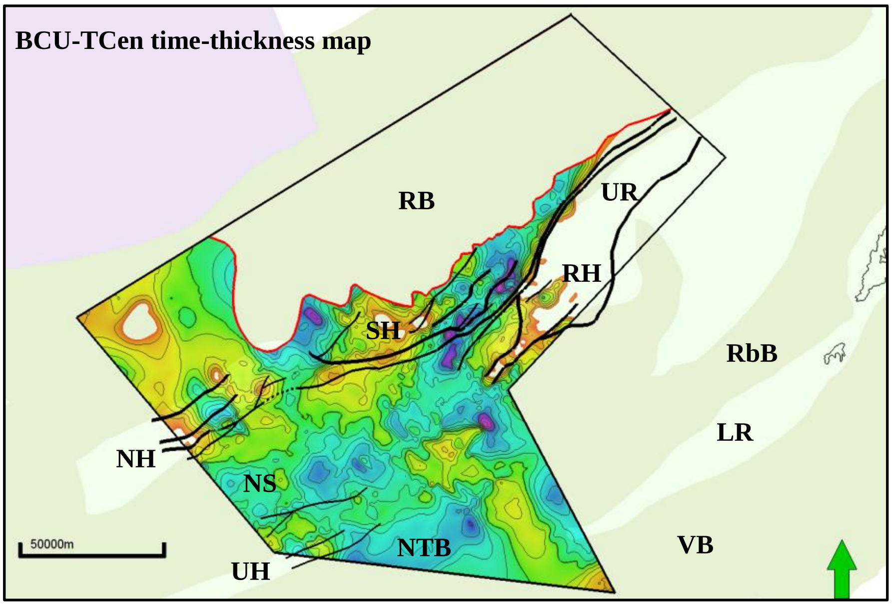

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http://www.duo.uio.no/

Trykk: Reprosentralen, Universitetet i Oslo

Abstract

The northern Vøring and southern Lofoten margins are located offshore northern Norway; and are separated by the Bivrost Lineament. While the Vøring margin is extensively studied, the Lofoten-Vesterålen margin is one of the least explored areas on the Norwegian continental shelf. The Lofoten-Vesterålen margin lacks deep-target commercial wells, which makes it difficult to correctly estimate sediment distribution and thicknesses, as well as age and timing of tectonic events. It has a complex geological history, and there have been several attempts to account for the evolution of the area. Although challenging, the better understanding of the geological evolution of the Lofoten-Vesterålen margin is of great importance as the margin represents the link between the mid-Norwegian, SW Barents and conjugate NE Greenland margins, and is a key area to study the rift-basin architecture and tectono-sedimentary evolution of the NE Atlantic margins. The current study aims to improve the understanding of the Cretaceous to Cenozoic tectono-stratigraphic evolution of the northern Vøring and southern Lofoten-Vesterålen margin.

The tectono-stratigraphic evolution of the southern Lofoten and northern Vøring margins has been studied in detail utilizing several datasets, consisting of: 2D multi-channel seismic reflection profiles, well-to-seismic ties and stratigraphic information from four exploration wells, in addition to gravity and magnetic data. The main focus of the work has been on seismic and structural interpretation in order to refine the rift phases that affected the study area and to decipher the eventual role of the Bivrost Lineament, as well as to improve the understanding of the evolution the West Røst High Fault Complex and the outer Lofoten margin. Furthermore, the southern Lofoten and northern Vøring margin segments have been studied in a regional and conjugate margin setting in order to get a better understanding of the crustal structure and pre-breakup basin evolution.

Four main rift phases have been recognised and refined in the study area. Late-Jurassic-earliest Cretaceous rifting controlled the initial structuring of the main structural elements. Mid Cretaceous rifting is responsible for initiation of faulting in the West Røst High Fault Complex, while rifting continued during Late Cretaceous and led to a westward propagation of fault activity. Paleocene rifting reactivated several Late Jurassic-earliest Cretaceous and

Cretaceous faults, prior to continental breakup and seafloor spreading initiation at the Paleocene-Eocene transition. The Bivrost Lineament is recognized as a major margin boundary with an uncertain exact location, which segments highs and sub-basins on the northern Vøring and southern Lofoten margins. Furthermore, the presence of two dome shaped features has been observed on the southern Lofoten margin, which probably experienced several phases of growth from Late Cretaceous to Miocene times, reaching its maximum dimension in mid Miocene.

The tectono-stratigraphic evolution of the southern Lofoten and northern Vøring margins has been compared to the conjugate Northeast Greenland margin, to get a better understanding of the evolution in a regional and conjugate context. Comparison of sequences along the conjugate margins implies that the northern part of the NE Greenland margin and the Vøring margin have experienced extensive pre-breakup crustal stretching, while the Lofoten margin experienced only moderate pre-breakup extension. The Bivrost Lineament separates the northern Vøring and southern Lofoten margins and is believed to have a conjugate equivalent on the NE Greenland margin. Similarly prominent Late Cretaceous low-angle detachment faults have been also observed on both conjugate counterparts.

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Preface

This master thesis has been submitted as the final part of the two years master program with specialization in "Petroleum geology and petroleum geophysics" at the University of Oslo. The thesis has been supervised by Professor Filippos Tsikalas and Professor Jan Inge Faleide.

Acknowledgements

I would like to express my deepest gratitude to my supervisors at the University of Oslo for all their help during the work with this thesis. Their support and knowledge have been highly appreciated. I would also like to express my gratitude to Dr. Michael Heeremans for preparing the dataset used in this thesis, to TGS and NPD for providing the data, and to Schlumberger for making the Petrel software available.

Thanks to all my fellow students at the Department for motivation during the work with the thesis, and a special thanks to Rikke and Kathrine for support, encouragement, and peculiar discussions. A big thank you to my family and friends for their support, encouragement and understanding through this period. And Oddmund, thank you for being so patient and giving me chocolate in my darkest hours. I couldn't have done this without all of you.

Amra Kalač

Contents

1 Introduction

The Vøring and Lofoten-Vesterålen margins are located in the Norwegian Sea offshore Norway (Fig. 1.1). The combined length of the two margins is approximately 800 km. The northern Vøring margin (NVM) is, here, conventionally defined as the northern part of the composite Vøring volcanic margin that is comprised of three geological provinces (from west to east): the Vøring Marginal High, Vøring Basin, and the Trøndelag Platform (Blystad et al. 1995; Hjelstuen et al., 1999). The Vøring margin borders the Møre margin in the south and the Lofoten-Vesterålen margin in the north. The Lofoten-Vesterålen margin (LVM) is a 400-km-long continental margin characterized by a narrow continental shelf and a steep continental slope (Fig. 1.1a). The Lofoten-Vesterålen archipelago lies east of LVM and consists of high-grade metamorphic Precambrian rocks (Hansen et al., 2012). The LVM is separated from the shear-dominated SW Barents Sea margin in the north by the Senja Fracture Zone, while the Bivrost Lineament separates it from the Vøring margin in the south (Fig. 1.1b).

While the Vøring margin is extensively studied, the Lofoten-Vesterålen margin is one of the least understood areas on the Norwegian continental shelf (Mjelde et al., 2003). The LVM lacks deep-target commercial wells, which makes it difficult to correctly estimate sediment distribution and thicknesses, and age and timing of tectonic events. The LVM has a complex geological history, and there have been several attempts to account for the evolution of the area, mainly based on lateral segmentation along the margin (e.g. Tsikalas et al., 2001; Tasrianto and Escalona, 2015). Although challenging, the better understanding of the geological evolution of the LVM is of great importance as the margin represents the link between the mid-Norwegian, SW Barents and conjugate NE Greenland margins, and is a key area to study the rift-basin architecture and tectono-sedimentary evolution of the NE Atlantic margins (Faleide et al., 2008; Hansen et al., 2012; Tsikalas et al., 2012).

The study area of the thesis includes the southern and southwestern parts of the Lofoten-Vesterålen margin (referred in the thesis as the southern Lofoten margin) and the northern Vøring margin (Fig. 1.1). The main objectives include the following:

- Improve the understanding of the tectono-stratigraphic evolution of the northern Vøring Basin and margin, and the southern Lofoten margin. This includes understanding the role of the Bivrost Lineament during Cretaceous and Cenozoic times.
- Study the tectono-stratigraphic evolution of the West Røst High Fault Complex (informal name, defined in the thesis).
- Understand the Cenozoic tectono-stratigraphic evolution of the outer Lofoten margin, consisting of the Røst Basin.
- Study the northern Vøring and southern Lofoten margin segments in a regional and conjugate margin setting, including crustal structure and pre-breakup basin evolution.

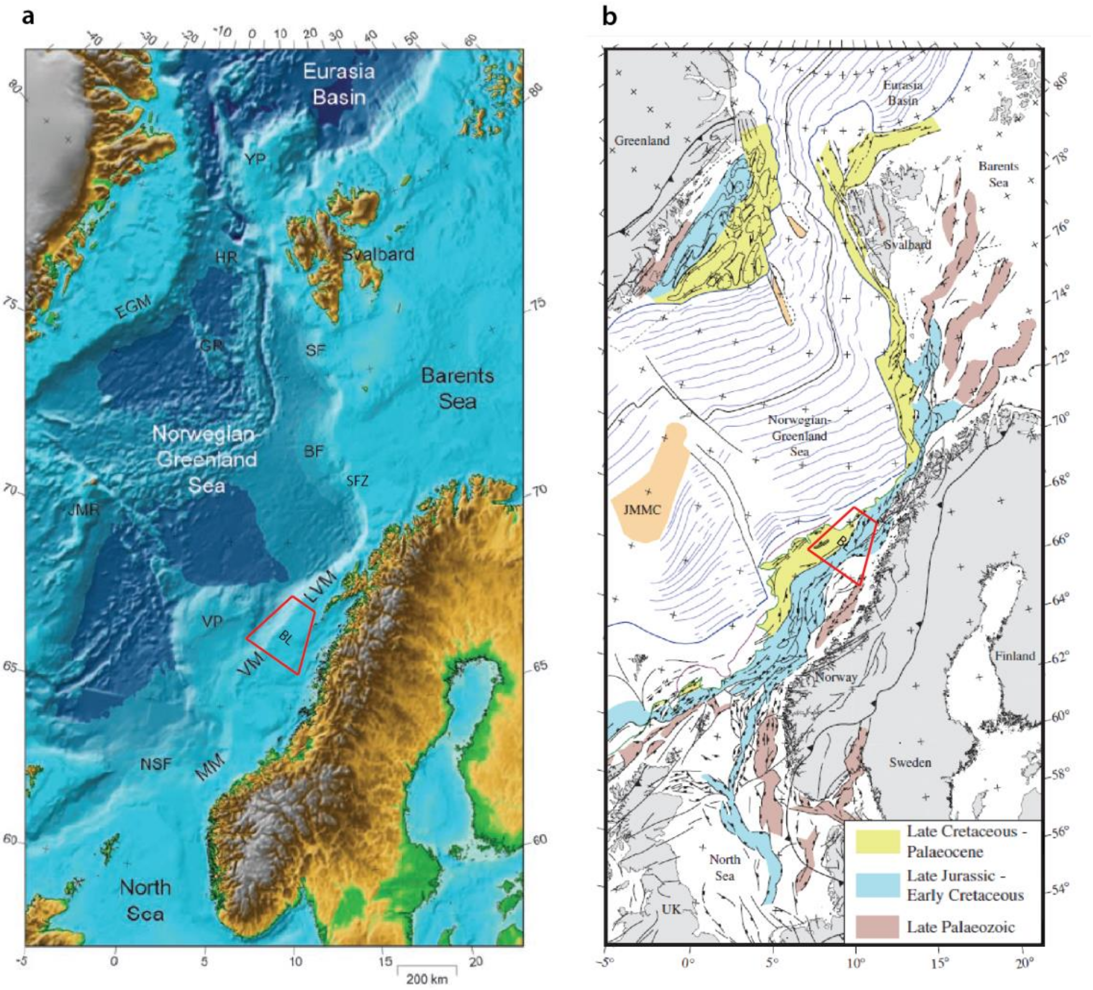


Fig. 1.1: (a) *Regional setting of the Norwegian continental margin. The location of the study area is marked with a red polygon. YP: Yermak Plateau, EGM: East Greenland Margin, HR: Hovgård Ridge, GR: Greenland Ridge, SF: Storfjorden Fan, BF: Bjørnøya Fan, JMR: Jan Mayen Ridge, LVM: Lofoten-Vesterålen Margin, VP: Vøring Plateau, VM: Vøring Margin, NSF: North Sea Fan, MM: Møre Margin, BL: Bivrost Lineament, SFZ: Senja Fracture Zone.* ***(b)*** *Main structural elements of the Norwegian continental shelf and adjacent areas. The structural elements are related to the main rift phases affecting the NE Atlantic region. JMMC: Jan Mayen micro-continent. Modified from Faleide et al. (2015).*

2 Geological framework

The conjugate margins off mid-Norway and East Greenland are underlain by Caledonian basement. Following the collapse of the Caledonides during Devonian time, the area was affected by several rift phases, until continental breakup at early Cenozoic and formation of the Norwegian-Greenland Sea (Faleide et al., 2008) (Fig. 2.1c). Rifting and initiation of sea-floor spreading during breakup at the Paleocene-Eocene transition (~55 Ma) was accompanied by igneous activity (Eldholm et al. 2002). Further widening and deepening led to increased accommodation, which allowed for sediment deposition and subsequent subsidence, and the formation of the Vøring passive volcanic and Lofoten-Vesterålen margins (Figs. 2.1a-b).

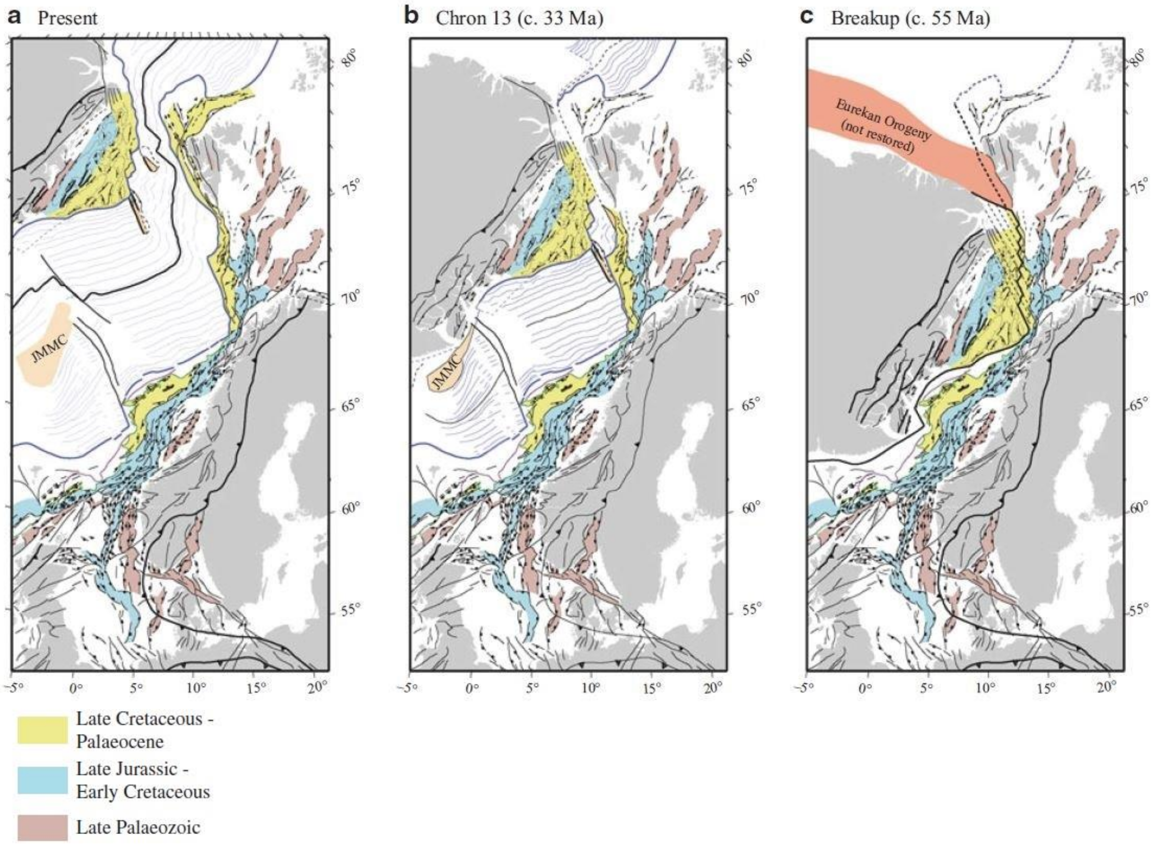


Fig. 2.1: *Plate tectonic reconstructions of the NE Atlantic (modified from Faleide et al. 2015).* ***(a)*** *Present,* ***(b)*** *~33 Ma,* ***(c)*** *~55 Ma, time of breakup. JMMC: Jan Mayen micro-continent.*

2.1 Northern Vøring margin

The Vøring passive volcanic margin is approximately 400 km long and 500 km wide. The northern Vøring margin (NVM) is defined as the northern part of the composite Vøring volcanic margin that is comprised of: the Vøring Marginal High, Vøring Basin, and the Trøndelag Platform (Blystad et al., 1995; Hjelstuen et al., 1999). NVM is bordered by the Surt Lineament in the south and the Bivrost Lineament in the north (Fig. 2.2). This study focuses mainly on the northern Vøring Basin, which can be divided into several highs and sub-basins: Træna Basin, Utgard High, Någrind Syncline, Nyk High, Hel Graben, and Naglfar Dome.

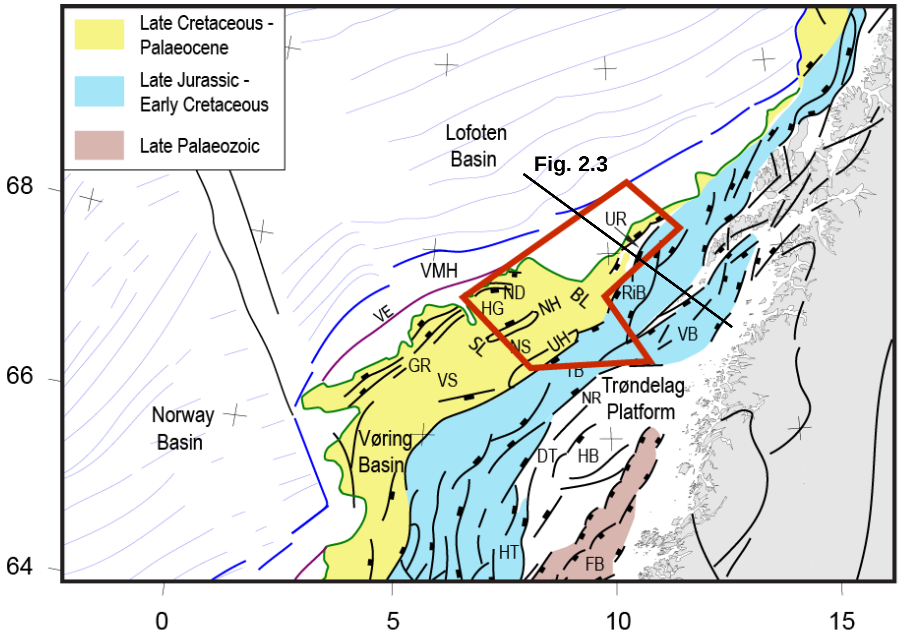


Fig. 2.2: *Main structural elements of the mid-Norwegian margin and adjacent areas (modified from Faleide et al. 2015). The red polygon represents the study area. BL: Bivrost Lineament, DT: Dønna Terrace, FB: Froan Basin, GR: Gjallar Ridge, HT: Halten Terrace, HB: Helgeland Basin, HG: Hel Graben, NH: Nyk High, NR: Nordland Ridge, NS: Någrind Syncline, RiB: Ribban Basin, TB: Træna Basin, UH: Utgard High, UR: Utrøst Ridge, VE: Vøring Escarpment, VB: Vestfjorden Basin, VMH: Vøring Marginal High, VS: Vigrid Syncline, SL: Surt Lineament, ND: Naglfar Dome.*

The northern Vøring margin experienced several rifting episodes since the end of the Caledonian Orogeny. Although the exact timing remains debated, it is believed that the main episodes occurred in Carboniferous-Permian, late Middle Jurassic-Early Cretaceous, and Late Cretaceous-early Cenozoic times (Mjelde et al., 2003; Ren et al., 2003; Faleide et al., 2008; Tsikalas et al., 2012).

During continental breakup at the late Paleocene-early Eocene transition, the northern Vøring margin together with the Vøring Basin experienced massive intrusive and extrusive activity (Mjelde et al., 2003; Ren et al., 2003). Following breakup, the margin subsided due to sediment loading and lithospheric thermal contraction during post-Paleocene sea-floor spreading, leading to a deepening of the Vøring Basin (Hjelstuen et al., 1997; Eldholm et al., 2002; Ren et al., 2003). Sedimentation was modest and the climate was generally cooling at post-breakup times. During late Pliocene and Pleistocene, uplift and glaciations followed, increasing the erosion and sedimentation (Ren et al., 2003). The present day margin configuration is the result of the combination of pre-breakup rifting and post-breakup regional subsidence, followed by uplift.

2.2 Southern Lofoten-Vesterålen margin

The Lofoten-Vesterålen margin (LVM) is a part of the Northeast Atlantic margin (Tsikalas et al., 2001; Hansen et al., 2012). It is located between the Vøring margin in the south and the shear-dominated SW Barents Sea margin in the north. The Lofoten-Vesterålen archipelago lies on the eastern side of the LVM. The margin exhibits a narrow continental shelf and a steep continental slope on the western side, with a margin width in the southern part of ~150 km and ~35 km in the northern part (Fig. 2.2) (Tasrianto and Escalona, 2015). Crustal thicknesses are varying, with a crustal thickness beneath the mainland of ~30 km (Fig. 2.3a). The crust beneath the shelf is ~26 km thick and thins beneath the Lofoten-Vesterålen islands, while the oceanic crust is ~6-7 km thick (Mjelde et al., 1993; Tsikalas et al., 2005a).

The exact timing of the rift phases that took place along the Lofoten-Vesterålen margin is difficult to determine, as a consequence of the sparse coverage of seismic data and lack of wells. There is, however, some agreement that the main rift phases occurred in Late Permian-earliest Triassic, Middle/Late Jurassic-Early Cretaceous, mid Cretaceous, and Late Cretaceous-Paleocene (Tsikalas et al., 2001; Eig and Bergh, 2011; Færseth, 2012; Hansen et al., 2012; Henstra and Rotevatn, 2014). The LVM commenced to develop as a passive continental margin during Eocene, following the continental breakup (Fig. 2.3b) (Hansen et al., 2012).

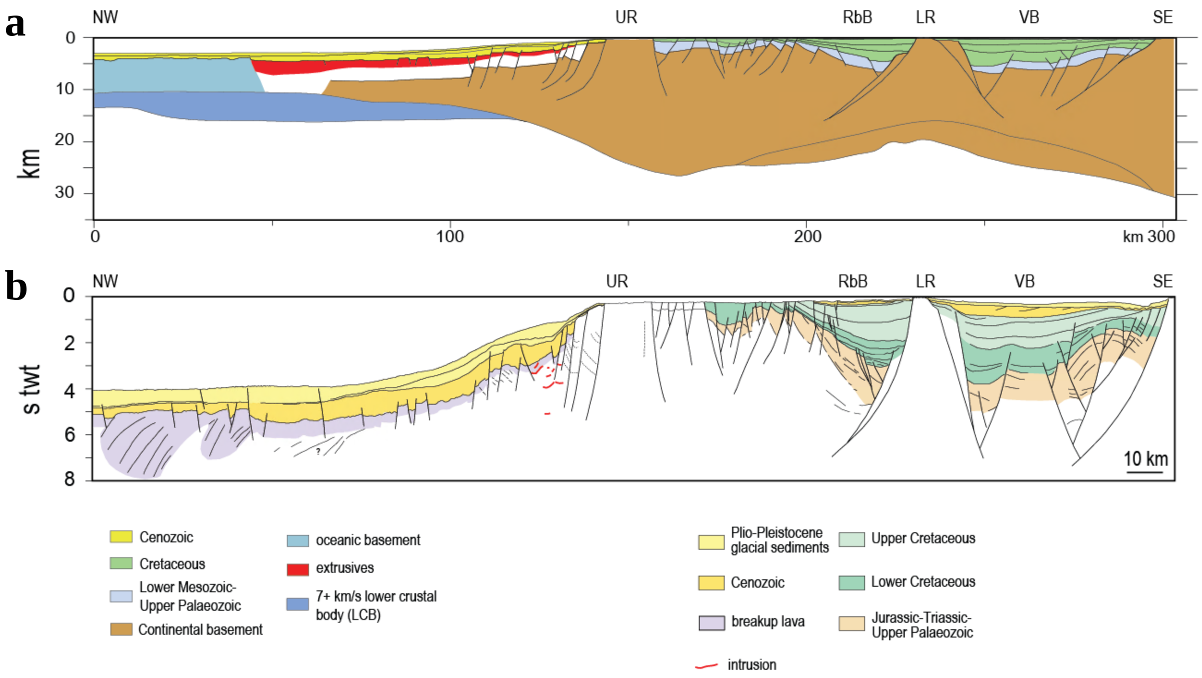


Fig. 2.3: ***(a)*** *Regional crustal transect across the Lofoten-Vesterålen margin,* ***(b)*** *Regional profile across the Lofoten-Vesterålen margin. See Fig. 2.2 for location of transect and profile. UR: Utrøst Ridge, RbB: Ribban Basin, LR: Lofoten Ridge, VB: Vestfjorden Basin. Modified from Faleide et al. (2015).*

Although there are several accounts and studies dealing with its segmentation, the Lofoten-Vesterålen margin can be divided into two main segments (from south to north): the Lofoten and Vesterålen segments (Hansen et al., 2012). The Lofoten segment is dominated by westward dipping faults, and includes the Lofoten islands and the part of the margin to the southwest. The Vesterålen segment is dominated by eastwards dipping faults, and includes the Vesterålen islands and the part of the margin to the northeast (Fig. 2.2).

The Lofoten-Vesterålen margin has a complex geological history, and there have been several attempts to account for the evolution of the area, mainly based on lateral segmentation along the margin:

- Tsikalas et al. (2001) divided the Lofoten-Vesterålen margin into segments by considering fault geometries, dip polarities and bounding transfer systems. The three segments were Lofoten, Vesterålen, and Andøya.
- Bergh et al. (2007) suggested some changes to the previous model by Tsikalas et al. (2001). A lateral segmentation was suggested as a result of temporal and spatial initiation of offshore faults related to the onshore fault-fracture evolution.
- Færseth (2012) suggested segmentation of the Lofoten-Vesterålen margin into two segments bounded by an accommodation zone.

- Tasrianto and Escalona (2015) supported the model of Tsikalas et al. (2001), although they suggested in addition a time transgressive segmentation from south to north, dividing the margin into the Southern Lofoten, Northern Lofoten and Vesterålen-Andøya segments.

2.3 Bivrost Lineament

The Bivrost Lineament is a highly debated structural element. Its exact location is uncertain, but it is defined as a lineament bounding the Lofoten-Vesterålen margin from the Vøring margin (Fig. 2.2). Blystad et al. (1995) described the Bivrost Lineament as a dextral shift in the top breakup lava boundary. The lineament has also been described as the shift between the wide and lower lying northern Vøring margin (NVM) and the more narrow and elevated Lofoten-Vesterålen margin (LVM). The transition between NVM and LVM shows a rather abrupt change in top crystalline crust depth from ~6 km on the Vøring margin to ~2 km on the Lofoten-Vesterålen margin (Mjelde et al., 1998; Tsikalas et al., 2005a).

There are, however, several additional definitions of the Bivrost Lineament. Olesen et al. (2002) suggested that the lineament most likely represents a folded detachment that is gently dipping 5-15° to the southwest. The same study, based mainly on aeromagnetic data, considered Bivrost as the possible offshore extension of the Nesna Shear Zone. Mjelde et al. (2003) suggested that the Bivrost Lineament could be a representation of an old weakness zone, which controlled the onset of Eocene spreading geometry. The same study further suggested that this weakness zone could have been periodically active since the collapse of the Caledonian Orogeny. Nevertheless, it is evident that the Bivrost Lineament marks a boundary, with deacreasing volcanic thicknesses to the north of it and deepening of the Moho southwards of the lineament (Mjelde et al., 2003).

2.4 Tectonic setting

A basement horst is exposed at the Lofoten-Vesterålen archipelago with surrounding asymmetric basins of Mesozoic-Cenozoic age (Fig. 2.3). The Lofoten-Vesterålen area has undergone several rifting events, with variable degree of extension and transtension (Eig and Bergh, 2011). Transtensional regions have shear zones where there is a presence of both extensive and shear slip structures, often including faults that have components of both shear types. These faults are called oblique faults, and are often observed with changing fault directions.

It has been postulated that three sets of fault systems are observed along the LVM:

- NNE-SSW trending normal and oblique-normal faults that were active during Permian-Jurassic and at the end of Early Cretaceous (Løseth and Tveten, 1996; Tsikalas et al., 2005a).
- ENE-WSW trending normal and oblique-normal faults that are thought to be formed as a consequence of reactivation of the previously existing faults during Late Cretaceous and Early Paleocene (Løseth and Tveten, 1996; Tsikalas et al., 2005a; Bergh et al., 2007; Henstra et al., 2015).
- NW-SE trending faults on the western side of the Lofoten Islands, which are less dominant than the other fault sets. According to Eig and Bergh (2011), these faults are the youngest, and were formed during Late Cretaceous and/or early Cenozoic. Although there are numerous faults and fractures, this set of faults is not well understood because of inadequate seismic data coverage (Eig and Bergh, 2011).

Several suggestions for the evolution of the above described fault system sets have been proposed. Bergh et al. (2007) suggested a time-progressive evolution, while Wilson et al. (2006) suggested that the dominating fault trends were the result of transtension or oblique-normal faulting. Hansen et al. (2012) suggested that the dominating fault sets were formed during synchronous Middle/Late Jurassic to Early Cretaceous tectonic activity.

2.5 Structural elements

Several main structural elements of the northern Vøring and southern Lofoten margins are located within the study area (Fig. 2.4). The following formal definitions of the structural elements are based on the work of Blystad et al. (1995) and seismic observations. Locations of all structural elements described in this section can be seen in Fig. 2.4.

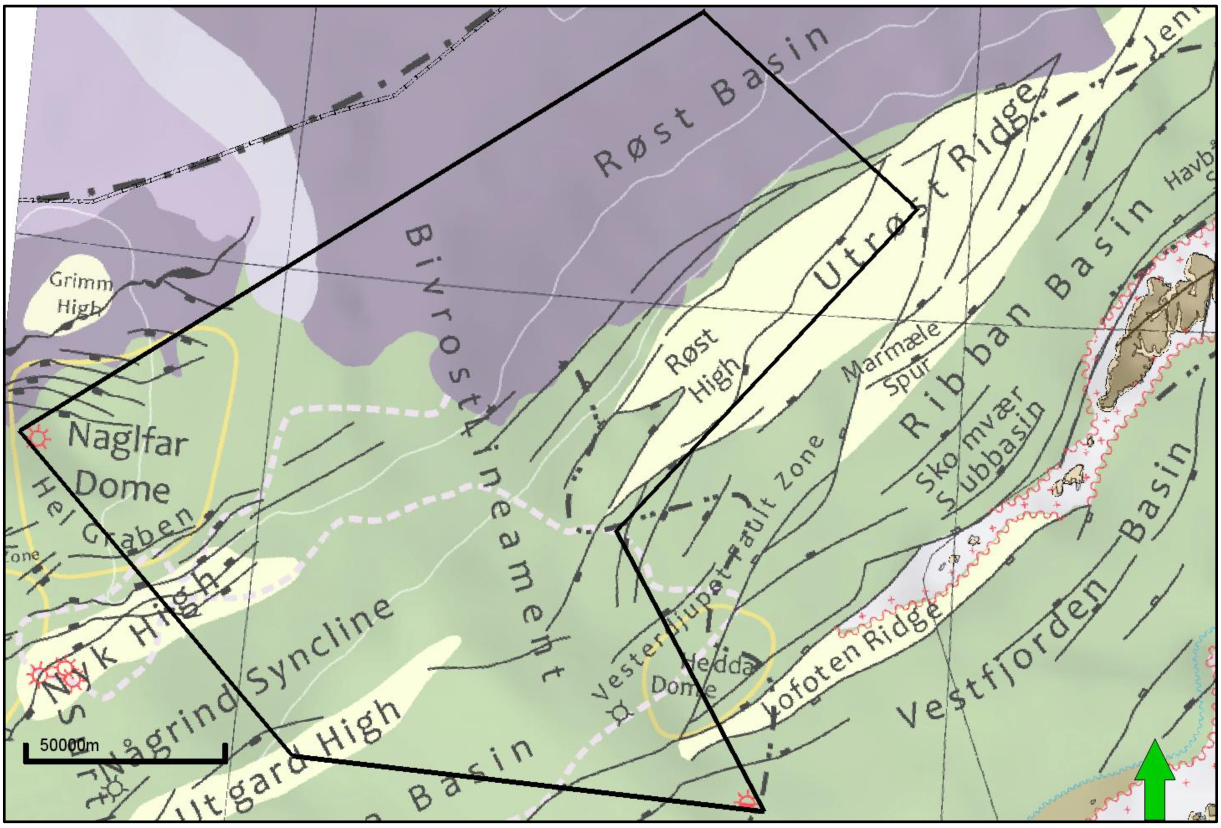


Fig. 2.4: Main structural elements on the southern Lofoten-Vesterålen margin and the northern Vøring margin (modified from Blystad et al. 1995). The study area is defined by the black polygon.

Hel Graben

The Hel Graben is located within the northwestern part of the Vøring margin and south of the Naglfar Dome. It has a, more or less, curved shape and NW-NE trend, and is bounded in the south by the Nyk High. The age of Hel Graben is probably Early to Late Cretaceous. There is, however, an ongoing debate concerning Paleocene rifting in the Hel Graben.

Naglfar Dome

The Naglfar Dome is located within the Hel Graben, and follows the underlying outline of the graben. The axis of the dome has a N-S trend, and several sedimentary sequences onlap the sides of the structure. The dome is truncated on top by a thin Pliocene succession. Its age is most likely Eocene to Pliocene.

Nyk High

The Nyk High is located south of Naglfar Dome and Hel Graben. It is a NE-SW trending high, with length of about 70 km and width of 15-20 km. The Nyk High is a relatively shallow structure, and is covered only by few hundred meters of late Cenozoic sediments in some places. The present Nyk High is probably of Late Cretaceous to early Cenozoic age.

Någrind Syncline

The Någrind Syncline is bounded by the Utgard and Nyk highs in southeast and northwest, respectively. It is also bounded by the Bivrost Lineament at northeast and the Surt Lineament at southwest. The syncline has a NE-SW trend, and its northern continuation and spatial termination are debated. The present Någrind Syncline is most likely of Late Cretaceous to early Cenozoic age.

Røst Basin

The Røst Basin is located between the Utrøst Ridge in the southeast and the Lofoten Basin in the northwest. It contains thick Cenozoic sequences, reaching up to several hundred meters in thickness.

Røst High

The Røst High is located at the southwestern side of the Utrøst Ridge, with a NE-SW trend. It coincides with strong anomalies on gravimetric and magnetic anomaly maps, indicating a basement high with a very thin sediment cover above it. The Røst High is considered as part of the composite Utrøst Ridge, and is bounded by large basement faults on all sides. The present high is dominated by erosional features, which makes its exact age dating difficult. However, the present day configuration of the high is most likely of Late Cretaceous to early Cenozoic age.

Træna Basin

The Træna Basin is located southeast of the Utgard High, and is an elongated basin with a NE-SW trend. The basin is bounded by the Vesterdjupet Fault Zone in the northeast, with the northward continuation of the basin bounded by the Utrøst Ridge. Its age is probably Middle Jurassic to Early Cretaceous.

Utgard High

The Utgard High is located between the Någrind Syncline in the northwest and the Træna Basin in the southeast. It is also bounded by the Bivrost Lineament in northeast and the Surt Lineament in southwest. It has a length of ~100 km, a width of ~10-15 km and a NE-SW trend. The Utgard High coincides with strong anomalies on gravimetric and magnetic anomaly maps, indicating a basement high with a very thin sediment cover above it. The Utgard High is most likely of Late Cretaceous to early Cenozoic age.

Utrøst Ridge

The Utrøst Ridge is located between the Røst Basin in the northwest and the Ribban Basin in the east. The ridge consists of three adjacent highs: Røst High, Marmæle Spur, and Jennegga High. The Utrøst Ridge has a NE-SW trend, and coincides with strong anomalies on gravimetric and magnetic anomaly maps, indicating a basement high with a very thin sediment cover above it. Like the Røst High, the Utrøst Ridge is dominated by erosion, which makes its exact age dating difficult. The present day configuration of the high is most likely of Late Cretaceous to Early Cenozoic age.

2.6 Stratigraphic framework

Pre-Cretaceous

Most of the NVM and LVM area has been for long time an elevated region, where only thin Triassic and Jurassic sediments were deposited (Mjelde et al., 1998; NPD, 2010; Henstra et al., 2015). The Triassic sequences consist mainly of sandstones and conglomerates (Hansen et al., 2012; Tasrianto and Escalona, 2015). The Late Triassic sequences are mainly interpreted as continental sequences, representing proximal alluvial fan deposits. These were deposited in a dry climate, consisting of some fine grained material which is cut by sandy channels (NPD, 2010). Towards the end of Late Triassic, the climate became more arid, and the sediments were more influenced by marine processes.

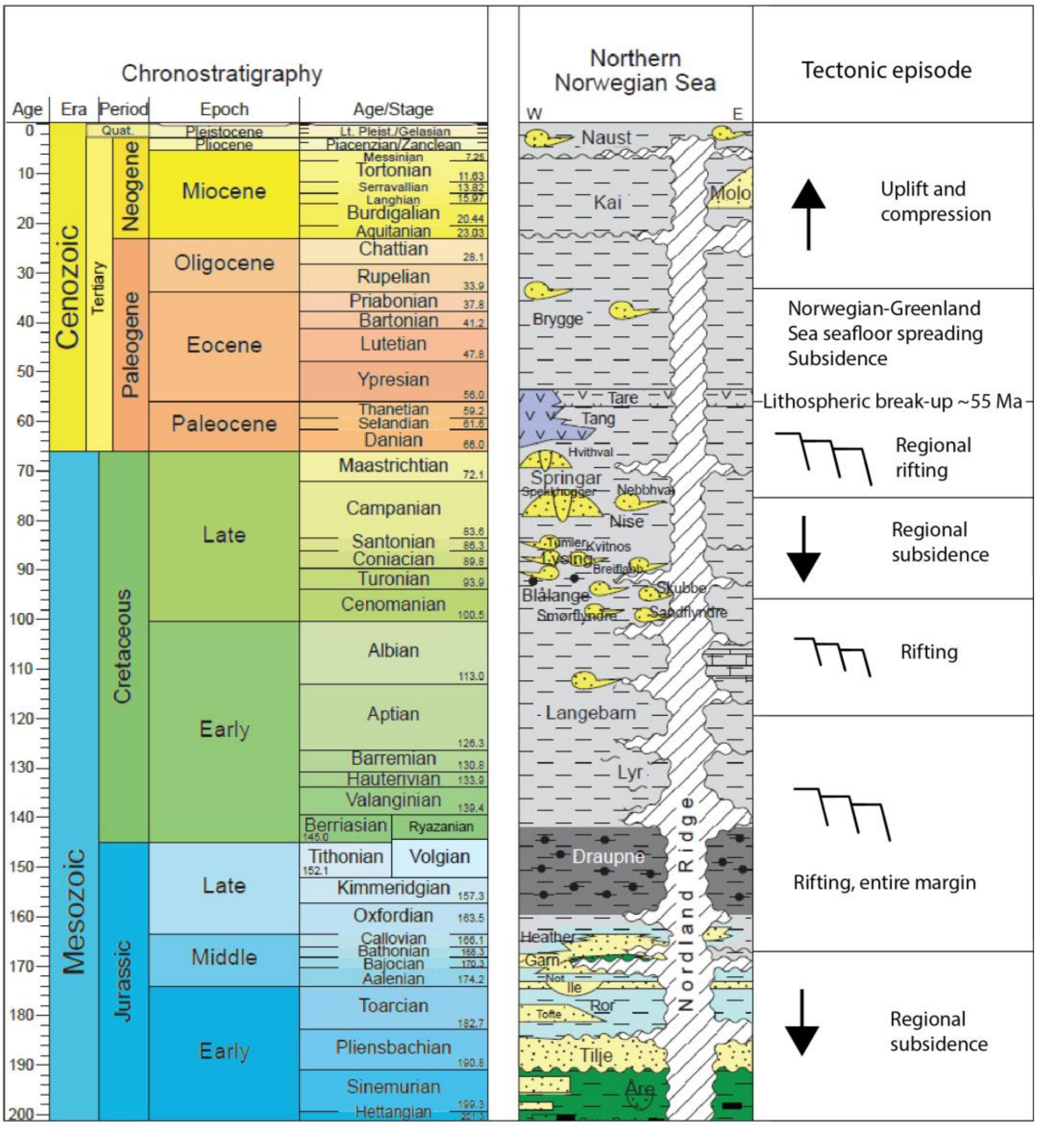


Fig. 2.5: *Chronostratigraphic and lithostratigraphic charts of the Northern Norwegian Sea (modified from Norlex, 2012 and Tsikalas et al., 2012).*

Sandstones were deposited in the Early and Middle Jurassic (Fig. 2.5) (NPD, 2010; Hansen et al., 2012; Tasrianto and Escalona, 2015). These Jurassic sandstones represent one of the most important reservoir rocks on the Norwegian continental shelf (NCS), and usually have high porosities and good permeability. According to NPD (2010), the Jurassic reservoir sandstones in the Lofoten-Vesterålen area are mainly younger than the ones deposited in the Norwegian Sea area. This is because there was not enough accommodation space for sediment deposition on the elevated LVM area until the Middle-Late Jurassic transgression. The oldest Jurassic sandstones represent shallow marine and deltaic deposits (Hansen et al., 2012), with sandstones being covered by clays deposited during the Middle-Late Jurassic transgression, thus altering the depositional conditions towards a shelf depositional environment. Some of the Upper Jurassic claystones are several hundred meters thick and contain a large amount of total organic carbon (TOC). These represent some of the most important source rocks in the NCS (NPD, 2010). As seen in Fig. 2.3b, the Upper Paleozoic to Jurassic sedimentary strata are thicker in the deeper parts of the Vøring and Ribban basins, and thin out towards the Lofoten and Utrøst ridges.

Lower Cretaceous

Some subsidence of the Lofoten-Vesterålen area occurred during Late Jurassic, although the main subsidence phase took place during Early Cretaceous, along with the main infill of sediments in the extensional basins. Marine claystones and siltstones are the main deposits (Fig. 2.5) (Tasrianto and Escalona, 2015). Erosion occurred on the highs at the same time as subsidence took place in the basins. According to NPD (2010), parts of the basement and sedimentary rocks have been eroded during this period. The latter is assumed because uplifted fault blocks show a distinct erosional shape.

Upper Cretaceous

The Upper Cretaceous sedimentary succession is hundreds of meters thick at the Lofoten-Vesterålen margin, and consists mainly of claystones and siltstones (Fig. 2.5) (NPD, 2010; Hansen et al., 2012). According to Hansen et al. (2012), the Upper Cretaceous sequence represents outer shelf deposits, also containing some sandstones. There is lack of seismic evidence of the presence of the sequence in the northern Lofoten segment. Late Cretaceous was characterized by considerable tectonic activity and uplift. Seismic surveys show uplift of the Utrøst Ridge between Early and Late Cretaceous (NPD, 2010). This is indicated by the pinching out of the Upper Cretaceous sedimentary sequence towards the Utrøst Ridge (Fig. 2.3b). The top of the Upper Cretaceous sequence is marked by the Base Tertiary Unconformity (BTU).

Cenozoic

The Paleogene succession contains sandstones and claystones in shallowing upward sequences (Fig. 2.5) (Hansen et al., 2012; Tasrianto and Escalona, 2015). According to Hansen et al. (2012), these sequences contain upper slope to inner shelf deposits and can be found in the Vøring and Ribban basins, and they are sourced from the elevated Utrøst Ridge

(Fig. 2.3). Plio-Pleistocene glacial sediments overlie the Paleogene successions and are much thicker in the western part of LVM (Fig. 2.3) (Faleide et al., 2015).

2.7 Nordland VI: oil and gas exploration

The study area of the thesis is mainly located within Nordland VI, containing well 6710/10-1. In addition, wells 6610/3-1 R2 and 6608/2-1 ST2 from Nordland III, and well 6706/6-1 from Vøringbassenget I lie in the near proximity. Nordland VI is an oil and gas exploration area/province in the Norwegian Sea, located southwest of the Lofoten archipelago. It has significant exploration potential, and is believed to be the area with the highest yet-to-find prospect resources in the northern Norwegian Sea. The Norwegian Petroleum Directorate (NPD) estimated in 2010 the mean total recoverable hydrocarbon resources potential of the area to be 76 million Sm^3 (~478 Mboe).

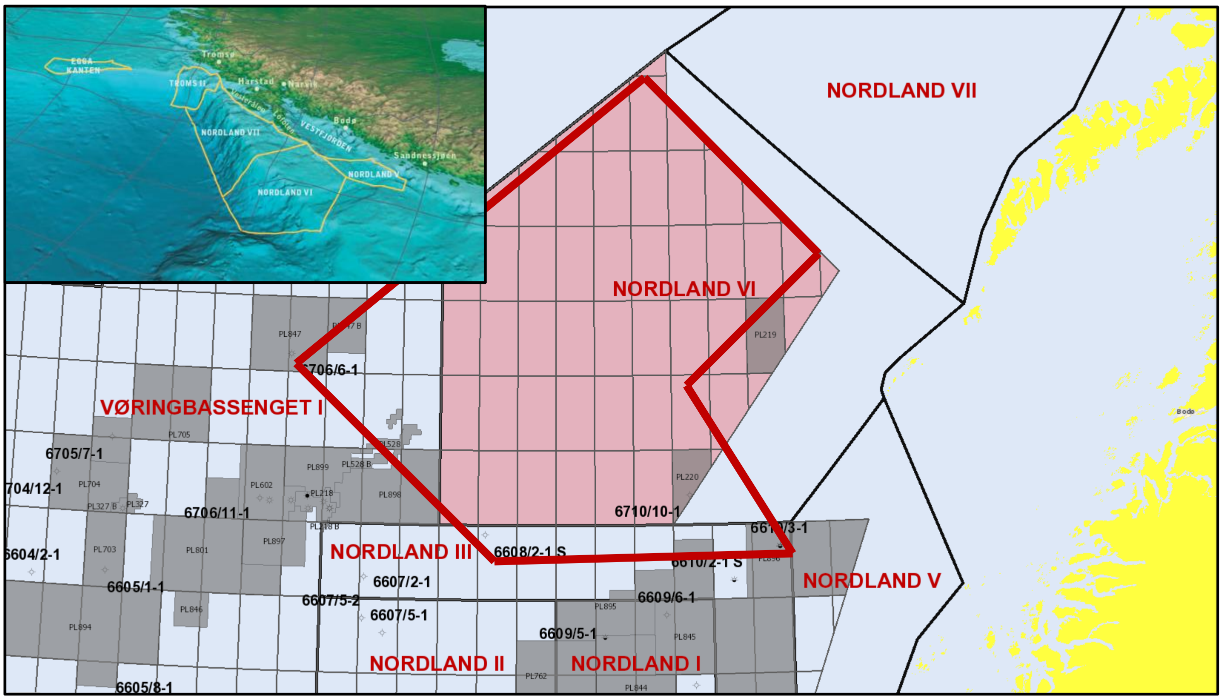


Fig. 2.6: Oil and gas exploration areas and wells on the Lofoten-Vesterålen and northern Vøring margins (map retrieved from NPD, 2017a). The pink raster indicates that Nordland VI is not currently open for exploration. Red polygon represents the study area. Inset: bathymetry data depicting the margin morphology (NPD, 2010).

Nordland VI was opened for exploration in 1994 after a comprehensive environmental impact assessment, and well 6710/10-1 was drilled in 2001 (resulted dry) as the first well in the area (NPD, 2010). The Lower-Middle Jurassic play is considered the one with the highest potential for success. Upper Jurassic claystones are the most important source rock, while Lower-Middle Jurassic sandstones are considered the most likely reservoir rocks. Most of the traps are structural, including rotated fault blocks and dome structures. The exploration model does, however, have some critical elements: leakage from traps and the degree of erosion of the large fault blocks (NPD, 2010). In addition, the limited number of exploration wells makes the area and its geologic understanding to be associated with large uncertainties.

Drilling activity in Nordland VI was stopped in 2001, after complaints from environmental organisations that raised heated debates. The area remains closed for petroleum exploration, and currently renewed discussions on the matter have raised a highly heated and controversial debate in Norwegian politics.

3 Data

3.1 Seismic reflection data

The seismic database of the study comprises approximately 9100 km of conventional 2D multi-channel seismic reflection profiles (MCS) (Fig. 3.1 and Table 3.1). The coverage of 2D MCS profiles in the study area is rather sparse compared to other areas on the Norwegian continental shelf (NCS), with an average profile line-spacing of 3-5 km. The most dense coverage of MCS profiles is south of the Røst High and the unquestionably most sparse coverage exists in the Røst Basin (Fig. 3.1).

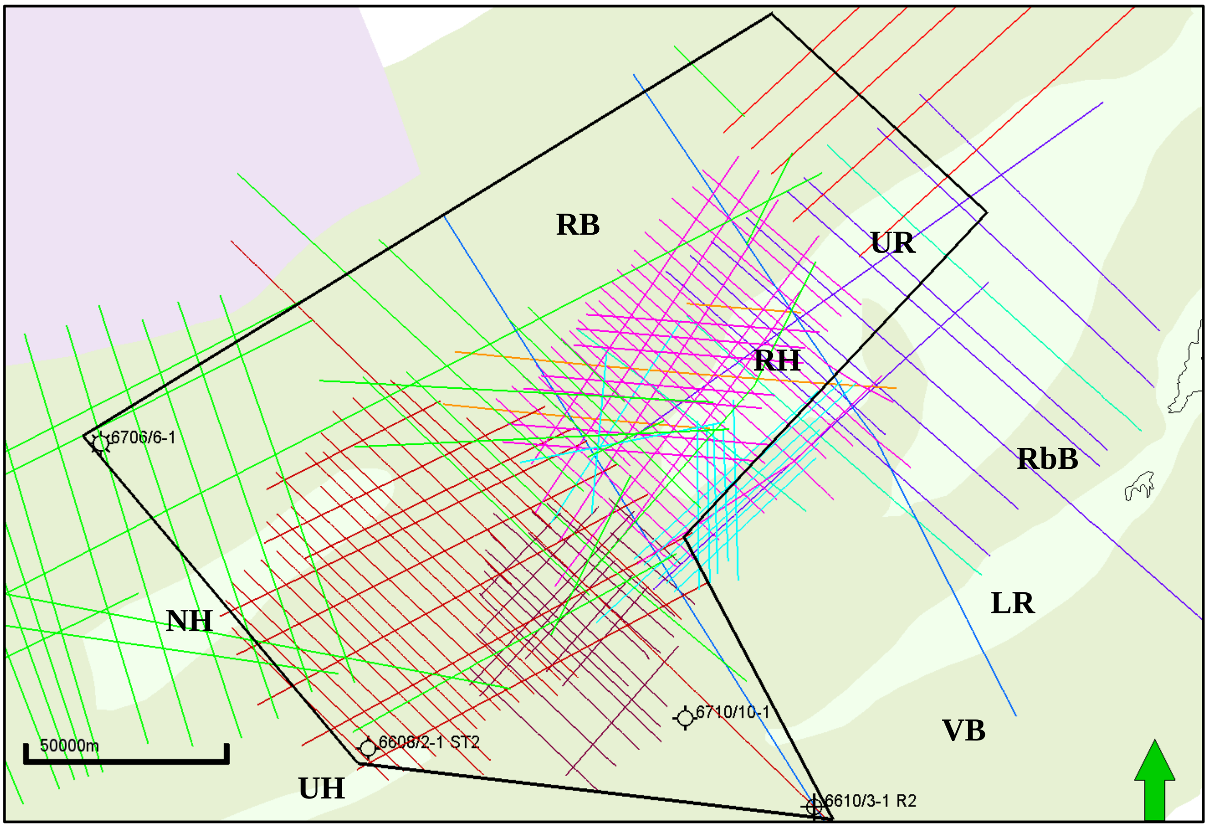


Fig. 3.1: *Total coverage of conventional multi-channel seismic reflection profiles (MCS) and location of wells within the study area (black polygon). NH: Nyk High, UH: Utgard High, RH: Røst High, UR: Utrøst Ridge, RB: Røst Basin, RbB: Ribban Basin, LR: Lofoten Ridge, VB: Vestfjorden Basin.*

Table 3.1: *Seismic reflection surveys that are utilized in this study.*

Survey name	**Year**	**Company/authority**	**Recording time (TWT, s)**	**Resolution quality**
LO-86	1986	NPD	7	Moderate
LO-87	1987	NPD	7	Moderate
LO-88	1988	NPD	6	Moderate
LO-08	2008	NPD	8	Poor
AMR-N6T	1992	TGS	8	Moderate to good
GMNR-94	1994	Geco	14	Good
AMR_TBN96	1996	TGS	8	Good
AMR_RHW96	1996	TGS	8	Good
LIVB89	1989	NPD	8	Good
RHS98	1998	Geoteam Exploration	8	Moderate to good

The resolution quality in the different seismic surveys is variable (Table 3.1). Resolution ranges from poor to good, and the recording time of the various surveys range between 6-14 s TWT (two-way travel-time). The northern part of the study area shows lowest resolution with depth, possibly because of shallow water depths that increase the presence of seismic artefacts. This makes it very difficult to interpret the basement configuration and the deepest sequences, and thus only the upper sequences have been mapped in this area. Sea-bottom multiples and other artefacts can be seen on most of the 2D MCS profiles in the study area, and mostly in the vintage LO-survey profiles. The GMNR-94 and AMR_RHW96 profiles display the best resolution with depth. Diffractions can, however, be seen in the GMNR-94 and LIVB89 profiles across the study area.

3.2 Well data

Four exploration wells located within the study area have been used in the study (Fig. 3.1 and Table 3.2). Although located far from each other, the wells provide good stratigraphic control points. However, the main problem is exactly the fact that the wells are located far apart from each other. This limits the extrapolation of the well-to-seismic ties to the interpretations of seismic sequences, which in turn leads to uncertainties in age constraints. Nevertheless, the available wells have been used to define the best possible well-to-seismic ties and correlation, although the confidence of age constraints is naturally somewhat reduced.

Table 3.2: *Table of wells that are utilized in this study.*

Well name	**Completion year**	**Location**	**Type**	**Operator**	**Coordinates (UTM zone: 32)**
6608/2-1 ST2	2013	Utgard High	Exploration	RWE Dea	x: 212016.56 m y: 7443371.84 m
6706/6-1	2003	Naglfar Dome	Exploration	Esso	x: 146807.56 m y: 7517697.35 m
6610/3-1 R2	1996	Vestfjorden Basin	Exploration	Statoil	x: 320851.84 m y: 7429098.06 m
6710/10-1	2013	Vesterdjupet Fault Zone	Exploration	Statoil	x: 289382.83 m y: 7450687.1 m

Available well-tops are provided in true vertical depth sub-sea (TVDSS, meters) (NPD, 2017b). Interval velocity information (Table 3.3) and well-logs were used to calculate depth-TWT conversions. These were used to constrain the necessary well-to-seismic ties in the 2D seismic profiles.

Table 3.3: *Interval velocities (km/s) based on stacking velocities from seismic data processing and well data (continental shelf part) used for depth-TWT conversions (Tsikalas et al., 2005a).*

Sequence/unit	**Interval velocity (km/s)**
Water	1.46
Plio-Pleistocene glacial sediments	1.80-1.85
Tertiary	2.45
Upper Cretaceous	2.70-2.80
Lower Cretaceous	3.75-3.80

3.3 Potential field anomaly data

Gravity and magnetic data were available for this study (Fig. 3.2). Gravimetric anomalies represent differences between the observed gravity value and the theoretically calculated value at a given point on Earth, and these are related to lateral density variations. Negative anomalies indicate light densities like sedimentary layers, while positive anomalies indicate dense rocks. Magnetic anomalies are local variations in the Earth’s magnetic field, as a result of differences in rock magnetism and chemistry (Olesen et al., 2010).

Potential field anomaly data can often provide information in areas with a lack of seismic data, making it a useful tool when identifying basement highs and sedimentary basins. Basement highs with a thin sedimentary cover often appear as strong positive anomalies, while negative anomalies most often represent sediment-filled basins. Gravity and magnetic anomaly data were generally used affirmatively in this study, as a tool to confirm structural trends, identified basement highs, and lateral distribution of faults in areas where the seismic coverage is sparse. In addition, in few cases the potential field data have been used to locally guide seismic interpretation and to constrain interpolation and extrapolation of defined faults.

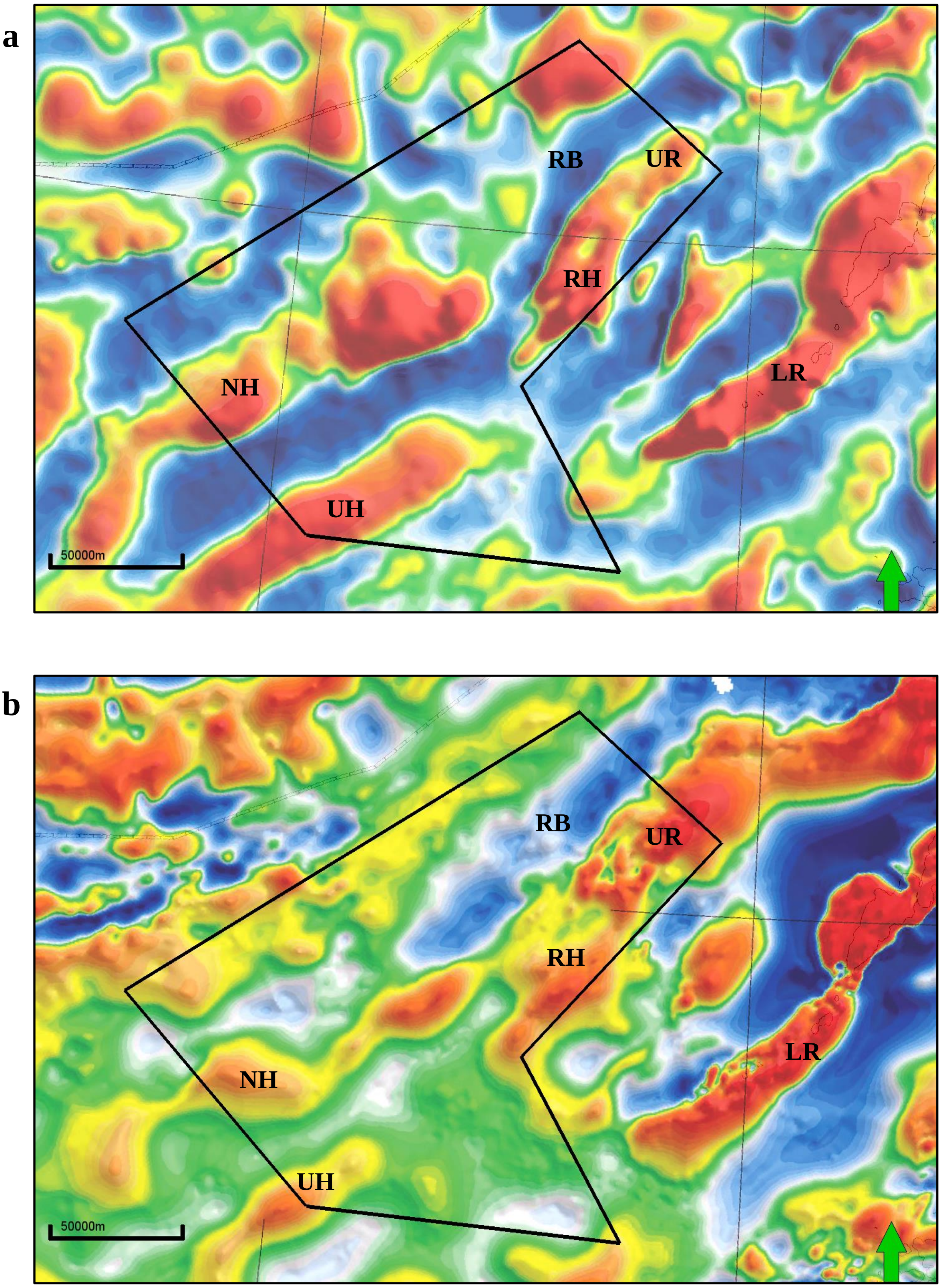


Fig. 3.2: (a) *50 km high-pass filtered gravity anomaly data.* ***(b)*** *100 km high-pass filtered magnetic anomaly data. Black polygon marks the study area. Gravity and magnetic data courtesy of TGS. Red indicates strong positive anomalies, while blue indicates strong negative anomalies. NH: Nyk High, UH: Utgard High, RH: Røst High, UR: Utrøst Ridge, RB: Røst Basin, LR: Lofoten Ridge.*

4 Seismic and structural interpretation

4.1 Workflow and approach

The Schlumberger software Petrel was used as the interpretation tool in this study. The primary objective was to get a better understanding of the evolution of the southern Lofoten and northern Vøring margins. This was done by mapping seven (eight including the seabed) main horizons (Table 4.1, Fig. 4.1). Mapping of the Base Cretaceous Unconformity (BCU) provided the outline of the Late Jurassic-earliest Cretaceous structural elements in the study area, while mapping of the Top Cenomanian horizon provided the mid Cretaceous basin configuration and allowed for time constraints when mapping faults mainly in the western part of the study area. Additionally, five Cenozoic horizons were mapped in order to decipher the tectono-stratigraphic evolution of the study area, and especially the outer Lofoten margin west of the landward breakup lava boundary.

Time-structure surfaces and time-thickness maps were generated to get a better understanding of the lateral and vertical configuration of the stratigraphic sequences, as well as to visualise the tectono-stratigraphic evolution. Faults were mapped in order to gain a better knowledge of the structural development in the study area. Potential field anomaly data have been used to identify structural trends and elements, and to confirm the lateral extent of faults where coverage of 2D MCS profiles was inadequate or lacking.

4.2 Well correlation

The study area, and especially the Lofoten-Vesterålen margin, contains a limited amount of exploration wells and shallow stratigraphic coreholes. In addition, poor seismic coverage and locally poor resolution combined with structural complexity makes the interpretation challenging, and causes large uncertainties when trying to provide precise age constraints. The utilised exploration wells summarized in Table 3.2 were used to provide well-to-seismic ties for the seven horizons that were mapped in detail across the study area (Figs. 4.2-4.5).

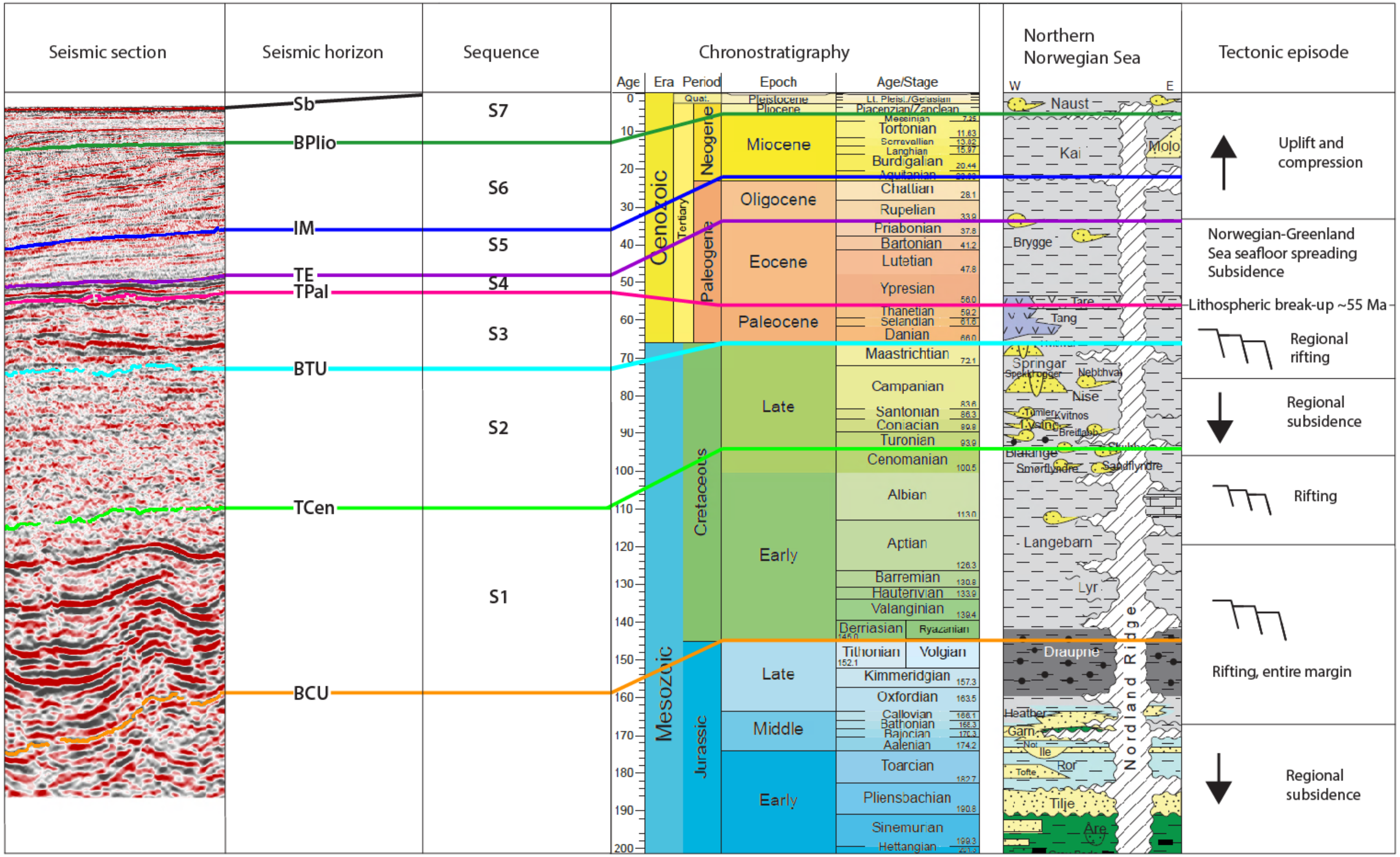
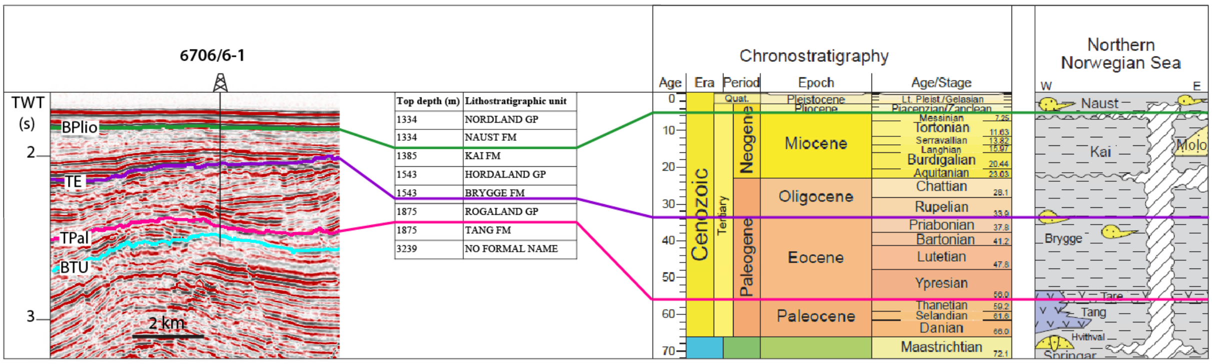


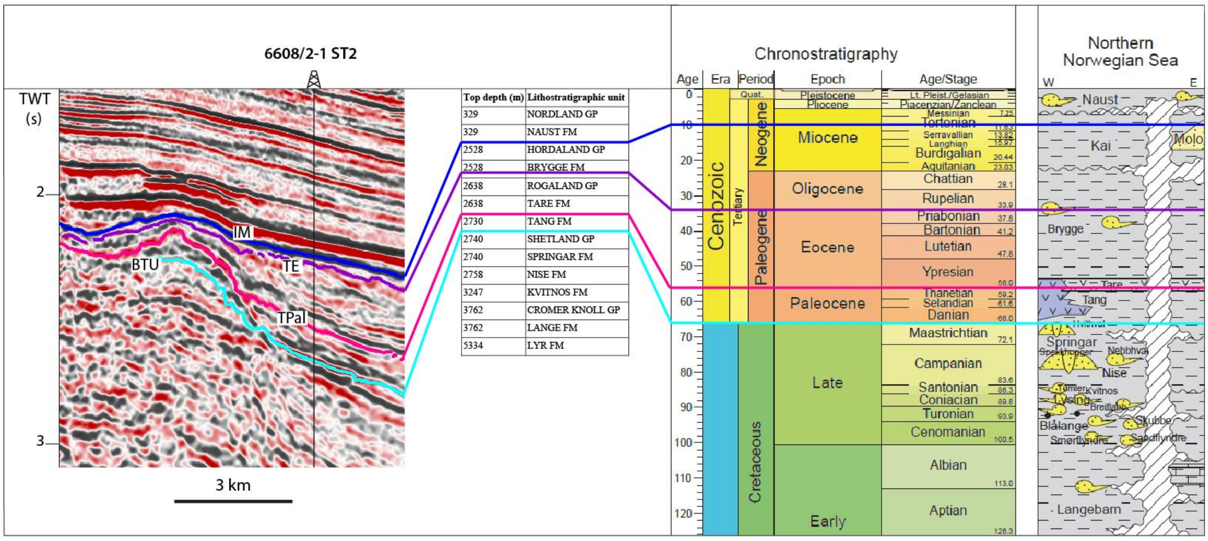
Fig. 4.1: *Seismic stratigraphic framework for the southern Lofoten and northern Vøring margins. Seven (eight including the seabed) interpreted horizons bound seven seismic sequences. Sb: sea bottom, BPlio: Base Plio-Pleistocene, IM: Intra Miocene, TE: Top Eocene, TPal: Top Paleocene, BTU: Base Tertiary Unconformity, TCen: Top Cenomanian, BCU: Base Cretaceous Unconformity. Chronostratigraphic and lithostratigraphic charts of the Northern Norwegian Sea modified from Norlex (2012), tectonic episodes based on Tsikalas et al. (2012).*

The interval velocities based on stacking velocities from seismic data processing and well data displayed in Table 3.3 were used in conversions from depth in meters to TWT in milliseconds. These were then used in the well-to-seismic ties to pick the TWT reflector/formation-top when interpreting the 2D seismic profiles. Earlier interpretations in the vicinity of the study area by Hjelstuen et al. (1999), Tsikalas et al. (2001), Ren et al. (2003), NPD (2010), Henstra et al. (2015), Wilhelmsen (2016), in addition to shallow IKU boreholes have been used as reference and guidance.



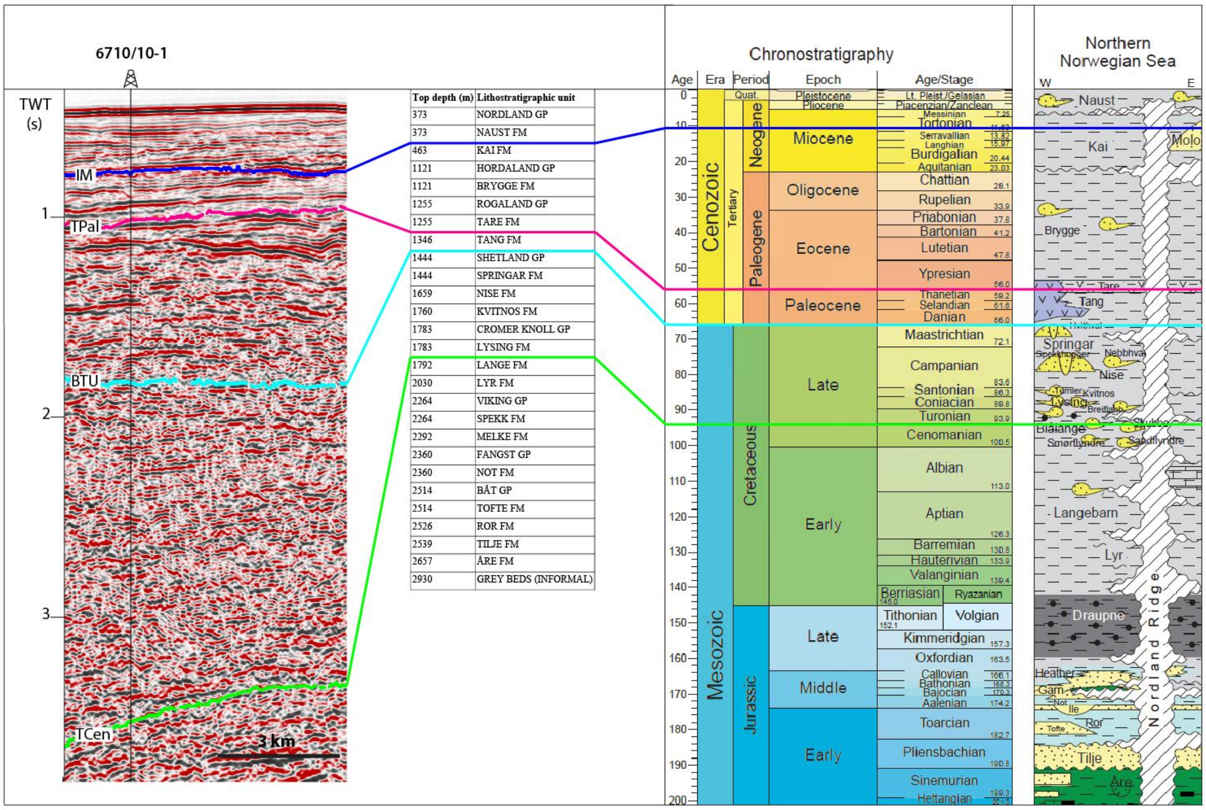
Top depth (m)	Lithostratigraphic unit
1334	NORDLAND GP
1334	NAUST FM
1385	KAI FM
1543	HORDALAND GP
1543	BRYGGE FM
1875	ROGALAND GP
1875	TANG FM
3239	NO FORMAL NAME

Fig. 4.2: *Well-to-seismic tie of exploration well 6706/6-1 (seismic panel from profile LIVB9-89). Lithostratigraphic charts from NPD and Norlex have been used to tie interpreted horizons to formations and geological ages. See Fig. 3.1 for well location and Fig. 4.1 for stratigraphic framework.*



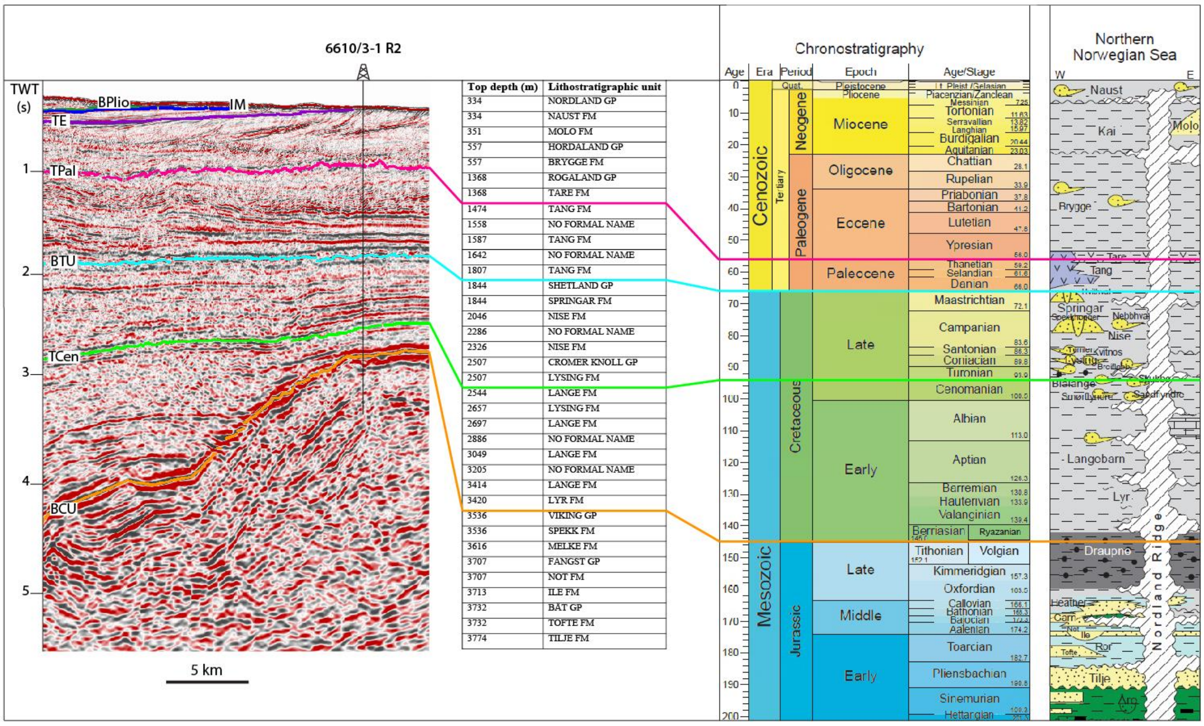
Top depth (m)	Lithostratigraphic unit
329	NORDLAND GP
329	NAUST FM
2528	HORDALAND GP
2528	BRYGGE FM
2638	ROGALAND GP
2638	TARE FM
2730	TANG FM
2740	SHETLAND GP
2740	SPRINGAR FM
2758	NISE FM
3247	KVITNOS FM
3762	CROMER KNOLL GP
3762	LANGE FM
5334	LYR FM

Fig. 4.3: *Well-to-seismic tie of exploration well 6608/2-1 ST2 (seismic panel from profile AMR_TBN96-102). Lithostratigraphic charts from NPD and Norlex have been used to tie interpreted horizons to formations and geological ages. See Fig. 3.1 for well location and Fig. 4.1 for stratigraphic framework.*



Top depth (m)	Lithostratigraphic unit
373	NORDLAND GP
373	NAUST FM
463	KAI FM
1121	HORDALAND GP
1121	BRYGGE FM
1255	ROGALAND GP
1255	TARE FM
1346	TANG FM
1444	SHETLAND GP
1444	SPRINGAR FM
1659	NISE FM
1760	KVITNOS FM
1783	CROMER KNOLL GP
1783	LYSING FM
1792	LANGE FM
2030	LYR FM
2264	VIKING GP
2264	SPEKK FM
2292	MELKE FM
2360	FANGST GP
2360	NOT FM
2514	BÅT GP
2514	TOFTE FM
2526	ROR FM
2539	TILJE FM
2657	ÅRE FM
2930	GREY BEDS (INFORMAL)

Fig. 4.4: *Well-to-seismic tie of exploration well 6710/10-1 (seismic panel from profile N6-92R00-121). Lithostratigraphic charts from NPD and Norlex have been used to tie interpreted horizons to formations and geological ages. See Fig. 3.1 for well location and Fig. 4.1 for stratigraphic framework.*



Top depth (m)	Lithostratigraphic unit
334	NORDLAND GP
334	NAUST FM
351	MOLO FM
557	HORDALAND GP
557	BRYGGE FM
1368	ROGALAND GP
1368	TARE FM
1474	TANG FM
1558	NO FORMAL NAME
1587	TANG FM
1642	NO FORMAL NAME
1807	TANG FM
1844	SHETLAND GP
1844	SPRINGAR FM
2046	NISE FM
2286	NO FORMAL NAME
2326	NISE FM
2507	CROMER KNOLL GP
2507	LYSING FM
2544	LANGE FM
2657	LYSING FM
2697	LANGE FM
2886	NO FORMAL NAME
3049	LANGE FM
3205	NO FORMAL NAME
3414	LANGE FM
3420	LYR FM
3536	VIKING GP
3536	SPEKK FM
3616	MELKE FM
3707	FANGST GP
3707	NOT FM
3713	ILE FM
3732	BÅT GP
3732	TOFTE FM
3774	TILJE FM

Fig. 4.5: *Well-to-seismic tie of exploration well 6610/3-1 R2 (seismic panel from profile AMR_TBN96-115). Lithostratigraphic charts from NPD and Norlex have been used to tie interpreted horizons to formations and geological ages. See Fig. 3.1 for well location and Fig. 4.1 for stratigraphic framework.*

4.3 Interpreted key horizons/reflectors and sequences

Correlation with the exploration wells described above was the basis for the stratigraphic framework, which enabled a detailed seismic interpretation. The interpreted horizons are summarized in Table 4.1 and in Fig. 4.1. The well-to-seismic correlations for the wells in Table 3.2 are seen in Figures 4.6-4.9.

Table 4.1: *Summary of mapped horizons/reflectors in the study area.*

Reflector	**Abbreviation**	**Seismic reflection character**	**Well tie**
Base Plio-Pleistocene	BPlio	Continuous reflector, high amplitude	6706/6-1
Intra Miocene	IM	Continuous reflector, high amplitude	6608/2-1 ST2, 6710/10-1
Top Eocene	TE	Semi-continuous reflector, high amplitude	6706/6-1, 6608/2-1 ST2
Top Paleocene	TPal	Semi-continuous to continuous reflector, high amplitude	6706/7-1, 6608/2-1 ST2, 6610/3-1 R2, 6710/10-1
Base Tertiary Unconformity	BTU	Discontinuous reflector, low to medium amplitude	6608/2-1 ST2, 6610/3-1 R2, 6710/10-1
Top Cenomanian	TCen	Semi-continuous reflector with a low to medium amplitude strength, although higher amplitude in fault blocks	6610/3-1 R2, 6710/10-1
Base Cretaceous Unconformity	BCU	Regional erosional unconformity, semi-continuous reflector with medium to strong amplitude	6610/3-1 R2

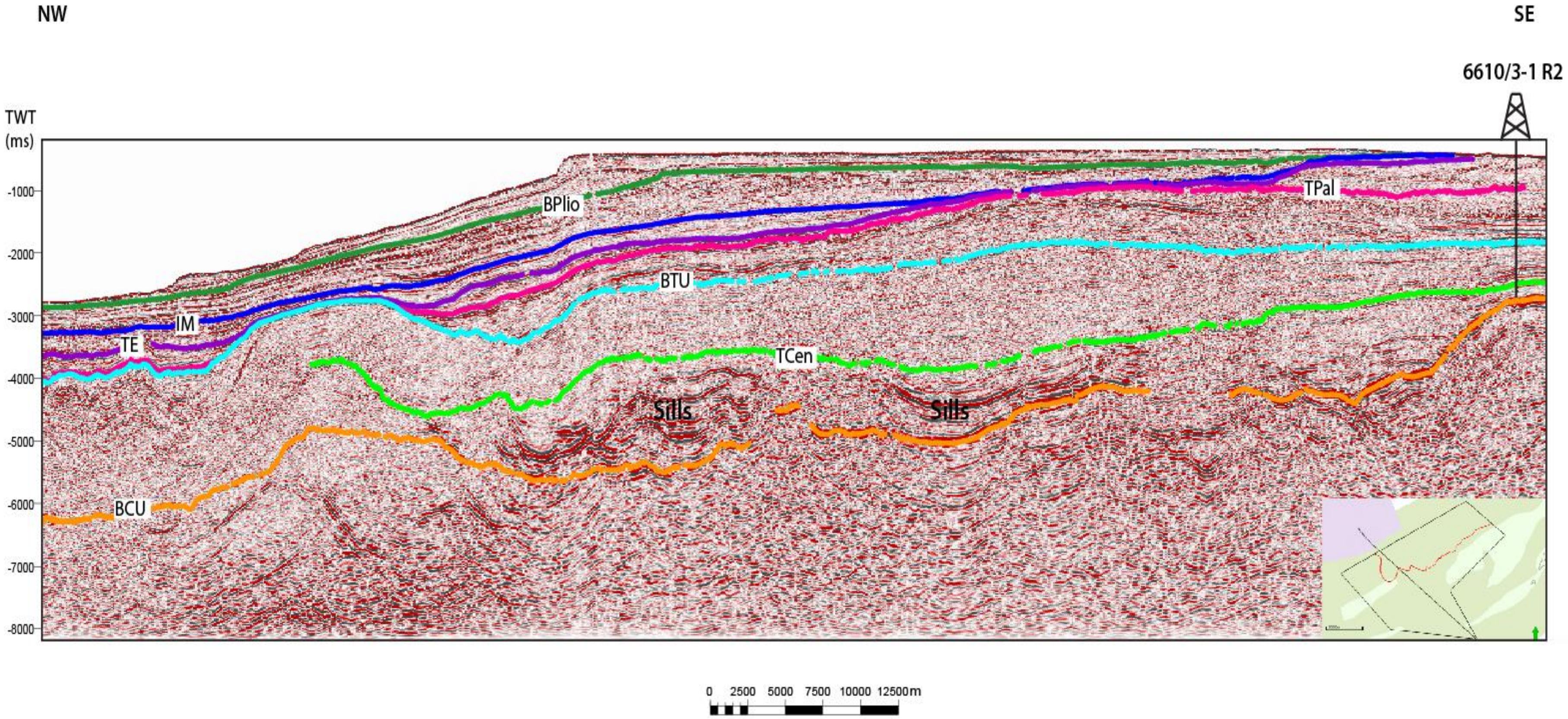


Fig. 4.6: *Correlation of exploration well 6610/3-1 R2 in the Vestfjorden Basin to the NW-SE trending AMR_TBN96-115 profile. Horizon abbreviations in Table 4.1.*

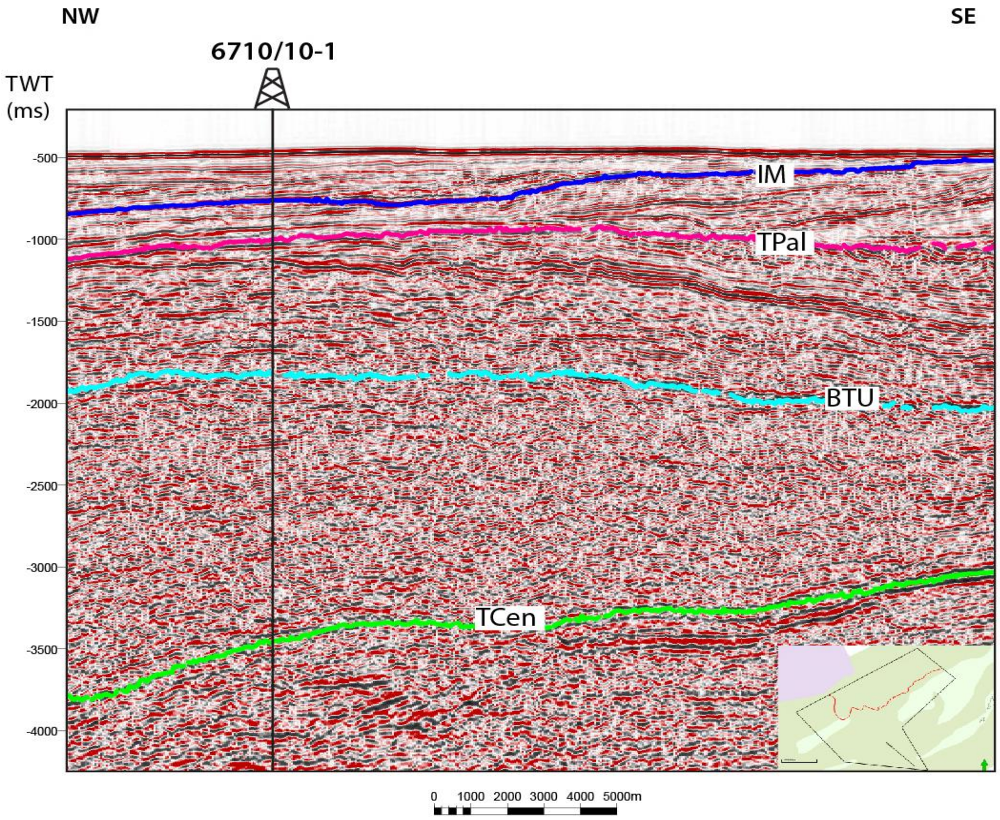


Fig. 4.7: *Correlation of exploration well 6710/10-1 in the Vesterdjupet Fault Zone to the NW-SE trending N6-92R00-121 profile. Horizon abbreviations in Table 4.1.*

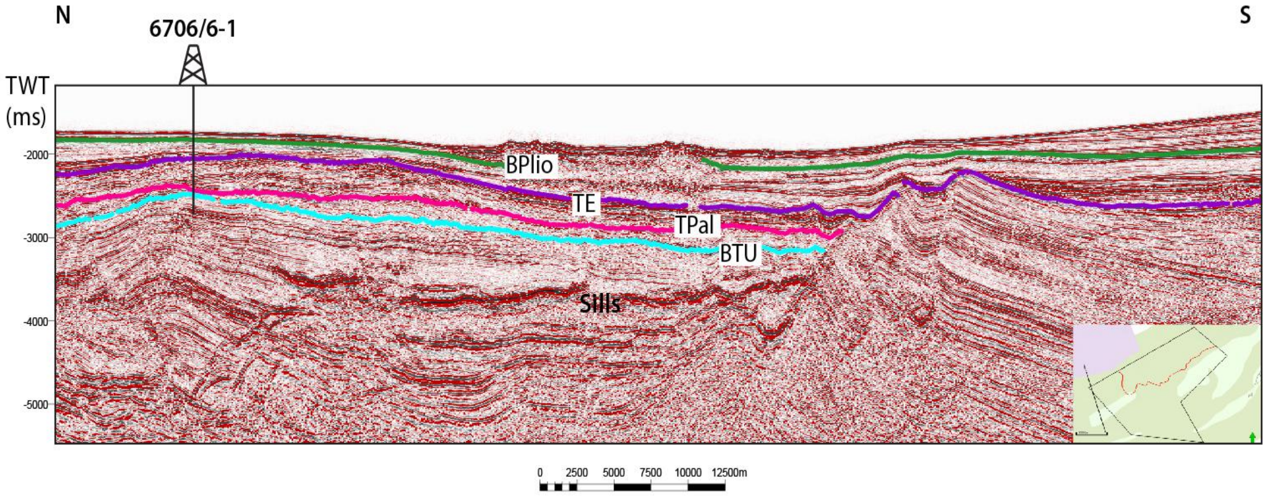


Fig. 4.8: *Correlation of exploration well 6706/6-1 in the Naglfar Dome to the N-S trending LIVB9-89 profile. Horizon abbreviations in Table 4.1.*

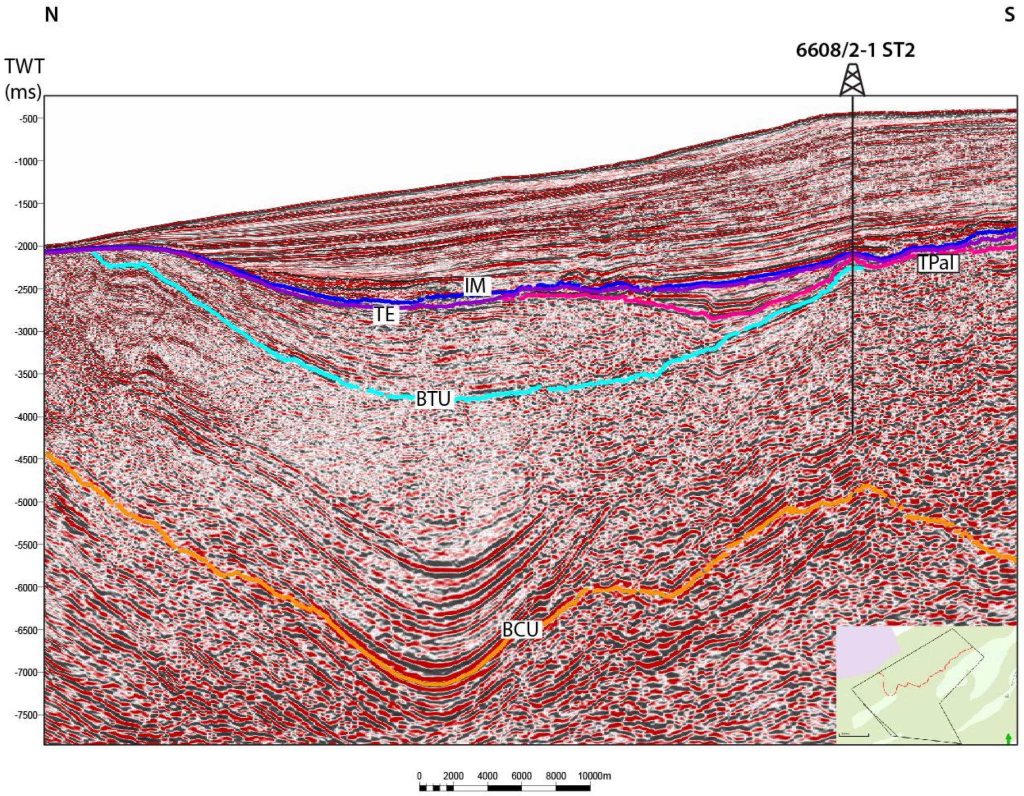


Fig. 4.9: *Correlation of exploration well 6608/2-1 ST2 in the Utgard High to the NW-SE trending AMR_TBN96-102 profile. Horizon abbreviations in Table 4.1.*

4.3.1 Cretaceous reflectors and sequences

The Cretaceous reflectors and sequences are tied to exploration wells 6610/3-1 R2 and 6710/10-1 in the western part of the Vestfjorden and Træna basins, respectively (Fig. 3.1). The Cretaceous successions are mainly composed of marine claystones and siltstones, and they also contain some outer shelf sandstones (Tasrianto and Escalona, 2015; Hansen et al., 2012).

Base Cretaceous Unconformity (BCU)

The Base Cretaceous Unconformity is tied to exploration well 6610/3-1 R2 in the Vestfjorden Basin (Fig. 4.5 and Fig. 4.6). BCU is a regional erosional unconformity, often recognized by onlapping reflections on it (Fig. 4.10). The reflector is offset by large faults at the Røst High/Utrøst Ridge, but it is, however, still possible to correlate it across faults. It is possible to map BCU in almost the entire study area, although its position in the Någrind Syncline is strongly debated due to extensive intrusions in the area (Blystad et al., 1995). The Base Cretaceous Unconformity is a medium to strong seismic amplitude and semi-continuous reflector.

Seismic sequence S1 (BCU-TCen)

The lower boundary of seismic sequence S1 is the BCU reflector (Fig. 4.10). The sequence is preserved to some degree in almost the entire study area, although the thickest successions are located in the southwestern part of the Røst High, the Någrind Syncline and the northern Træna Basin. There is limited well information for this sequence and especially for the thickest part of the succession. This limits the confidence for its precise stratigraphic correlation. Nonetheless, the sequence is interpreted to be of early Valanginian to Albian age, and may possibly be correlated to the Lyr and Lange formations (Fig. 4.1). The Lyr Formation consists of light grey to light greyish-green marls with interbedded carbonates deposited in open marine conditions (NPD, 2017b). The Lange Formation is interpreted to consist of light grey to green and brown claystones with interbedded carbonates and sandstones deposited in a marine environment (NPD, 2017b). The internal seismic character and configuration of the sequence is semi-transparent in some places (Fig. 4.10). Its character is also locally chaotic across parts of the study area, due to embedded magmatic intrusions. Reflections become more apparent and distinct towards the upper boundary of the sequence, interpreted as the Top Cenomanian reflector (Fig. 4.11).

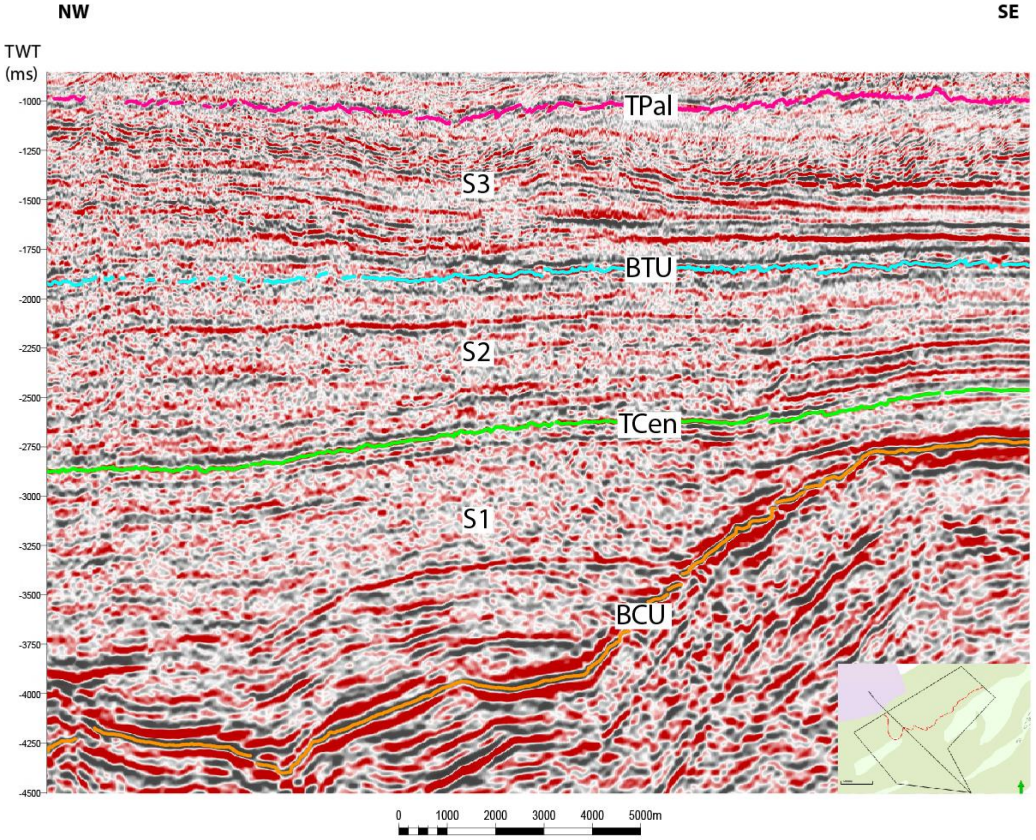


Fig. 4.10: *Seismic section (AMR_TBN96-115) showing the BCU, TCen, BTU, and TPal horizons, in addition to S1, S2, and S3 sequences. Horizon abbreviations in Table 4.1.*

Top Cenomanian (TCen) reflector

Top Cenomanian is tied to exploration wells 6610/3-1 R2 and 6710/10-1, in the Vestfjorden Basin and Vesterdjupet Fault Zone, respectively (Fig. 4.4-4.7). The reflector has been eroded on the Røst High/Utrøst Ridge, in the northeast part of the study area. Top Cenomanian could not be interpreted beneath the lava cover of the Røst Basin, as the seismic reflections and signal are disturbed by the breakup lavas, making seismic interpretation difficult. The interpretation of Top Cenomanian in the southwestern part of the Røst High is based on a regional tie, making the stratigraphic correlation uncertain. The reflector is also offset by large faults in this area, further increasing the uncertainty of the interpretation. The Top Cenomanian reflector is semi-continuous with a medium amplitude strength that increases in the fault blocks in the southwestern part of the Røst High.

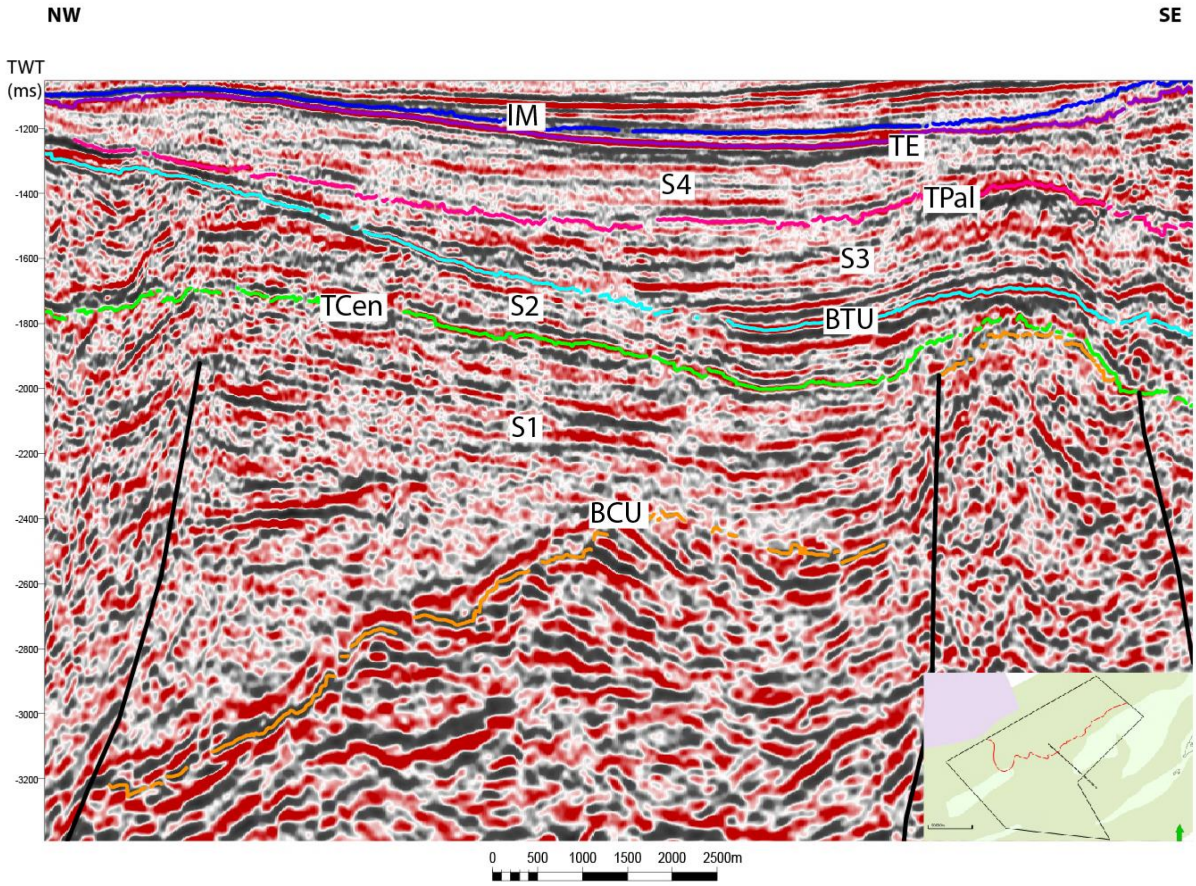


Fig. 4.11: *Seismic section (AMR_RHW96-116) showing the BCU, TCen, BTU, and TPal horizons, in addition to S1, S2, and S3 sequences. Horizon abbreviations in Table 4.1.*

Seismic sequence S2

The lower boundary of seismic sequence S2 is the Top Cenomanian reflector (Fig. 4.10). The sequence is preserved in the southern part of the study area, with the thickest successions being in the southwestern part of the Røst High, the Någrind Syncline and the northern Træna Basin. There is limited well information for this sequence, and especially on the northern Vøring Margin in the western part of the study area. Furthermore, there are no deep wells at the Røst High/Utgard Ridge, and this limits the confidence of the stratigraphic correlation. In spite of this, the sequence is interpreted to be of late Cenomanian to early Danian age, and may possibly be correlated to the Lysing Formation and the Shetland Group (Fig. 4.1). The Lysing Formation is interpreted to consist of fine to medium grained white-grey sandstone interbedded with shales, deposited in a shallow marine to deep marine environment, possibly as submarine fan deposits (NPD, 2017b). The Shetland Group is represented by the Nise and Springar formations in well 6610/3-1 R2 and the Springar Formation in well 6710/10-1. The Nise Formation consists of grey and greyish-green claystones with interbedded sandstones and carbonates, deposited in an open marine environment (NPD, 2017b). The Springar Formation is quite similar to the Nise Formation, consisting of greyish-green claystones with interbedded sandstones and carbonates, deposited in an open marine environment (NPD, 2017b). The internal seismic character and configuration of the sequence is semi-transparent in some places, and very clear and distinct in fault blocks in the Røst High/Utrøst Ridge. Reflections generally become more apparent and distinct towards the upper boundary of the sequence. Reflections of different ages onlap and toplap the Base Tertiary Unconformity reflector, which is interpreted as the upper boundary of the sequence (Fig. 4.11).

4.3.2 Cenozoic reflectors and sequences

Cenozoic successions are tied to exploration wells 6608/2-1 ST2, 6706/6-1, 6610/3-1 R2, and 6710/10-1 located in the Utgard High, Naglfar Dome, Vestfjorden Basin, and Vesterdjupet Fault Zone, respectively (Fig. 3.1). The Cenozoic successions consist of Paleogene upper slope to inner shelf, shallowing upward sandstones and claystones (Hansen et al., 2012; Tasrianto and Escalona, 2015). They are overlain by Plio-Pleistocene glacial sediments (Faleide et al., 2015).

Base Tertiary Unconformity (BTU) reflector

The Base Tertiary Unconformity reflector is tied to exploration wells 6608/2-1 ST2, 6610/3-1 R2, and 6710/10-1, located at the Utgard High, Vestfjorden Basin, and Vesterdjupet Fault Zone, respectively (Figs. 4.3-4.7 and Fig. 4.9). The reflector overlies both Lower and Upper Cretaceous strata, and exhibits an angular unconformity character. The reflector is seen as discontinuous with low to medium seismic amplitude, and it is possible to map it in almost the entire study area. Its locally weak seismic character does, however, make it difficult to interpret the reflector confidently in some parts of the study area, but it can still be recognized due to the downlapping and onlapping reflections (Fig. 4.11).

Seismic sequence S3

The lower boundary of seismic sequence S3 is the Base Tertiary Unconformity reflector (Fig. 4.10 and Fig. 4.11). The sequence is present in large parts of the study area, except for the Røst High/Utrøst Ridge. The thickest successions are seen in the Någrind Syncline and the northern Træna Basin. Reliability of the interpretation in the northeastern part of the study area is questionable, as there is lack of deep wells at the Røst High/Utrøst Ridge. Nevertheless, the sequence is interpreted to be of early Danian to late Thanetian age, possibly correlating with the Tang Formation (Fig. 4.5). The Tang Formation is interpreted to consist of dark grey to brown claystones with some sandstone and limestone interbeddings, deposited in a deep marine environment (NPD, 2017b). The internal configuration in the eastern part of the study area shows sub-parallel to wavy medium-to-high amplitude reflections that downlap and onlap the Base Tertiary Unconformity (Fig. 4.10 and Fig. 4.11). In the western part of the study area, the sequence exhibits chaotic sediments with intrusions, bounded by the top of breakup lavas (Fig. 4.12). It is possible to identify some onlaps on the BTU reflector. In the southern part of the study area, the sequence is slightly chaotic and it is recognized by the BTU onlaps and downlaps. The upper boundary of sequence S3 is the Top Paleocene reflector (Fig. 4.11).

Top Paleocene (TPal) reflector

The Top Paleocene reflector has been tied to exploration wells 6706/7-1, 6608/2-1 ST2, 6610/3-1 R2, and 6710/10-1 (Figures 4.2-4.5 and Figures. 4.6-4.9). The reflector has been interpreted as the top Tang Formation, and is correlated with the top of the breakup lavas in the northwestern part of the study area. The interpretations of Tsikalas et al. (2001), Ren et al.

(2003) and NPD (2010) are conformable with the performed interpretation and were used to tie the seismic interpretation of the reflector in parts of the study area. It is possible to map the Top Paleocene reflector in almost the entire study area as it exhibits a semi-continuous to continuous reflector character with high seismic amplitude. The Top Paleocene reflector has been eroded in parts of the Røst High/Utrøst Ridge in the northeast part of the study area. Due to older strata top-lapping the Top Paleocene reflector in some places, the reflector has locally an angular unconformity character (Fig. 4.10).

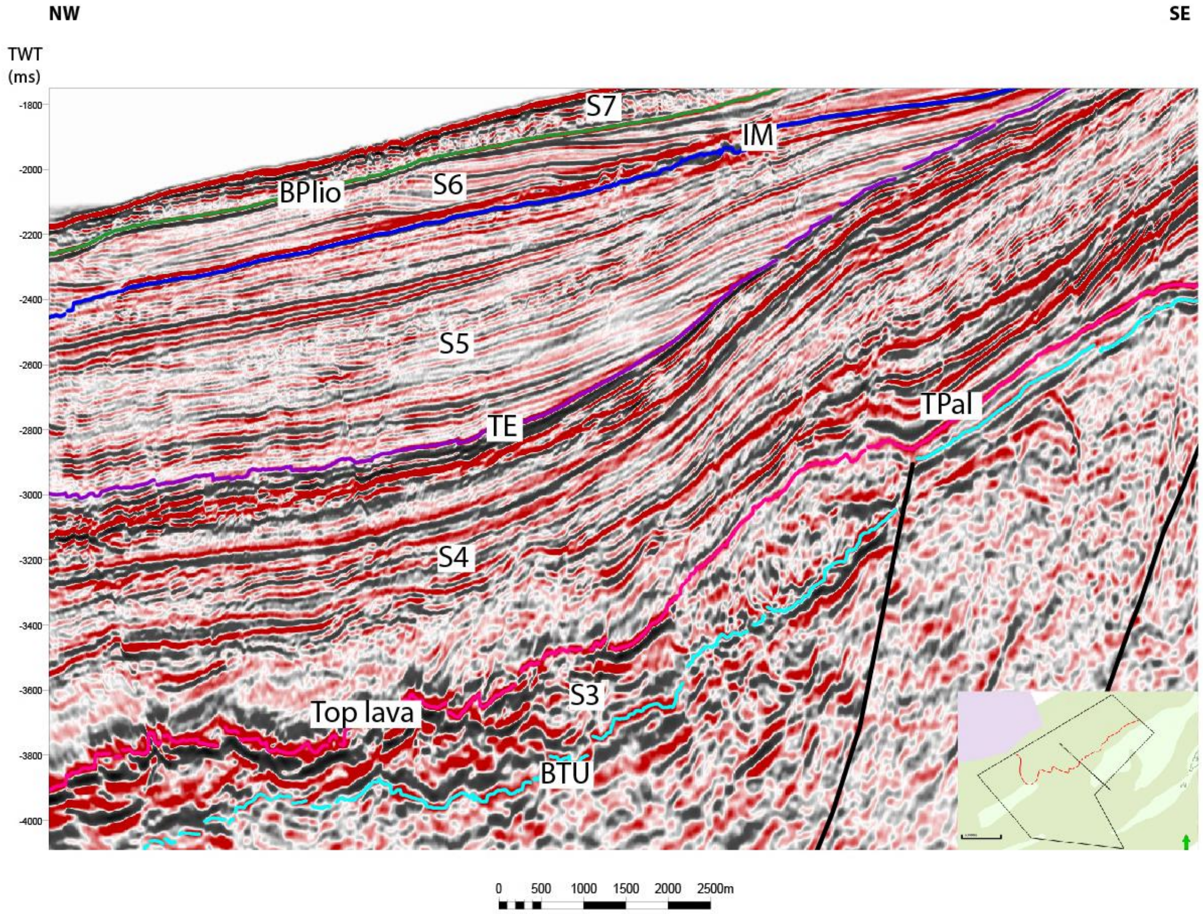


__Fig. 4.12:__ Seismic section (AMR_RHW96-114) showing the BTU, TPal, TE, IM, and BPlio horizons, in addition to S3, S4, S5, S6, and S7 sequences. Horizon abbreviations in Table 4.1.

Seismic sequence S4

The lower boundary of seismic sequence S4 is the Top Paleocene reflector (Fig. 4.11) The sequence is present in large parts of the study area, even though it is eroded in parts of the Røst High/Utrøst Ridge and in the northern Vøring margin. The thickest parts of the sequence are seen in the Røst Basin, while the thinnest successions are seen in the southern part of the study area at the northern Vøring margin. The sequence is interpreted to be of late Thanetian to late Priabonian age, correlating with the Brygge Formation. The Brygge Formation is interpreted to mainly consist of claystones with interbedded sandstones, siltstones, limestones and marls deposited in a marine environment. The sandstones can contain fragments of pyrite, glauconite and shell fragments (NPD, 2017b). Clinoforms with high seismic amplitude make up the internal configuration of the sequence at the outer Lofoten margin/Røst Basin (Fig. 4.12), while subparallel to wavy medium amplitude reflections onlap the BTU and downlap on the Top Paleocene reflector in the eastern part of the study area (Fig. 4.11). The internal configuration of the sequence in the northern Vøring margin also shows subparallel to wavy reflections. The upper part of the sequence shows top-lapping reflections bounded by the Top Eocene reflector in most parts of the study area, but also subcropping reflections close to the seafloor in the eastern part of the study area (Fig. 4.5).

Top Eocene (TE) reflector

The Top Eocene reflector has been tied to exploration wells 6706/6-1 and 6608/2-1 ST2 (Figs. 4.2-4.3 and Figs. 4.8-4.9). The reflector has been interpreted as an Intra Brygge Formation reflector, and the interpretations of Tsikalas et al. (2001), Ren et al. (2003) and NPD (2010) are conformable with the performed interpretation and were used to tie the seismic interpretation of the reflector. It is possible to map the Top Eocene reflector in almost the entire study area, as it exhibits in parts of the study area a semi-continuous to continuous reflection character with high seismic amplitude. The Top Eocene reflector has been eroded in parts of the Røst High/Utrøst Ridge, in the northeast part of the study area. Due to younger strata of different ages onlapping and downlapping the reflector, it has locally an angular unconformity character (Fig. 4.12). In some places on the southern Lofoten and northern Vøring margins, the reflector interferes with the Opal A/CT boundary.

Seismic sequence S5

The lower boundary of seismic sequence S5 is the Top Eocene reflector (Fig. 4.12). The sequence is present in large parts of the study area, although some parts of it have been eroded on the Røst High/Utrøst Ridge and the northern Vøring margin. The sequence is thickest at the outer Lofoten margin in the Røst Basin, and thins in the south towards the northern Vøring margin. The sequence is interpreted to represent Oligocene to lowermost Miocene sediments of early Rupelian to Aquitanian age, correlated with the Brygge Formation (NPD, 2017b). The sequence consists of gently dipping clinoforms with increasing high seismic amplitude at the outer Lofoten margin, and contains sub-parallel and high-amplitude reflections that onlap the Top Eocene reflector and toplap the Intra Miocene reflector at the upper boundary (Fig. 4.12). The sequence is subcropping close to the seafloor in the eastern part of the study area (Fig. 4.5).

Intra Miocene (IM) reflector

The Intra Miocene reflector has been tied to exploration wells 6608/2-1 ST2 and 6710/10-1 (Figs. 4.3-4.4, Fig. 4.7, Fig. 4.9). The interpretation of Tsikalas et al. (2001) has been used for comparison of the performed seismic interpretation. It is possible to map the Intra Miocene reflector in almost the entire study area, as it is a continuous reflector with high seismic amplitude. The reflector has been eroded on the Røst High/Utrøst Ridge in the northeast part of the study area. Due to stratigraphically younger downlapping and onlapping strata, the reflector has an angular unconformity character (Fig. 4.12). It also overlies both Eocene and Oligocene strata.

Seismic sequence S6

The lower boundary of seismic sequence S6 is the Intra Miocene reflector (Fig. 4.12). The sequence is present in almost the entire study area, with some parts of it being eroded on the Røst High/Utrøst Ridge in the northern part of the study area. The sequence is thickest in the Någrind Syncline and the northern Træna Basin, and thins out towards the Røst Basin and Utrøst Ridge towards the north. The sequence is interpreted to represent Miocene sediments of Aquitanian to late Messinian age, correlated with the Kai and Molo formations (Fig. 4.1). The Kai Formation is interpreted to consist of alternating claystone, siltstone, and sandstone with interbedded limestone, deposited in a marine environment with varying water depths (NPD, 2017b). The Molo Formation displays varying lithology. It mainly consists of red to yellow coloured sand, with some sections also containing well rounded, rust-tinted pebbles, and glauconitic and mica-rich sand. The formation has been deposited in a coastal, shallow marine to prograding deltaic depositional environment, probably with strong wave influence (NPD, 2017b). The sequence consists of gently dipping clinoforms with high seismic amplitude reflections, and reflections downlapping onto the Intra Miocene reflector. Reflections toplap the upper boundary of the sequence (Fig. 4.12), the Base Plio-Pleistocene horizon, and the sequence is also subcropping close to the seafloor in the eastern part of the study area (Fig. 4.6).

Base Plio-Pleistocene (BPlio) reflector

The Base Plio-Pleistocene reflector has been tied to exploration well 6706/6-1 at the northern Vøring margin (Fig. 3.1). The interpretation of Ren et al. (2003) has been used for comparison of the performed seismic interpretation. It is possible to map the Base Plio-Pleistocene reflector in almost the entire study area, as it is a continuous reflector with high seismic amplitude. It has probably been eroded on the Røst High/Utrøst Ridge in the northeast part of the study area. Due to stratigraphically younger strata downlapping and onlapping the reflector, it has an angular unconformity character (Fig. 4.12). The Base Plio-Pleistocene reflector represents the lower boundary of the glacial sedimentary sequence.

Seismic sequence S7

The Base Plio-Pleistocene reflector is the lower boundary of seismic sequence S7 (Fig. 4.12). The sequence is present in the entire study area, being thickest on the northern Vøring margin and thinning towards the Røst High/Utrøst Ridge at the northeast part of the study area. The sequence is interpreted to range from Pliocene to present day, consisting of Pliocene and Quaternary sediments. It is interpreted to correspond to the Naust Formation, representing interbedded claystone, siltstone and sand, with occasional coarse clastic sediments in the upper part (Fig. 4.1). The Naust Formation was probably deposited in a marine environment, with a transition to glaciomarine environments in the upper part. The base of the glaciomarine environments is poorly defined (NPD, 2017b). The upper boundary of seismic sequence S7 is the seafloor.

4.4 Time-structure maps

Time-structure maps have been generated from the interpreted horizons in order to visualise the evolution, in space and time, of the various structural elements at the southern Lofoten and northern Vøring margins at different time intervals. Seven time-structure maps have been generated as a means of illustrating the geological events in the study area. The time-structure maps cannot be used as a direct representation of topographical relief at the specific time intervals, as they are the result of accumulated geological events. A general eastward shallowing trend is observed, reflecting margin subsidence and tilting. Some of the horizons are also restricted in lateral spatial distribution due to, amongst other, erosion and masking by the breakup extrusive lavas. Top Cenomanian is the only interpreted horizon that does not result in a continuous time-structure map across the entire study area, as it is not possible to confidently interpret it in the area west of the Røst High beneath the breakup lavas. Nevertheless, all the seven time-structure maps are used to improve the understanding of the tectono-stratigraphic evolution on the southern Lofoten and northern Vøring margins.

4.4.1 Cretaceous

Base Cretaceous Unconformity

The BCU time-structure map represents the deepest interpreted level in the study area. In general, all the present-day structural elements are evident in the map (Fig. 4.13). The time-structure map is dominated by NNE-SSW trending faults, and large basin bounding faults are evidenced by abrupt depth variations seen by densely spaced contour lines. Elevated structural highs are easily seen in Fig. 4.13, and especially the Røst High/Utrøst Ridge is bounded by major basin bounding faults separating it from the Røst Basin on the outer Lofoten margin. The depth of the horizon varies significantly throughout the entire study area, ranging from ~7000 ms in the deepest part of the Någrind Syncline to ~1000 ms and less on the Røst High/Utrøst Ridge. An abrupt elevation representing the Røst High/Utrøst Ridge is seen towards northeast, while a more gradual elevation represents the Nyk and Utgard highs. The Utgard High is perhaps the least prominent of the present-day structural elements. A general northwards shallowing trend is observed, with a trough in the northern termination of the Nyk High. Local depth variations across the Røst High are evident, with depth differences in the order of ~500 ms. There is little alteration of the horizon relief across the Røst High. The Nyk and Utgard highs are dominated by more frequent, local-scale alterations of the horizon relief. Limited seismic coverage restrains detailed interpretation of the outer Lofoten margin, and also the Utrøst Ridge in the northern part of the study area. Nevertheless, the current seismic coverage still offers a decent interpretation of the Late Jurassic-earliest Cretaceous basin configuration.

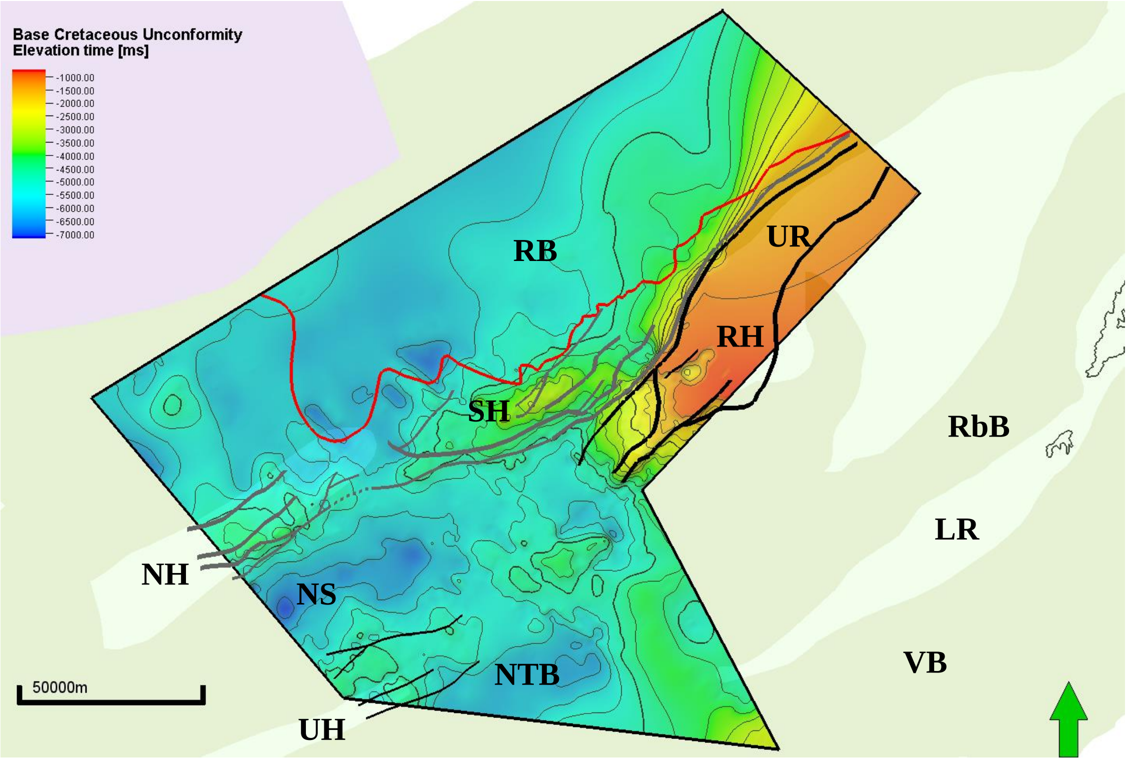


Fig. 4.13: *Time-structure map of the Base Cretaceous Unconformity (BCU) horizon (contour interval 500 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The NPD structural element outline is included in the background for comparison. RB: Røst Basin, RH: Røst High, UR: Utrøst Ridge, SH: Sandflesa High, NH: Nyk High, UH: Utgard High, NS: Någrind Syncline, NTB: northern Træna Basin, VB: Vestfjorden Basin, LR: Lofoten Ridge, RbB: Ribban Basin.*

Top Cenomanian

The Top Cenomanian time-structure map has the least lateral seismic interpretation as its confident interpretation is restricted landward of the breakup lava boundary. It does, however, illustrate in general all present-day structural elements (Fig. 4.14). The time-structure map is dominated by NNE-SSW trending faults, with basin bounding faults being evidenced by abrupt depth variations seen by densely spaced contour lines. Elevated structural highs are easily identified, with the Røst High/Utrøst Ridge being the most evident. The horizon time depth varies significantly throughout the study area, ranging from ~5500 ms in the deepest part of the Någrind Syncline to ~1000 ms and less on the Røst High, which is also depicted by an abrupt elevation towards northeast. The Nyk and Utgard highs are associated with a more gradual elevation, and the Utgard High represents the least prominent of the present-day structural elements. A general northwards shallowing trend is observed, with a trough at the northern termination of the Nyk High. There is little alteration of the horizon relief across the Røst High. The Nyk and Utgard highs are dominated by more frequent, local-scale alterations of the horizon relief. The limited seismic coverage hampers detailed interpretation on the outer Lofoten margin and the Utrøst Ridge, in addition to the deeper Røst Basin that is concealed by extrusive lavas. This makes the time-structure map to be associated with large uncertainties, but it is the best current approximation of the mid Cretaceous basin configuration.

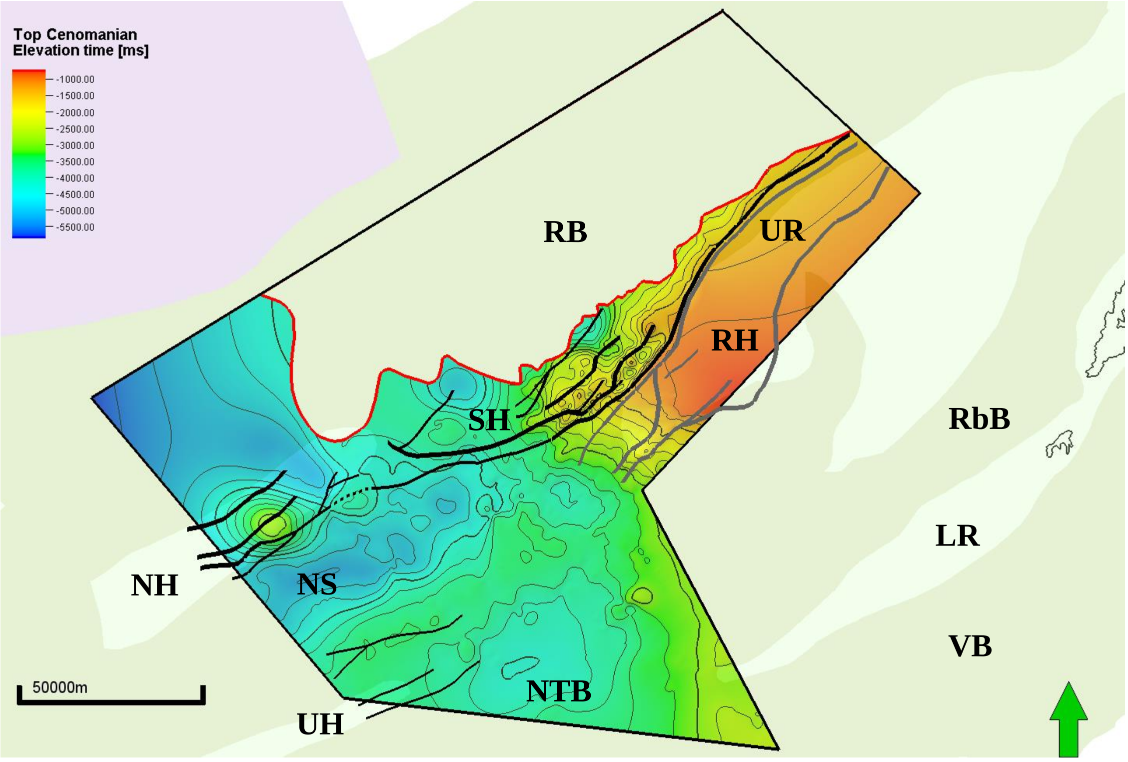


Fig. 4.14: Time-structure map of the Top Cenomanian (TCen) horizon (contour interval 300 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The red polygon illustrates the landward breakup lava boundary. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig. 4.13.

4.4.2 Cenozoic

Base Tertiary Unconformity

The Base Tertiary Unconformity (BTU) time-structure map depicts all the present-day structural elements, and it is dominated by NNE-SSW trending faults (Fig. 4.15). Elevated structural highs are easily seen in Fig. 4.15, with the Røst High being the most prominent. The time depth to the horizon varies significantly throughout the study area, ranging from ~5500 ms in the Røst Basin to ~1000 ms and less on the Røst High, which is also represented by an abrupt elevation towards northeast. The Nyk and Utgard highs are associated with a more gradual elevation, with the Nyk High being the most prominent of the present-day structural elements. A general shallowing eastwards trend is observed, with a trough in the northern termination of the Nyk High. There is little alteration of the horizon relief across the Røst High. The Nyk and Utgard highs are dominated by more frequent, local-scale alterations of the horizon relief. The limited seismic coverage makes the detailed seismic interpretation on the outer Lofoten margin and the Utrøst Ridge challenging, as well as into the deeper Røst Basin that is concealed by extrusive lavas.

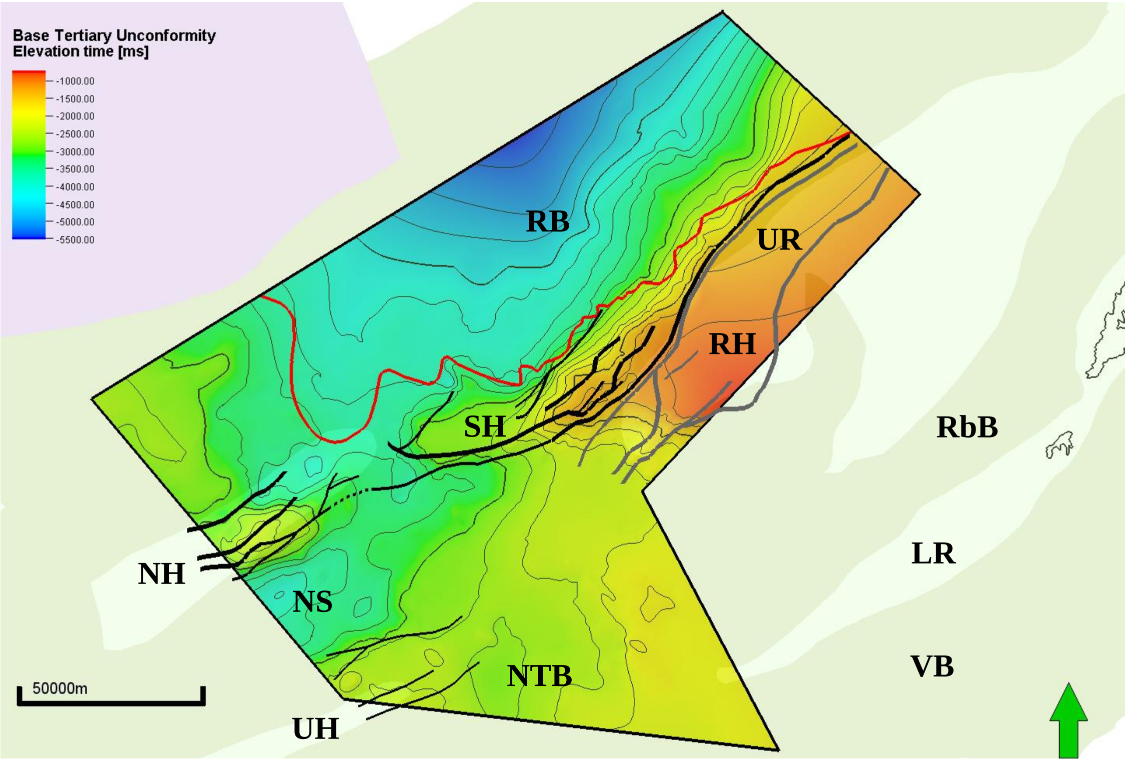


Fig. 4.15: *Time-structure map of the Base Tertiary Unconformity (BTU) horizon (contour interval 300 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The red polygon illustrates the landward breakup lava boundary. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig. 4.13.*

Top Paleocene

The Top Paleocene time-structure map depicts the Røst and Nyk highs, with the Nyk High being the least prominent (Fig. 4.16). The time depth to the horizon varies significantly throughout the study area, ranging from ~5000 ms in the Røst Basin to ~1000 ms and less on the Røst High and the Vestfjorden Basin. The Røst High is associated with an abrupt elevation, while the Nyk High shows a more gradual elevation. A general shallowing eastwards trend is observed, with a weak trough separating the Nyk and Røst highs. There is little alteration of the horizon relief across the Røst High, even though the rest of the study area is dominated by more frequent alterations of the horizon relief. The limited seismic coverage makes the detailed seismic interpretation more challenging on the outer Lofoten margin and the Utrøst Ridge.

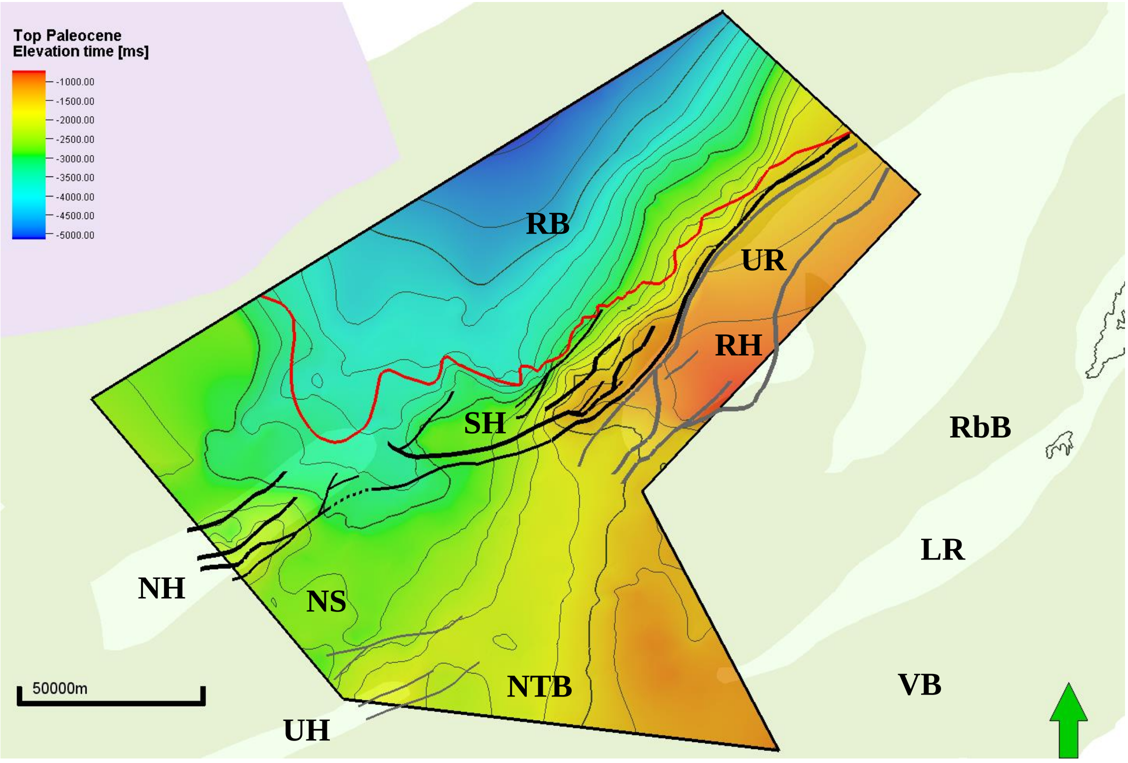


Fig. 4.16: *Time-structure map of the Top Paleocene (TPal) horizon (contour interval 300 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The red polygon illustrates the landward breakup lava boundary. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig. 4.13.*

Top Eocene

The Top Eocene time-structure map depicts the Røst and Nyk highs, with the Nyk High being the least prominent (Fig. 4.17). The time depth to the horizon varies significantly throughout the study area, ranging from ~5000 ms in the Røst Basin to ~1000 ms and less in the Vestfjorden Basin. The Røst High is associated with a relatively abrupt elevation, while the Nyk High shows a more gradual elevation. A general eastwards shallowing trend is observed, and a separation between the Nyk and Røst highs is evident. This trend is observed in all Cenozoic time-structure maps, reflecting margin subsidence and tilting. There is little alteration of the horizon relief across the Røst High, even though the rest of the study area is dominated by more frequent alterations of the horizon relief. The limited seismic coverage makes the detailed interpretation more challenging on the outer Lofoten margin and the Utrøst Ridge.

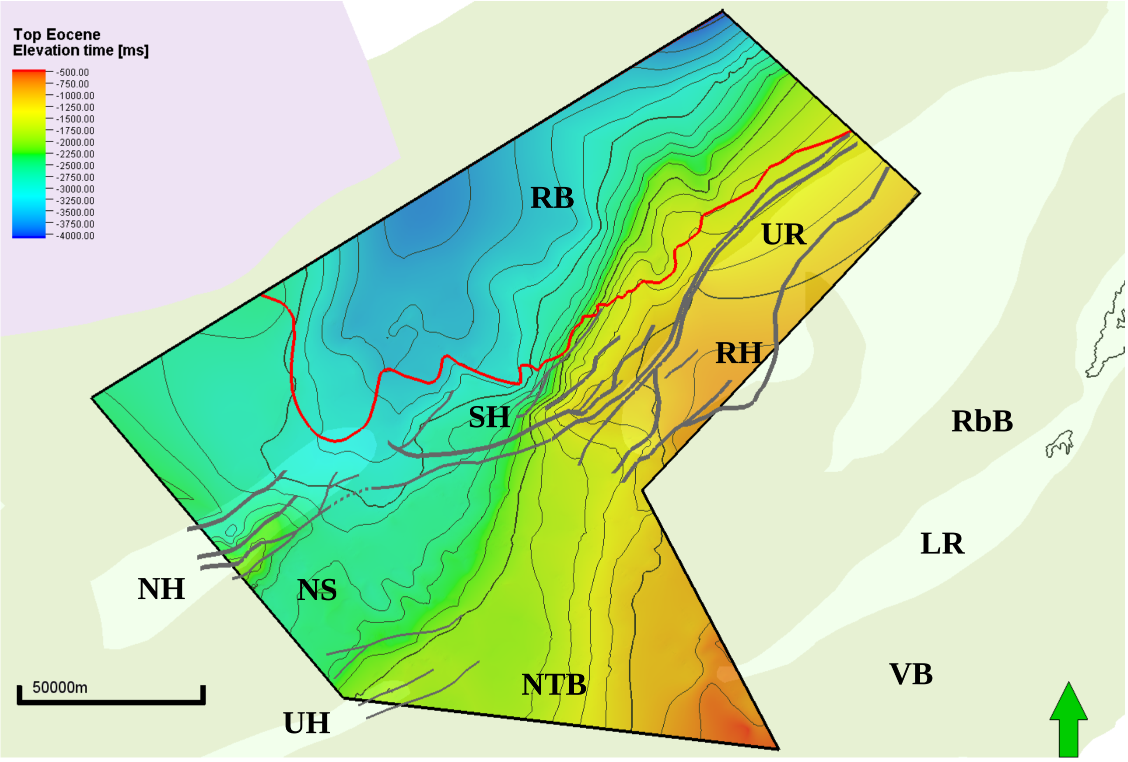


Fig. 4.17: *Time-structure map of the Top Eocene (TE) horizon (contour interval 200 ms). Inactive faults are displayed in grey. The red polygon illustrates the landward breakup lava boundary. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig. 4.13.*

Intra Miocene

The Intra Miocene time-structure map depicts the Røst and Nyk highs, with the Nyk High being the least prominent (Fig. 4.18). All structural highs are associated with a relatively smooth elevation. The time depth to the horizon varies significantly throughout the study area, ranging from ~4000 ms in the Røst Basin to ~500 ms and less on the Røst High. A general eastwards shallowing trend is observed, and a separation between the Nyk and Røst highs is evident. There are generally frequent alterations of the horizon relief across the study area. Detailed interpretation on the outer Lofoten margin and the Utrøst Ridge is, somewhat, impeded by the limited seismic coverage.

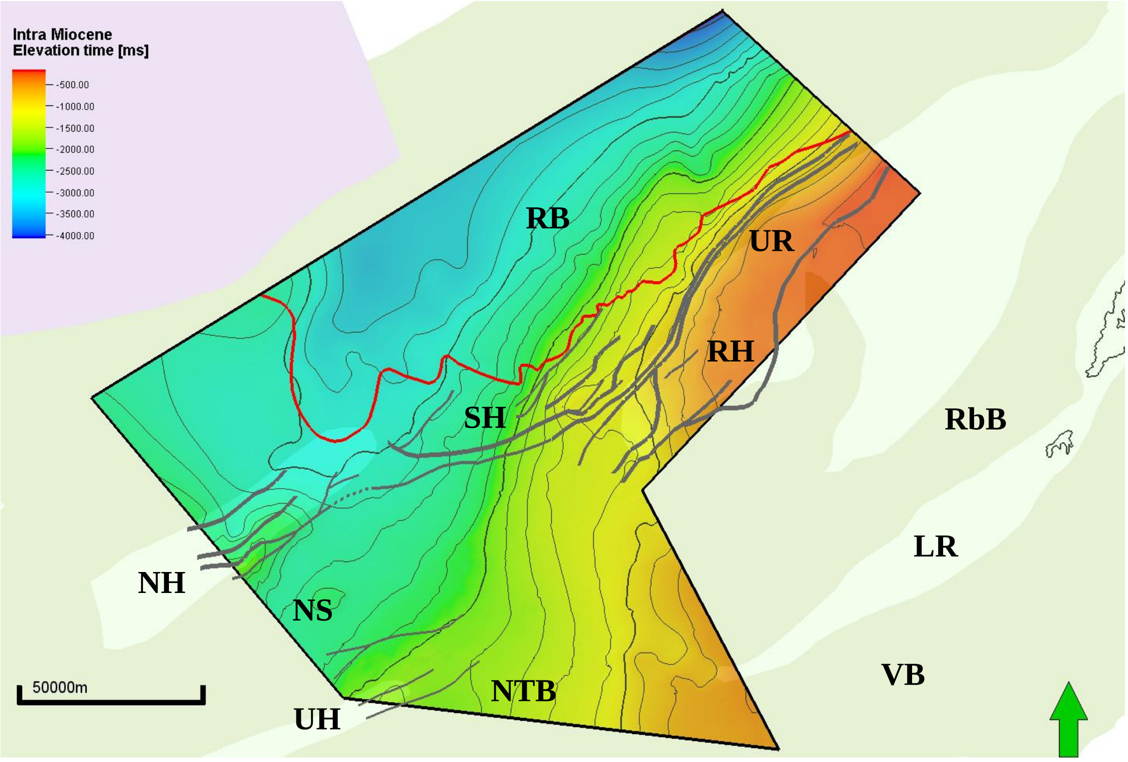


Fig. 4.18: *Time-structure map of the Intra Miocene (IM) horizon (contour interval 200 ms). Inactive faults are displayed in grey. The red polygon illustrates the landward breakup lava boundary. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig. 4.13.*

Base Plio-Pleistocene

The Base Plio-Pleistocene time-structure map only depicts the Røst High/Utrøst Ridge of all the present-day structural elements (Fig. 4.19). The time depth to the horizon varies from ~4000 ms in the Røst Basin to ~500 ms and less on the Utrøst Ridge. A generally eastwards shallowing trend is observed, with a relatively gradual elevation. There is little alteration of the horizon relief along the Utrøst Ridge, even though the rest of the study area is dominated by more frequent alterations of the horizon relief across the study area. The limited seismic coverage makes the detailed seismic interpretation more challenging on the outer Lofoten margin and the Utrøst Ridge.

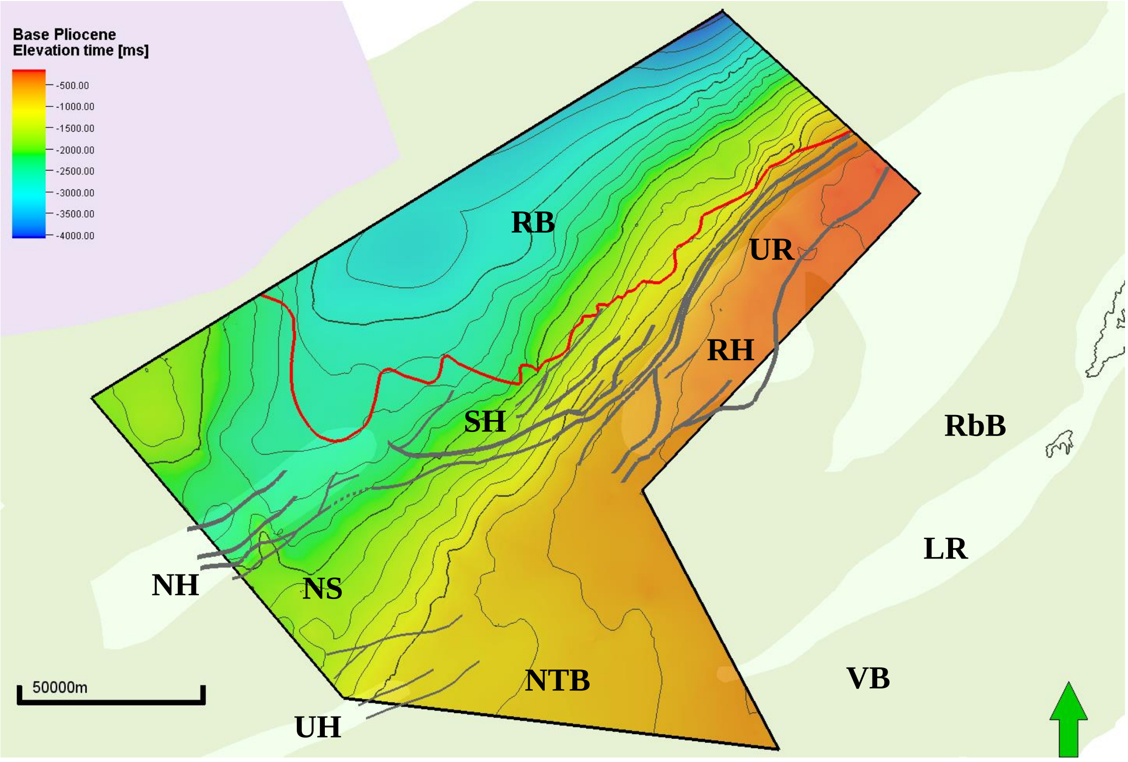


Fig. 4.19: *Time-structure map of the Base Plio-Pleistocene (BPlio) horizon (contour interval 200 ms). Inactive faults are displayed in grey. The red polygon illustrates the landward breakup lava boundary. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig. 4.13.*

4.5 Main structural elements

4.5.1 West Røst High Fault Complex

The area west of the Røst High that exhibits prominent and intense faulting is named (informally) in the thesis as West Røst High Fault Complex. The West Røst High Fault Complex is mainly characterised by NE-SW trending and west-dipping faults (Figs. 4.20 and 4.21). Several small-scale antithetic faults are also present in the western part of the fault complex. The easternmost fault in the fault complex has a curvilinear outline that coincides with the edges of strong positive and elongated potential field data anomalies (Fig. 4.22). In general, the faults in the complex have a planar shape in the upper parts of the complex, and sole out at ~3000 ms to become more low-angle with depth. The low-angle fault propagation at depth causes rotation of Cretaceous strata. The eastern fault forms a detachment/décollement plane that mostly runs sub-parallel to the underlying Base Cretaceous Unconformity (BCU). The detachment plane forms a pathway for fault propagation at depth. The maximum throw of the faults is ~1000 ms, and can be observed in the central parts of the fault complex. Fault-throw displacement generally increases towards south and west. In addition, it seems that faults become steeper towards west, as some are probably able to reactivate pre-existing structures (Fig. 4.24). The West Røst High Fault Complex is draped by the Base Tertiary Unconformity (BTU). The latter exhibits a strong erosional surface character at the fault complex location, affecting both the footwall and hanging-wall. This indicates that the faults in the fault complex could have been more pronounced than what is evident in the seismic profiles today, and may have affected a thicker package of sedimentary sequences that are currently missing due to erosion. In the western part of the fault complex, BTU is offset by most of the faults, although these exhibit only minor throws (Figs. 4.20 and 4.21).

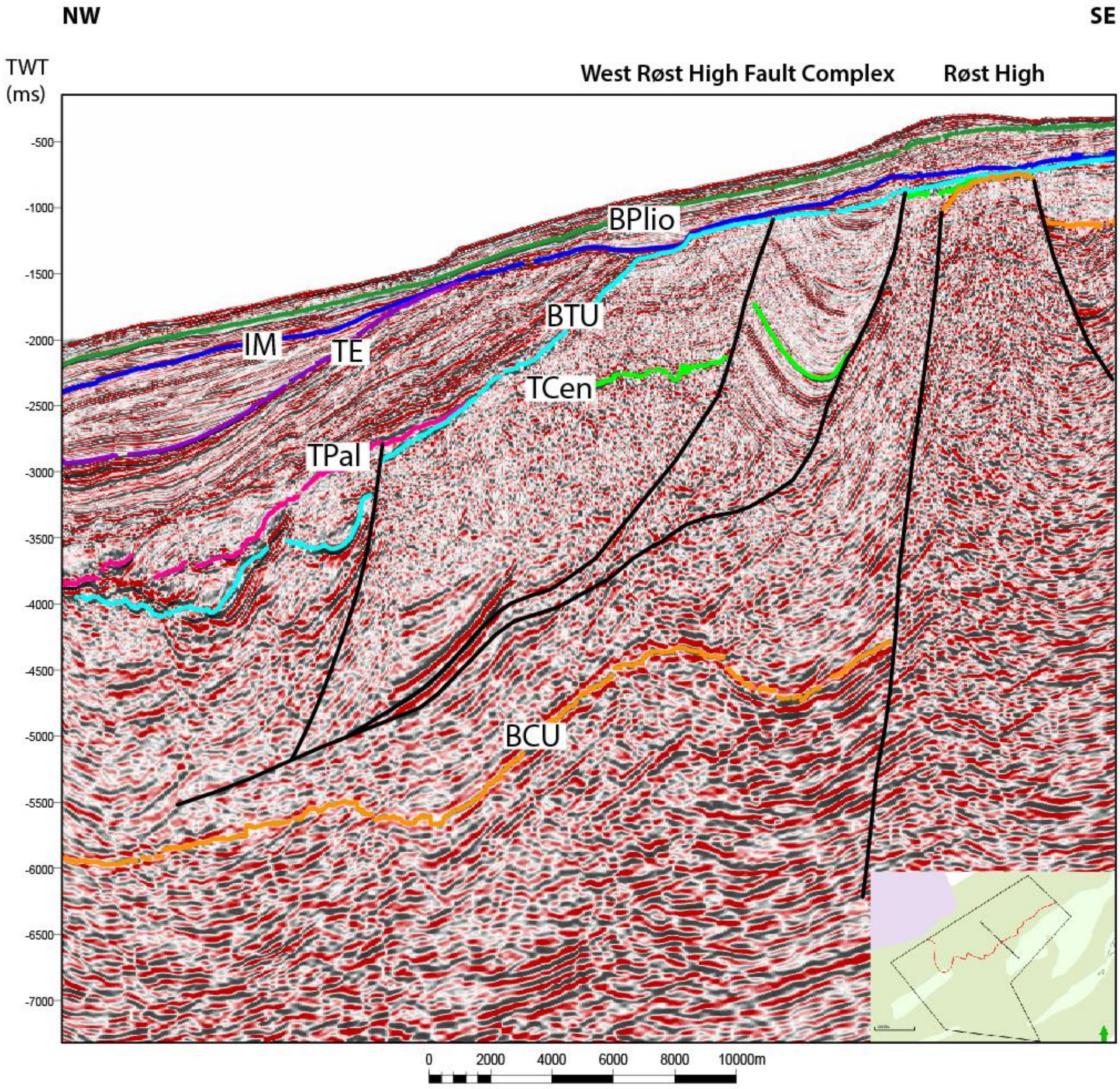


__Fig. 4.20:__ Seismic profile AMR_RHW96-111 illustrating the Røst High and West Røst High Fault Complex. Horizon abbreviations in Table 4.1.

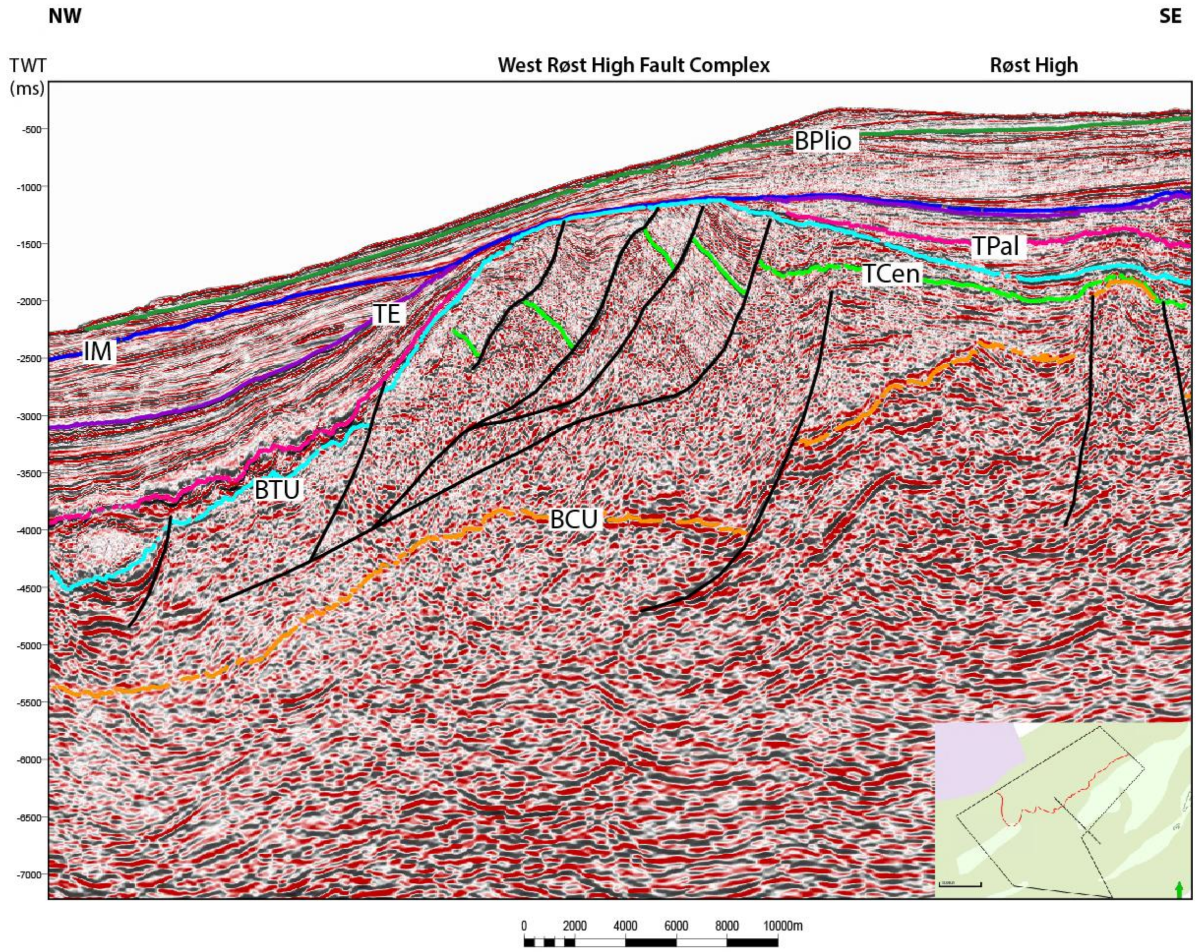


Fig. 4.21*: Seismic profile AMR_RHW96-116 illustrating the West Røst High Fault Complex. Horizon abbreviations in Table 4.1.*

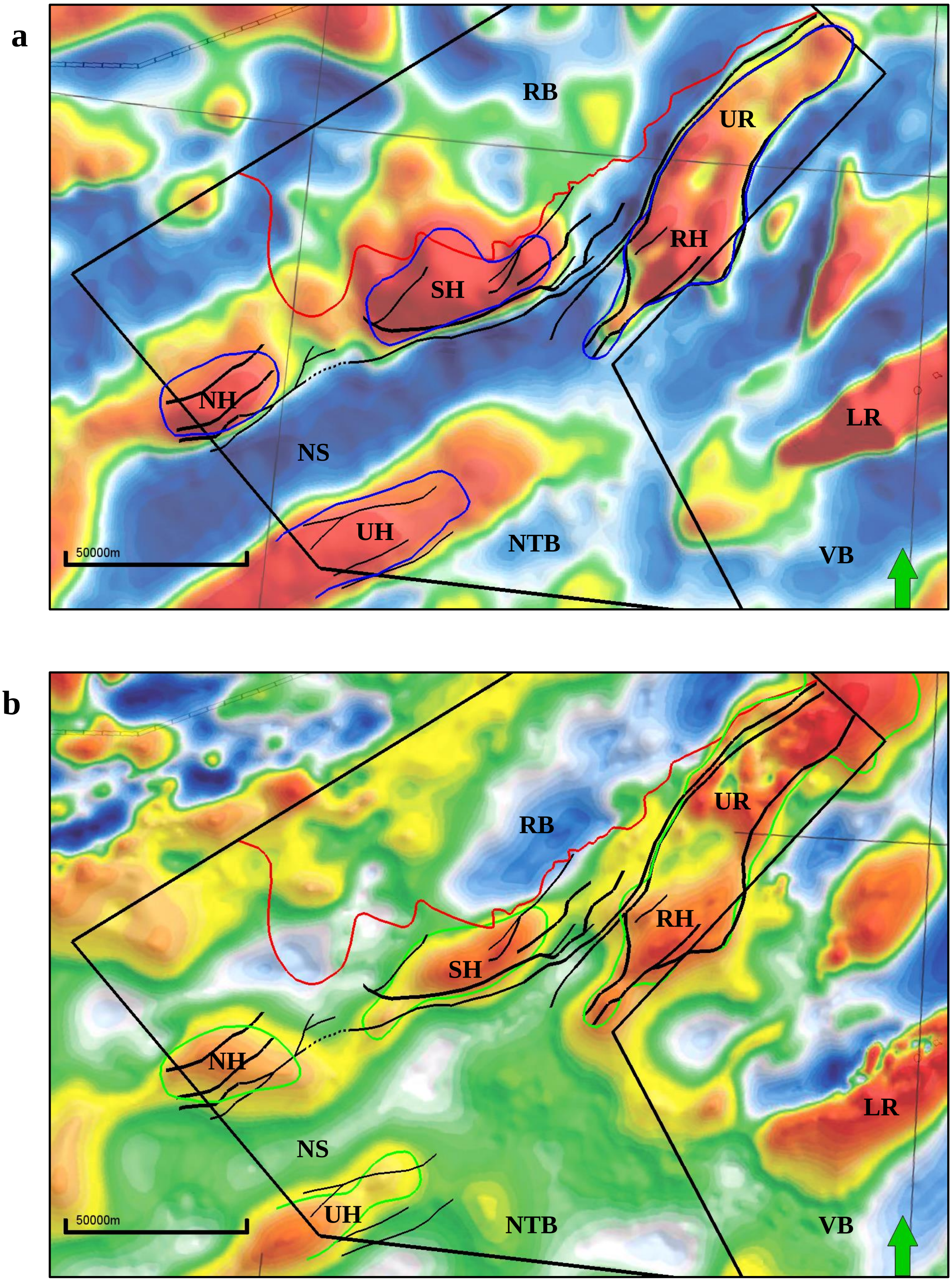


Fig. 4.22: ***(a)*** *50 km high-pass filtered gravity anomaly data, with interpreted faults draped above. BCU basement highs are indicated with blue polygons.* ***(b)*** *100 km high-pass filtered magnetic anomaly data, with interpreted faults draped above. BCU basement highs are indicated with green polygons. Black polygon marks the study area. Gravity and magnetic data courtesy of TGS. Red indicates strong positive anomalies, while blue indicates strong negative anomalies. NH: Nyk High, UH: Utgard High, RH: Røst High, UR: Utrøst Ridge, RB: Røst Basin, SH: Sandflesa High, NTB: northern Træna Basin, VB: Vestfjorden Basin, NS: Någrind Syncline, LR: Lofoten Ridge.*

4.5.2 Nyk High

The Nyk High is mainly characterised by NE-SW trending and west-dipping faults, which have slight zig-zag outlines (Fig. 4.22). Faults are generally high-angle and planar, but become more listric and low-angle at ~4000 ms in the deeper parts of the Nyk High (Fig. 4.23). The Nyk High coincides with strong positive potential field data anomalies (Fig. 4.22). Sedimentary layers are mostly planar and parallel in the southwestern part of the high, while low-angle fault propagation at depth leads to rotation of strata. The maximum throw of the faults is ~750 ms, and can be observed in the northern parts of the high. Fault-throw displacement generally increases towards north, and towards the same direction faults become less steep. The Nyk High is draped by the Top Eocene reflector, which has a local angular unconformity character and, only locally, is downthrown by few faults. Erosion has affected both the footwall and hanging-wall of the Nyk High.

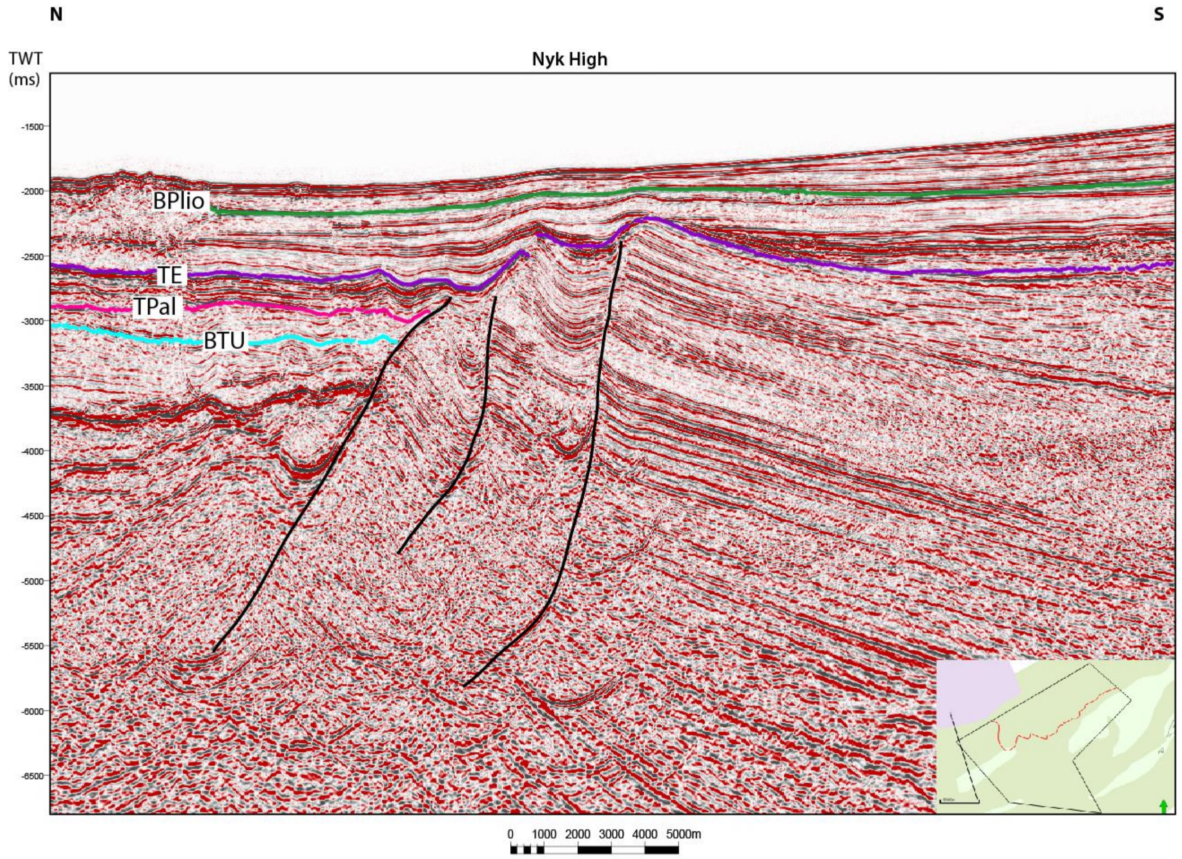


Fig. 4.23*: Seismic profile LIVB9-89 illustrating the Nyk High. Horizon abbreviations in Table 4.1.*

4.5.3 Sandflesa High

The Sandflesa High is a basement high situated southwest of the Røst High, near the landward break-up lava boundary (Fig. 4.22). It was earlier described in very general terms by Olesen et al. (2002) on the basis of potential field data, while in the current study the Sandflesa High is more properly defined on detailed seismic and integrated potential field observations and mapping. Mapping of the Base Cretaceous Unconformity (BCU) horizon led to observations of a prominent elevated high, located beneath the West Røst High Fault Complex. Furthermore, the Sandflesa High appears to coincide with a strong positive anomaly in the potential field data, situated southwest of the Røst High (Fig. 4.22). The northwest side of the high appears to be faulted, exhibiting abrupt horizon time depth changes for the BCU horizon (Fig. 4.24). The faults are NE-SW trending, and display a curvilinear outline in the potential field data (Fig. 4.22). Although the southeast side of Sandflesa High shows a slightly more gradual horizon time depth change, it also shows abrupt elevation. Sill intrusions are evident on seismic sections within and in the near vicinity of the Sandflesa High as seen in Fig. 4.24. The figure further shows mid/Late Cretaceous-Paleocene faults propagating into a detachment/décollement plane that appears to be rotated because of the presence of the basement high just beneath it.

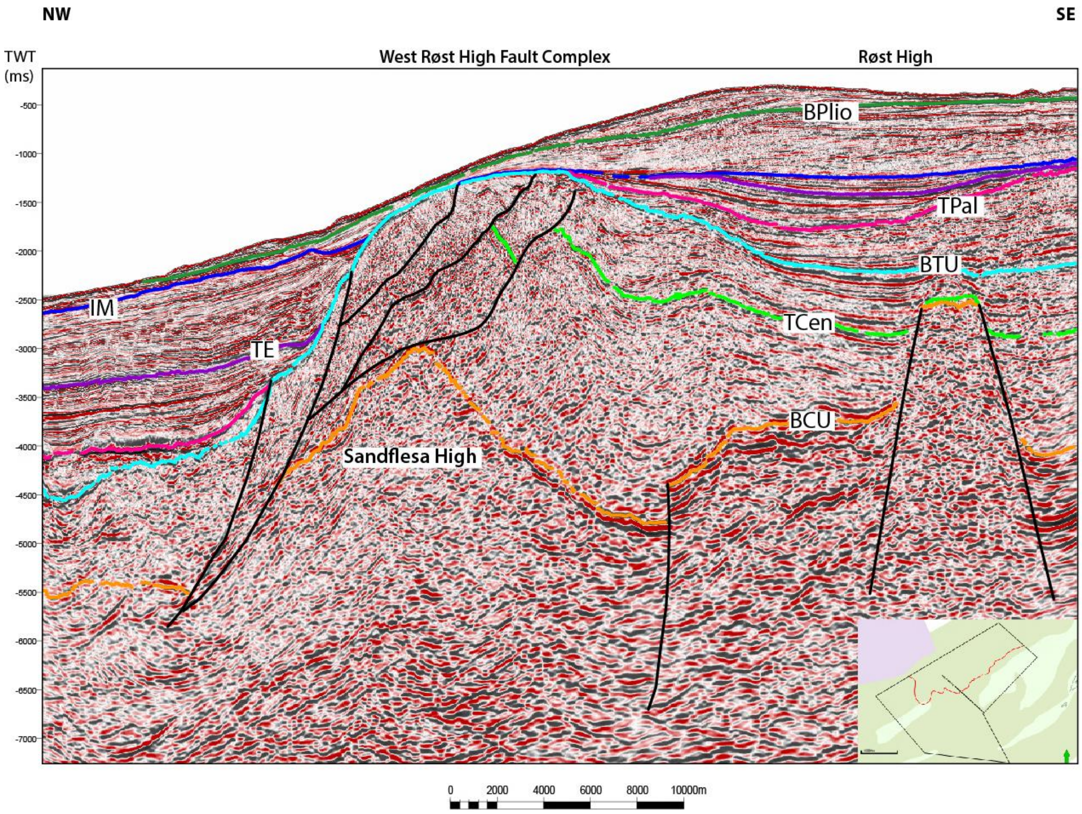


Fig. 4.24: *Seismic profile AMR_RHW96-118 illustrating the Sandflesa High as an elevation of the BCU reflector beneath the West Røst High Fault Complex. Horizon abbreviations in Table 4.1.*

5 Discussion

5.1 Southern Lofoten and northern Vøring margins: Cretaceous to Cenozoic tectono-stratigraphic evolution

The southern Lofoten and northern Vøring margins are dominated by extensional fault systems, as a result of multiple rift phases. Fault distribution is also confirmed by gravity and magnetic anomaly data (Fig. 4.22). Potential field data show that major border faults coincide with the edges of strong positive elongated anomalies.

Numerous faults have been active at different stages. Footwall erosion makes it difficult to determine the exact age of the faults. In addition, there are disagreements among the different workers on the exact timing of the various rift phases. This study builds and expands on earlier mapping in the area by Tsikalas et al. (2001), Mjelde et al. (2003), Ren et al. (2003), Faleide et al. (2008), Eig and Bergh (2011), Færseth (2012), Hansen et al. (2012), Tsikalas et al. (2012), and Henstra and Rotevatn (2014). Based on the current study, there is evidence of four tectonic events within the southern Lofoten and northern Vøring margins:

1. Late Jurassic-earliest Cretaceous
2. mid Cretaceous (Aptian-Albian)
3. Late Cretaceous
4. Paleocene, leading to lithospheric breakup and initiation of seafloor spreading at the Late Paleocene-Early Eocene transition

The following sub-chapters attempt to shed light on the tectono-stratigraphic evolution of the southern Lofoten and northern Vøring margins. In this context, the interplay between the tectonic activity and resulting sedimentary deposition is a key issue to decipher. This was done by examining thickness variations across faults, in addition to using time-thickness maps as a means to illustrate the lateral thickness variation of sequences and the tectono-stratigraphic evolution through time. Seismic sections are used to illustrate detailed observations. Furthermore, understanding the role of the Bivrost Lineament during

Cretaceous and Cenozoic times contributes to the understanding of the regional evolution of the area.

5.1.1 Late Jurassic-earliest Cretaceous tectonic episode

The Late Jurassic-earliest Cretaceous tectonic episode is the most prominent seismically resolvable tectonic episode that has shaped the Norwegian continental shelf (Faleide et al., 2008). Several NE-SW trending normal faults are the result of the Late Jurassic-earliest Cretaceous rifting that is well-defined on the southern Lofoten margin, mainly in the vicinity of the Utrøst Ridge. Figures 5.1 and 5.3 show a faulted BCU horizon, indicating Late Jurassic-earliest Cretaceous rifting that has shaped the Utrøst Ridge. Most of the Late Jurassic-earliest Cretaceous faults offset BCU and terminate within the S1 sequence, further confirming the time of the rifting. The extent of the faults can be seen in Figure 5.2. Several smaller faults are connected to the larger faults, and mainly appear near structural highs, coinciding with positive anomalies shown in the potential field data (Fig. 4.22). The smallest mapped faults reach throws of ~100 ms.

Border faults are generally observed with curvilinear orientation, and coincide well with the edges of strong positive elongated gravity and magnetic anomalies that represent basement highs. The Røst High/Utrøst Ridge is separated from the Røst Basin by a border fault with the largest throw exceeding ~3000 ms (~15 km) (Fig. 4.20). This particular fault has been mapped for approximately a distance of ~130 km.

5.1.2 Early Cretaceous

Seismic sequence S1

Sequence S1 exhibits wedge-shaped growth strata in both the Røst Basin and the northern Træna Basin. Chaotic and transparent reflections can be seen near the fault-plane on the western side of the Røst High/Utrøst Ridge. There is no apparent onlap to the fault-plane, even though the reflections show a more dragged character (Fig. 5.1). On the western side of the Røst High/Utrøst Ridge, the sequence exhibits a wedge-shape character with subparallel internal configuration and reflections that appear to be dragged along the fault-plane. On the eastern side of the Røst High, sequence S1 is located on top of rotated fault blocks. In summary, sequence S1 shows syn-rift depositional character in both the eastern and western sides of the Utrøst Ridge (Fig. 5.1). The sequence is absent on the Utrøst Ridge (Fig. 5.7), probably due to Middle/Late Jurassic footwall uplift of the fault-blocks that comprise the ridge, thus limiting available accommodation space. The greatest accumulation of the sequence is seen west of the Røst High, where it forms a local depocenter. This is also the area with the greatest thickness variations, thus revealing the existence of Lower Cretaceous basin infill deposited in a syn-rift basin (Figs. 5.1-5.3).

The Jurassic sequence below contains shallow marine and deltaic sandstones, overlain by clays deposited during the Middle-Late Jurassic transgression (Hansen et al., 2012). A shift towards a shelf depositional environment, together with Early Cretaceous subsidence resulted in the main infill of sediments in the extensional basin (Tasrianto and Escalona, 2015). While erosion took place on the highs at the same time as subsidence took place in the basins, it is reasonable to believe that the uplifted Røst High/Utrøst Ridge was a likely source area for the Lower Cretaceous basin infill.

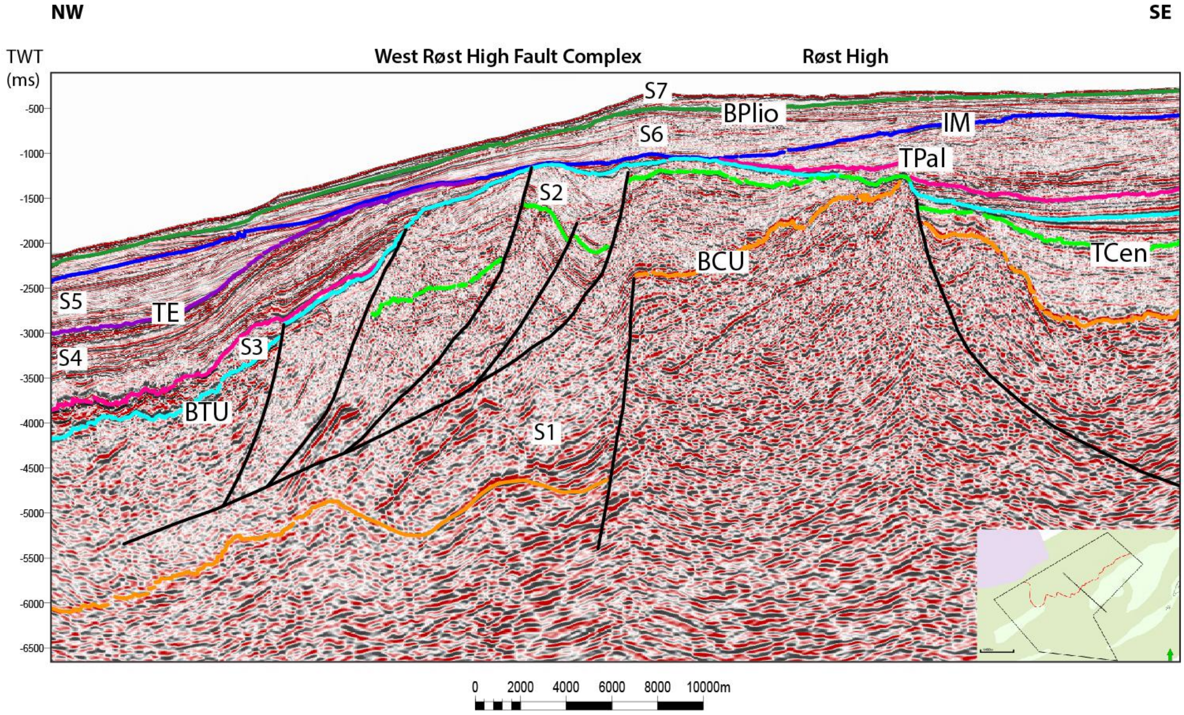


Fig. 5.1: *Seismic profile AMR_RHW96-114 illustrating major interpreted faults in the West Røst High Fault Complex and the Røst High. Horizon abbreviations in Table 4.1.*

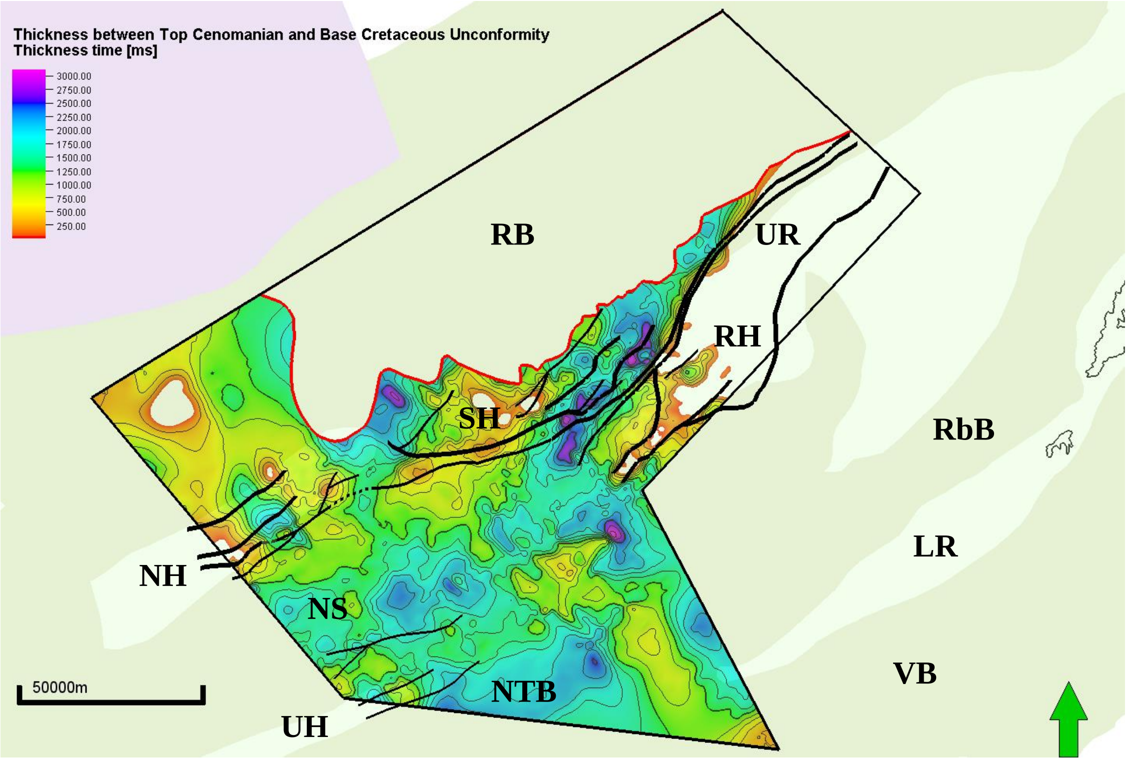


Fig. 5.2: *Time-thickness map of the S1 sequence (Early Cretaceous: BCU to TCen) (contour interval 250 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The NPD structural element outline is included in the background for comparison. RB: Røst Basin, RH: Røst High, UR: Utrøst Ridge, SH: Sandflesa High, NH: Nyk High, UH: Utgard High, NS: Någrind Syncline, NTB: northern Træna Basin, VB: Vestfjorden Basin, LR: Lofoten Ridge, RbB: Ribban Basin.*

Mid Cretaceous rift phase

The upper part of seismic sequence S1 represents the onset of a mid Cretaceous Aptian-Albian rifting event (Figs. 4.1 and 5.3). The sequence exhibits wedge shaped strata across faults, indicating a growth sequence. The rifting event resulted in NE-SW trending normal faults that are especially well-defined in vicinity of the Utrøst Ridge. Lateral thickening of sequences across faults towards west is evident especially in the southwestern Røst High (Figs. 5.1 and 5.3). Deposition of these sequences is interpreted to have started during mid Cretaceous. The mid Cretaceous tectonic event is interpreted to have experienced only moderate rifting activity. Faulting did, however, continue during Late Cretaceous rifting.

5.1.3 Late Cretaceous

The majority of faults in the study area exhibit a listric character, with a planar upper part of the fault that gradually curves into a more low-angle fault-plane with depth (Figs. 5.1 and 5.3). Based on the conducted seismic and structural interpretation these faults are interpreted to be Late Cretaceous in age. The Top Cenomanian reflector is strongly faulted, indicating

Late Cretaceous rifting (Fig. 5.3). The lower part of a listric fault often soles out to a detachment/décollement plane, where several synthetic faults detach at depth. Synthetic faults have the same dip as the main fault, while antithetic faults have an opposite dip from the main fault. Listric faults often indicate large-scale tectonism and displacement, associated with long-lasting faulting activity (Lister et al., 1991; Blaich et al., 2011). Continuous faulting often leads to generation of detachment in two possible ways. A detachment can be formed by low-angle faulting, or as a result of rotation of initially high-angle normal faulting. The latter evolution is suggested for the study area, which exhibits basement highs that control fault nucleation and propagation (Fig. 4.24). In addition, low-angle faults lead to rotation of fault-blocks (Fig. 5.3).

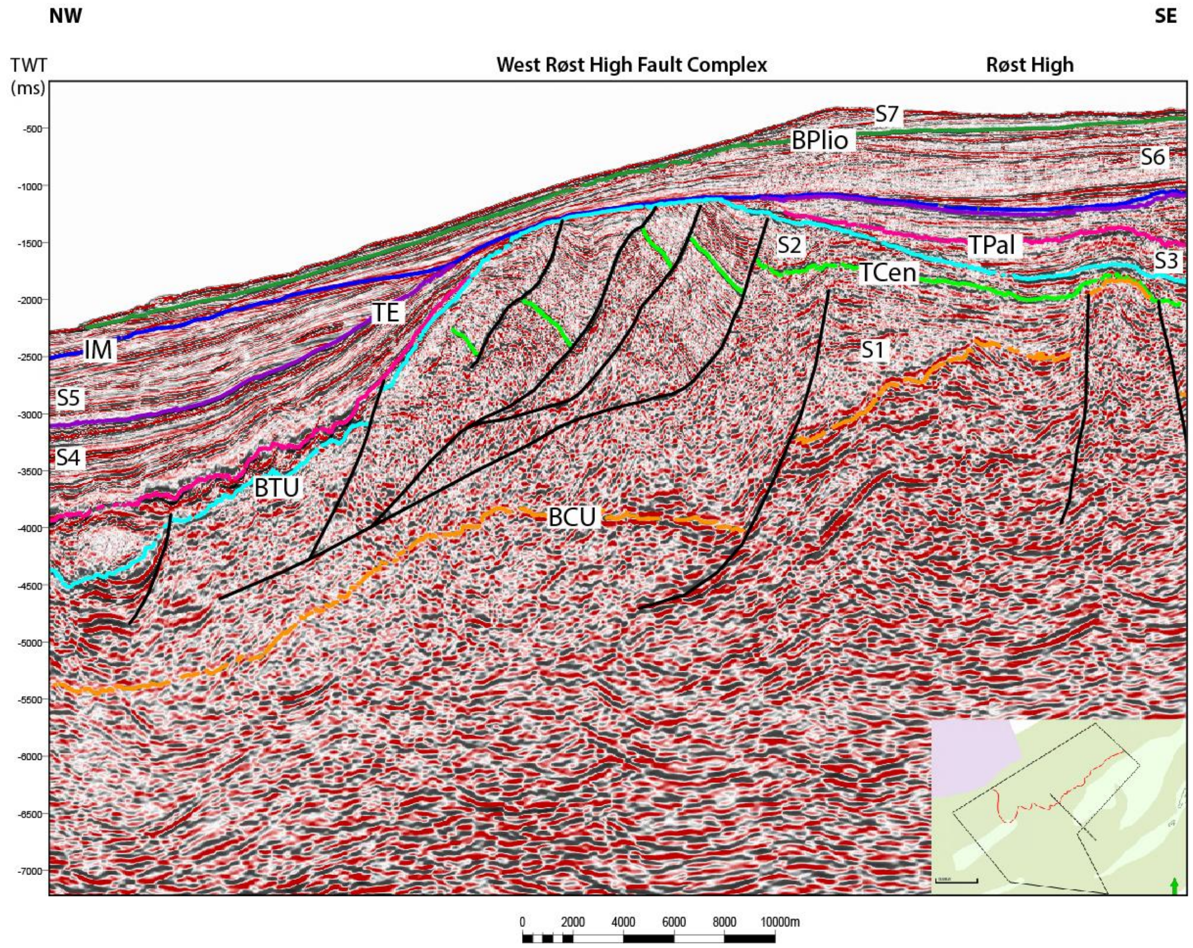


Fig. 5.3: *Seismic profile AMR_RHW96-116 illustrating faults in the West Røst High Fault Complex and the Røst High. Horizon abbreviations in Table 4.1.*

Seismic sequence S2

Seismic sequence S2 represents the Late Cretaceous sedimentary succession. Within the time interval of the sequence the onset of a Late Cretaceous rift event took place resulting in NE-SW trending normal faults (Fig. 5.4). The events are especially well-defined in the West Røst High Fault Complex, southwest of the Røst High/Utrøst Ridge. The lower boundary of the sequence, the Top Cenomanian reflector, is strongly faulted, while the upper boundary, the Base Tertiary Unconformity (BTU) reflector, is only slightly faulted (Fig. 5.3). In, addition, it is possible to see lateral thickness variations across faults. These observations provide evidence for major fault activity during Late Cretaceous. There is a possibility that BTU, with its erosional character, has obliterated large parts of the West Røst High Fault Complex, and with that masking evidence of the full extent of Late Cretaceous rifting.

Although the Hel Graben is one of the areas with least confidence for the interpreted Top Cenomanian horizon, it is likely that this is where the greatest accumulation of sequence S2 can be found. Otherwise, the thickest sedimentary successions can be found in the Någrind Syncline and the northern Træna Basin. The sequence pinches out and disappears towards the Røst High/Utrøst Ridge, indicating Late Cretaceous uplift of the ridge (Fig. 5.4) (NPD, 2010).

The Upper Cretaceous sequence is hundreds of meters thick south of the Røst High/Utrøst Ridge and on the northern Vøring margin, and consists mainly of outer shelf clays and siltstones (NPD, 2010; Hansen et al., 2012). This indicates segmentation in the study area; the southern Lofoten margin was uplifted, while the northern Vøring margin had adequate accommodation space to store a thick Upper Cretaceous sequence.

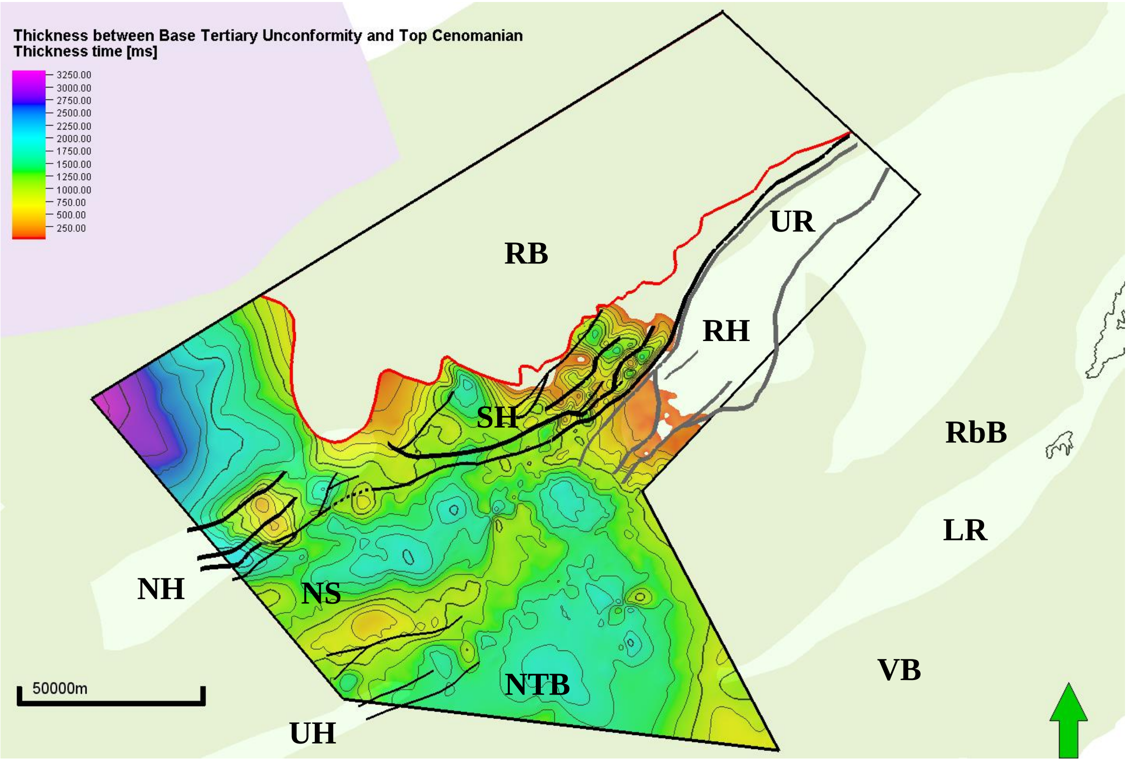


Fig. 5.4: *Time-thickness map of the S2 sequence (Late Cretaceous: TCen to BTU) (contour interval 200 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

5.1.4 Paleogene

Seismic sequence S3

Seismic sequence S3 exhibits evidence of Paleocene rifting (Fig. 5.3). The lower boundary of the sequence, the Base Tertiary Unconformity (BTU), is faulted on the West Røst High Fault Complex and the outer Lofoten margin. The faulted BTU indicates a likely reactivation of faults during Paleocene. Wedge-shaped growth strata that thicken to the west suggest a westward migration of fault activity. In addition, the wedge shape confirms that the sequence represents syn-rift deposits. Furthermore, seismic sequence S3 exhibits evidence of the onset of seafloor spreading at the Paleocene-Eocene transition (~55 Ma). Seafloor spreading between Norway and Greenland was accompanied by massive, igneous activity (Eldholm et al., 2002). The events are best defined on the outer Lofoten margin. The sequence exhibits evidence of NE-SW trending faults, and the largest throws are found near the edge of the landward breakup lava boundary (Figs. 4.20 and 5.3). Several magmatic intrusions are embedded within sequence S3 and the bottom of the sequence, the Top Paleocene horizon, coincides with the top of breakup lavas on the outer Lofoten margin.

The Paleocene sequence contains mainly upper slope to inner shelf sandstones and claystones in shallowing upward sequences (Fig. 4.1) (Hansen et al., 2012; Tasrianto and Escalona, 2015). The thickest accumulations of the sequence are found in the Någrind Syncline and the northern Træna Basin. A Paleocene wedge pinches out and disappears towards the Røst High/Utrøst Ridge and towards the northern part of the study area. Differences in sequence thickness between the northern Vøring and southern Lofoten margins indicate segmentation in the study area, and confirm that the southern Lofoten margin was uplifted, while basins on the northern Vøring margin still had adequate accommodation space to store thick successions of Paleocene sediments. Paleocene deposits were probably sourced from the elevated Røst High/Utrøst Ridge.

Indications of a dome-like feature/structure can be seen in the Bivrost Lineament area (Dome 1, Figs. 5.5-5.6). The feature/structure is surrounded by local depocenters in southwest and southeast, and a slight doming shape of the Top Paleocene reflector is observed on seismic sections (Fig. 5.5).

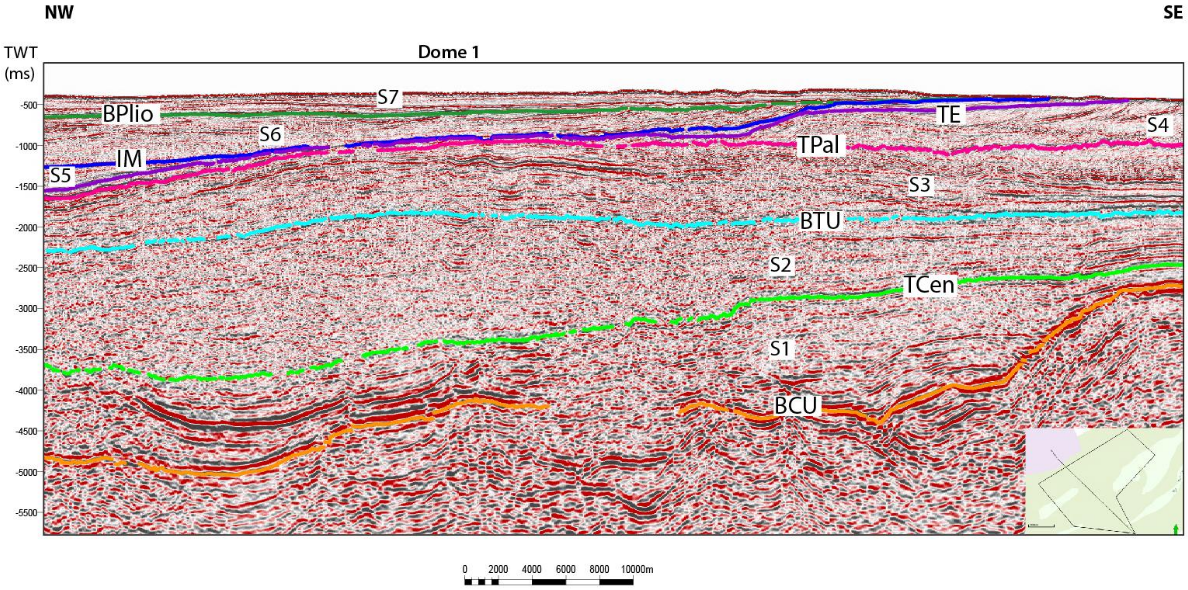


Fig. 5.5: *Seismic profile AMR_TBN96-115 illustrating a slight doming shape of sequence S3 in the Bivrost Lineament area. Horizon abbreviations in Table 4.1.*

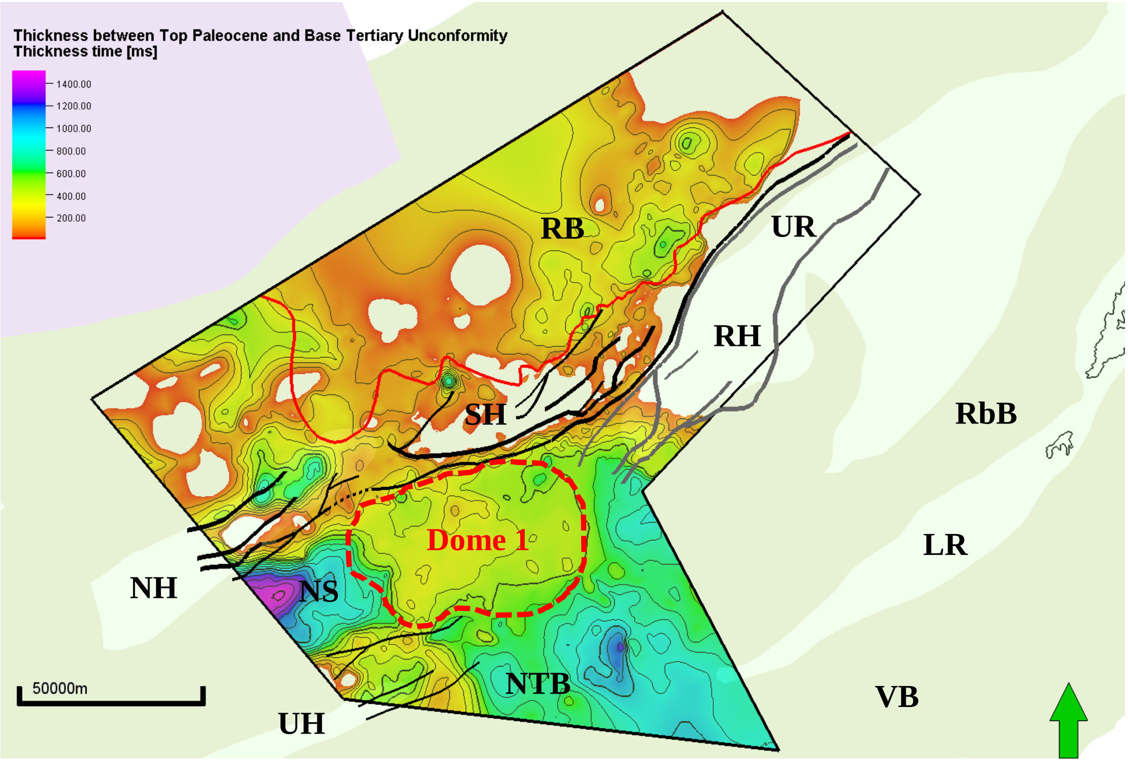


Fig. 5.6: Time-thickness map of the S3 sequence (Paleocene: BTU to TPal) (contour interval 100 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The red stippled line indicates the location of Dome 1. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.

Seismic sequence S4

Seismic sequence S4 comprises sediments deposited after the margin started developing into a passive continental margin. The sequence consists mainly of upper slope to inner shelf claystones and sandstones in shallowing upward sequences (Fig. 2.5) (Hansen et al., 2012; Tasrianto and Escalona, 2015). Reflections downlap the Paleocene sequence and a clear onlap to BTU is observed on the outer Lofoten margin (Fig. 5.7). Clinoforms with high seismic amplitude are observed west of the Røst High/Utrøst Ridge, indicating sediment supply from east, possibly sourced from the Utrøst Ridge (Figs. 5.7-5.6). The sequence has an elevated (slightly dome-shape) character in the Bivrost Lineament area (Dome 1, Figs. 5.5 and 5.8). In addition, a dome shape is observed on the outer Lofoten margin (Dome 2, Figs. 5.7-5.8), which can possibly indicate evidence of compression affecting in the area. There is a depocenter located in the Røst Basin west of the assumed dome on the outer Lofoten margin (Dome 2, Fig. 5.8).

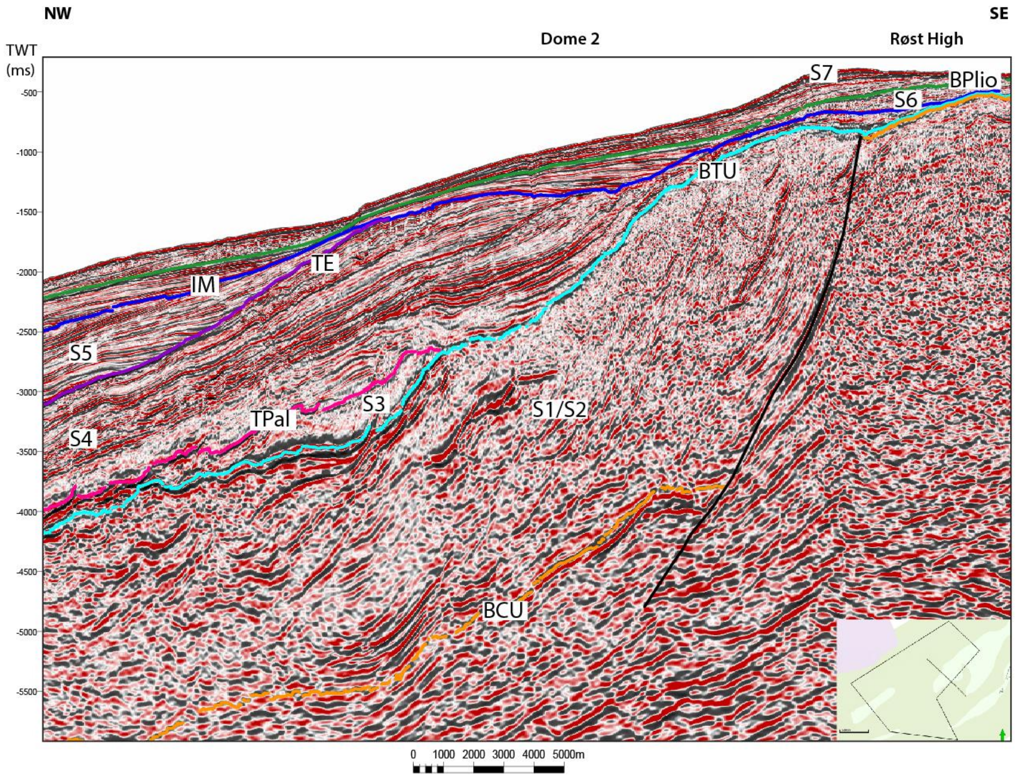


Fig. 5.7: *Seismic profile AMR_RHW96-108 illustrating a doming shape of sequence S4 on the western side of the Røst High. Horizon abbreviations in Table 4.1.*

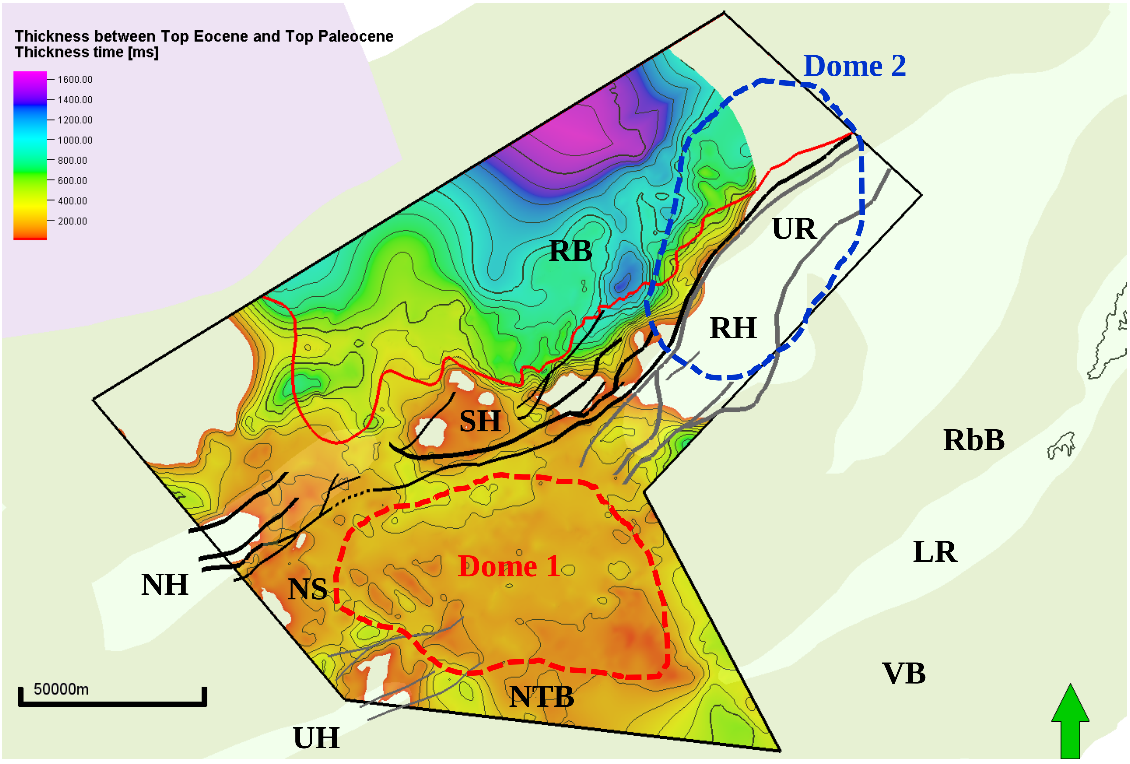


Fig. 5.8: *Time-thickness map of the S4 sequence (Eocene: TPal to TE) (contour interval 100 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The stippled lines indicate the dome locations. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

Although seismic coverage in the Røst Basin is sparse, the interpretation still implies that the thickest accumulation of the sequence can be found here (Fig. 5.8). The thinnest accumulation of the sequence can be seen in the Bivrost Lineament area, and on the northern Vøring margin. The sequence is subcropping close to the seafloor in the eastern part of the study area (Fig. 5.5). In addition, reflectors are top-lapping the Top Eocene reflector in most parts of the study area, making it an angular unconformity (Fig. 5.1). These observations possibly suggest subsidence on the outer Lofoten margin, combined with possible uplift along the inner margin during Eocene time.

Seismic sequence S5

Seismic sequence S5 consists of Oligocene to earliest Miocene sediments containing mainly upper slope to inner shelf claystones and sandstones in shallowing upward sequences (Fig. 2.5). The sequence consists of gently dipping clinoforms with increasing high seismic amplitude towards the top, which can point to an increasing sand content. Clinoforms onlap the Top Eocene reflector, indicating an uplift that was already ongoing in late Eocene and which also continued throughout Oligocene (Fig. 5.7).

The thickest accumulation of the sequence is found in the Røst Basin (Fig. 5.9), while the sequence thins toward the Røst High/Utrøst Ridge and the northern Vøring margin. Furthermore, the sequence is subcropping close to the seafloor in the western part of the study area (Fig. 5.5). The sequence is also eroded along parts of the northern Vøring margin and the Røst High/Utrøst Ridge (Fig. 5.7), exhibiting further evidence of margin uplift. The eroded highs could be the source of Oligocene sediments, and together with the observed clinoforms and the time-thickness map indicate possible sediment source areas in the east (Figs. 5.7 and 5.9). The sequence toplaps the Intra Miocene reflector, making it an angular unconformity (Fig. 5.7). Toplaps indicate that the sediments were eroded, probably in a shallow marine environment, as a result of Oligocene to earliest Miocene uplift. Uplift on the southern Lofoten margin may have been a result of regional uplift combined with some compressional forces, as the sequence exhibits a dome-like character in the vicinity of the Røst High/Utrøst Ridge (Fig. 5.7).

The extensive Røst Basin depocenter seen in Figure 5.8 appears to have become smaller during sequence S5, indicating a contraction of Dome 2 (Fig. 5.9). Figure 5.9 indicates a southward migration of the depocenter, and thus possibly a southward migration of the apex of the dome.

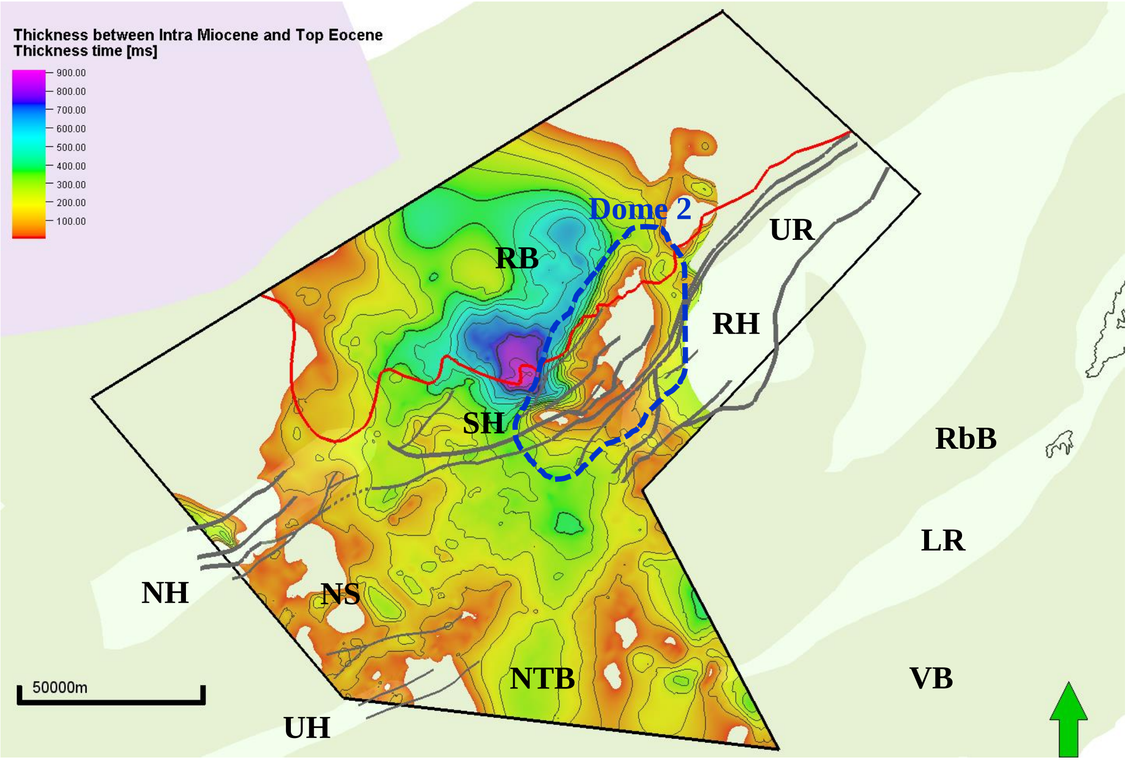


Fig. 5.9: Time-thickness map of the S5 sequence (Oligocene to earliest Miocene: TE to IM) (contour interval 75 ms). Inactive faults are displayed in grey. The blue stippled line indicates the location of Dome 2. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.

5.1.5 Neogene-Quaternary

Seismic sequence S6

The thickest accumulation of the sequence can be found in the Någrind syncline and in the northern Træna Basin (Fig. 5.11). The thinnest part of seismic sequence S6 is seen in the Røst Basin and Røst High/Utrøst Ridge (Fig. 5.7). The sequence consists of gently dipping clinoforms that downlap the Intra Miocene reflector, while the top of the sequence toplaps the Base Plio-Pleistocene reflector (Figs. 5.7 and 5.10b). These observations indicate a mid to late Miocene outbuilding as a consequence of a regional, moderate uplift of Fennoscandia (Faleide et al., 2008). Sequence S6 has been interpreted to originate in a coastal, shallow marine to prograding deltaic depositional environment, probably with strong wave influence (NPD, 2017b). Parts of the sequence are eroded in the northern parts of the study area, in addition to some parts subcropping close to the seafloor in the easternmost parts of the study area (Fig. 5.5). The observations in this study contradict to some extent with the observations of Eidvin et al. (Fig. 5.10) (2007), who suggested that the sequence is up to several hundred meters thick on the Røst High/Utrøst Ridge. Figures 5.11 shows that seismic sequence S6 appears to be very thin and possibly eroded and/or probably bypassed on the southern Lofoten margin because of uplift.

Observations indicate that the southern Lofoten margin has been uplifted to a larger extent in comparison to the northern Vøring margin. This is supported by the southwards migration of the Røst Basin depocenter seen in Fig. 5.6. Another cause for the observed extensive erosion could be the late Plio-Pleistocene glaciations.

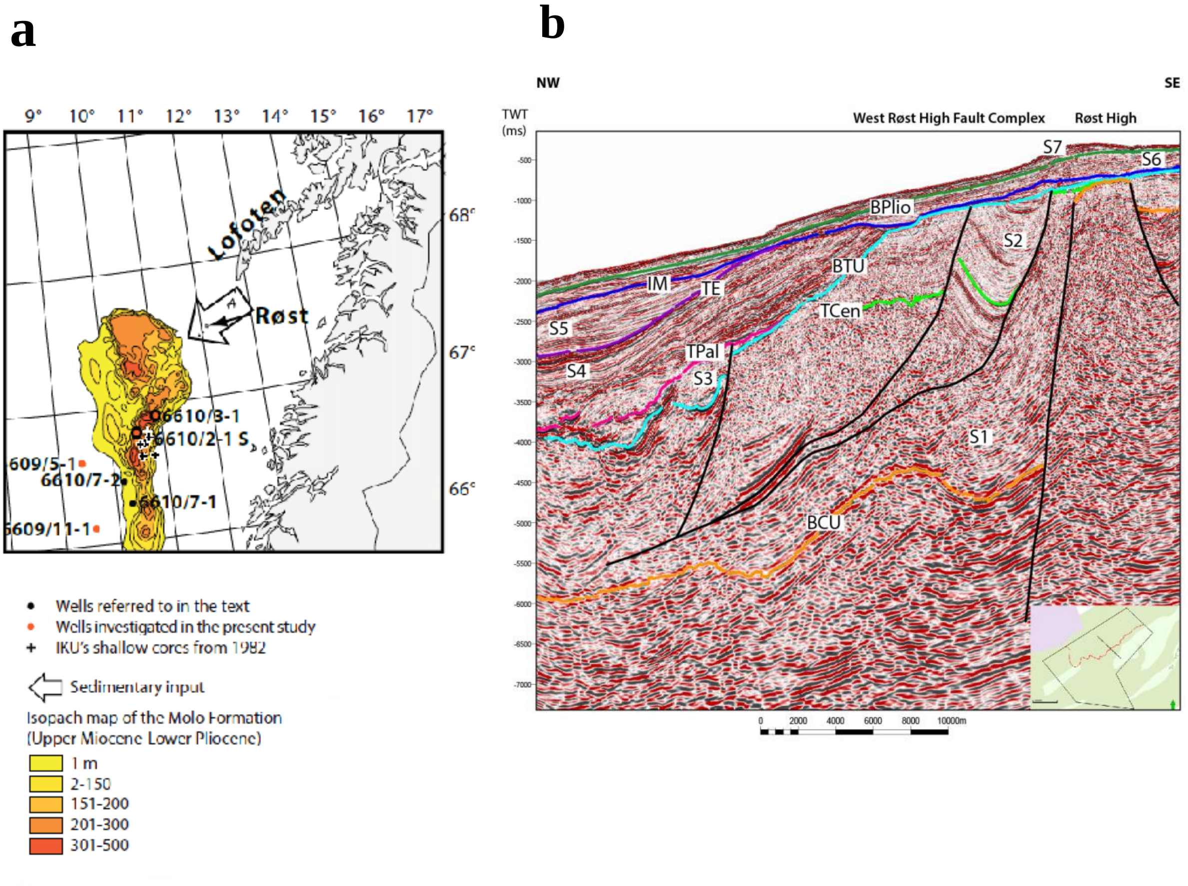


__Fig. 5.10:__ __(a)__ Time-thickness map of the Molo Formation (Eidvin et al., 2007). __(b)__ Seismic profile AMR_RHW96-111 illustrating the Røst High and West Røst High Fault complex. Note that sequence S6 is relatively thin on the Røst High. Horizon abbreviations in Table 4.1.

The extensive Røst Basin depocenter seen in Figure 5.6 appears to have increased in size during late Miocene-Plio-Pleistocene time, indicating a possible growth of Dome 2 (Fig. 5.11). Figure 5.11 indicates a southward migration of the depocenter, and thus possibly a southward migration of the apex of the dome.

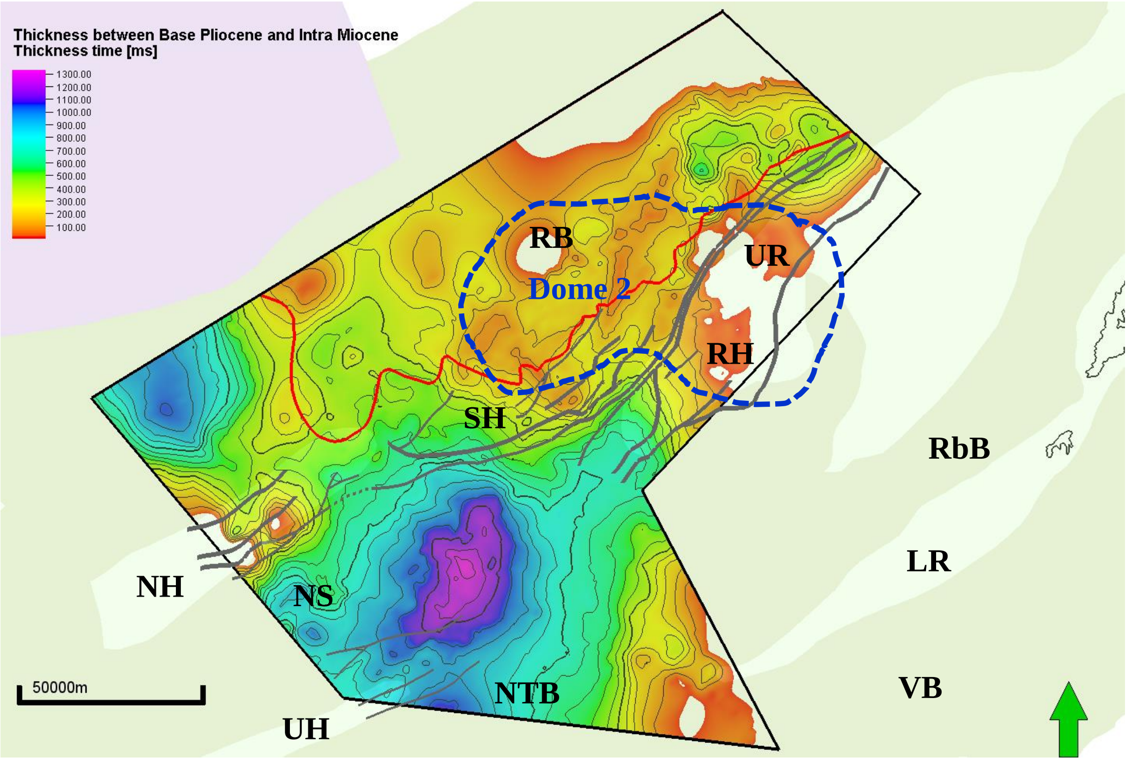


Fig. 5.11: Time-thickness map of the S6 sequence (Miocene: IM to BPlio) (contour interval 75 ms). Inactive faults are displayed in grey. The blue stippled line indicates the location of Dome 2. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.

Seismic sequence S7

Seismic sequence S7 consists of Plio-Pleistocene glacial sediments. The sequence is relatively thin on the southern Lofoten margin (Fig. 5.7), and thickens considerably in the Någrind Syncline on the northern Vøring margin (Fig. 5.12). The sequence has been probably eroded and/or bypassed on the southern Lofoten margin because of uplift, while the lower lying Vøring margin had adequate accommodation space to store a thicker sequence of glacial sediments.

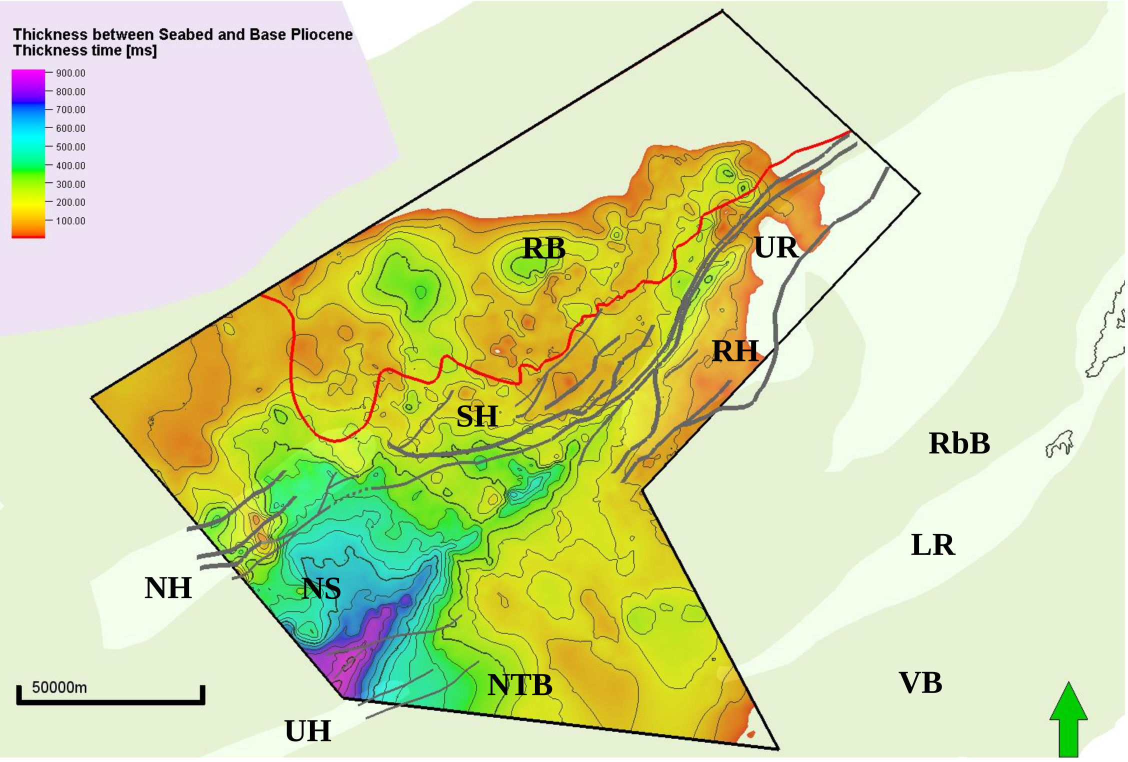


Fig. 5.12: Time-thickness map of the S7 sequence (Plio-Pleistocene: BPlio to seabed) (contour interval 60 ms). Inactive faults are displayed in grey. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.

5.1.6 Bivrost Lineament

The northern Vøring and southern Lofoten margins are separated by the Bivrost Lineament (Blystad et al., 1995; Tsikalas et al., 2005b). The Bivrost Lineament is a major margin boundary with an uncertain exact location, but it represents the shift between the wide and lower lying northern Vøring margin and the more narrow and elevated Lofoten-Vesterålen margin. The Bivrost Lineament segments different highs and sub-basins, and is related with a lateral offset of structural elements (Tsikalas et al., 2005b). In addition, there is a slight shift in the trend of structural elements from NE on the northern Vøring margin to a more NNE trend on the southern Lofoten margin. The Bivrost Lineament also appears to control the northward termination of the Nyk and Utgard highs, in addition to southward termination of border faults on the Røst High/Utrøst Ridge. The BCU time-structure map (Fig. 4.13) implies that the Bivrost Lineament is a low-relief Late Jurassic-Early Cretaceous “corridor” and accommodation zone, which experienced reactivation during Late Cretaceous-Paleocene rifting (Tsikalas et al., 2005b). The segmentation between the highs is supported by potential field data (Fig. 4.22). Furthermore, as it was shown earlier the Bivrost Lineament location exhibits an elevated/dome-shape character during Paleocene (sequence S3, Figs. 5.5-5.6), a slightly elongated depocenter character during Oligocene (sequence S5, Fig. 5.9) that turns into a major depocenter during Miocene (sequence S6, Fig. 5.8). Similarly, Figures 5.2 and 5.13-5.15 show a weak NWW-SEE increased thickness trend filling in the assumed Bivrost corridor.

Blystad et al. (1995) and Doré et al. (1999) favoured a dextral motion along the Bivrost Lineament, and thus a northerly continuation of the Nyk High to the Røst High. Tsikalas et al. (2005b) favoured a sinistral motion along the Bivrost Lineament, and thus a northerly continuation of the Utgard High to the Røst High. This study suggests that both alternatives could be, in a way, feasible. Previously in this chapter, the presence of an Early Cretaceous basin between the Sandflesa High and Røst High/Utrøst Ridge has been pointed out (Fig. 5.2). Therefore, it is suggested that the northern continuation of the Nyk High could be the Sandflesa High below the West Røst High Fault Complex. The northern continuation of the Utgard High is proposed to be the Røst High/Utrøst Ridge. The highs are separated by the Någrind Syncline on the northern Vøring margin, and the suggested northward continuation is the Early Cretaceous basin separating the Sandflesa High and the Røst High/Utrøst Ridge.

Observations indicate a possibly more NWW-SEE trend of the Bivrost Lineament than previously suggested, in contrast to previous work by among others Olesen et al. (2002) who suggested that the lineament most likely represented a folded detachment gently dipping 5-15° to the southwest.

Hansen et al. (2012) have previously related Early to Middle Jurassic uplift of the Lofoten-Vesterålen margin to the proto rift stage, resulting in doming and uplift caused by increased heat flow during rift initiation and prior to faulting. This has led to the suggestion that the Bivrost Lineament represents an old weakness zone that was periodically active since the collapse of the Caledonian Orogeny (Mjelde et al., 2003). The crust was thinned because of post-Caledonian rifting, making the area receptive to the influence of possible increased heat flow. The Bivrost Lineament area exhibits a dome-shape character during Paleocene (Dome 1, Figs. 5.5-5.6), that appears to reach its maximum dimension at the onset of seafloor spreading (Fig. 5.8). This has led to the suggestion that the Bivrost Lineament was possibly represented by a rift dome in the Early Cenozoic that controlled the onset of Eocene spreading geometry.

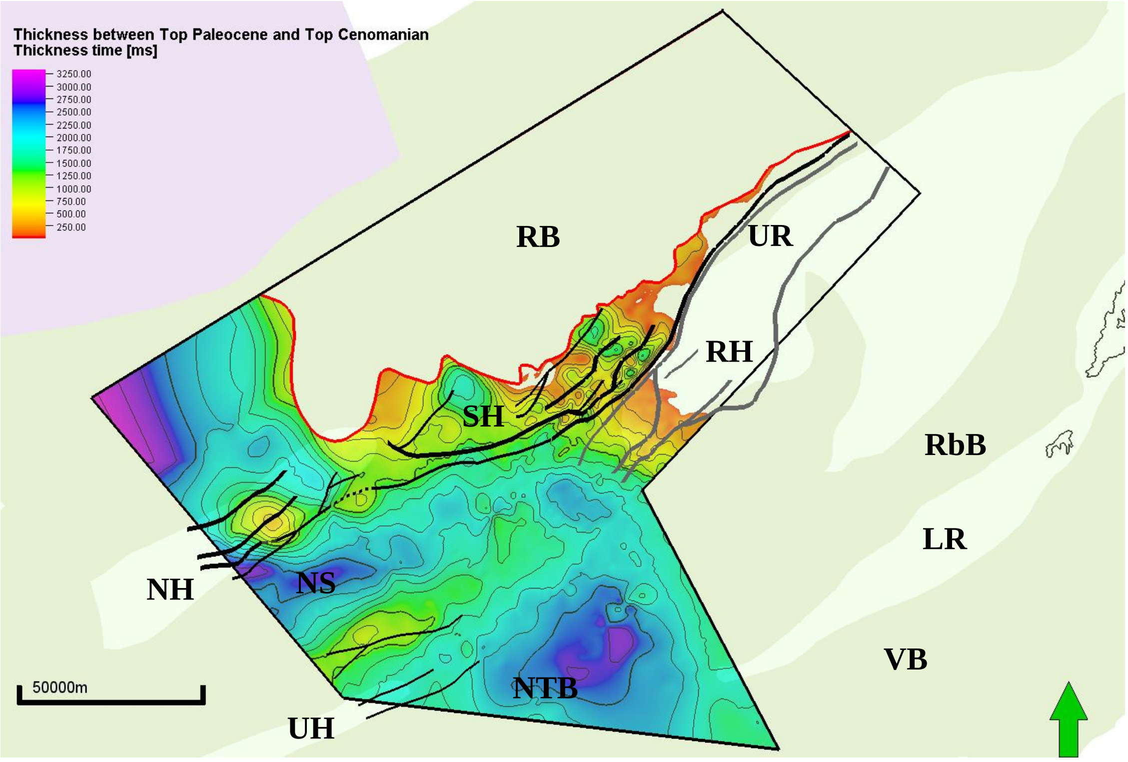


Fig. 5.13: *Time-thickness map of the S2-S3 sequences (Late Cretaceous to Paleocene: TCen to TPal) (contour interval 250 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

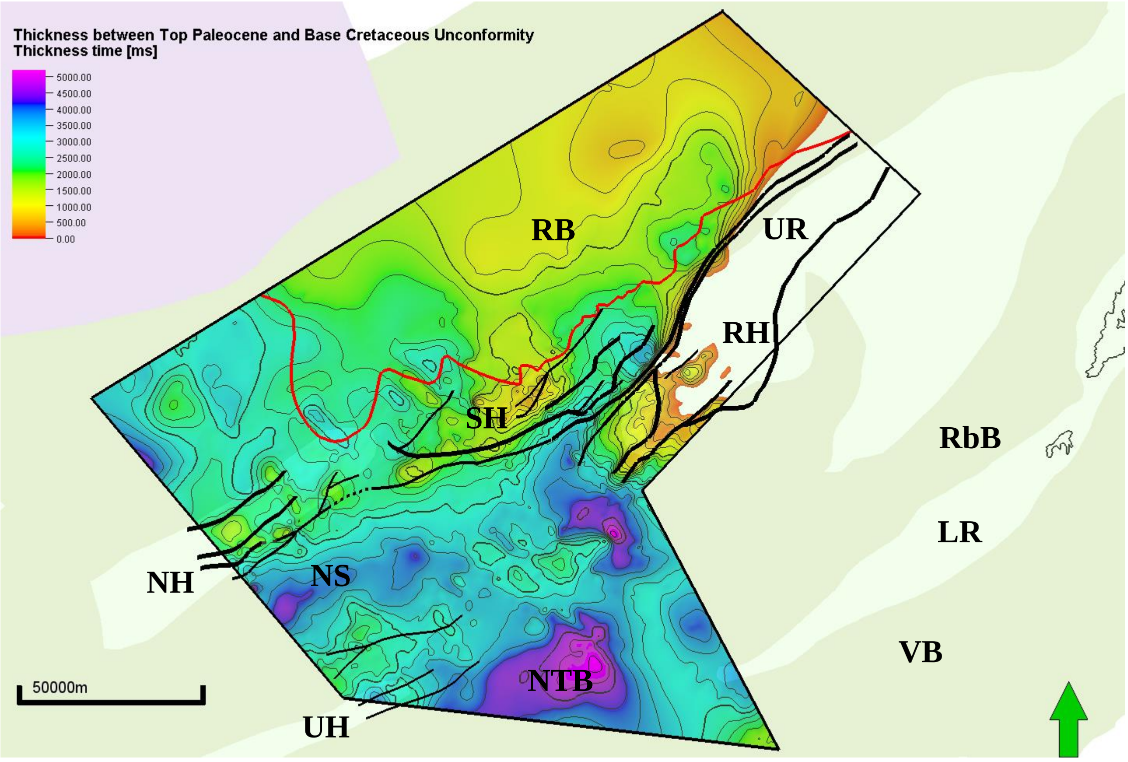


Fig. 5.14: *Time-thickness map of the S1-S3 sequences (Cretaceous to Paleocene: BCU to TPal) (contour interval 300 ms). All active faults are illustrated in black. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

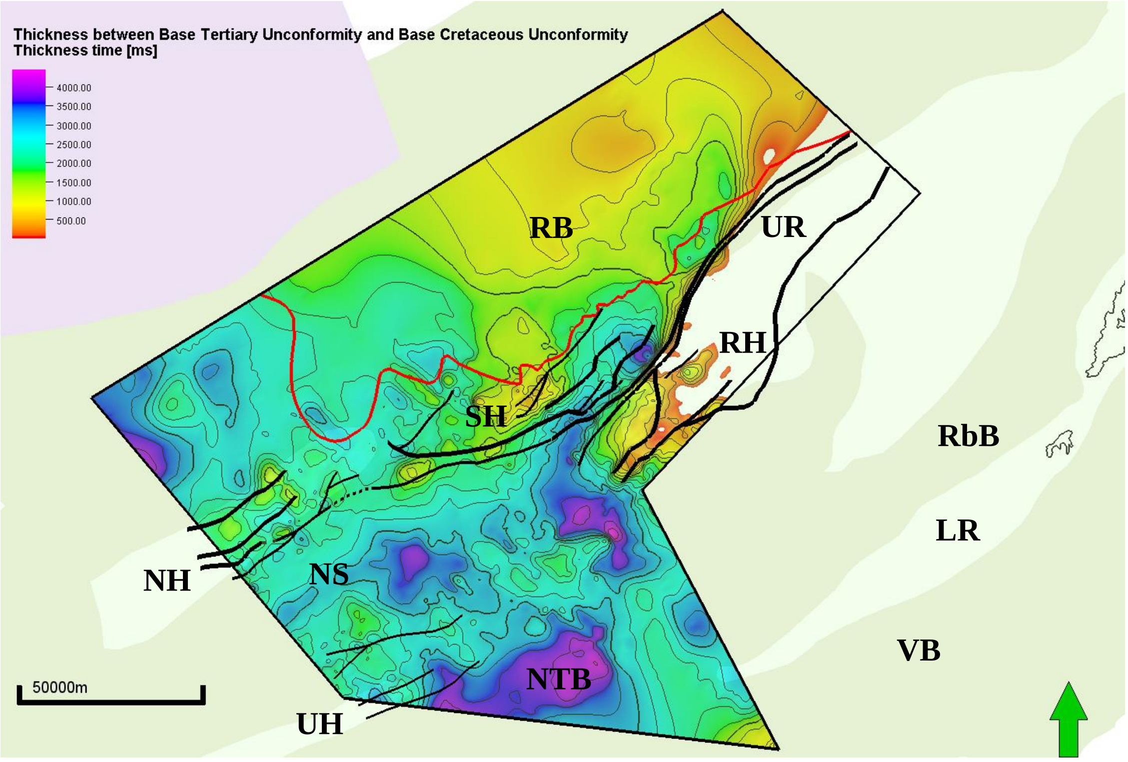


Fig. 5.15: *Time-thickness map of the S1-S2 sequences (Cretaceous: BCU to BTU) (contour interval 300 ms). All active faults are illustrated in black. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

5.2 West Røst High Fault Complex: tectono-stratigraphic evolution

The West Røst High Fault Complex was initiated with the formation of the Cretaceous depocentre west of the Røst High/Utrøst Ridge. The main subsidence phase in the area took place during Early Cretaceous, giving rise to the deposition of thick sedimentary strata in the extensional basins (Fig. 5.2) (Tasrianto and Escalona, 2015). Erosion took place at the highs at the same time as subsidence took place in the basins, and parts of the basement and sedimentary rocks were eroded (NPD, 2010). Erosion is assumed because uplifted fault-blocks show distinct erosional character (Figs. 5.1, 5.3 and 5.16), making it likely that eroded sediments became part of the Lower Cretaceous basin infill. Faults A, B and C are evidence of the Late Jurassic-earliest Cretaceous rifting episode that shaped the Røst High/Utrøst Ridge (Fig. 5.16).

Detailed seismic correlations and structural interpretation has been performed within the West Røst High Fault Complex in an effort to decipher the imposed Cretaceous and early Cenozoic rift phases. In this context, Table 5.1 was constructed to depict, through lateral thickness variations across the faults, the fault activity at the various rift phases/stages. Several of the detailed observations are described below.

In particular, fault F1 in Fig. 5.16 is believed to be, relatively, the first fault initiated during the mid Cretaceous rift phase. To the west of fault F1, layer-1 ("violet" raster) and layer-2 ("orange" raster) (Fig. 5.16) show some thickening from southeast to northwest. Deposition of these layers is interpreted to have started during the mid Cretaceous rift phase, with the fault still being active during Late Cretaceous. It is difficult to see lateral thickness variations across faults for layer-5 ("blue" raster), as it is draped by the erosional Base Tertiary Unconformity (BTU). Fault F1 experienced some reactivation during Paleocene rifting, as BTU is slightly faulted. Continuous faulting led to the formation of a detachment/décollement plane, with the fault-plane propagating sub-parallel to the BCU. Soling out of the fault at deeper levels led to rotation of fault-blocks.

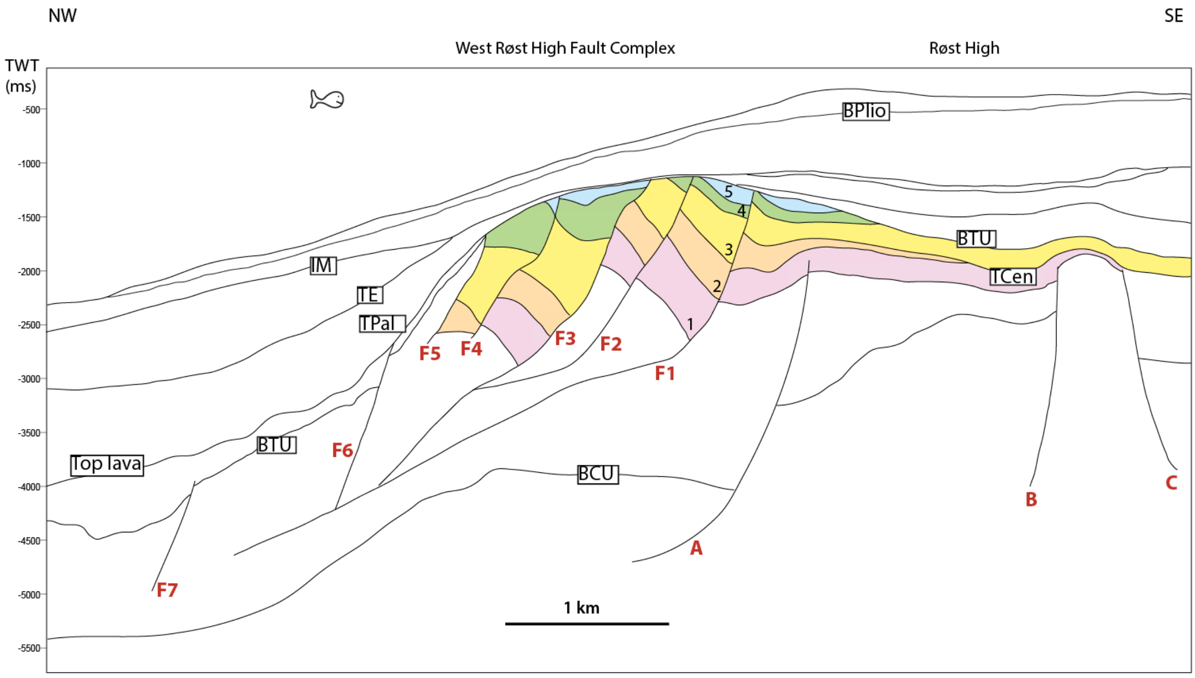


Fig. 5.16: *Interpreted AMR_RHW96-116 seismic profile illustrating detailed structural interpretation and relative fault timing across the West Røst High Fault Complex.*

Layer-1 (“violet”) and layer-2 (“orange”) show only minor thickness variations across faults F2 and F1, indicating that these faults were initiated during the mid Cretaceous rift phase, although fault activity was only modest to moderate. Both faults were active in Late Cretaceous, with fault F3 exhibiting the largest thickness variations imaged across faults in the area (layer-4, “green”, and layer-3, “yellow”; Fig. 5.16). A westward migration of fault activity is seen already from fault F1 to fault F3. Both faults slightly offset BTU, providing evidence of a reactivation during Paleocene.

Late Early/mid Cretaceous rifting is possible for fault F5, although strong evidence is lacking. Fault F4 does, however, show slight thickness variations across faults for layer-2 (“orange”) layer, indicating some activity during the late Early/mid Cretaceous rift phase (Fig. 5.16). There is no evidence of fault activity for fault F5 during Late Cretaceous, as following the sequence all the way through the fault complex is challenging. On the contrary, fault F4 exhibits large fault throw during Late Cretaceous, and reactivation in Paleocene. Furthermore, fault F7 offsets the BTU reflector (Fig. 5.16). This, in addition to the wedge-shaped Paleocene sequence, indicates that this fault was generated during Paleocene. Furthermore, fault F6 also appears to be an early Cenozoic fault, as the fault throw offsetting BTU is considerable. There is a possibility that fault F6 reactivated pre-existing structures as seen on the northwest side of the Sandflesa High in Figure 4.24. This is, however, highly uncertain for the interpreted AMR_RHW96-116 seismic profile in Figure 5.16, as seismic imaging is not of the best quality beneath the breakup lava on the outer Lofoten margin.

The West Røst High Fault Complex is mainly characterised by NE-SW trending and west-dipping normal faults (Fig. 5.16). Faults are steep in the upper part of the fault complex, and sole out in the deeper parts at a detachment/décollement plane. As previously mentioned, continuous faulting can lead to two possible detachment evolutions. The faults in the fault complex are believed to have started as steep planar normal faults that rotated because of the presence of the Sandflesa basement high underneath, as the latter appears to have affected and controlled fault propagation patterns in the fault complex. At locations where there is a more prominent basement high this makes the detachment/décollement plane to be more rotated and become more low-angle, and thus increasing the internal rotation of Cretaceous fault-blocks. On the contrary, at locations where there is a less prominent basement high this makes the plane propagate sub-parallel to the underlying BCU reflector.

The Base Tertiary Unconformity, with its strong erosional surface character, drapes the West Røst High Fault Complex. This means that the fault complex was uplifted during Late Cretaceous and early Cenozoic. Small-scale antithetic faults are indicative of a possible compressional/transpressional tectonic event. Possible causes of compressional deformation for the southern Lofoten margin are mentioned in sub-chapter 5.3. Early Cenozoic erosion affects both the footwall and hanging-wall, making it reasonable to assume that Late Cretaceous faults could have been more pronounced than what is evident in seismic profiles at present. The BTU reflector appears slightly faulted at the West Røst High Fault Complex, indicating Paleocene-Eocene reactivation of Cretaceous faults. BTU exhibits only minor fault-throws above the fault complex, with throws increasing towards the outer Lofoten margin and the landward breakup lava boundary.

It appears that fault-throw displacements for the faults in the West Røst High Fault Complex, in general, increase towards south and west. This may indicate a migration of fault activity towards the outer Lofoten margin. In addition, faults become steeper towards west, and mainly the faults that are associated with Paleocene rifting. The faults with a clear Paleocene affinity are located west of the West Røst High Fault Complex. The Sandflesa High is located east of the landward breakup lava boundary, giving room for the Paleocene faults to propagate towards the basement and permits them to possibly cross-cut the BCU reflector, which is illustrated in Figure 4.24. This means that Paleocene faults are in some areas, most likely, reactivating Late Jurassic-earliest Cretaceous faults, contributing in this way to a late phase tectonic activity at the West Røst High Fault Complex. The fault complex must have been formed before initiation of seafloor spreading at the Paleocene-Eocene transition, as the breakup lava cannot flow uphill.

In summary, the West Røst High Fault Complex consists of Lower Cretaceous basin infill in the lower parts of the complex, overlain by Upper Cretaceous syn-rift deposits. Several faults experience multiple rift phases giving evidence for four rift phases: Late Jurassic-earliest Cretaceous, mid Cretaceous, Late Cretaceous, and Paleocene rifting. Fault-throw displacements increase towards the outer Lofoten margin, indicating a westward migration of fault activity that culminated with the Late Paleocene-Early Eocene continental breakup and subsequent seafloor spreading.

Table 5.1: *Summary of interpreted faults indicative for the West Røst High Fault Complex (Fig. 5.16), and associated rift activity/phases. The size of "X"/"x" indicates major against minor tectonic activity, respectively.*

Sequences	**Faults**										**Main phase**
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**A**	**B**	**C**	
Blue: Late Cretaceous-Paleocene	x	x	x	x	x	X	X				Late Cretaceous and Paleocene
Green: Late Cretaceous		x	X	X							Late Cretaceous
Yellow: Early Late Cretaceous	x	x	X	X							Late Cretaceous
Orange: Late Early Cretaceous/mid Cretaceous	x	x	x	x	x						Mid Cretaceous
Pink: Late Early Cretaceous/mid Cretaceous	x	x	x	x	?						Mid Cretaceous
BCU-base pink: Early Cretaceous								x	x	x	Late Jurassic-earliest Cretaceous
Pre-BCU: Middle-Late Jurassic								X	X	X	Late Jurassic-earliest Cretaceous

5.3 Outer Lofoten margin/Røst Basin: tectono-stratigraphic evolution

In the previous sub-chapters, the presence of dome-shaped features/structures on the outer Lofoten margin has been pointed out (Dome 2 Figs. 5.7- 5.9 and 5.11, hereby also referred to as the southern Lofoten margin dome). The Eocene sequence has been divided into three sub-sequences on the outer Lofoten margin/Røst Basin, in order to get a better understanding of the Cenozoic tectono-stratigraphic evolution. The lower Eocene sequence is bounded by the Top Paleocene (TPal) reflector in the bottom, and the Intra Eocene 1 (IE1) reflector in the top. The middle Eocene sequence is bounded by the IE1 reflector in the bottom, and the Intra Eocene 2 (IE2) reflector in the top. Finally, the upper Eocene sequence is bounded by the IE2 reflector in the bottom, and the Top Eocene (TE) reflector in the top. Although the rate of deformation cannot be calculated directly from isopach differences, time-thickness maps have been used in an attempt to account for the timing and evolution of the dome-shape features/structures on the outer Lofoten margin. Because of extensive erosion in the vicinity of the Røst High/Utrøst Ridge, it is at this point challenging to give an accurate indication of the shape and extent of the southern Lofoten margin dome. The western flank of the dome is therefore likely associated with the most reliable observations.

Figure 5.17 depicts the presence of two local depocenters, one to the northwest and one to the southwest parts on either side of the Røst High/Utrøst Ridge. The Paleocene sequence appears to be absent between the depocenters above the Røst High/Utrøst Ridge, indicating that the southern Lofoten margin dome was already formed in Paleocene time. Figure 5.18 shows a smaller depocenter west of the Utrøst Ridge, implying that the relief of the dome decreased during early Eocene. Figure 5.20 shows a larger depocenter, which suggests an increase in dome relief in middle Eocene. A general thinning of the upper Eocene sequence (Fig. 5.21) in the eastern part of the study area suggests that the wavelength of the lateral extent of dome influence increased in size during late Eocene. Figure 5.22 shows a southward migration of the depocenter west of the Utrøst Ridge, and thinning and erosion of the Oligocene sediments towards the Røst High/Utrøst Ridge. The extent and depth of the depocenter appears to increase during late Oligocene and early Miocene. A general southwards migration of the depocenter implies increased uplift of the southern Lofoten margin during Cenozoic, compared to the northern Vøring margin.

Line-drawing interpretations of several profiles have been constructed and are used to depict key observations for the evolution (in time and space) of the outer Lofoten margin/Røst Basin Cenozoic evolution. Table 5.2 summarizes observations done on the outer Lofoten margin, and Figure 5.23 shows line-drawing interpretations of profiles from north to south along the west side of the Røst High/Utrøst Ridge. Figure 5.23a depicts a thin Paleocene sequence that onlaps the BTU reflector and is overlain by lower-middle Eocene sequences that onlap the BTU reflector. The upper Eocene sequence toplaps the IM reflector, and the Oligocene sequence is absent and has been probably eroded during middle Miocene. This is indicated by the angular unconformity character of the Intra Miocene reflector, which is eroded by the Base Plio-Pleistocene reflector. Figures 5.23b-e show Paleocene-middle Eocene onlap to the BTU reflector, and a gradual doming of the Eocene sequences. Upper Eocene sequences are toplapping the Intra Miocene reflector. A thin Oligocene to earliest Miocene sequence appears in Figure 5.23b and becomes thicker and more tilted towards south as it is shown in Fig. 5.23e, where the Oligocene to earliest Miocene sequence starts to toplap the Intra Miocene reflector. Figures 5.23f-h show a thinning and decreased dome shape of the Eocene sequences, which could indicate a decreased relief of the dome. The Oligocene to earliest Miocene sequence increases in lateral and vertical extent towards the southern part of the southern Lofoten margin, where it still toplaps the Intra Miocene reflector. The Røst High/Utrøst Ridge is generally more uplifted in the north, and the Cenozoic successions show a general thickening from north to south (Figs. 5.23a-h). All the above observations possibly suggest a southern migration and late tectonic evolution of the dome, and that the most probable sediment source area for the developing depocentres around the southern Lofoten margin dome is the Røst High/Utrøst Ridge. In addition, observations suggest that the southern Lofoten margin dome exhibits a pulsating behaviour from Late Cretaceous to late Cenozoic.

Table 5.2: *Summary of the interpreted evolution of the outer Lofoten margin (Fig. 5.23).*

Time interval	**Sequence character**	**West Røst High Fault Complex: vertical movement and effective impact wavelength**
Plio-Pleistocene	Downlap on BPlio reflector. Truncated by sea bottom.	Uplift to stable, large wavelength. Probably eroded and or bypassed on the southern Lofoten margin due to uplift.
Early to late Miocene	Downlap on IM reflector. Toplap on BPlio reflector. Truncated by BPlio reflector.	Uplift, large wavelength.
Oligocene to earliest Miocene	Onlap on TE reflector. Toplap on IM reflector.	Uplift, large wavelength.
Upper Eocene	Onlap on IE2 reflector. Toplap on TE and IM reflectors. Clearly truncated by TE and IM reflectors.	Uplift, short wavelength.
Middle Eocene	Onlap on IE1 reflector. Toplap on IE2 and IM reflectors. Clearly truncated by IM reflector.	Uplift, short wavelength.
Lower Eocene	Onlap on BTU and TPal reflectors.	Uplift, short wavelength.
Paleocene	Onlap and downlap on BTU reflector.	Uplift, large wavelength.
Latest Cretaceous	Truncated by the BTU reflector and the Paleocene sequence.	Uplift, large wavelength.
Early Late Cretaceous	Truncated by BTU reflector.	Subsidence, short wavelength.
Late Early/mid Cretaceous	Truncated by BTU reflector.	Subsidence, short wavelength.

Intra-basin inversion features are common regional compression features seen along the North Atlantic margin (Vågnes et al., 1998; Tsikalas et al., 2005b), and it is natural to compare the southern Lofoten dome described above to the nearby Naglfar Dome on the northern Vøring margin. Timing and significance of the mid-Cenozoic compressional deformation, in addition to single-phase versus multiphase growth evolution for the observed domes is debated. Doré et al. (1999) suggested a late Oligocene-Miocene evolution of the Naglfar Dome, while Hjelstuen et al. (1997) suggested a multiphase growth of the dome during Paleocene and late Oligocene-Miocene times.

A multiphase growth evolution is suggested for the southern Lofoten dome based on the observations presented in this study. Observations suggest a dome that was already formed prior to Cenozoic. A possible initiation of the dome could have started already at the time of the structural initiation of the West Røst High Fault Complex. The dome was most likely formed already during Late Cretaceous, and could have been enhanced by differential compaction (Hjelstuen et al., 1997; Tsikalas et al., 2005b). The dome probably experienced several phases of growth from Late Cretaceous to Miocene times. Paleocene doming could represent an initial inflation of the dome, while the dome could have deflated in early Eocene. The constructed time-thickness maps for the middle Eocene to middle Miocene sequences (Figs. 5.20-5.21) suggest that the dome could have reached its maximum extent during middle Miocene.

Compressional deformation in the mid-Norwegian margin is well established, indicated by the presence of reverse faults, local domes, and broad basin inversion (Blystad et al., 1995; Vågnes et al., 1998; Lundin and Doré, 2002). Lundin and Doré (2002) suggested that the main driving force for mid-Cenozoic post-breakup deformation in the margins off mid-Norway was plume-enhanced ridge push. This study dismissed any significant impact from the Alpine Orogeny on mid-Cenozoic domes. The same study further discussed that changes in spreading rates were an unlikely cause of compressional deformation, as this would not have generated sufficient deformational forces. Vågnes et al. (1998) suggested different models for Cenozoic inversion of basins off northwestern Europe. However, the most likely causes for Cenozoic contraction deformation were suggested by the same study to be ridge push from the north Atlantic mid-oceanic ridge system and far-field effects reflecting episodes of deformation in the Late Mesozoic-Cenozoic Alpine Orogeny. The interpretation of Vågnes et al. (1998) is favoured in this thesis as a potential causal mechanism for the formation of the southern Lofoten margin dome. Similar observations are assigned to the far-field effects of the onset of Alpine contraction deformation further south in the Central North Sea. This raises the question of how far north the effective impact wavelength of the Alpine orogeny actually reached.

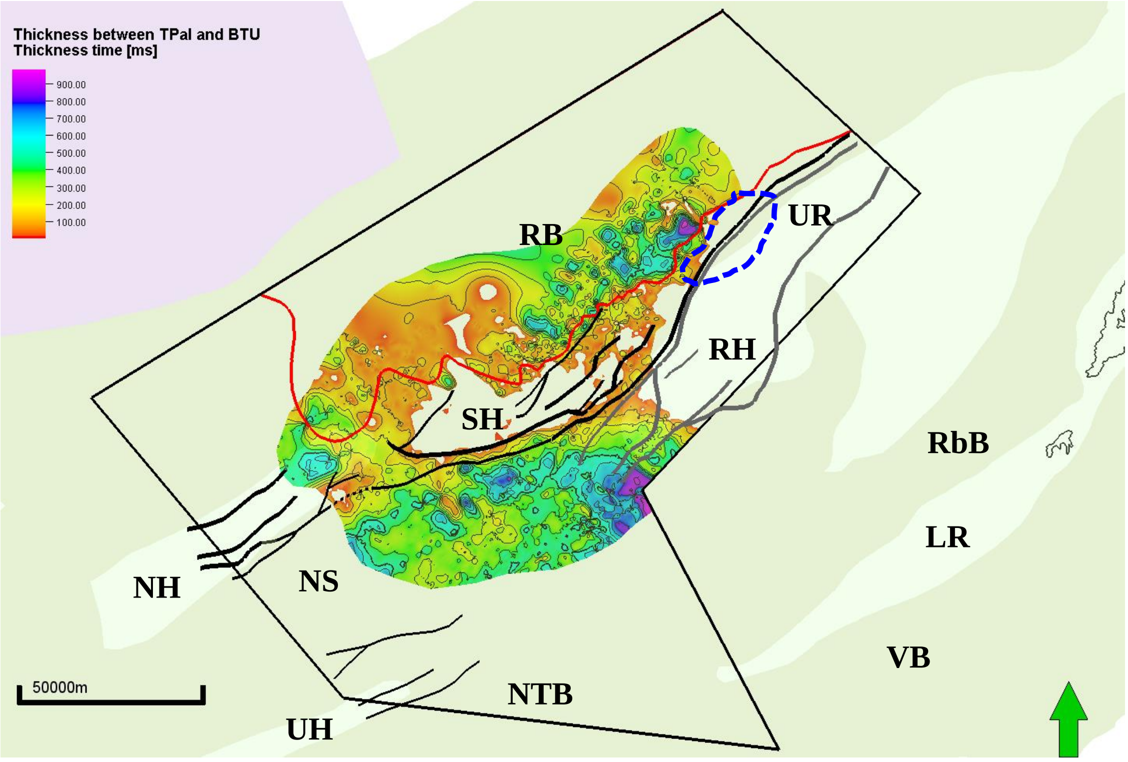


Fig. 5.17: *Time-thickness map of the Paleocene sequence (BTU to TPal) (contour interval 100 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The blue stippled line indicates the location of the southern Lofoten margin dome. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

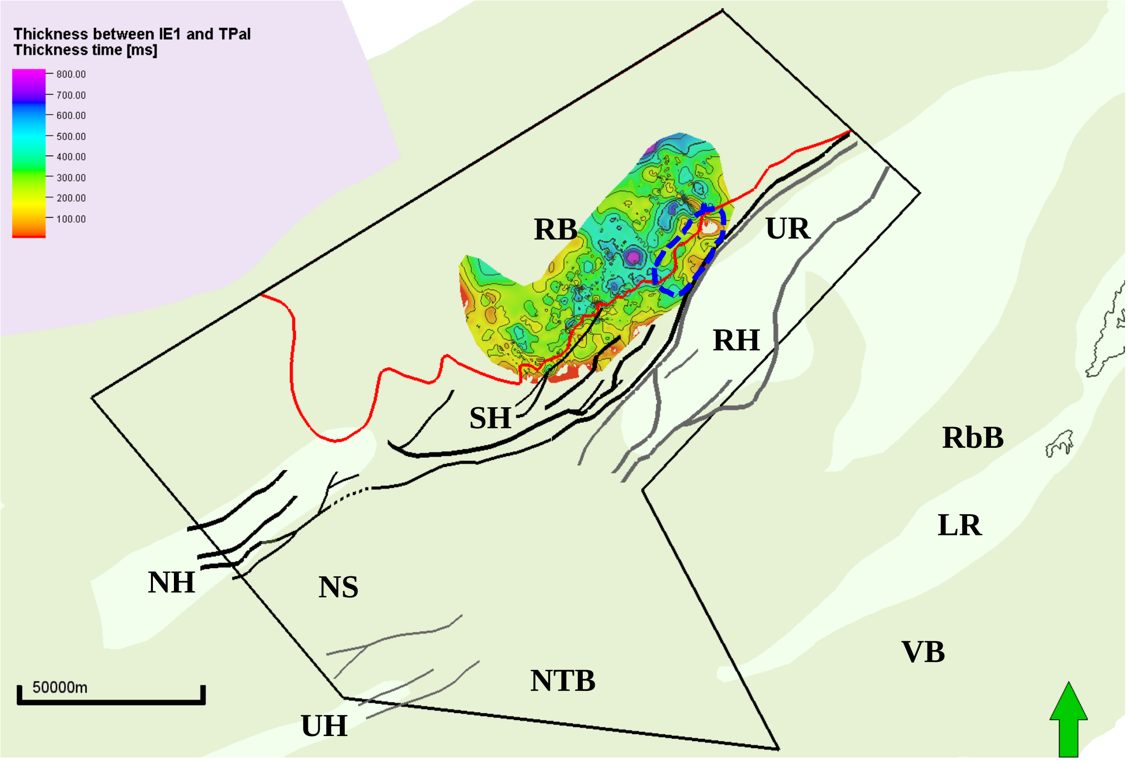


Fig. 5.18: *Time-thickness map of the lower Eocene sequence (TPal to IE1) (contour interval 100 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The blue stippled line indicates the location of the southern Lofoten margin dome. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

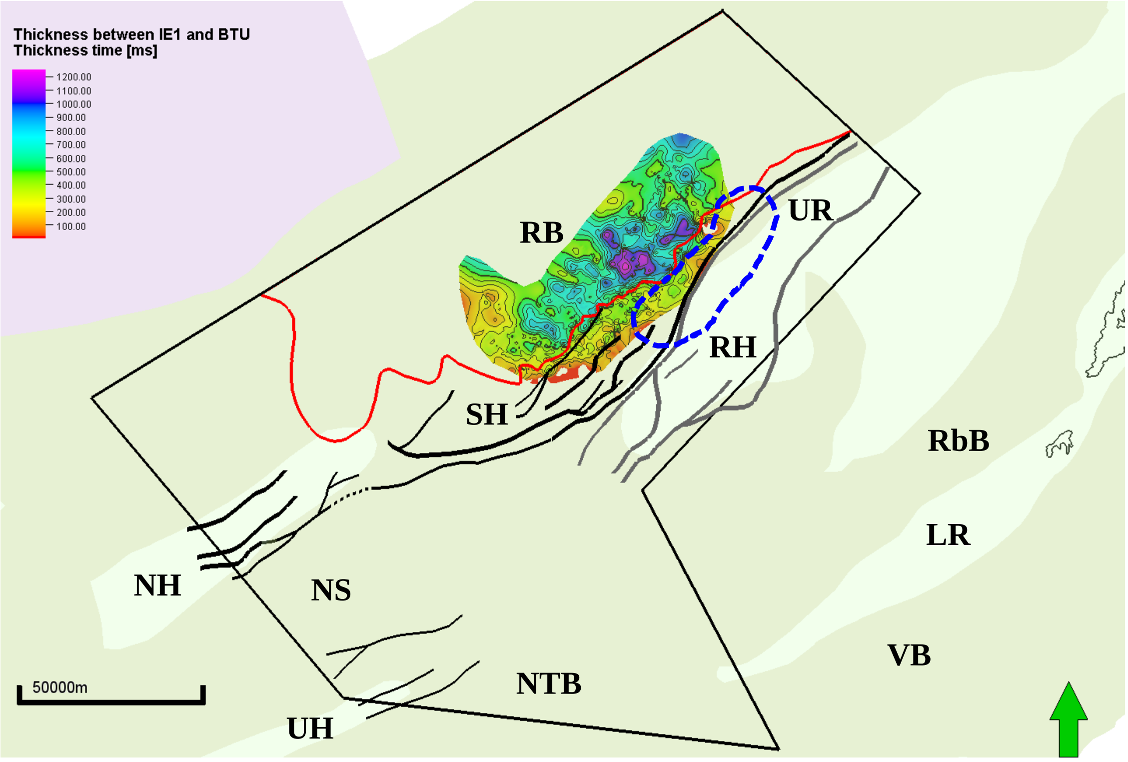


Fig. 5.19: *Time-thickness map of the Paleocene to lower Eocene sequences (BTU to IE1) (contour interval 100 ms). All active faults are illustrated in black, while inactive faults are displayed as grey. The blue stippled line indicates the location of the southern Lofoten margin dome. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

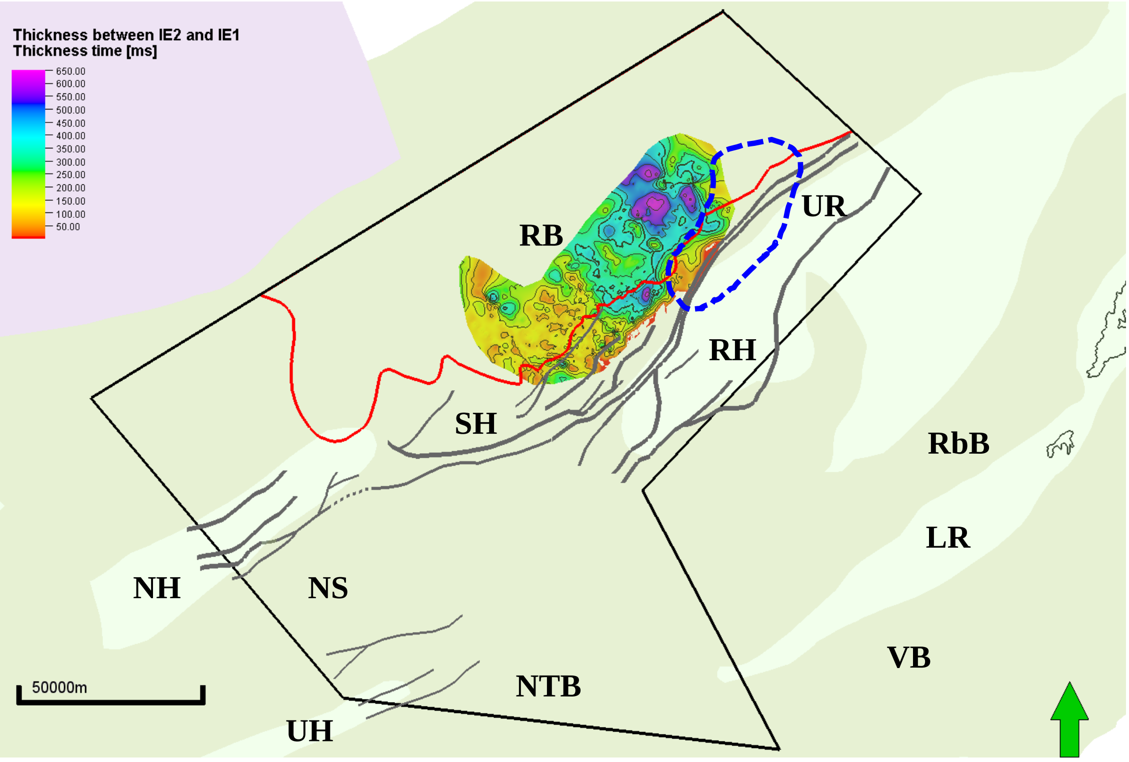


Fig. 5.20: *Time-thickness map of the middle Eocene sequence (IE1 to IE2) (contour interval 75 ms). All inactive faults are illustrated in grey. The blue stippled line indicates the location of the southern Lofoten margin dome. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

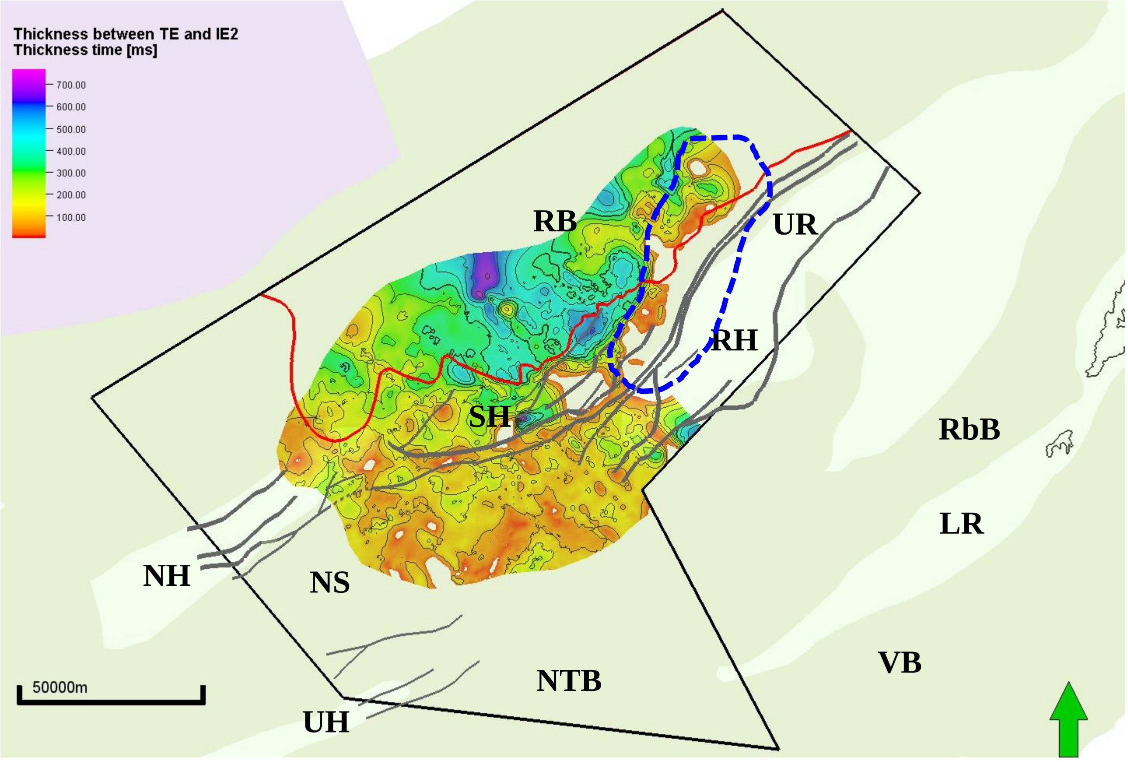


Fig. 5.21: *Time-thickness map of the upper Eocene sequence (IE2 to TE) (contour interval 75 ms). All inactive faults are illustrated in grey. The blue stippled line indicates the location of the southern Lofoten margin dome. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

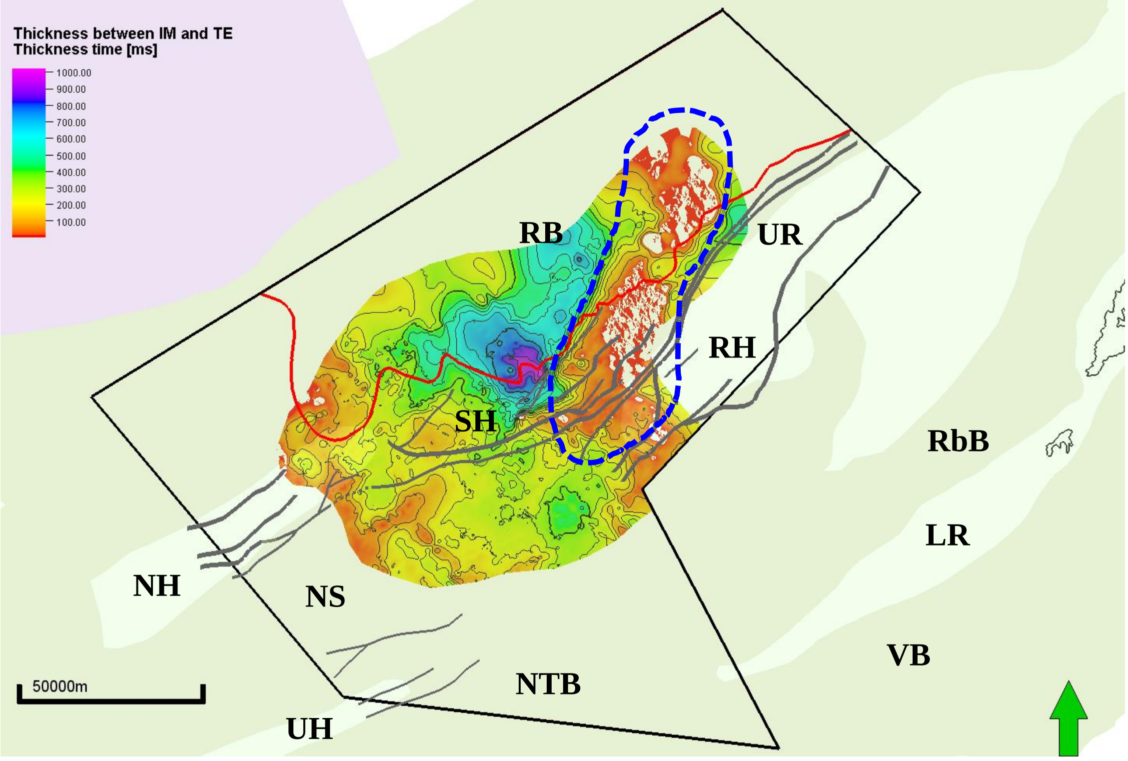


Fig. 5.22: *Time-thickness map of the Oligocene to earliest Miocene sequence (TE to IM) (contour interval 75 ms). All inactive faults are illustrated in grey. The blue stippled line indicates the location of the southern Lofoten margin dome. The NPD structural element outline is included in the background for comparison. Abbreviations in Fig.5.2.*

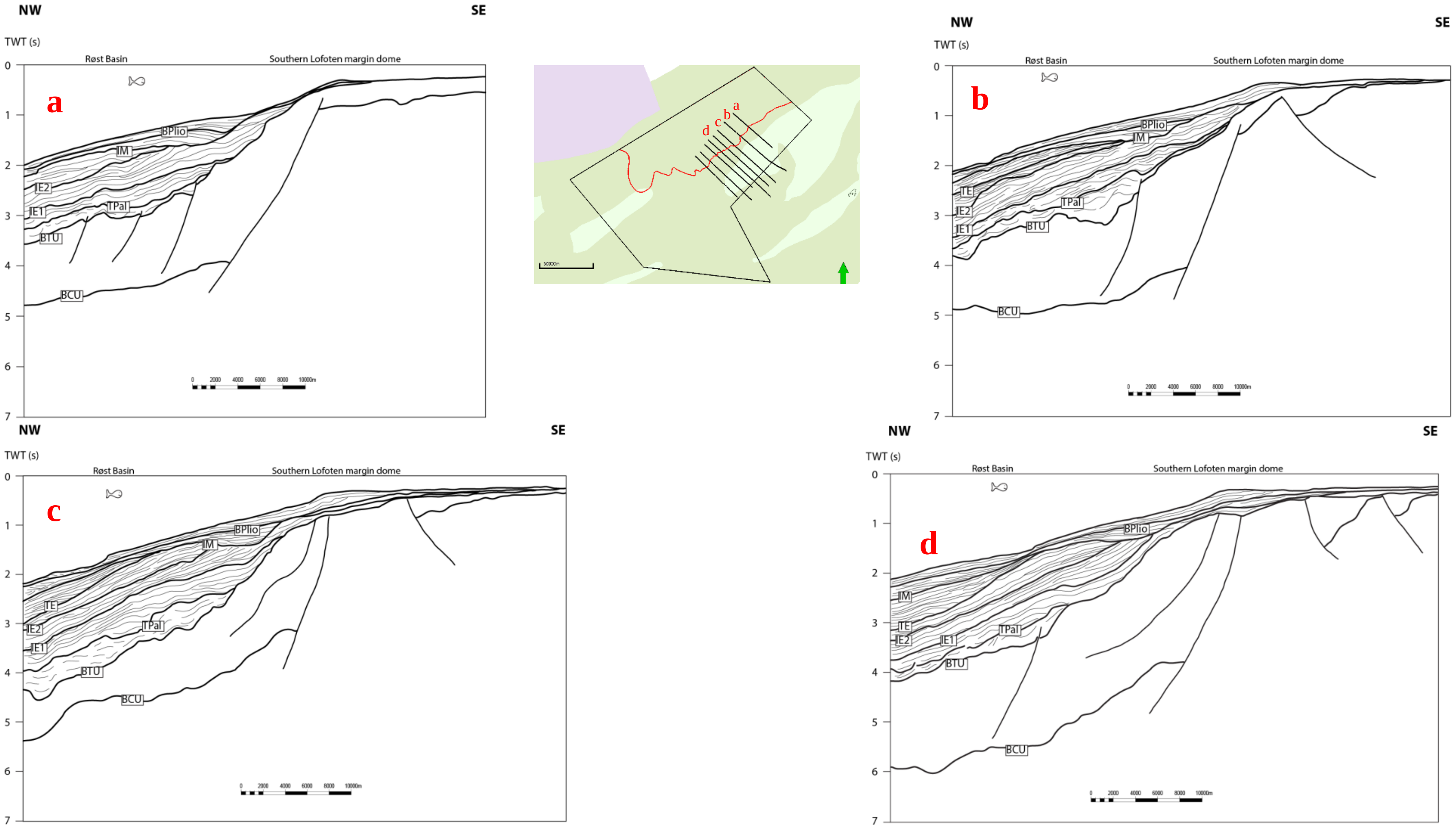


Fig. 5.23: *Interpreted* ***(a)*** *AMR_RHW96-102,* ***(b)*** *AMR_RHW96-104,* ***(c)*** *AMR_RHW96-106,* ***(d)*** *AMR_RHW96-108 seismic profiles illustrating the Røst Basin on the outer Lofoten margin.*

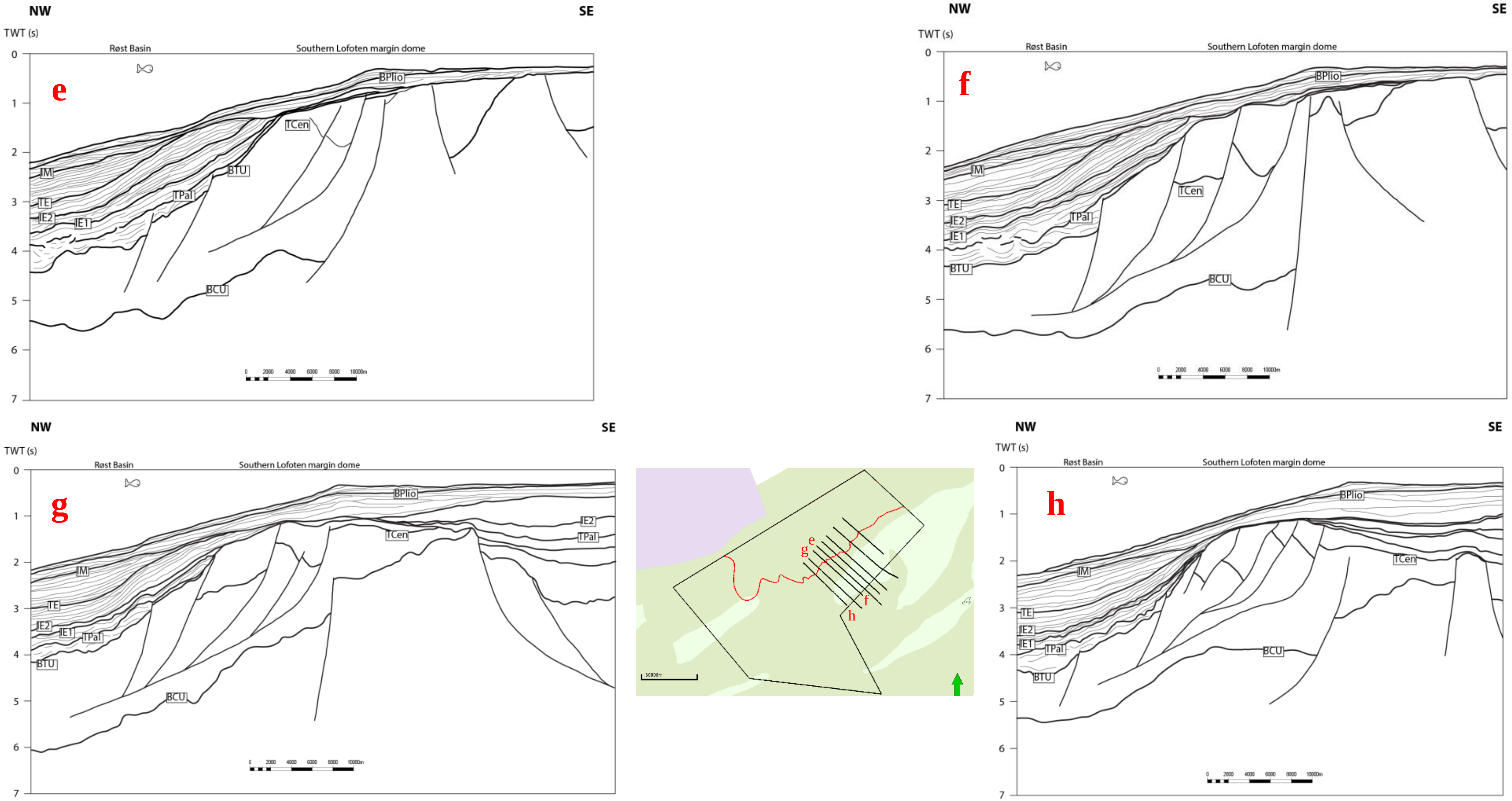


Fig. 5.23(cont.): Interpreted (e) AMR_RHW96-110, (f) AMR_RHW96-112, (g) AMR_RHW96-1114, (h) AMR_RHW96-116 seismic profiles illustrating the Røst Basin on the outer Lofoten margin.

5.4 Northern Vøring and southern Lofoten margin segments in a regional and conjugate setting

Recent plate reconstructions (Fig. 5.24) combined with seismic profiles and conjugate crustal transects between the Northeast Greenland and the Vøring and Lofoten margins (Figs. 5.25, 5.27, and 5.28), have been used for comparison between the Norwegian continental margin (NCM) and the conjugate Northeast Greenland continental margin.

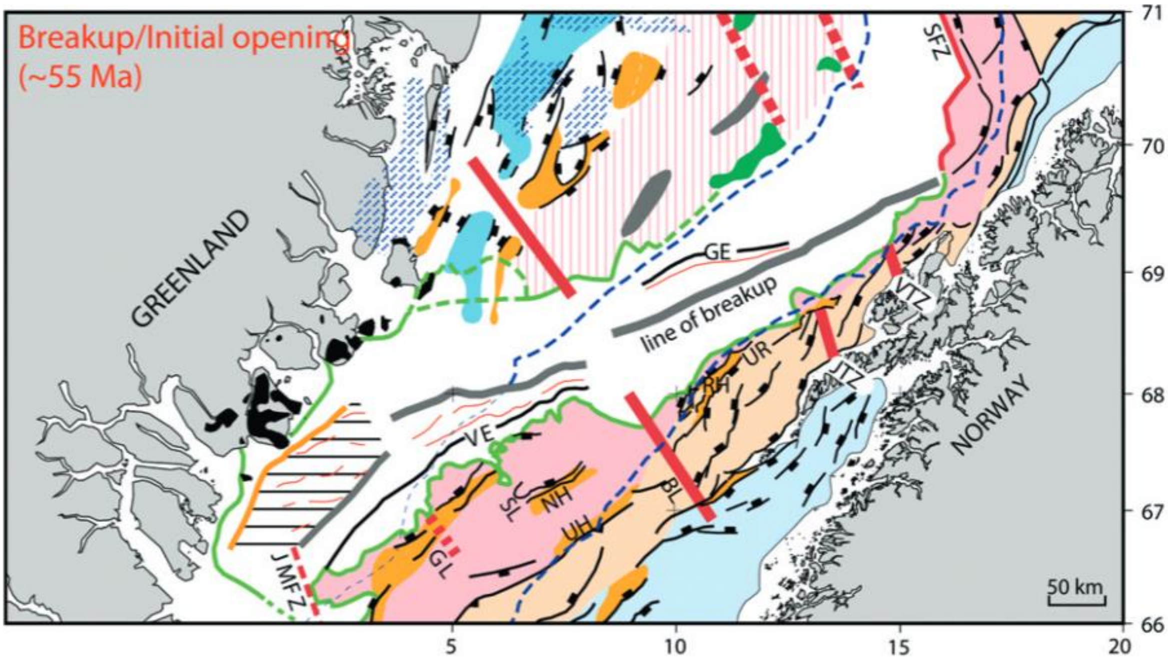


Fig. 5.24: Plate reconstruction at break-up (~55 Ma) (Tsikalas et al., 2012). VE: Vøring Escarpment, SL: Surt Lineament, NH: Nyk High, UH: Utgard High, BL: Bivrost Lineament, RH: Røst High, UR: Utrøst Ridge.

5.4.1 Crustal structure

Post-Caledonian rifting events resulted in Late Cretaceous-Paleocene rifting within a region of greatly thinned lithosphere (Tsikalas et al., 2012). Rifting events culminated with initiation of seafloor spreading at the Paleocene-Eocene transition ~55 Ma, followed by the formation of a passive margin (Fig. 5.24) (Eldholm et al., 2002).

The continental crust beneath the Lofoten margin is associated with moderate pre-breakup extension, opposed to the greatly extended crust on the northern Vøring margin (Fig. 5.25) (Faleide et al., 2015). Crustal thickness reaches its maximum of ~35-38 km beneath mainland Norway, and decreases to ~26 km beneath the slope (Fig. 5.25). Figure 5.25 further shows a distinct continent ocean boundary (COB) and a homogeneous and thick crust. Crustal thickness decreases southwards towards the northern Vøring margin, which is associated with a more heterogeneous crustal structure. Furthermore, the Vøring margin has an attenuated crust and has experienced more breakup-related magmatism than the Lofoten-Vøring margin. Figure 5.25 also suggests that the narrow and thick Lofoten-Vesterålen margin is a conjugate to a wide and thin Northeast Greenland margin, while a wide and thin Vøring margin is a conjugate to a narrow Northeast Greenland margin. These observations point to a northward decrease of crustal thickness on the Northeast Greenland margin, and a northward increase of crustal thickness towards the Lofoten-Vesterålen margin on the mid-Norwegian margin.

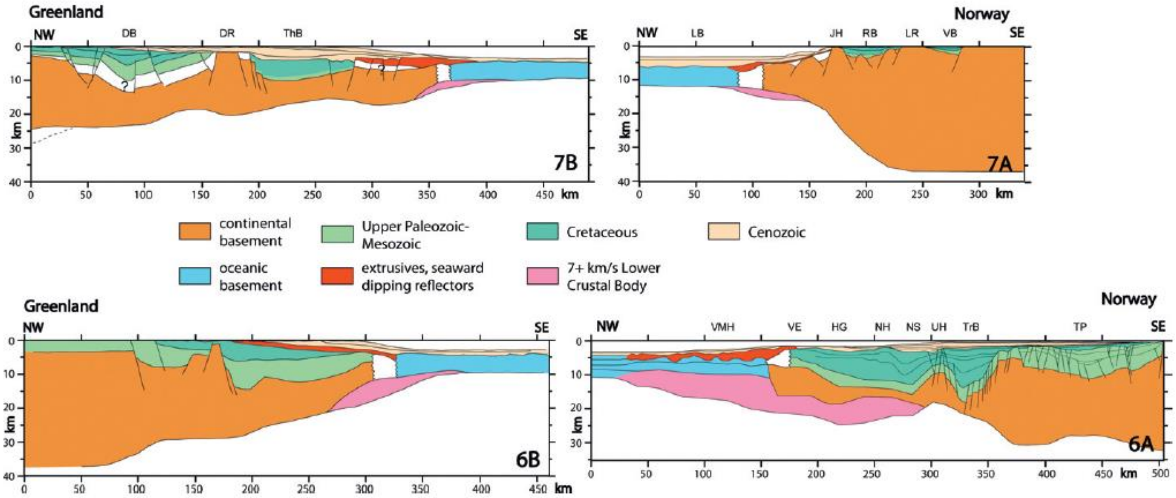


Fig. 5.25: *Conjugate crustal transects across the Vøring, Lofoten-Vesterålen, and NE Greenland margins (Tsikalas et al., 2012). DB: Danmarkshavn Basin, DR: Danmarkshavn Ridge, HG: Hel Graben, JH: Jennegga High, LB: Lofoten Basin, LR: Lofoten Ridge, NH: Nyk High, NS: Någrind Syncline, RB: Ribban Basin, ThB: Thetis Basin, TP: Trøndelag Platform, TrB: Trøna Basin, UH: Utgard High, VB: Vestfjorden Basin, VE: Vøring Escarpment, VMH: Vøring Marginal High.*

The Bivrost Lineament separates the northern Vøring and southern Lofoten margins. Figure 5.26 shows great differences on the northern and southern side of the Bivrost Lineament, among others, a dextral shift of the landward breakup lava boundary from the northern Vøring to the southern Lofoten margin. Figure 5.26a shows that the depth to Moho reaches a greater local maximum on the southern Lofoten margin, than on the northern Vøring margin (Mjelde et al., 2003; Maystrenko et al., 2017). In addition, the Moho gradient is sharper on the steep and narrow southern Lofoten margin, compared to the adjacent wider Vøring margin. Figure 5.26b depicts the crystalline basement thickness map. It shows that on the northern side of the Bivrost Lineament, the thickness reaches a large local maximum in the vicinity of the Utrøst Ridge (Maystrenko et al., 2017). The northern Vøring margin, however, reaches a large local minimum. In addition, the transition between the northern Vøring and southern Lofoten margins shows a rather abrupt change in top crystalline crust depth from ~6 km on the Vøring margin to ~2 km on the Lofoten-Vesterålen margin (Mjelde et al., 1998). An additional observation that is illustrated in Figure 5.26b is that the approximate location of the Bivrost Lineament bounds the Lofoten-Vesterålen platform in the south.

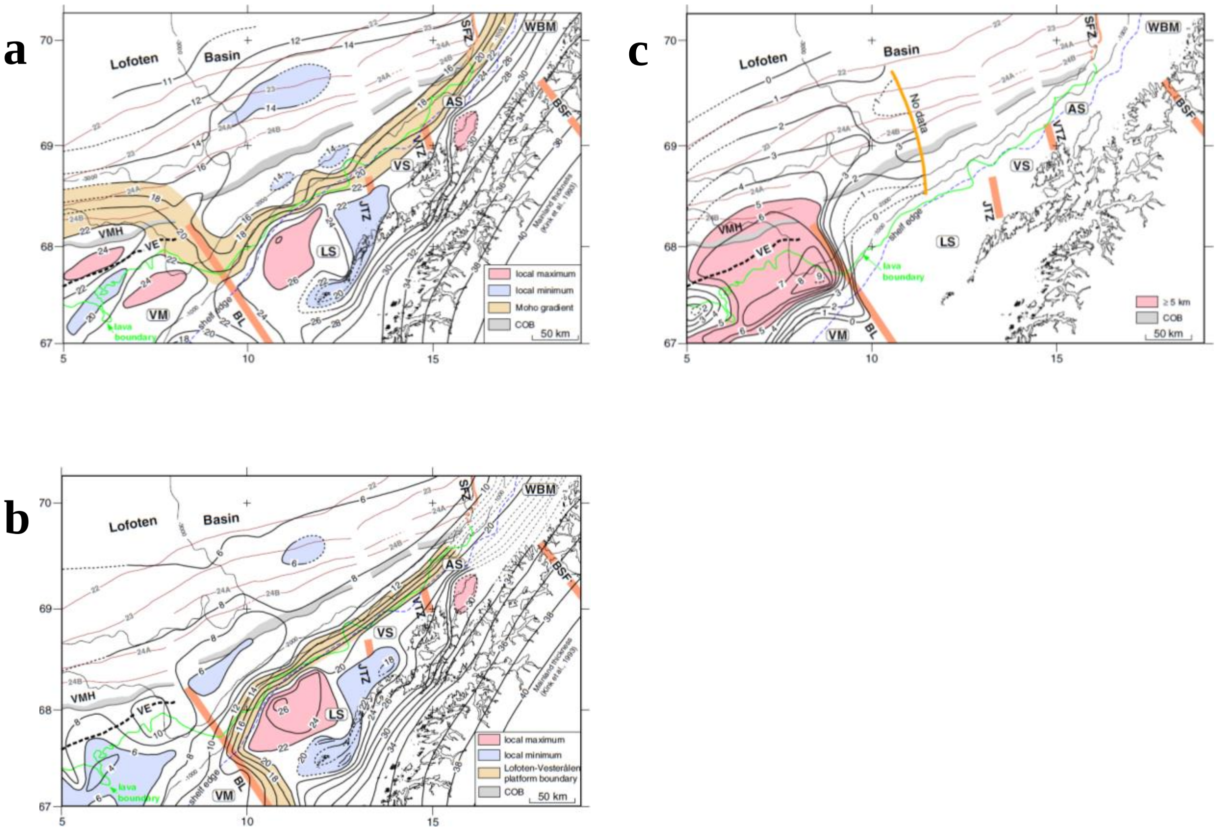


*Fig. 5.26: **(a)** Depth to Moho map. Contour interval 2 km. **(b)** Crystalline basement thickness map (top crystalline basement/top lava to Moho). Contour interval 2 km. **(c)** Thickness map of high-velocity (7+ km/s) lower crustal body. Contour interval 1 km. COB: continent-ocean boundary, A: Andøya; L: Lofoten Islands; V: Vesterålen Islands. AS, LS, and VS: Andøya, Lofoten, and Vesterålen margin segments, respectively; VM, LVM, and WBM: Vøring, Lofoten–Vesterålen, and Western Barents Sea margin provinces, respectively. JMFZ, BFZ, JFZ, VFZ, and SFZ: Jan Mayen, Bivrost, Jennegga, Vesterålen, and Senja fracture zones, respectively. BL, JTZ and VTZ: Bivrost Lineament, and Jennegga and Vesterålen transfer zones, respectively, BSF: Bothnian–Senja fault complex, GR: Gjallar Ridge, HB: Harstad Basin, JH: Jennegga High, LR: Lofoten Ridge, NH: Nyk High, RB: Røst Basin, RbB: Ribban Basin, RH: Røst High, TB: Træna Basin, VB: Vestfjorden Basin, VE: Vøring Escarpment, VMH: Vøring Marginal High, UH: Utgard High, UR: Utrøst Ridge. From Tsikalas et al. (2005a).*

Figure 5.26c shows the thickness map of a high-velocity (7+ km/s) lower crustal body that (also depicted in Fig. 5.25) indicates that the thicknes of the lower crustal body exceeds 5 km on the northern Vøring margin, which is also consistent with the work conducted by Mjelde et al. (2016). Although it appears as if the lower crustal body is not present beneath the southern Lofoten margin, Figure 5.25 indicates that there is indeed a thin body present beneath the continent-ocean boundary. When comparing the two adjacent margins, it becomes clear that the northern Vøring margin has experienced far more magmatism than the southern Lofoten margin. Finally, the Bivrost Lineament is believed to have a conjugate equivalent on the NE Greenland margin (Fig. 5.24) (Tsikalas et al., 2005a).

5.4.2 Cretaceous basin evolution

The NE Greenland continental shelf shows a basin architecture similar to the mid-Norwegian margin (Figs. 5.25 and 5.27). Interpretations of both seismic and potential field data show that both margins are dominated by NNE-trending basins and highs (Hamann et al., 2005; Tsikalas et al., 2005b; Faleide et al., 2008).

Comparison of sequences along the conjugate margins

The Late Jurassic-earliest Cretaceous rifting episode was a dominant event on the NE Greenland margin, creating prominent structures that have similarities with same aged structures off mid Norway (Hamann et al., 2005; Tsikalas et al., 2005b). Both margins show lateral thickness variations across faults in the Lower Cretaceous sequences (Figs. 5.25 and 5.27), indicating continued mid Cretaceous rifting. Cretaceous successions on the NE Greenland margin display northward thinning of Cretaceous sequences, similar to the Cretaceous successions on the conjugate Norwegian margin (Fig.5.22).

The onset of Late Cretaceous rifting is believed to have initiated in the middle Campanian time on the NE Greenland margin, similar to the northern Vøring margin (Tsikalas et al., 2005). Low-angle Late Cretaceous detachment faults are characteristic for both conjugate margins (Fig. 5.28), in addition to showing an apparent seaward propagation of fault activity (Fig., 5.27). Figure 5.28 does, however, show some differences between the two conjugate margins. The West Røst High Fault Complex (Fig. 5.28d) consists of rotated Cretaceous fault blocks, with very clear reflectivity and layering. The fault complex is dome shaped and lies very close to the landward breakup lava boundary. At the NE Greenland margin, however, the Late Cretaceous structuring consists of larger in dimensions rotated fault-blocks just east of prominent basement ridges and are located at some distance away from the landward lava boundary (Fig. 5.28a-b). In addition, reflectivity and layering doesn’t seem as distinct and intense as on the conjugate mid-Norwegian margin. Furthermore, it seems as though the mid-Norwegian margin contains considerably more magmatic intrusions.

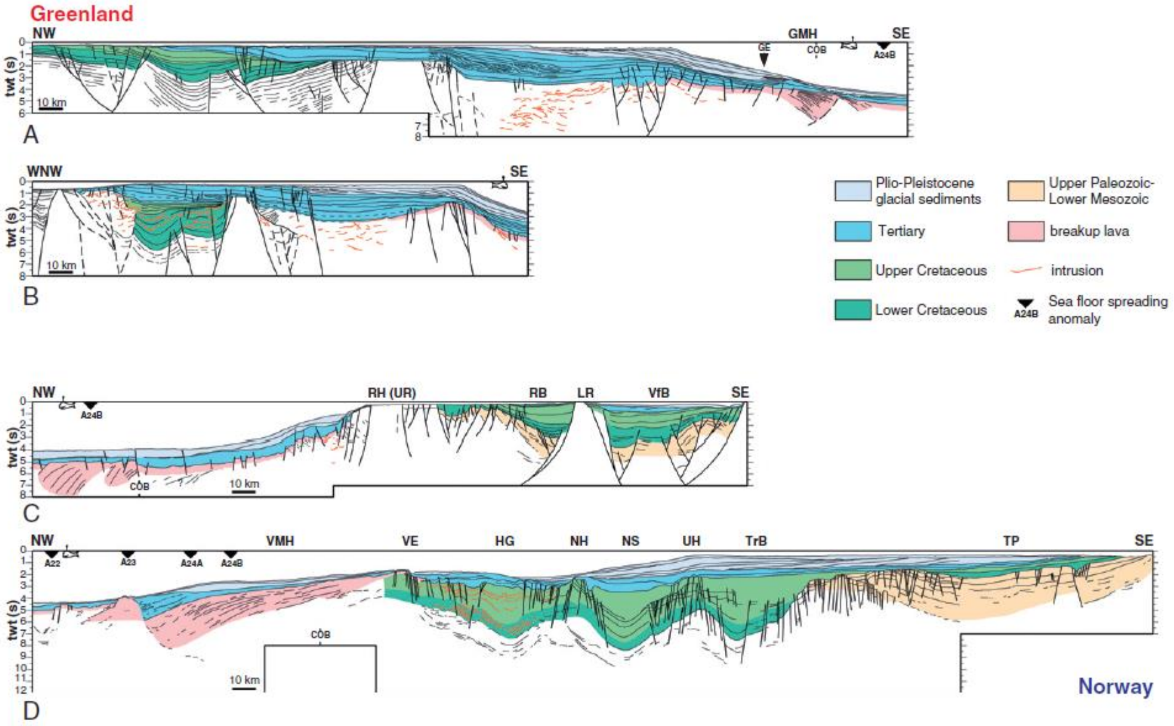


Fig. 5.27: *Interpreted regional seismic profiles from the conjugate mid-Norway and NE Greenland continental margins (Tsikalas et al., 2005b). GMH: Greenland Marginal High, HG: Hel Graben, LR: Lofoten Ridge, NH: Nyk High, NS: Någrind Syncline, RB: Ribban Basin, RH: Røst High, TP: Trøndelag Platform, TrB: Træna Basin, UH: Utgard High, UR: Utrøst Ridge, VE: Vøring Escarpment, VfB: Vestfjorden Basin, VMH: Vøring Marginal High.*

Late Cretaceous rifting was followed by smaller scale rifting during Paleocene, with continued extension and reactivation of previous faults. Paleocene is associated with regional uplift, erosion and intrusive igneous activity on both conjugate margins. Paleocene uplift is indicated by early Cenozoic truncation of Cretaceous successions (Fig. 5.28). Thick and highly reflective Cenozoic successions cover both conjugate margins. The slightly thinner Cenozoic succession on the outer Lofoten margin is deposited on top of the dome shaped West Røst High Fault Complex during uplift, and is overlain by a thin sequence of Plio-Pleistocene glacial sediments. However, the fault blocks on the NE Greenland margin are overlain by very thick successions of Cenozoic sequences, with a wedge shaped Plio-Pleistocene sequence above.

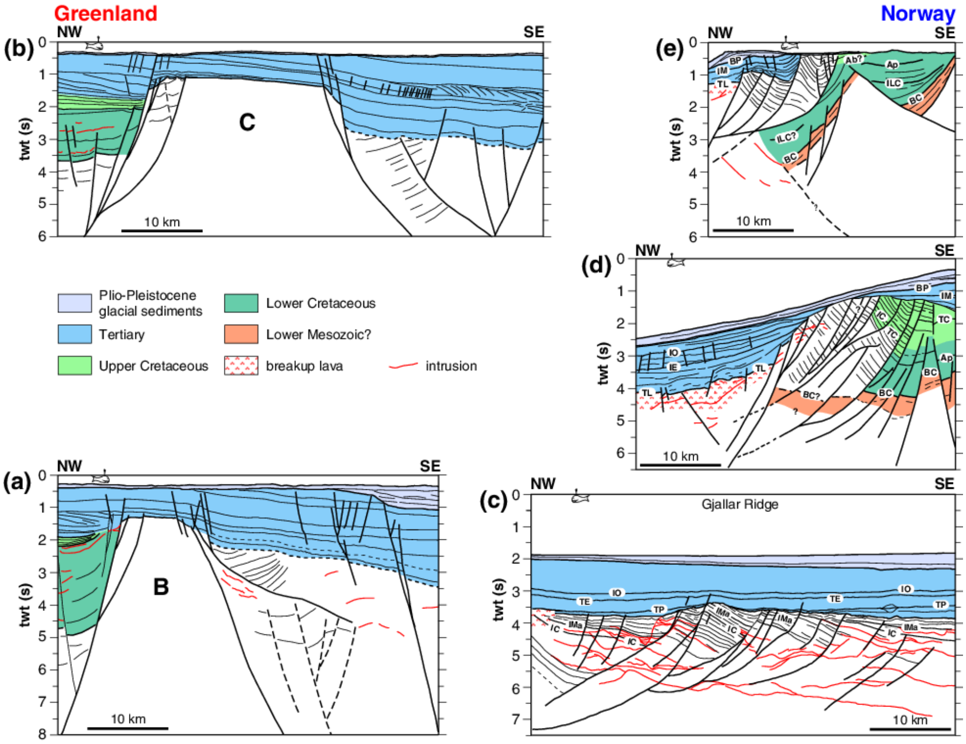


Fig. 5.28: *Interpreted seismic profiles illustrating Late Cretaceous low-angle detachment systems (Tsikalas et al., 2005b)*

6 Summary and conclusions

The Cretaceous to Cenozoic tectono-stratigraphic evolution of the southern Lofoten and northern Vøring margins has been studied in detail utilizing several datasets, consisting of: 2D multi-channel seismic reflection profiles, well-to-seismic ties and stratigraphic information from four exploration wells, in addition to gravity and magnetic data. The main focus of the work has been on seismic and structural interpretation in order to refine the rift phases that affected the study area and to decipher the eventual role of the Bivrost Lineament, as well as to improve the understanding of the evolution the West Røst High Fault Complex and the outer Lofoten margin. Furthermore, the southern Lofoten and northern Vøring margin segments have been studied in a regional and conjugate margin setting in order to get a better understanding of the crustal structure and pre-breakup basin evolution.

Four main rift phases have been recognised and refined in the study area. Late Jurassic-earliest Cretaceous rifting controlled the initial structuring of the main structural elements. Mid Cretaceous rifting was responsible for the initiation of faulting at the West Røst High Fault Complex, while rifting continued during Late Cretaceous and led to a westward propagation of fault activity. Paleocene rifting reactivated several Late Jurassic-earliest Cretaceous and Cretaceous faults, prior to continental breakup and seafloor spreading initiation at the Paleocene-Eocene transition.

The Bivrost Lineament is a major along-margin boundary with an uncertain exact location, that represents the shift between the wide and lower lying northern Vøring margin to the more narrow and elevated Lofoten-Vesterålen margin. The Bivrost Lineament is related to the termination of prominent structural highs and is associated with a slight shift in the trend of NE-trending structural elements on the northern Vøring margin, to a more NNE-trend on the southern Lofoten margin. Furthermore, the Bivrost Lineament represented a low-relief “corridor” and accommodation zone during Late Jurassic-Early Cretaceous, and exhibited a more elevated dome-shaped character during early Cenozoic. The current study suggests that the northern continuation of the Nyk High could be the Sandflesa High below the West Røst High Fault Complex, while the northern continuation of the Utgard High is proposed to be the

Røst High/Utrøst Ridge. The highs are separated by the Någrind Syncline on the northern Vøring margin, and the suggested northward continuation of it is the Early Cretaceous basin separating the Sandflesa High and the Røst High/Utrøst Ridge.

The presence of a dome-shaped feature (named southern Lofoten margin dome) has been observed on the southern Lofoten margin. The Røst High/Utrøst Ridge is generally more uplifted in the north, and the Cenozoic successions show a general thickening from north to south. A general southwards migration of the main depocenter in the study area implies increased uplift of the southern Lofoten margin during Cenozoic, compared to the adjacent northern Vøring margin. Observations indicate that the Røst High/Utrøst Ridge is the most probable sediment source area for the deposited Cenozoic succession. A multiphase growth evolution is suggested for the southern Lofoten margin dome based on the observations presented in this study. The dome was most likely formed already in the Late Cretaceous, and could have been enhanced by differential compaction. The dome probably experienced several phases of growth from Late Cretaceous to Miocene times, reaching its maximum extent during middle Miocene. The most likely causes for Cenozoic contraction deformation were suggested to be ridge push from the north Atlantic mid-oceanic ridge system and far-field effects reflecting episodes of deformation from the Alpine Orogeny.

The tectono-stratigraphic evolution of the southern Lofoten and northern Vøring margins has been compared to the conjugate Northeast Greenland margin, to get a better understanding of the evolution in a regional and conjugate context. Comparison of sequences along the conjugate margins implies that the northern part of the NE Greenland margin and the Vøring margin have experienced extensive pre-breakup crustal stretching, while the Lofoten margin experienced only moderate pre-breakup extension. The Bivrost Lineament separates the northern Vøring and southern Lofoten margins and is believed to have a conjugate equivalent on the NE Greenland margin. Similarly prominent Late Cretaceous low-angle detachment faults have been also observed on both conjugate counterparts.

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