Cretaceous tectono-stratigraphic evolution of the Ribban and northern Træna basins at the Lofoten margin, offshore northern Norway

Hanne Christine Rolstad Wilhelmsen

Master Thesis in Geosciences
Discipline: Petroleum Geology and Petroleum Geophysics
30 credits

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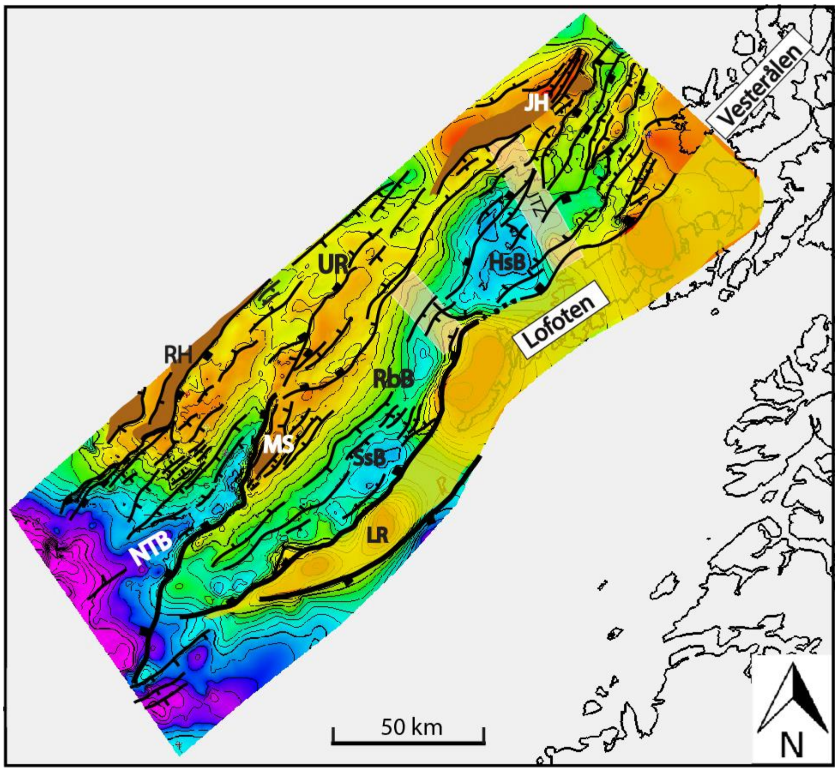

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Abstract

The Lofoten margin segment is located offshore northern Norway, in between the volcanic rifted Vøring and Vesterålen margins. Several available datasets have been integrated in order to study in detail the tectono-stratigraphic evolution of the eastern part of the Lofoten rifted margin segment, comprising the northern Træna and Ribban basins, with main emphasis on fault evolution and the Cretaceous basin infill history. The utilized datasets include: available 2D multi-channel seismic reflection profiles; well-to-seismic ties and stratigraphic information from one exploration well and published information from all IKU shallow boreholes in the area together with the Andøya onshore outcrop; and gravity and magnetic data.

Structural and stratigraphic interpretations have been conducted in order to obtain a picture of the basin architecture and evolution through time. Nine sequences ranging in age from Triassic-Early Jurassic to Cenozoic have been interpreted and analysed in terms of lateral geometries and vertical thickness variations, in order to detect important phases of tectonic activity and to better understand the interplay between faulting and deposition.

The study area is dominated by NNE-SSW trending extensional basins and shelf-parallel basement ridges, generated from several phases of rifting. The northern Træna and Ribban basins have proven to be highly dynamic, with records of at least four main rift events. The basins developed within the context of the North Atlantic rift system, and are predominately filled with Cretaceous successions. Following the main Late Jurassic rift phase, these basins further evolved during the Early Cretaceous with extension continuing into earliest Cretaceous and a separate rift phase taken place during Aptian. Both tectonic events were followed by subsidence. Renewed rifting during Late Cretaceous-Early Tertiary times is mainly concentrated west of the study area, but some reactivation along the border faults of the northern Træna and Ribban basins are observed. This is related to the continental breakup and onset of sea floor spreading in the Norwegian-Greenland Sea at the Paleocene-Eocene transition.

The first-order tectono-stratigraphic evolution of the Lofoten margin has been compared with the Vøring margin and the conjugate Northeast Greenland margin, and this reveals that the Lofoten margin experienced only moderate pre-breakup extension compared to the adjacent and conjugate margin counterparts. The conjugate mid-Norwegian and Northeast Greenland continental margins clearly show an asymmetrical crustal architecture, with the line of breakup being oblique to the Cretaceous basin trend and resulting in breakup at different locations with respect to the pre-existing rift systems on either side of the Bivrost transfer system.

Preface

This thesis (30 ECTS) is the final part of the two year master program with specialization in "Petroleum geology and petroleum geophysics" at the University of Oslo, Department of Geosciences. The thesis has been supervised by Professor Jan Inge Faleide and Professor Filippos Tsikalas.

Acknowledgements

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

Thanks to all my fellow students, in particular the students in room 210, for inspiration and motivation during the period of writing this thesis. A special thanks to Wibecke, Silje and Kristine for discussions and late night company at the computer lab. Last but not least, thanks to my friends and family for their patience and support through this process.

Hanne Wilhelmsen

Contents

1 Introduction

The 400-km-long Lofoten-Vesterålen continental margin (LVM) is located offshore northern Norway west of the Lofoten-Vesterålen archipelago (Fig. 1.1). It is considered to represent the transition between the passive, and much wider, volcanic rifted Vøring Margin and the sheared Barents Sea Margin. The LVM is separated to the south from the Vøring Margin by the Bivrost Lineament (BL), and is bounded to the north by the Senja Fracture Zone (SFZ) (Blystad et al., 1995).

Within the context of the Norwegian continental passive margin, the Lofoten-Vesterålen margin (LVM) is the least explored and understood segment. This is mainly because of the Norwegian Authorities' restrictions that have closed the area for petroleum exploration, and consequently no deep-target commercial wells have been drilled in the area (Bergh et al., 2007; Færseth, 2012; Henstra et al., 2015). Lack of adequate well data causes uncertainties in age determination, thickness and distribution of sediments, and further timing of tectonic events.

The Lofoten-Vesterålen margin is structurally complex, and several models have been proposed to explain the structural evolution and present-day margin architecture. All models agree that the margin is segmented, with some discrepancies regarding orientation and initiation. Essentially three main geological models have been proposed to describe the geological evolution of the LVM:

- *Tsikalas et al. (2001)* proposed the initial model, consisting of three separate rifted margin segments (Lofoten, Vesterålen and Andøya) based on changes in fault geometry and dip-polarity generated by NW-SE trending transfer zones.
- *Bergh et al. (2007)* was critical to that model, because of the existence of lateral segmentation by the transfer zones. A revised model, which emphasizes on temporal and spatial initiation of the genetically related faults, was introduced. This included observations of different fault patterns that represent distinct rifting phases, and this was interpreted as the reason behind the lateral segmentation.

- The last model suggested by *Færseth (2012)*, is based upon the LVM consisting of two rift segments bounded by a transfer/accommodation zone, with no evidence of strike-slip motion.

The study area of the thesis is the eastern part of the Lofoten rifted margin segment (Fig. 1.1). Within this area, the main objective is to study the structural styles of the northern Træna and Ribban basins, with main emphasis on fault evolution and Cretaceous basin infill history. The basins are filled with predominately Lower and Upper Cretaceous successions, which can provide important information about the exerted tectonic phases. Through the thesis work, the sedimentary deposits within the study area have been mapped in both space and the time period they represent, and in this way assigned to different phases of rifting, thereby increasing the structural and stratigraphic understanding in the northern Træna and Ribban basins.

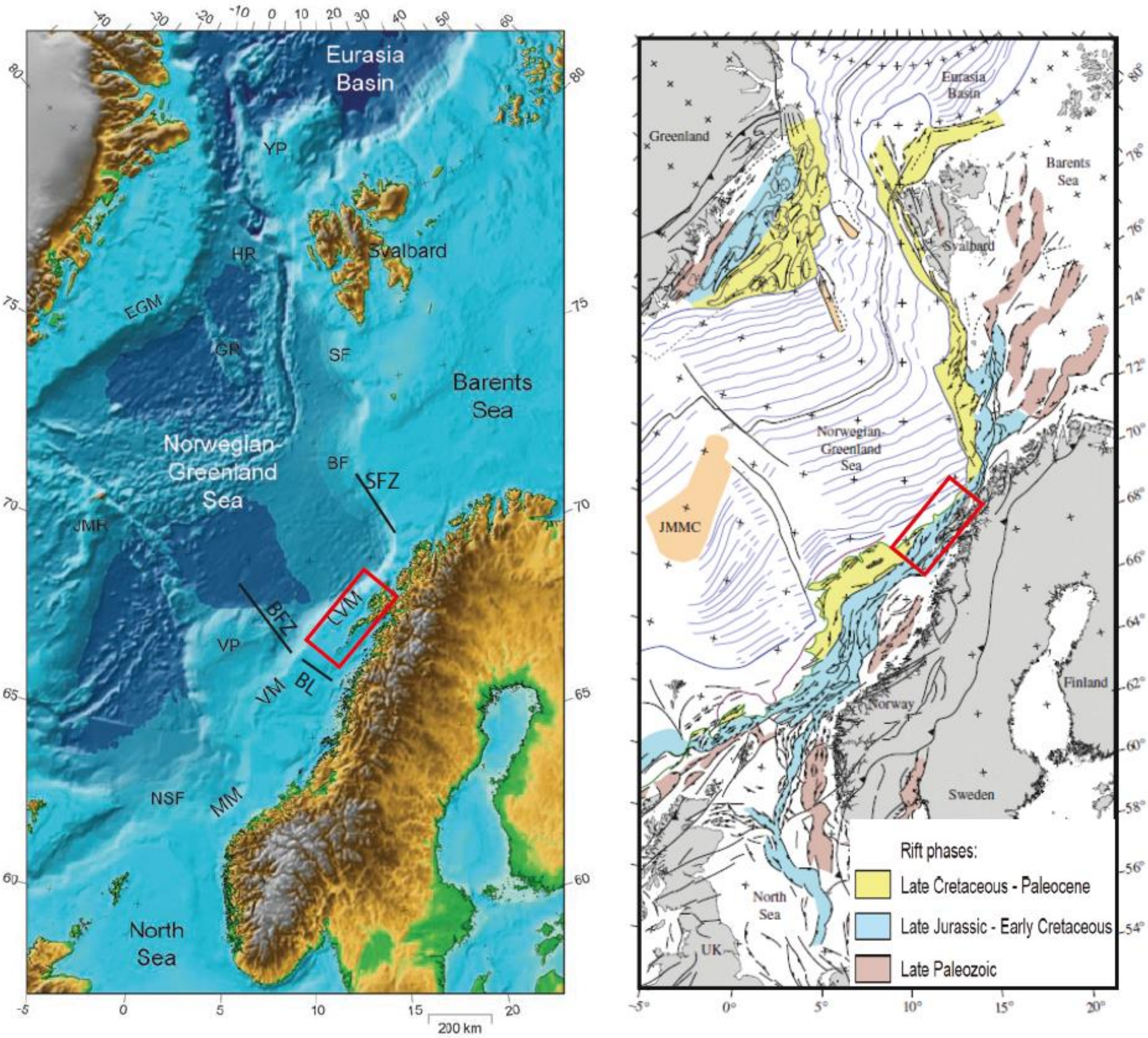


Fig. 1.1: (a) Regional setting and location of the study area. **(b)** Main structural elements of the Norwegian continental shelf related to several phases of rifting phases in the NE Atlantic region. The rectangle represents the Lofoten-Vesterålen margin (LVM). BF: Bjørnøya Fan, BFZ: Bivrost Fracture Zone, BL: Bivrost Lineament, EGM: East Greenland Margin, GR: Greenland Ridge, HR: Hovgård Ridge, JMMC: Jan Mayen Micro Continent, MM: Møre Margin, NSF: North Sea Fan, SF: Storfjorden Fan, SFZ: Senja Fracture Zone, VM: Vøring Margin, VP: Vøring Plateau, YP: Yermak Plateau, (modified after Faleide et al., 2008).

2 Geological framework

Prior to continental breakup, the Norwegian continental shelf was connected to a major epicontinental sea covering the northern Pangea. Several tectonic phases have been recorded from Paleozoic to Cenozoic, with final break-up and seafloor spreading at the Paleocene-Eocene transition, ~55 Ma, resulting in the initial opening of the Norwegian-Greenland Sea (Eldholm et al., 2002). The post-opening history of vertical motion has led to significant differences in terms of crustal properties, structural and magmatic styles, and sediment thickness in the Lofoten-Vesterålen margin compared to the adjacent Vøring and West Barents Sea margins (Tsikalas et al., 2001; NPD, 2010).

2.1 Lofoten-Vesterålen margin

The Lofoten-Vesterålen margin is a part of the mid-Norwegian margin, and is situated between the Bivrost and the Senja Fracture Zones (Fig. 1.1). In contrast to the rest of the Norwegian continental margin, the LVM is very noticeable due to the presence of the Lofoten-Vesterålen archipelago. The margin is structurally complex and typified by a very narrow continental shelf with a steep slope (Fig. 2.1). The approximate width in the southern part is ~150 km and decreases to ~35 km in the northern part (Tasrianto and Escalona, 2015). Bathymetry data illustrate regional physiographic features, and highlight the outline of the narrow shelf and the rapid transition from shallow to deeper water (Fig 2.1). Furthermore, the bathymetry data can be used to locate structural elements, as basement highs and prominent border faults can be correlated to prominent escarpments in the bathymetry (Hansen et al., 2012).

The collapse of the Caledonian orogeny initiated a series of crustal- and lithospheric-stretching from Paleozoic to Cenozoic times. There are some disagreements regarding timing of the main post-Caledonian rifting events. However, it is believed that the most pronounced rifting phases occurred in Permo-Triassic, Late Jurassic-earliest Cretaceous, mid-Cretaceous and Cretaceous and Late Cretaceous-Early Tertiary, with ensuing late Cenozoic compression and uplift (Tsikalas et al., 2001; Færseth, 2012; Davids et al., 2013). The crustal stretching led to weakening of the crust, and gravity data demonstrate that the crust is significantly thinned towards west, ranging in thickness from 27 km westwards to 20 km (Løseth and Tveten, 1996), while an apparent increase in crustal thickness is evident towards the north along the Vesterålen Margin (Fig. 2.5) (Tsikalas et al., 2005). Shelf-parallel basement ridges and intra-continental basins situated above spoon-shaped depressions within the basement represent the main structural elements (Blystad et al., 1995). The exposed basement highs are very characteristic for the LVM, and they are emphasised in the gravity and magnetic anomaly maps as elongated anomaly belts with similar NE-SW trends (Fig. 2.2).

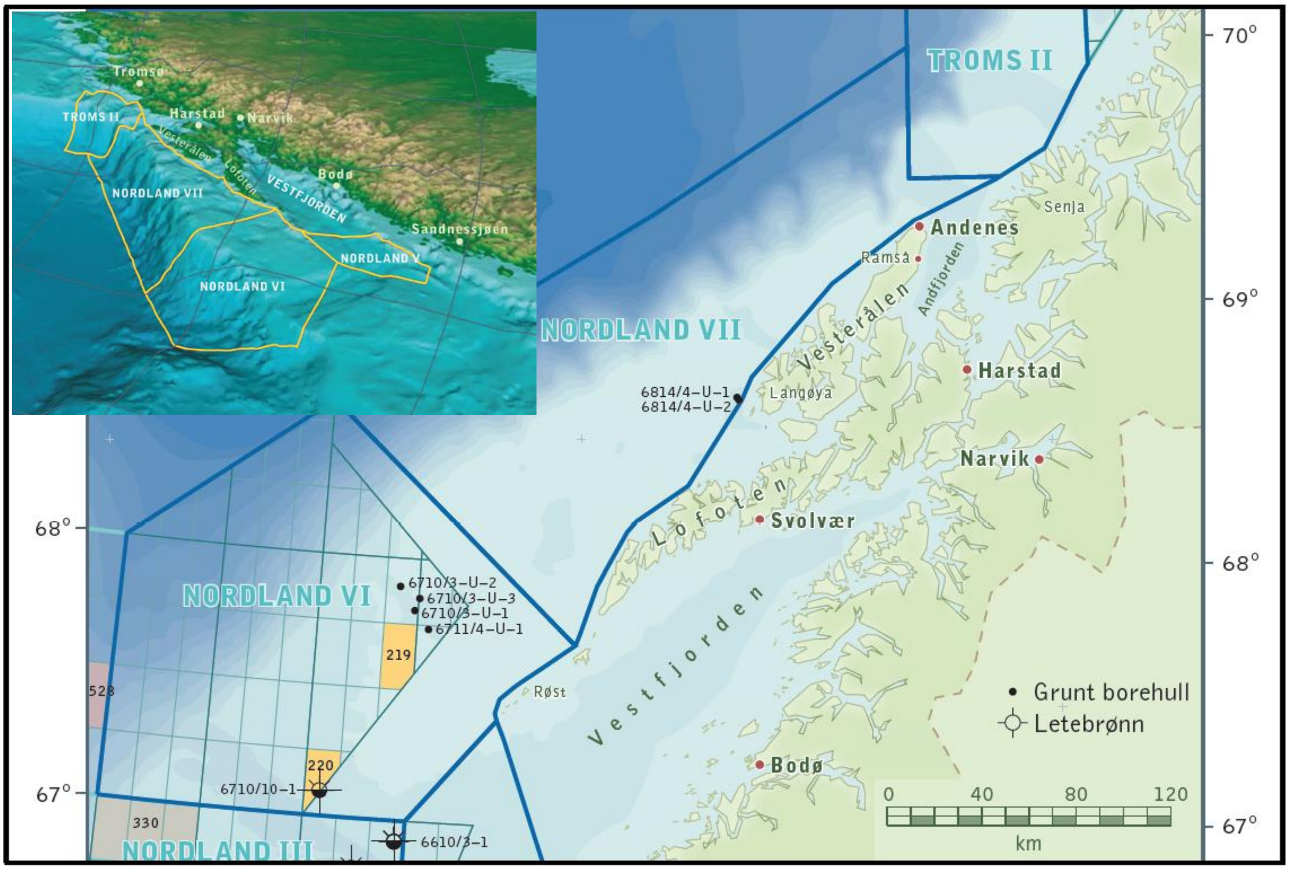
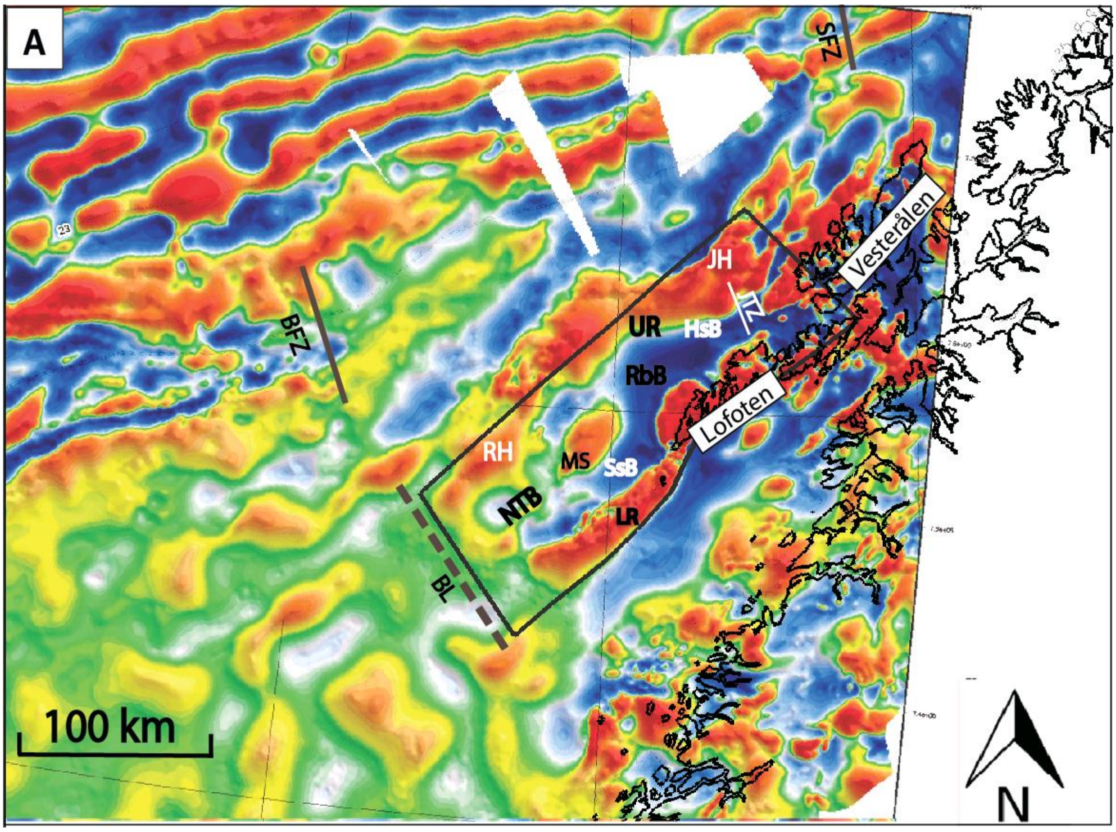


Fig. 2.1: Bathymetry data depicting the margin morphology and the narrow and steep slope along the Lofoten-Vesterålen margin (LVM). Inset: General outline of the LVM, combined with the encompassing licenses/blocks (both pictures retrieved from NPD (2010)).



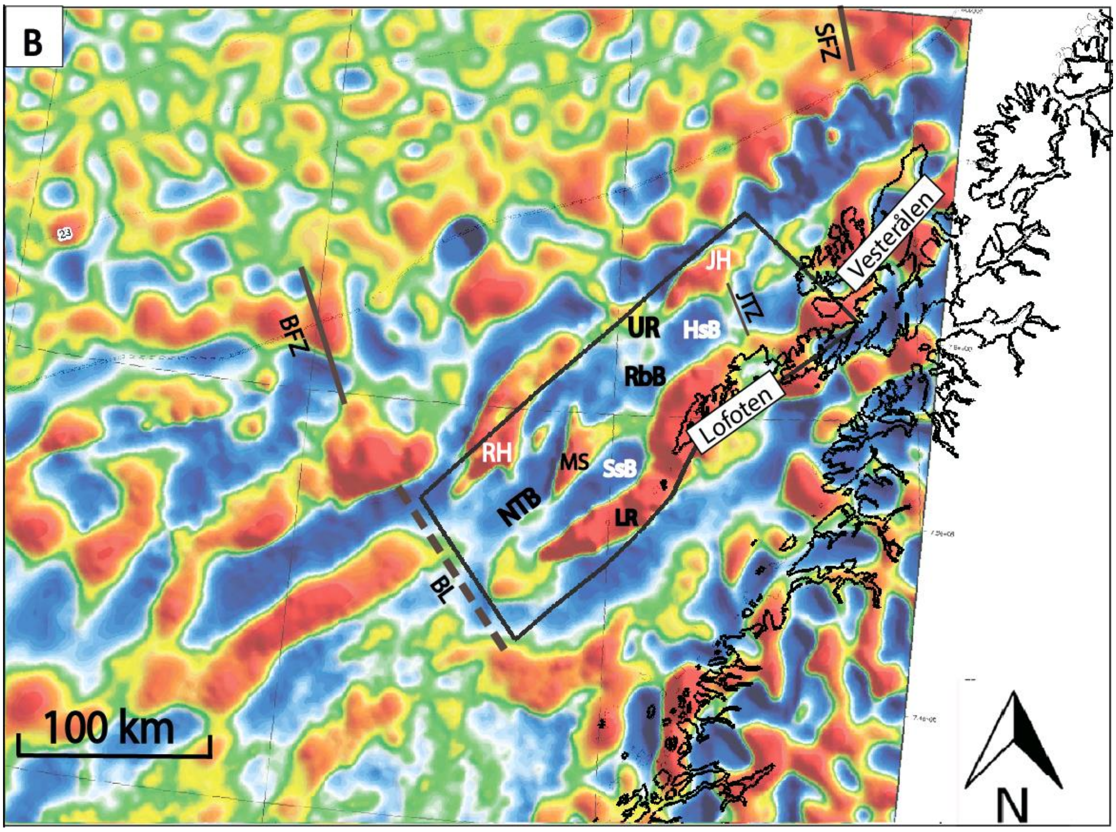


Fig. 2.2: (a) 100-km high-pass filtered magnetic anomaly data. **(b)** 50-km high-pass filtered gravity anomaly data. Rectangle marks the study area. Gravity and magnetic data courtesy of TGS.

Along-strike changes in structural style and fault-dip polarity have been mapped, separating the margin into the Lofoten and the Vesterålen margin segments (Blystad et al., 1995). There have been some disagreements regarding the nature of the structural change, and this has been attributed to the variation in fault polarity, and segmentation due to the existence of a transfer zone (Olesen et al., 1997; Tsikalas et al., 2001; Færseth, 2012). Margins can be subdivided into segments according to the degree of extension or variations in orientation of dip-polarity of border faults as a result of transfer zones (Twiss and Moores, 2007). A transfer zone is a local deformation structure, which allows transfer of displacement between two adjacent larger fault systems. Transfer zones are also known as “accommodation zones,” “relay zones” and “segments boundaries” (Gawthorpe and Hurst, 1993). The model proposed by Bergh et al. (2007), interpreted the fault dip-polarity change as a result of different fault populations. East-dipping faults were interpreted to develop in Permian-Jurassic times and west-dipping faults during Late Jurassic-earliest Cretaceous. The margin segmentation was attributed to an accommodation zone, where the different populations of faults were linked.

The *Lofoten margin segment* is dominated by west-dipping normal faults and major boundary faults. The main basement highs are the Utrøst Ridge and the Lofoten Ridge, that are seen as two distinct, partly curved, NE-SW trending potential field anomalies which separate the offshore rift basins (Fig. 2.2). The central part of the shelf is dominated by two half-grabens, the Ribban and northern Træna basins, which are situated between the Lofoten and Utrøst ridges. The Vestfjorden Basin is located on the landward side of the Lofoten Ridge (Figs. 2.3 and 2.4) (Blystad et al., 1995; Hansen et al., 2012).

The *Vesterålen margin segment* is dominated by east-dipping normal faults, and there are no pronounced boundary fault separating the offshore rift basins from the Vesterålen islands (Hansen et al., 2012). The main structural elements are the northward continuation of the Utrøst Ridge, Jennegga High, and the Ribban Basin. The Vesterålen islands to the east are represented as elongated magnetic and gravity highs (Fig. 2.2).

2.2 Lofoten margin segment

2.2.1 Basin configuration

The Lofoten and Utrøst ridges consist of exhumed basement rocks, which were uplifted during Permian time (Færseth, 2012). The ridges consist of exposed crystalline rocks of presumed Caledonian age, which have remained as elevated features during Triassic-Jurassic and Early Cretaceous times. Several prominent highs within the Utrøst Ridge cause a further subdivision of the ridge. The most prominent of those are the Jennegga High in the north, the Røst High in the south-western part, and the Marmæle Spur as a partly rifted lineament in the south-eastern part (Fig. 2.3 and Table 2.1) (Blystad et al., 1995).

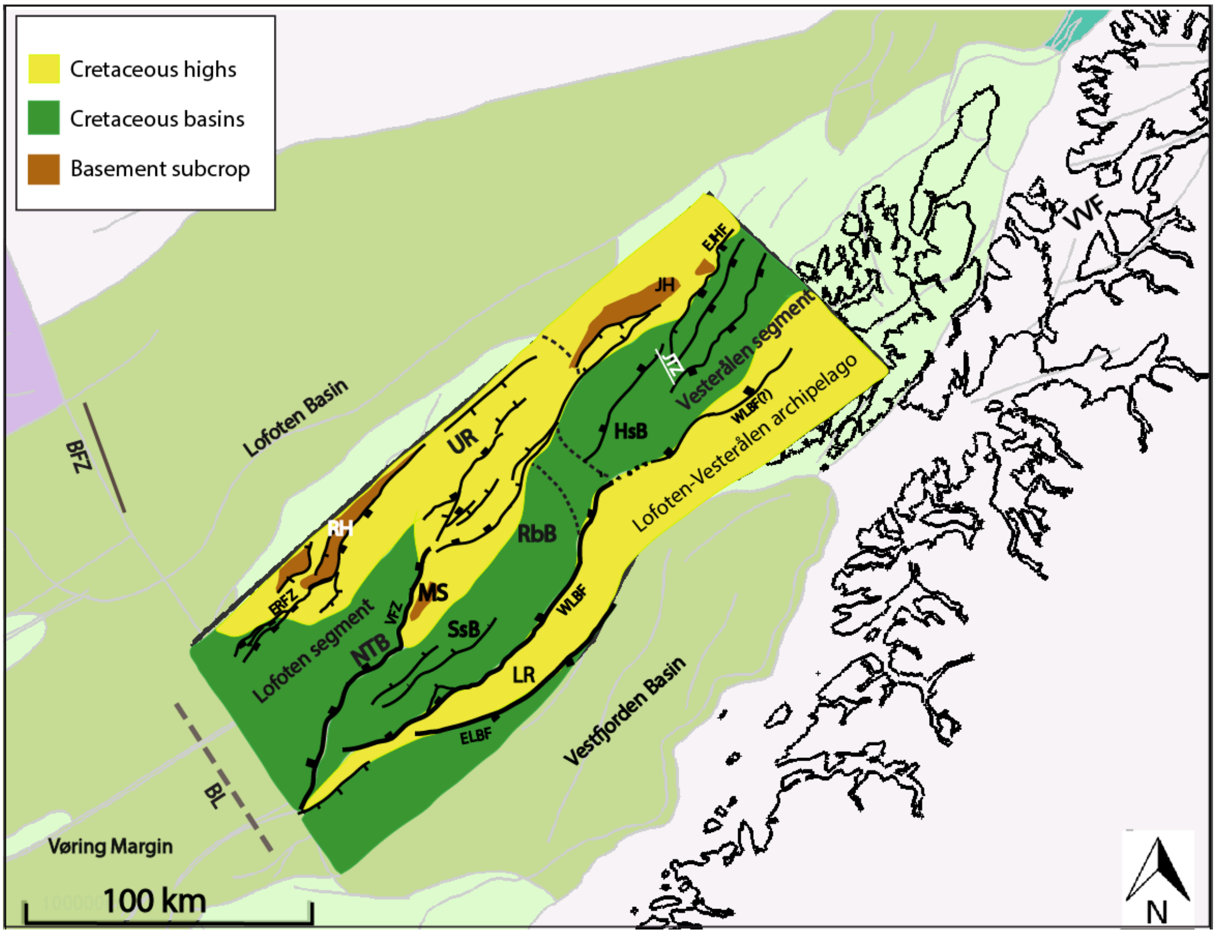


Fig. 2.3: The main structural elements within the study area are displayed, and the NPD FactMap is included in the background. Further abbreviations are summarized in Table 2.1.

Table 2.1. Main structural element abbreviations used in the thesis.

WLBF= West Lofoten Border Fault	RbB= Ribban Basin	LVM= Lofoten-Vesterålen margin
ELBF= East Lofoten Border Fault	SsB= Skomvær Sub-basin	UR= Utrøst Ridge
VFZ= Vesterdjupet Fault Zone	HsB= Havbåen Sub-basin	RH= Røst High
ERFZ= East Røst Fault Zone	NTB= northern Træna Basin	JH= Jennegga High
EJHF = East Jennegga High Fault	VB= Vestfjorden Basin	MS= Marmæle Spur
VVF= Vestfjorden-Vanna Fault Complex	LB= Lofoten Basin	LR= Lofoten Ridge

The fault complexes within the Lofoten Vesterålen margin are characterized by listric geometry with large-scale displacement and they run parallel to the ridges. The Lofoten Ridge includes the West Lofoten and East Lofoten Border Fault (WLBF and ELBF). The pronounced Vesterdjupet Fault Zone (VFZ) is located along the SE-part of the Utrøst Ridge (Marmæle Spur). The zone is composed of NE-SW and NNE-SSW trending faults dipping towards west, where a deeply rooted listric fault is the most dominant (Blystad et al., 1995). No pronounced border fault is evident along the Utrøst Ridge, which is composed by several east-dipping faults. The Røst and Jennegga highs exhibit indications of border faults, referred to as the East Røst Fault Zone (ERFZ) and East Jennegga High Fault (EJHF) (Fig. 2.3 and Table 2.1).

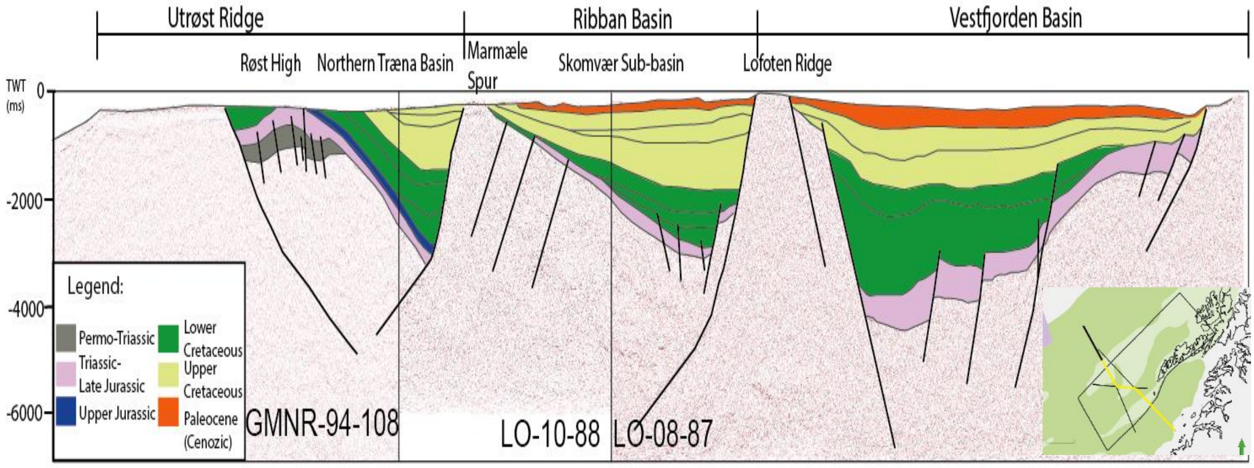


Fig. 2.4: Seismic profile revealing the basin geometry of the Vestfjorden, Ribban and northern Træna basins, separated by the Lofoten Ridge and the Marmæle Spur, respectively (modified from Blystad et al., 1995).

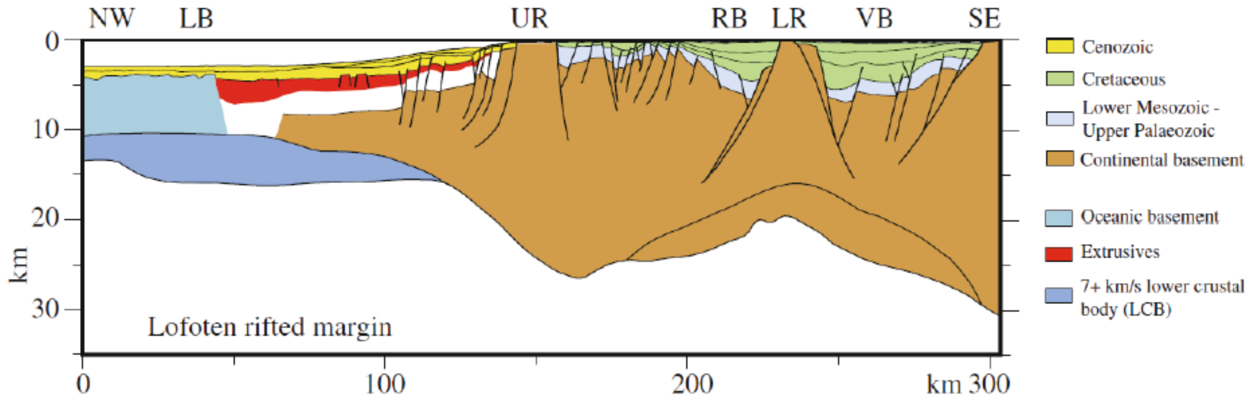


Fig. 2.5: Regional crustal transect across the Lofoten margin segment. LB: Lofoten Basin, UR: Utrøst Ridge, RB: Ribban Basin, VB: Vestfjorden Basin (modified from Faleide et. al., 2010). Transect location in close vicinity to seismic profile in Fig. 2.4.

The partly land-locked Vestfjorden Basin separates the Lofoten-Vesterålen archipelago from the mainland coast of Nordland to the east (figs. 2.3 and 2.4). The main basin bounding-fault is the East Lofoten Border fault to the west, generating a half-graben in the hanging-wall. An overall curved NNE-SSW trending axis is observed for the basin (Blystad et al., 1995).

West of the Lofoten Ridge, the Ribban Basin has been developed as a half-graben in the hanging-wall of the WLBF. The basin follows the curvilinear shape of the Utrøst Ridge towards the Vesterålen Islands, which forms the western margin of the basin. Due to the absence of border faults to the west, the basin terminates up-flank of the Utrøst Ridge. A structural high divides the basin into a northern and southern sub-basin, the Havbåen and Skomvær, respectively (Blystad et al., 1995). Both sub-basins are characterized by shallow and wide depressions, situated above east-trending basement highs. The Marmæle Spur separates the Ribban Basin from a prominent half-graben structure created in the down-faulted side of the Vesterdjupet Fault Zone (Fig. 2.4). The half-graben is interpreted as a continuation of the Træna Basin from the Vøring margin, referred to as the northern Træna Basin. The western boundary of the northern Træna basin is the East Røst Fault Zone. The Vesterdjupet Fault Zone juxtaposes the Ribban and northern Træna basins south of the Marmæle Spur (Fig. 2.3) (Blystad et al., 1995; Henstra et al., 2015).

Generation and configuration of the extensional basins are closely connected, and an initiation during the Middle Jurassic-earliest Cretaceous crustal stretching, and ensuing subsidence has been proposed. Lower to Upper Cretaceous sedimentary rocks predominately represent the basin infill, whereas the Lower Cretaceous sediments define the basin floor (Blystad et al., 1995). Basin architecture and filling patterns are largely controlled by the border faults, which created local and regional depo-centres.

The network of mapped fault complexes might, to some extent, have been controlled by ductile basement fabrics and Caledonian thrust nappes which overlay the basement in the east Lofoten margin. Løseth and Tveten (1996) and Bergh et al. (2007) noticed that internal basement fabrics could provide areas of weaker basement rocks, generating favorable pathways for brittle faulting. Furthermore, structural inheritance may have played an important role, as NE-SW trending faults could have developed along foliation and ductile shear zones generated in connection to the NNW-SSE trending Senja Fracture Zone (Bergh et al., 2007). Lastly, basement-inherited structures seem to affect the propagation of younger faults, which use these as template for further propagation (Færseth, 2012).

2.2.2 Stratigraphic framework

Sedimentation and erosion in the Lofoten-Vesterålen margin have been controlled by tectonic events, combined with eustatic sea-level changes and climate conditions. The post-orogenic sedimentation is characterized by several extensional phases with fault-block rotation (Færseth, 2012).

The Permo-Triassic rifting event generated large faults in the well-explored areas to the south known from the inner Vøring Margin. However, there is limited compelling evidence of this event in the Lofoten-Vesterålen margin (Færseth, 2012). Warm and arid climate characterizes the Triassic period, and the topography is interpreted to consist of a smooth, peneplane-basement relief. Due to subaerial exposure over a longer period the basement is severely weathered, and is overlaid by Triassic and Jurassic sediments. Late Triassic deposits were mainly continental, with sandstones and conglomerates deposited in shallow marine to fluvial environments (Smelror et al., 2001; Tsikalas et al., 2001; NPD, 2010). The Triassic to Early Jurassic period has been considered as relative tectonically quiet, in a post-rift setting (Faleide et al., 2010). Prior to onset of the next rifting phase the margin exhibited limited accommodation space, resulting in deposition of a very thin Triassic- Lower Jurassic sedimentary layer (NPD, 2010). The Late Jurassic-earliest Cretaceous rifting event climaxed around Middle/Late Jurassic, and the generation of the present-day structural elements were established (Færseth, 2012; Hansen et al., 2012). The Middle Jurassic strata consist of sandstones deposited in a deltaic environment, due to the uneven topography created by the block-faulting. Marine transgression combined with subsidence of the area during late Jurassic favoured shaly deposits. The subsidence continued into earliest Cretaceous time, and mud- and shale-rich deposits covered most of the Lofoten-Vesterålen margin, except for the Lofoten Ridge and some parts of the Utrøst Ridge, which remained as basement horsts. The major fault systems generated uplift of the ridges, which were further eroded during Early Cretaceous (NPD, 2010).

By mid-Cretaceous times most of the earlier structural relief was filled in by Lower-Cretaceous strata (Faleide et al., 2010). Increased quantities of sand characterize the mid-Cretaceous depositions, and the sandy deposits are mainly located on the basin flanks and around structural highs. The transition from Lower to Upper Cretaceous strata is marked by a pronounced subsidence within the Lofoten-Vesterålen margin. The subsidence has been related to a poorly understood mid-Cretaceous rifting event, which can possibly be correlated to a similar event along the Vøring margin, where a transition from neritic to bathyal conditions has occurred and reflected eustatic sea-level rise and regional tectonics (Tsikalas et al., 2001).

During the transition from Cretaceous to Paleogene, the Lofoten-Vesterålen margin was again subjected to rifting. The deformation and rifting were mainly focused west of the Utrøst Ridge, and the central part of the margin was rather unaffected. Pulses of coarser material from Early Cenomanian to Early Campanian interfere with the predominantly fine-grained clastic sediments of Upper Cretaceous, and indicate the initial stage of the rifting phase (Tsikalas et al., 2001; Hansen et al., 2012). This rifting event is distinguished from prior rifting events, due to dextral plate-movement between the Norwegian and Greenland plate. Consequently, the combination of transform and extensional forces resulted in an uplift of the currently Lofoten-Vesterålen area, and the shelf-edge was severely broken up by faults (NPD, 2010). Final breakup at the Paleocene-Eocene transition (~55Ma) was followed by thermal subsidence, leading to the deposition of Paleogene claystones (Hansen et al., 2012). Massive igneous activity connected with the onset of seafloor spreading near the Paleocene-Eocene transition is evident beneath the continental slope, but limited east of the Utrøst Ridge (Tsikalas et al., 2001; Bergh et al., 2007). Following the continental breakup, the Norwegian passive margin was subjected to a light compressional tectonic regime due to seafloor spreading (Blystad et al., 1995). Another prominent event during late Cenozoic was the Northern Hemisphere glaciations. Pliocene and Pleistocene glacial-related deposits overlie the Paleogene succession towards west, and there is evidence of prominent and deep-cutting erosion connected to the glaciation history (NPD, 2010).

In general terms, the Mesozoic and Cenozoic successions are mainly characterized by alternating sandstones and shales, with some minimal presence of carbonate layers. This reflects the margin evolution with several phases of uplift and subsidence. The tectono-stratigraphic evolution of the Lofoten-Vesterålen margin is further summarized in Figure 2.6, highlighting the most important tectonic phases on the mid-Norwegian margin.

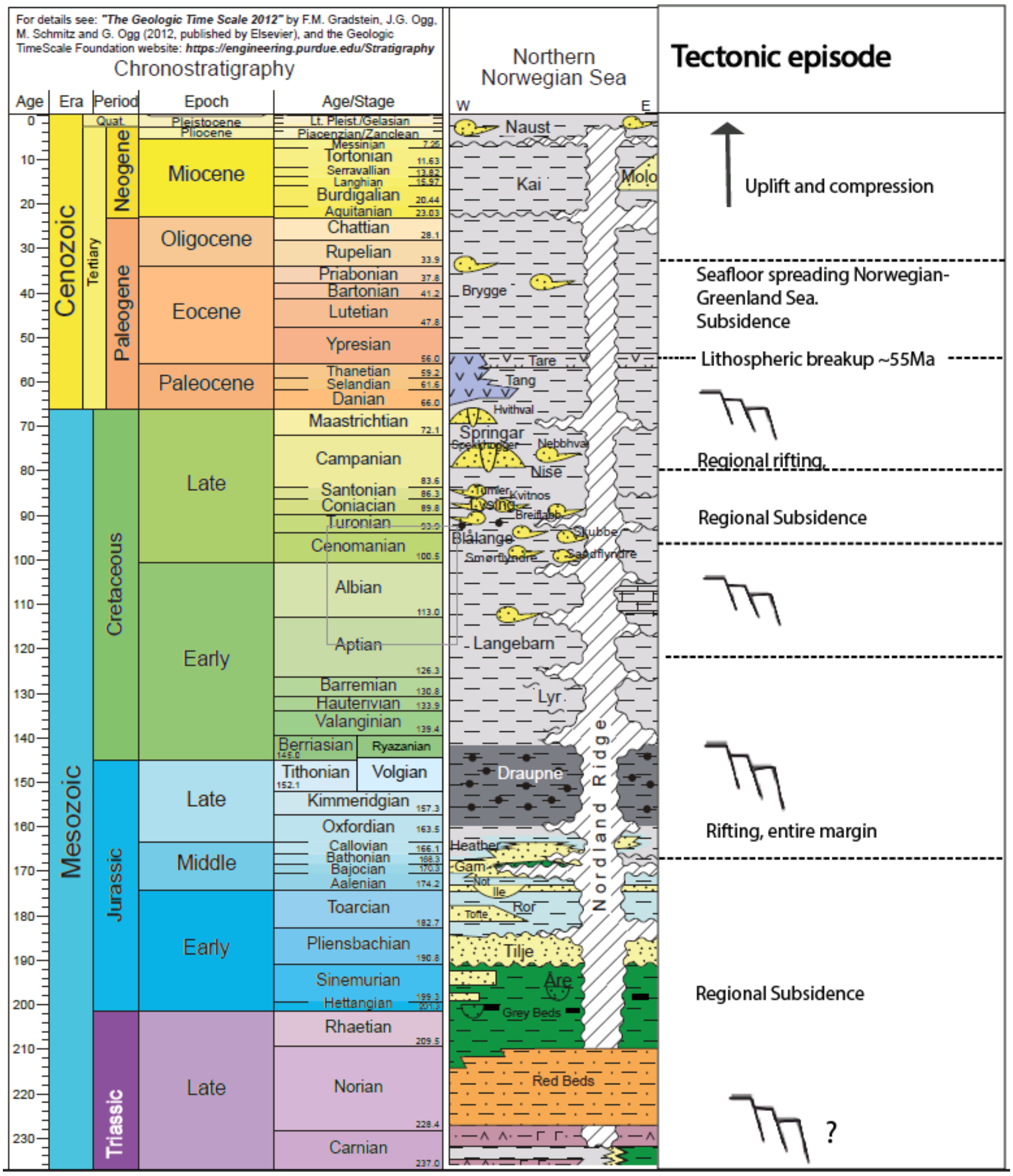


Fig. 2.6: Stratigraphic chart of the Northern Norwegian Sea, major phases of tectonic activity is included (modified from Tsikalas et al., 2012). Chronostratigraphic and lithostratigraphic chart retrieved from NORLEX .

2.3 Oil and gas exploration in Lofoten-Vesterålen margin

Significant exploration potential exists for the Lofoten-Vesterålen margin (LVM), when comparing the margin to the adjacent mid-Norwegian Sea and Barents Sea that both contain multiple discoveries of hydrocarbons. Still, with only two explorations wells drilled in the LVM, and one present in the study area, are large uncertainties connected to the area. The Norwegian Petroleum Directorate (NPD) accounts for the main resource evaluation of the area. According to the study and evaluation by NPD in 2010 the amount of potential recoverable resources is estimated to 76 Million Sm^3 (with 95% confidence). Furthermore, the same study has shown a number of petroleum systems at several stratigraphic levels, ranging in age from Paleozoic to Cenozoic (NPD, 2010). However, the probability for a working Jurassic petroleum system is considered by the NPD as the most realistic. Early to Middle Jurassic sandstones are interpreted as the most important reservoir rocks, and Late Jurassic shales are suggested as source rocks. The majority of the mapped traps are structural, with fault-blocks delaminated by normal fault systems. A curtail factor for these systems will be the degree of erosion of the major fault-blocks as a result of repeated uplift events (NPD, 2010).

The area north of 62^{o}N was first opened for petroleum exploration in 1979, and following drilling revealed the petroleum potential for the mid-Norwegian margin. The LVM encompasses three exploration macro-areas; Nordland VI, Nordland VII and Troms II (Fig. 2.1). The study area is located within the central and eastern parts of Nordland VI and the southern part of Nordland VII. The study area also comprises the northeastern corner of Nordland III, to include exploration well (6610/3-1 R2). The well was drilled in 1992-1993, and revealed traces of hydrocarbons. The western part of Nordland VI was opened for petroleum exploration in 1994, but only one conventional exploration well (6710/10-1, TD: uppermost Cretaceous, dry) was drilled before the area was closed for petroleum exploration in 2001. No petroleum activity is currently permitted in the Nordland VI, Nordland VII and Troms II areas (NPD, 2010).

3 Data

3.1 Seismic reflection data

The seismic dataset utilized in this study consists of approximate 9500 km in total of conventional 2D multi-channel seismic reflection profiles (MCS) (Fig. 3.1 and Table 3.1). The Lofoten-Vesterålen margin (LVM) is not extensively covered by 2D MCS profiles, and the average profile line-spacing is approximately 4-5 km within the study area. The densest line-spacing is within the northern Træna Basin (Fig. 3.1).

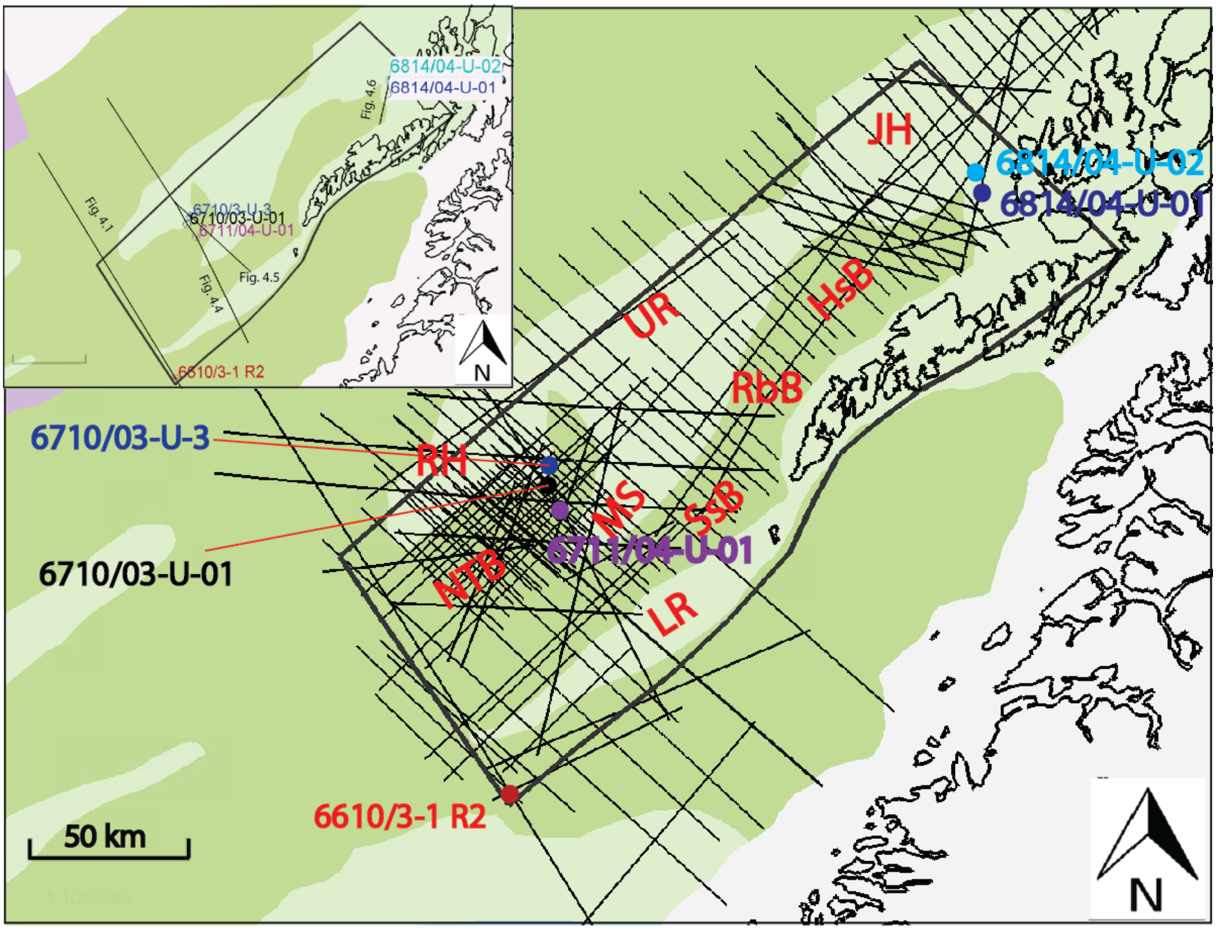


Fig. 3.1: Total coverage of seismic lines within the study area, and wells location. See Table 2.1 for abbreviations. Inset: location of wells and tie to seismic lines.

Table 3.1: Utilized seismic reflection surveys.

Survey name	**Year**	**Company/authority**	**Recording time (s, TWT)**	**Resolution Quality**
LO-86	1986	NPD	6	Good
LO-87	1987	NPD	6	Moderate to good
LO-88	1988	NPD	6	Moderate
UH-94R00	1994	TGS	7	Good
N6-92R00	1992	TGS	7	Very good
GMNR-94	1994	NPD	14	Very good
TB-87	1987	NPD	7	Good

Variations in seismic resolution are evident in the different surveys, ranging in quality from moderate to very good. In the majority of the study area, the 2D MCS profiles have a record time-depth of 6-7 s TWT (two-way traveltime). Lowest resolution with depth is observed in the northernmost part of the study area, where little or no internal basement configuration is possible to interpret. Still, the seismic is sufficient to map the deepest sequence. Artefacts, such as sea-bottom multiples, are present in the MCS profiles along the entire study area, and appear most frequently in the LO-survey profiles. The GMNR-94 survey profiles exhibit the best resolution with depth. However, some disturbances, such as diffractions, are present within the GMR-94 and N6-92R00 surveys in the vicinity of the Lofoten Ridge. Sparse profile line-spacing across the ridges causes visual interference, resulting in the illusion of local depressions.

3.2 Well data

The shallow IKU (Institute of Continental Shelf Research) boreholes (each with available 100-300 m continuous cores) within the study area have been utilized. In addition, exploration well 6610/3-1 R2 with penetrating depth down to 4172 m provided good stratigraphic control points (Fig. 3.1 and Table 3.2). The absence of widely distributed wells within the study area leads to limitations in stratigraphic and lithological constraints. Despite this, the wells were used for the best possible correlations of the seismic sequences. The available well-to-seismic ties were given in depth (TVDSS, True Vertical Depth Sub-Sea; meters). Based on earlier reported stacking interval velocity information for the area (Table 3.3), and the limited available well-logs, depth-time functions were constructed and used in the two-way-traveltime formation-top (reflector) picking in the MCS profiles.

Table 3.2. Utilized wells in the thesis.

Well name	**Location**	**Type**	**Operator**	**Coordinates**
6610/3-1 R2	Vestfjorden Basin	Exploration	Statoil	66° 55' 29.7" N 10° 54' 6.28" E
6711/04-U-01	Northern Træna Basin	Shallow stratigraphic	IKU	67° 44' 12.2 " N 11° 6' 34.3 " E
6710/03-U-01	Northern Træna Basin	Shallow stratigraphic	IKU	67° 48' 16.4 " N 10° 57' 25.3 " E
6710/03-U-03	Røst High	Shallow stratigraphic	IKU	67° 53' 34.7 " N 10° 48' 6.4 " E
6814/04-U-02	Havbåen Sub-basin	Shallow stratigraphic	IKU	68° 39' 45.8 " N 14° 9' 47.1 " E
6814/04-U-01	Havbåen Sub-basin	Shallow stratigraphic	IKU	68° 39' 10.9 " N 14° 11' 8.9 " E

Table 3.3. Stacking interval velocities for the area used in depth-time conversions for the formation-top (reflector) picking (after Tsikalas et al., 2005).

Unit	**Velocity (km/s) shelf**
Water	1.46
Plio-Pleistocene glacial sediments	1.80-1.85
Tertiary	2.45
Upper Cretaceous	2.70-2.80
Aptian-Albian	3.30
Lower Cretaceous	3.75-8.80
Pre-Cretaceous	4.10-4.45
Continental crystalline crust	6.0-6.8/7.1

3.3 Potential field anomaly data

Gravity and magnetic anomaly data compilations exist for LVM (NGU, Geological Survey of Norway; (Olsen et al., 2010)) (Fig. 2.2). Magnetic anomalies are a measure of local variations in the Earth's magnetic field, as a result of rocks being composed with differences in chemistry and magnetism. Gravimetric anomalies are a means to measure density differences. Surface rocks such as sandstones, limestones, granite etc. seldom exceed the density of the Earth's interior, and high density objects such as basement highs are highlighted (Mussett and Khan, 2009). Magnetic and gravity anomalies can provide important information in areas with limited seismic coverage, and have been proven to be useful to locally and more accurately delineate the basin configuration and basement highs. The basement highs are displayed as high positive anomalies, while low anomalies are observed in the sediment filled basins (Fig. 2.2). In this study, the magnetic and gravimetric data have mainly been used to confirm seismically determined tectono-stratigraphic trends and to extrapolate and identify linear offshore fault systems.

4 Seismic and structural interpretation

4.1 Workflow and approach

Schlumberger's software Petrel has been used as the main interpretation tool in this study. The initial approach and attempt was to gain an overall understanding of the margin architecture. This was achieved by mapping the Base Cretaceous Unconformity (BCU) reflector, which defines the base of the Cretaceous basins. Three distinct horizons representing the Lower Cretaceous basin infill were traced, together with two horizons representing the Upper Cretaceous sequences. This was done to gain knowledge of the sequence stratigraphy and structuring of the basins. Even though the main emphasis in this study is the Cretaceous basin configuration and infill, mapping of pre-Cretaceous and Paleogene horizons was also necessary. The objective of the latter step was to understand how events prior and after Cretaceous times may have influenced the configuration of the basins, within the context of the Lofoten-Vesterålen margin tectono-stratigraphic evolution.

Time-structure surfaces and time-thickness maps were generated to accomplish a lateral and vertical visualization of the infill and structural evolution. Potential field data (gravity and magnetics) have been used to identify and trace structural elements and lineaments that were only partially visible in the 2D MCS profiles. Then, a mapping of the complex fault systems was conducted. In this way, a better knowledge and understanding of the dynamics connected to the structural development of the study area was gained, together with further correlation of the observations with infill-history and tectono-stratigraphic trends.

4.2 Well correlation

Limited well information from the Lofoten-Vesterålen margin causes large uncertainties when conducting a stratigraphic analysis. The structural complexity combined with areas of low quality seismic reflection data makes, in addition, the interpretation difficult. The available exploration well 6610/3-1 R2 (Fig. 4.1) together with the five shallow IKU boreholes and the preserved onshore Andøya section (Fig. 4.2), have been used to identify and map nine distinct horizons/reflectors that overlie the Precambrian/Caledonian basement. Stacking interval velocities shown in Table 3.3 have been used in rough depth conversions; from milliseconds two-way travel-time (ms TWT) into meters in depth, and vice versa. Earlier interpretations performed by Tsikalas et al. (2001), NPD (2010), Hansen et al. (2012) and Henstra et al. (2015) have been used as reference.

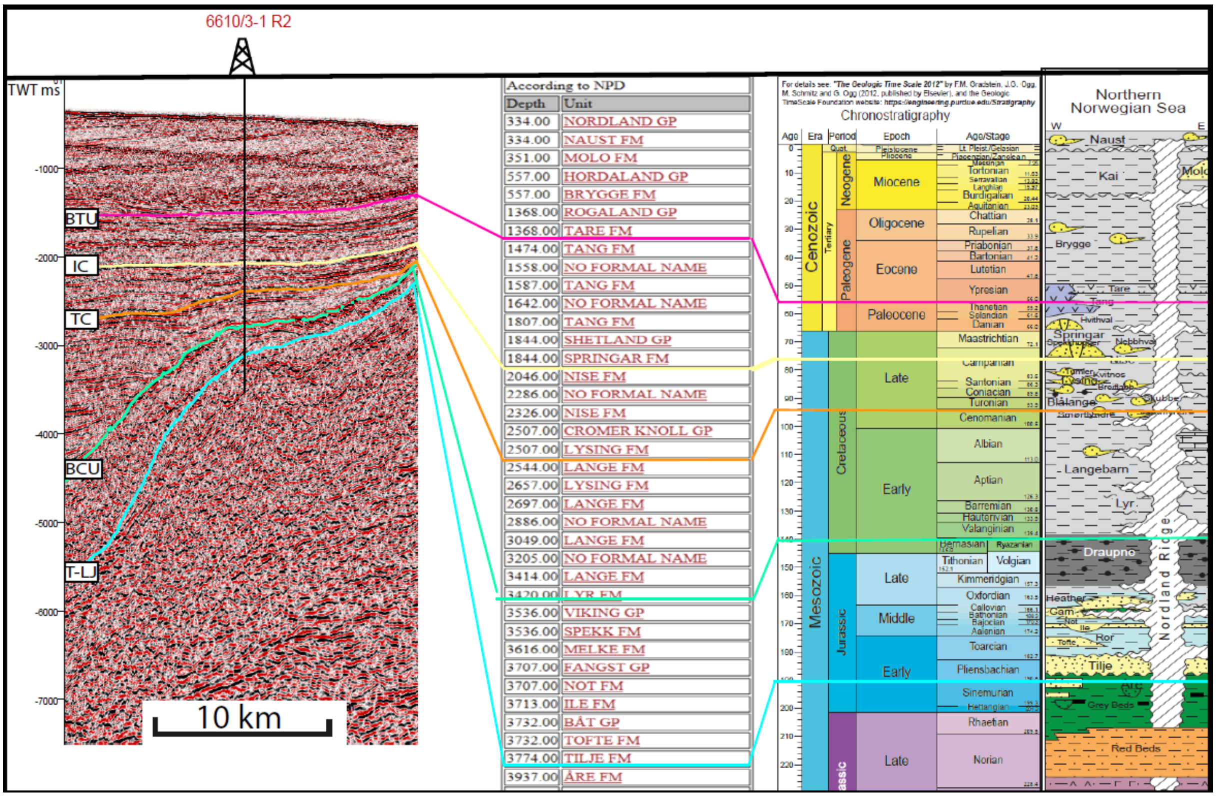


Fig. 4.1: Well-to-seismic tie of exploration well 6610/3-1 R2 (GMNR-94-320A). Available lithostratigraphy data from NPD have been used to tie the interpreted horizons to formations and the geological time-scale. See Fig. 3.1 for well location.

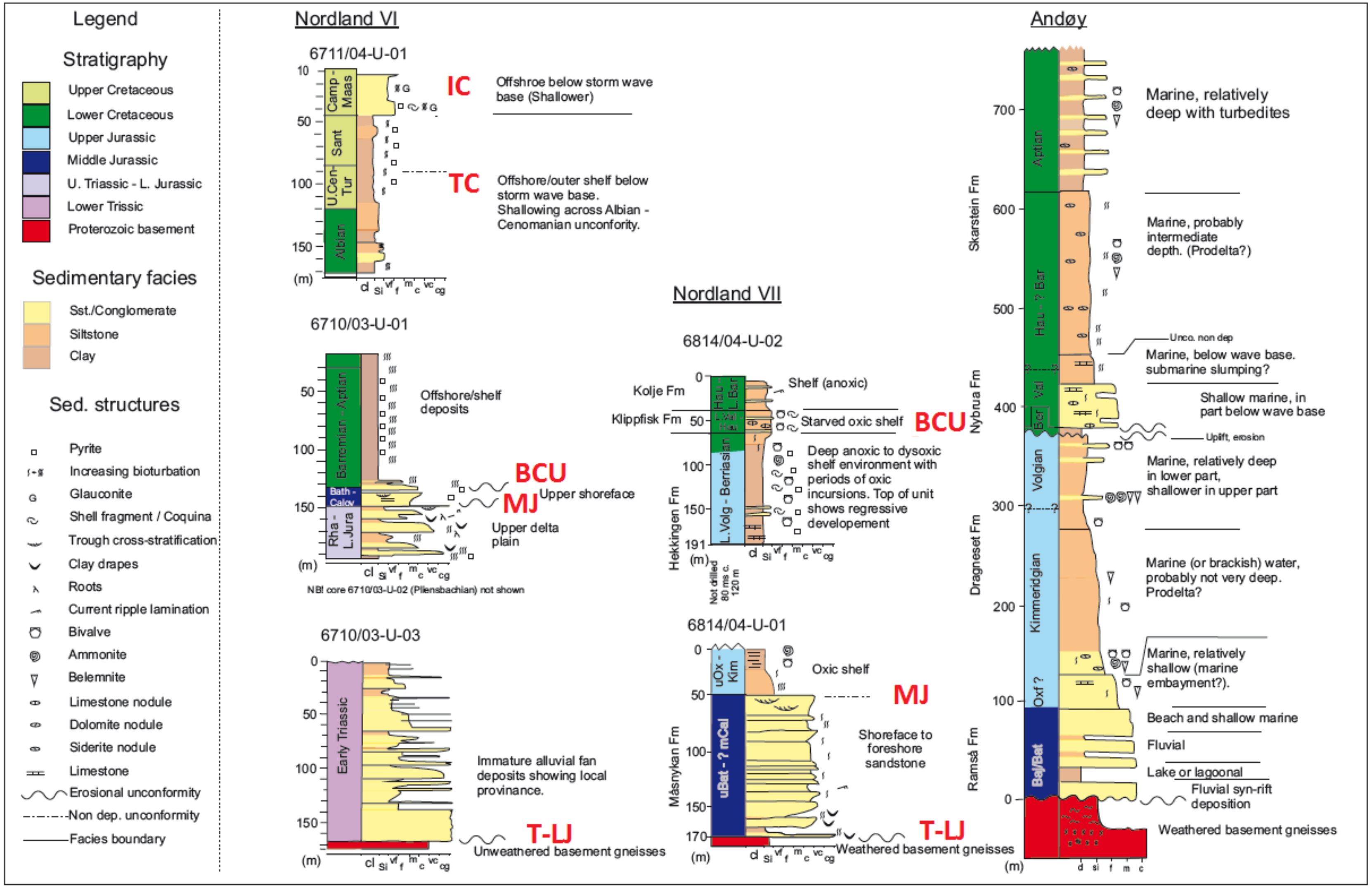


Fig. 4.2: Available information from the IKU shallow boreholes and onshore Andøya. Interpretations are compiled from Smelror et al. (2001) (after Hansen et al., 2012)

4.3 Interpreted key horizons/reflectors and sequences

Based on correlations to the available wells and boreholes described above, the seismic stratigraphic framework for the study area has been established and used in the detailed seismic interpretation (Fig. 4.3 and Table 4.1).

The seismic-to-well correlations for well 6610/3-1 R2, IKU shallow boreholes in the northern Træna Basin, and IKU shallow boreholes in the Havbåen Sub-basin are shown in Figures 4.4, 4.5 and 4.6, respectively.

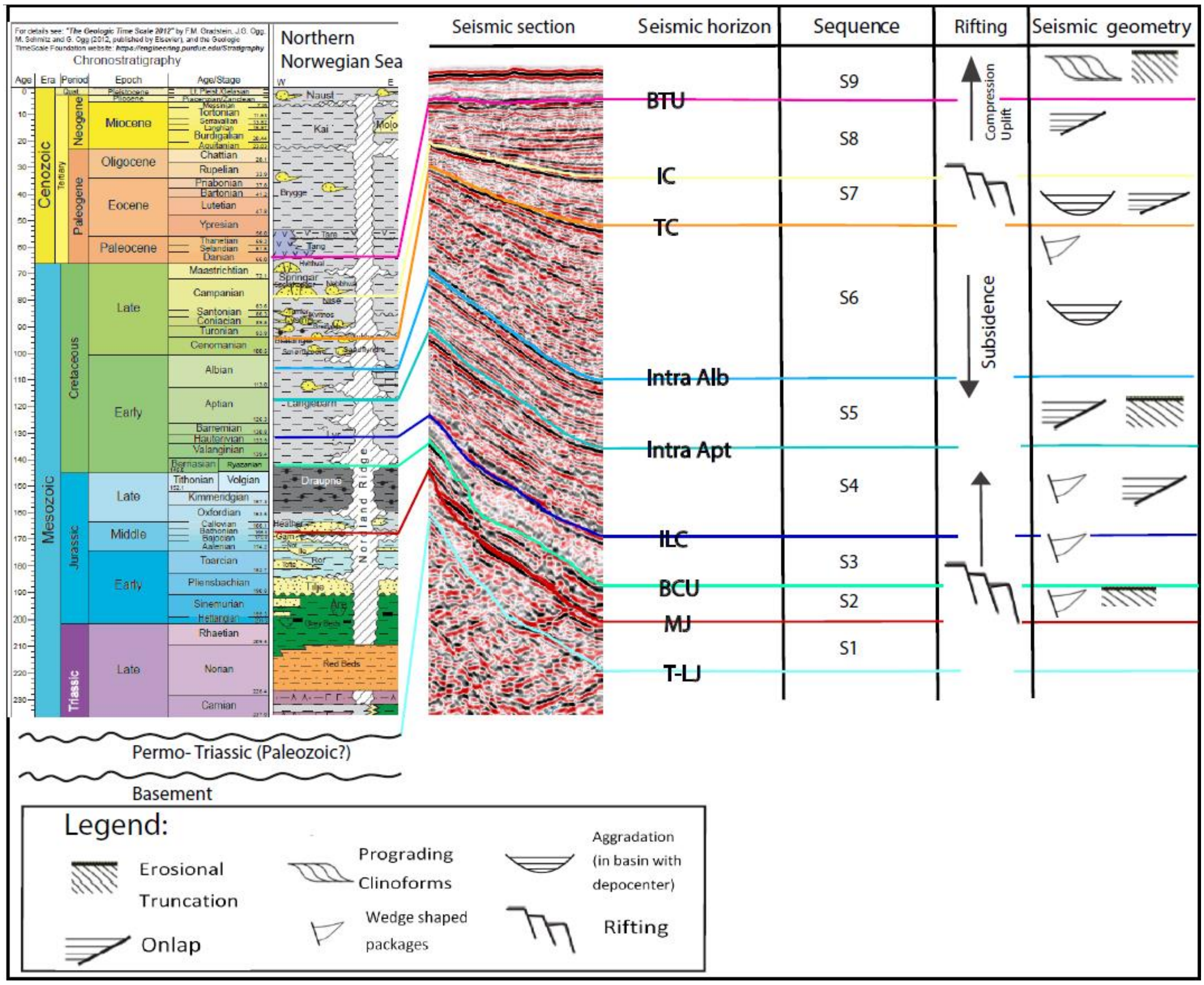


Fig. 4.3: Seismic stratigraphic framework of the Lofoten Vesterålen margin. The nine interpreted horizons bind in total nine sequences, which have been tied to the chronostratigraphy for the area utilizing the available shallow boreholes and the exploration well.

Table 4.1: Mapped horizons/reflectors within the study area.

Reflection	*Abbreviation*	*Seismic reflection character*	*Well tie*
Base Tertiary Unconformity	BTU	Chaotic and discontinuous reflector, with low amplitude	6610/3-1 R2
Intra Campanian	IC	Continuous high amplitude reflector	6610/3-1 6711/04-U-01
Top Cenomanian	TC	Strong continuous reflector, high amplitude	6610/3-1 R2 6711/04-U-01
Intra Albian	Alb	Semi-continuous reflector (continuous in the northern Træna Basin)	6711/04-U-01
Intra Aptian	Apt	Semi-continuous reflector with medium amplitude strength	6710/03-U-01
Intra Lower Cretaceous	ILC	Varying amplitude strength in the deepest part of the basins; semi-continuous reflector, with limited lateral distribution	Not drilled
Base Cretaceous Unconformity	BCU	Regional erosional unconformity; continuous reflector with distinctive strong amplitude	6610/3-1 R2 6710/03-U-01
Middle Jurassic	MJ	Semi-continuous lower amplitude reflector	6710/03-U-01 6814/04-U-01
Triassic-Lower Jurassic	T-LJ	Semi-continuous to continuous, varying amplitude intensity reflector	6710/03-U-03 6814/04-U-01 6610/3-1 R2
Paleozoic	Pl	Semi-continuous reflector, medium seismic amplitude; limited lateral distribution within the northern Træna Basin	Not drilled

Figure 4.7 displays the interpreted and mapped key horizons within the study area (Table 4.1). An overview of the interpreted horizons/reflectors and sequences is given below, providing details on seismic correlation issues and on the observed seismic character.

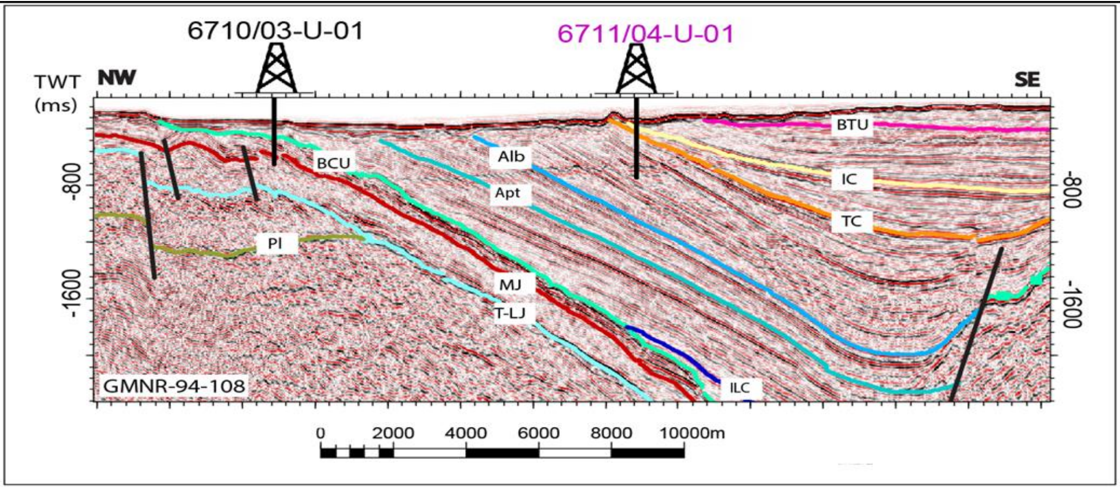


Fig. 4.4: Correlation of shallow boreholes 6710/03-U-02 and 6711/04-U-01 in the northern Træna Basin to the NW-SE trending GMNR-94-108 profile. Profile location in Fig. 3.1, and horizon abbreviations in Table 4.1.

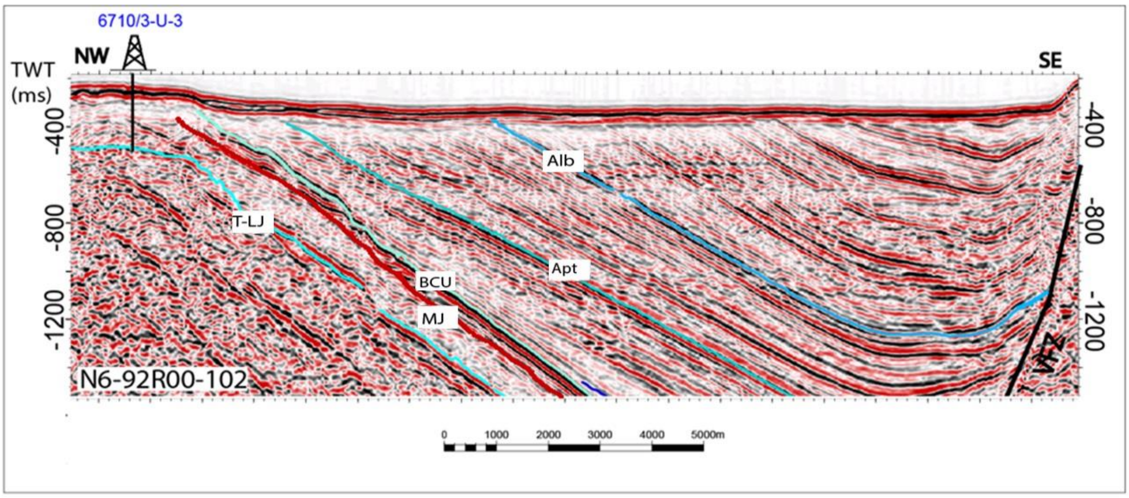


Fig. 4.5: Correlation of shallow borehole 6710/03-U-03 on the Røst High, to the NW-SE trending N6-92-R00-102 seismic profile. Profile location in Fig. 3.1, and horizon abbreviations in Table 4.1.

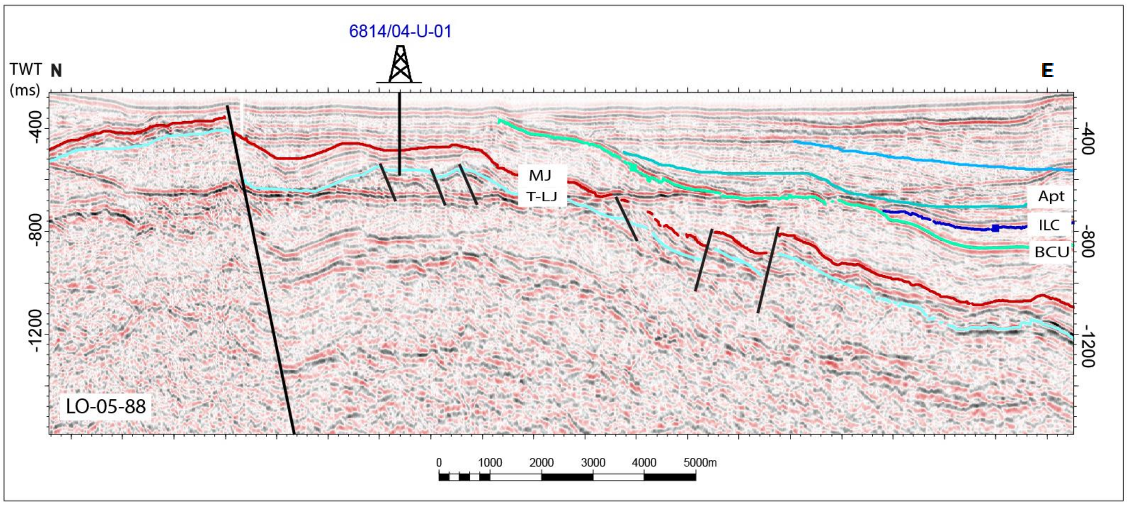


Fig 4.6: Correlation of shallow borehole 6814/04-U-01 in the Havbåen Sub-basin to the N-E trending LO-05-88 seismic profile. Profile location in Fig. 3.1, and horizon abbreviations in Table 4.1.

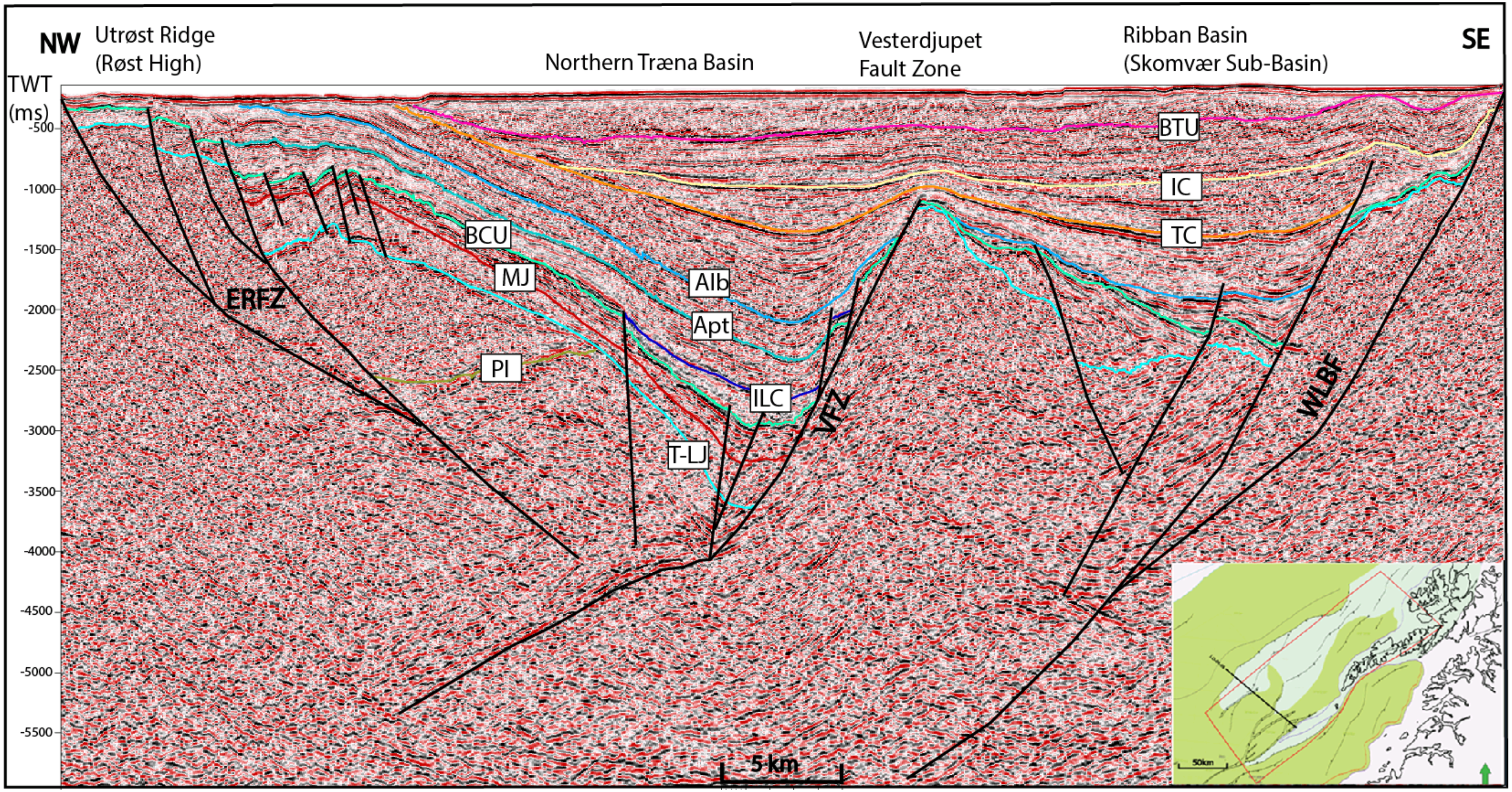


Fig. 4.7: A summary of the interpreted and mapped key horizons within the study area. The NW-SE trending seismic profile LO-04-86 shows the transition from the Skomvær Sub-basin to the northern Træna Basin. Horizon abbreviations in Table 4.1 and structural element abbreviations in Table 2.1.

4.3.1 Pre-Cretaceous reflectors and sequences

Basement/Triassic-Lower Jurassic (T-LJ) reflector

The presence of Precambrian basement is confirmed by the shallow borehole 6710/03-U-03 located at the Røst High, shallow borehole 6814/04-U-01 in the Havbåen Sub-basin, and well 6610/3-1 R2 in the Vestfjorden Basin (Figs. 4.1, 4.4, and 4.6). Core information from 6814/04-U-01 and 6710/3-U-03 reveals that the basement consists of strongly foliated gneiss, generated as a result of the Caledonian Orogenesis (Fig. 4.2). The internal basement configuration displays smooth folded reflections, which are locally faulted. No evidence of weathering is observed in borehole 6710/03-U-03 (Røst High). However, borehole 6814/04-U-01 (Havbåen Sub-basin) shows indication of weathering. Possible Permo-Triassic successions overlie the basement in the northern Træna Basin, and are seen as a wedge-shaped unit in the seismic section. Blystad et al. (1995) interpreted these successions as possible Paleozoic rift basins. The successions have not been confirmed by any well or shallow boreholes in the study area, and appear to be of limited extent. Little focus has been given to the Permo-Triassic successions in this work, due to their limited lateral extent and low seismic resolution, which caused difficulties in their mapping. However, this does not have any major implications of the work done in this study, as the main focus lies within Mesozoic rifting and basin evolution. Therefore, the Triassic-Lower Jurassic (T-LJ) reflector was the deepest mapped reflector within the entire extent of the study area, while the Paleozoic (Pl) reflector (Table 4.1) has been interpreted only in few seismic profiles just to indicate and reveal the possible presence of deeper Paleozoic basins within a restricted part of the study area (Fig. 4.7).

The Triassic-Lower Jurassic (T-LJ) reflector mainly represents the transition from sedimentary strata to the underlying basement in the study area, and has been tied to shallow borehole 6710/03-U-03 and well 6610/3-1 R2. However, in patchy areas along the northern Træna and the Ribban basins, the T-LJ reflector was placed above more continuous reflections, interpreted as Permo-Triassic successions. The T-LJ reflector is locally diffuse and slightly interrupted, and this makes the seismic pick difficult at some localities. In general, the reflector is semi-continuous to continuous and is interpreted to represent an increase in acoustic impedance.

Seismic sequence S1

The T-LJ horizon separates the S1 sequence from the basement and the possible Paleozoic unit (Fig. 4.3 and Table 4.1). The Triassic age Åre formation has been drilled in the northern Træna Basin (borehole 6710/03-U-03) and the Vestfjorden Basin (well 6610/3-1 R2), revealing conglomerates in the base of the sequence. Shallow borehole 6814/04-U-01 implies more sand-dominated succession in the upper portion of the sequence, and has been correlated to the Måsnykan Formation. The Måsnykan Formation has been interpreted as Middle Jurassic, Bathonian to middle Callovian, sandstones deposited in a shoreface to foreshore environment (Fig. 4.2) (Smelror et al., 2001). However, only 20 m of the sequence has been drilled in the northern Træna Basin, and there is an uncertainty whether the seismic resolution is good enough to actually reveal the formation in the seismic section (Fig. 4.5). The presence of Middle Jurassic sandstones are confirmed by the shallow borehole 6710/03-U-01, in the Havbåen Sub-basin, with a thickness of 120 m. Sequence S1 displays limited internal seismic stratification in its lower portions, and is represented by chaotic and transparent reflections. The upper portion of the sequence is recognized by strong sub-parallel reflections, due to the presence of sandstones. The sequence is frequently associated with rotated fault-blocks, where erosion and reactivation of the faults have led to pinching out of the sequence along foot-walls. This is especially evident in the Havbåen Sub-basin where a wedge-shaped geometry is observed (cf. Fig. 4.27). The upper boundary of the S1 sequence is represented by the Middle Jurassic (MJ) reflector (Table 4.1).

Middle Jurassic (MJ) reflector

The Middle Jurassic (MJ) reflector has been tied to borehole 6814/04-U-01 in the Havbåen Sub-basin, at a depth of ~50 m corresponding to ~0.40 s. In the northern Træna Basin, the MJ reflector is tied to borehole 6710/03-U-01 at ~0.55 s corresponding to a depth of ~150 m (Fig. 4.6). Due to uplift and erosion, only a limited lateral extent of the Middle Jurassic (MJ) reflector is observed in the Vesterålen margin and the reflector is truncated by the BCU reflector towards south in the Ribban Basin (Fig. 4.8). Hansen et al. (2012) refers to the MJ reflector in the Havbåen Sub-basin as the Callovian unconformity. In general, the MJ reflector is seen as high amplitude, continuous reflector on the Vesterålen margin and the northern part of the Lofoten margin. In the northern Træna Basin, the MJ reflector exhibits a semi-continuous lower amplitude seismic character.

Seismic sequence S2

The lower boundary of seismic sequence S2 is interpreted to be the MJ reflector, while its upper boundary is the BCU (Fig. 4.3). Only the IKU shallow boreholes in the Havbåen Sub-basin and the Andøya outcrop confirm the existence of Upper Jurassic strata within the study area. Boreholes 6710/03-U-01 and 6710/03-U-02 correlate the S2 sequence to the Hekkingen Formation (Figs. 4.2 and 4.6). The Hekkingen Formation is interpreted to be of Late Oxfordian-Kimmeridgian age (Fig. 4.2) (Smelror et al., 2001). The Hekkingen Formation can be divided into the Rauåte, Alge and Krill members. The Rauåte and Alge members were penetrated by borehole 6814/04-U-01, revealing that the Hekkingen Formation overlies the Måsnykan Formation unconformity. The Rauåte and Alge members consist of dark-grey, calcareous and micaceous muddy siltstones, which become more muddy and organic rich upwards. The Krill Member in borehole 6814/04-U-02 exhibits higher silt content and thin carbonate beds and nodules are present in the middle part. The Rauåte Member has been interpreted to represent open marine well-oxygenated environments. The Alge and Krill members indicate an upward deepening, and they were deposited in a shelf environment below wave-base in an anoxic to dysoxic shelf environment (Smelror et al., 2001).

The truncation by BCU and the evident erosion has caused a pinching out of the sequence towards south. Hence, the possible correlation of the sequence from the Havbåen Sub-basin to the northern Træna Basin is hampered. However, the S2 sequence has been interpreted in the northern Træna Basin, along the basin flank and terminated by the Vesterdjupet Fault Zone. The internal configuration of the seismic sequence is mainly recognized by chaotic and transparent reflections (Fig. 4.8).

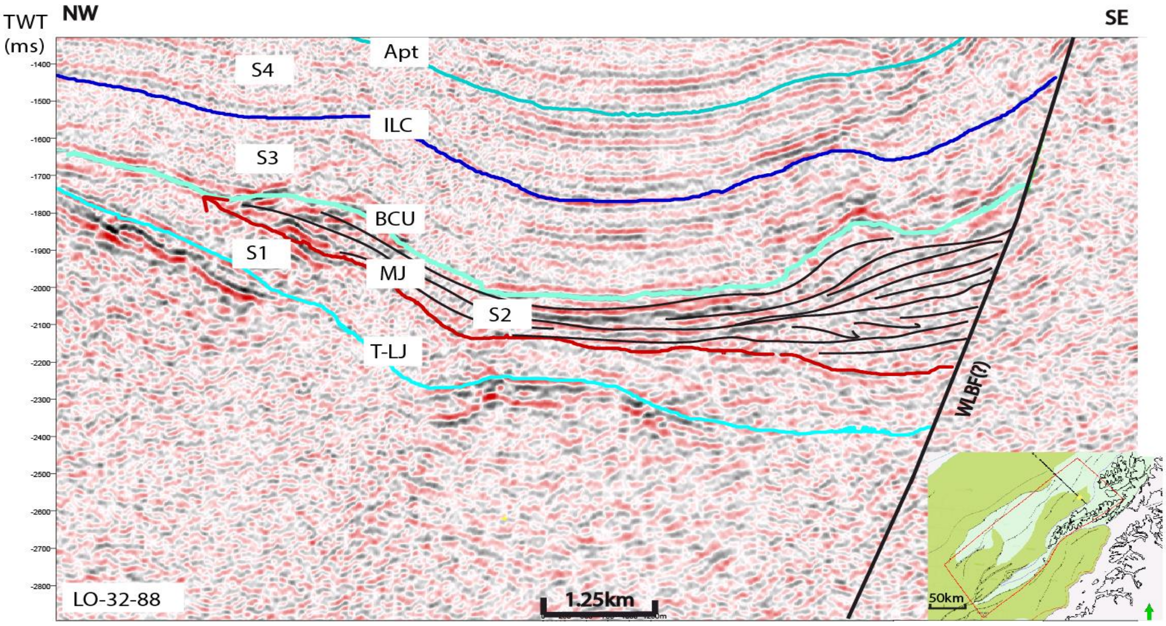


Fig. 4.8: Seismic section showing the MJ horizon truncated by the BCU horizon. The reflections shows chaotic configuration towards the WLBF(?).

4.3.2 Lower Cretaceous reflectors and sequences

The existence of Lower Cretaceous successions on the Lofoten-Vesterålen margin has been confirmed by the IKU shallow boreholes 6711/04-U-01, 6710/03-U-01 6814/04-U-02 and exploration well 6610/3-1 R2. Core information reveals Lower Cretaceous successions, characterized by marine clay succession with some sand interval deposited in a shelf to open marine environment (Smelror et al., 2001).

Base Cretaceous Unconformity (BCU) reflector

BCU is tied to the shallow borehole 6710/03-U-01 in the northern Træna Basin and the exploration well 6610/3-1 R2 in the Vestfjorden Basin. The reflection overlies sedimentary successions of different age and is interpreted to represent a condensed section, represented by a regional erosional unconformity. The reflector is often recognized due to progressively onlaping reflections (Fig. 4.10b). Faults offset the reflector to a varying extent, but it is possible to map the reflector in the entire study area, and correlate it across faults. A continuous reflector character with distinctive strong seismic amplitude characterizes the BCU.

Seismic sequence S3

The lower boundary of the seismic sequence S3 is the BCU reflector (Fig. 4.3 and Table 4.1). The sequence is mainly preserved in fault-bounded depocentres, located within the deepest parts of the basins (Figs. 4.7, 4.9 and 4.10b). Towards south, where the northern Træna Basin becomes progressively deeper, the sequence is present along the entire basin-floor (Fig. 4.10a). Limited well data exists for this sequence and, thus, hamper a detailed stratigraphic correlation. However, the sequence has been interpreted to be of late Valanginian to Hauterivian age, and may possibly be correlated to the Klippfisk Formation. Shallow borehole 6814/04-U-02 shows the Klippfisk formation overlying the Hekkingen Formation in the Havbåen Sub-basin (Fig. 4.2). The sequence is interpreted to consist of dark-grey to grey-green, calcareous siltstone interbedded with limestone layers. Marine fauna and the lack of sedimentary structures imply deposition below wave-base. The depositional environment has been suggested as well oxinated on an open starved shelf (Smelror et al., 2001). The internal configuration of the sequence is seen as transparent and chaotic, and more evident reflections are often observed towards the upper boundary of the sequence, interpreted as the Intra Lower Cretaceous (ILC) reflector (Fig. 4.3).

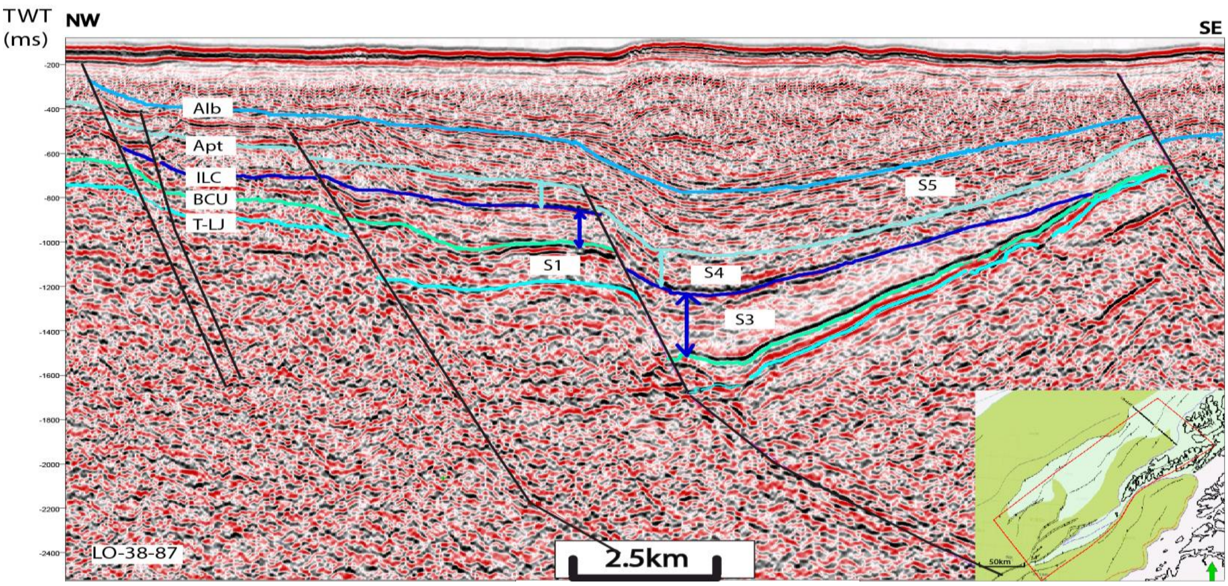


Fig 4.9: Seismic profile LO-38-87 located in the Vesterålen margin illustrating that the interpreted Intra Albian (Alb) horizon drapes above the faults, while the Intra Aptian (Apt) horizon is affected by faulting.

Intra Lower Cretaceous (ILC) reflector

The ILC reflector is mainly observed in the deepest part of the basins, and it is not possible to correlate it with the available well data. The reflector is discontinuous, with variations in its lateral distribution and seismic amplitude intensity within the deepest part of the basins.

Seismic sequence S4

In general, the ILC reflector represents the lower boundary of the seismic sequence S4 (Fig. 4.3 and Table 4.1). However, as the ILC reflector onlaps the BCU reflector towards west and terminates along the basin/depocenter flank, the sequence is also bounded (lower boundary) by BCU towards the Utrøst Ridge (Fig. 4.7). The sequence is proposed to be of Aptian age, and is penetrated in shallow borehole 6710/03-U-01 (Fig. 4.2). The Aptian successions are interpreted as offshore/shelf deposits, dominated by silt and claystones. The lower part of the sequence is dominated by dark-grey pyritic claystones with thin carbonate beds in the lower part. Evidence of dinoflagellates indicates a marine environment, possibly affected by restricted circulation (Smelror et al., 2001). Chaotic stratification, with tendency of sub-parallel reflections, mainly characterize the S4 sequence (Figs. 4.9 and 4.10a-c). More evident lamination of the sequence is observed towards structural elevated parts in the Ribban Basin (Fig. 4.10b-c). The upper boundary of the sequence is interpreted as the Intra Aptian (Apt) reflector (Fig. 4.3).

Intra Aptian (Apt) reflector

The Intra Aptian (Apt) reflector has been tied to shallow borehole 6710/03-U-01 in the northern Træna Basin. The seismic character of the Intra Aptian reflector differs within the study area. In the northern Træna Basin, the reflector is continuous and exhibits strong seismic amplitude. The seismic character within the Ribban Basin changes abruptly, and decreasing continuity of the reflector combined with reduced seismic amplitude intensity is observed towards north. Nevertheless, the reflector exhibits locally strong seismic amplitude, often near structural highs. The overall character of the Intra Aptian (Apt) reflector is semi-continuous with medium-amplitude.

Seismic sequence S5

The Intra Aptian (Apt) reflector represents the lower boundary of seismic sequence S5 (Fig. 4.3 and Table 4.1). The proposed age of the sequence is Albian, and it consists of sandstones and shales deposited in an offshore/outer shelf environment below storm wave-base (Fig. 4.2)

(Smelror et al., 2001). Sequence S5 is mainly characterized by tectonic stability (NPD, 2010), and the majority of faults terminate below or within the sequence. The internal configuration is represented by strong sub-parallel reflections (Fig. 4.10b, c). A gradually onlaping trend onto the BCU reflection is evident in the Skomvær Sub-basin (Fig. 4.10b). However, sequence S5 is mainly interpreted to overlay the S4 conformably, and is depicted with the same geometry in the majority of the study area (Figs. 4.7 and 4.10a-c). The sequence fills the rift topography effectively (Figs. 4.7 and 4.9), and possible wedge-shaped geometries lack indications of growth strata (Fig. 4.7). Sequence S5 often subcrops close to the sea-floor, in particular towards north (Fig. 4.10b-c). The Intra Albian (Alb) reflector represents the upper boundary of the sequence.

Intra Albian (Alb) reflector

The Intra Albian (Alb) reflector has been mapped in the entire study area, but is absent above structural highs. In most of the places, the Alb reflector overlies conformable the S4 sequence. However, the absence of sequence S4 in the southern part of the Havbåen Sub-basin, indicates a discontinuity in deposition and the reflector has been interpreted as an unconformity (Fig. 4.7). The reflection is semi-continuous with low amplitude in the northern part of the study area along the Vesterålen margin. The character of the reflector changes into more continuous and with higher amplitude in the northern Træna Basin and the Skomvær Sub-basin.

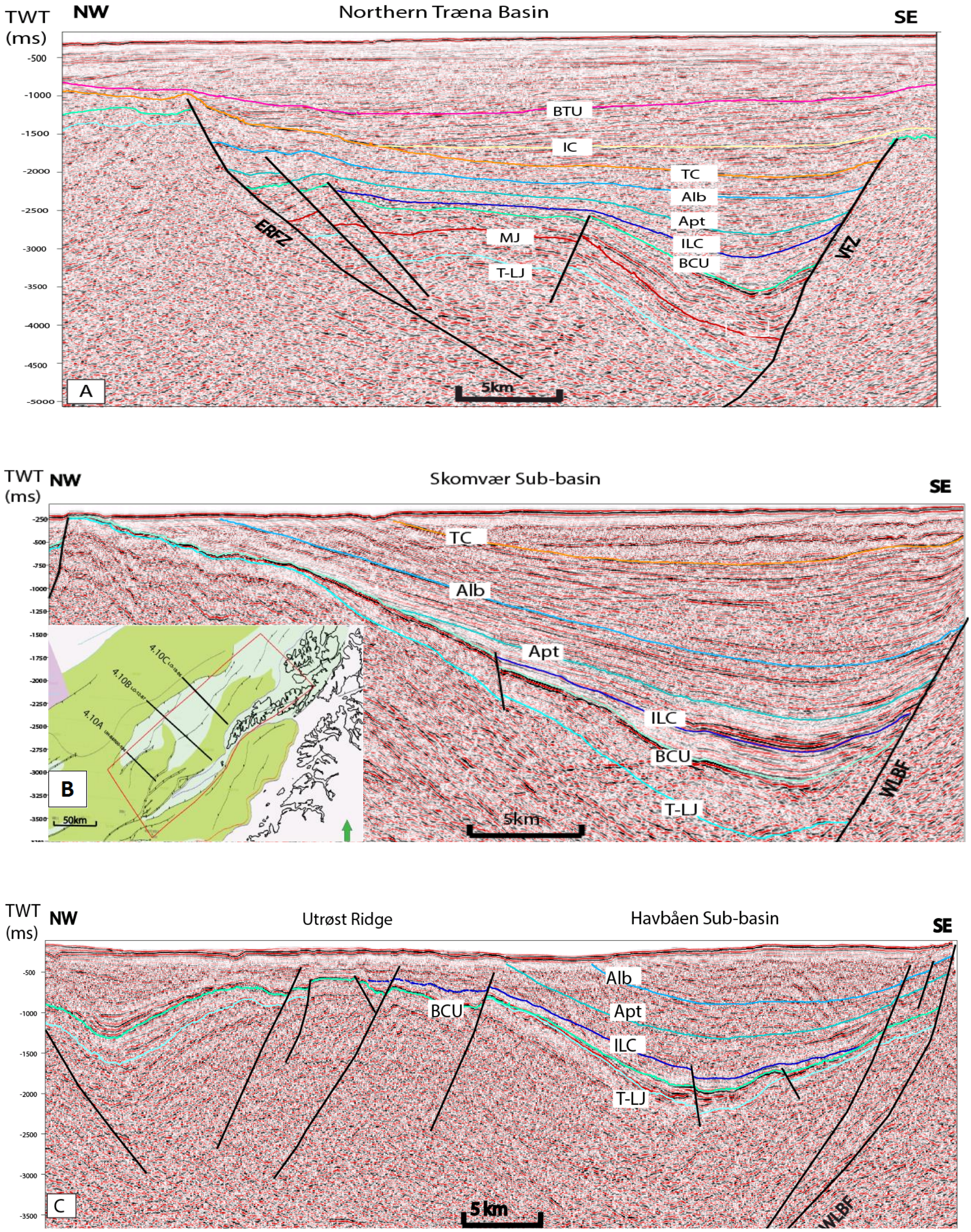


Fig. 4.10: (a) Lower Cretaceous successions are present along the entire basin floor of the northern Træna Basin (UH-94R00-104). (**b)** Sequences S3, S4 and S5 progressively onlap the BCU horizon towards the Utrøst Ridge (LO-12-87). **(c)** Seismic profile (LO-18-86) located in the transition from the Skomvær to Havbåen sub-basins, illustrating an up-doming of the Ribban Basin towards the West Loften Border Fault (WLBF). Note the decrease of fault displacement along WLBF from Fig. 4.10b to Fig. 4.10c.

4.3.3 Upper Cretaceous reflectors and sequences

The Lower and Upper Cretaceous sequences show similar depositional environment, interpreted to consist of offshore/outer shelf mud and siltstones (Hansen et al., 2012). The transition between Lower Cretaceous and Upper Cretaceous is debatable. Larger uplift in the northern parts of the study area has led to erosion and possible removal of Upper Cretaceous successions. In addition, lack of Upper Cretaceous succession in the Andøya outcrop questions the existence of Upper Cretaceous in the northern part. However, for simplicity and possible correlation between the northern and southern parts of the study area, the Intra Albian (Alb) reflector represents the transition between the Lower and Upper Cretaceous successions in the entire study area.

Seismic sequence S6

The base of seismic sequence S6 is defined by the Intra Albian (Alb) reflector (Fig. 4.3 and Table 4.1). The sequence is interpreted to be of Cenomanian age, and can be correlated to the Lange Formation (NPD, 2016b). The proposed age of the Lange Formation extends from Berriasian to Late Turonian. The formation is interpreted to be deposited in a marine environment, characterized by grey and brown claystones, while stringers of carbonates and sandstones are also present in the formation (NPD, 2016b). The sequence exhibits strong sub-parallel reflections with sagging geometry (Fig. 4.7). The upper sequence-boundary is represented by a change in infilling geometry, marked by the Top Cenomanian (TC) reflector. The S6 sequence is subcropping close to the sea floor in the northern part of the Lofoten margin and along the Vesterålen margin.

Top Cenomanian (TC) reflector

Most of the Top Cenomanian (TC) reflector has been eroded towards north, and the reflector is only preserved in the southern part of the study area, along the Skomvær Sub-basin and the northern Træna Basin. The reflector is tied to shallow borehole 6711/04-U-1 and well 6610/3-1 R2 (Figs. 4.1 and 4.4). Well 6610/3-1 R2 made it possible to correlate the reflector to the top Lange Formation (Figs. 4.1 and 4.3) (NPD, 2016b). Due to younger strata gradually onlaping the Top Cenomanian towards west, it appears that the reflector has locally an angular unconformity character. The Top Cenomanian reflector is observed as a strong seismic amplitude and continuous reflector, with a draping character both in the Skomvær

Sub-basin and in the northern Træna Basin (Fig. 4.7). However, in the southern part of the study area the reflector terminates along the Marmæle Spur.

Seismic sequence S7

The base of the seismic sequence S7 is defined by a sag geometry, represented by the Top Cenomanian (TC) reflector. The sequence is correlated to the Nise Formation (Fig. 4.1) (NPD, 2016b). The Nise Formation consists of claystones interbedded with carbonates and sandstone stringers, and its depositional environment has been interpreted as open marine, during Santonian to Campanian (NPD, 2016b). The sequence progressively onlaps the TC reflector and pinches out towards west. A divergent configuration of internal reflections within this sequence is observed towards east, and the sequence terminates against the West Lofoten Border Fault (WLBF) fault-plane (Fig. 4.7). Compared to previously described sequences, the S7 sequence is to a larger extent dominated by alternating transparent and high amplitude sub-parallel reflections. The seismic geometry indicates aggradational buildup of the seismic reflections (Fig. 4.7).

Intra Campanian (IC) reflector

The Intra Campanian (IC) reflector has been correlated to the top Nise Formation (NPD, 2016b), and it is tied to well 6610/3-1 R2 (Fig. 4.1). The reflector is only mapped in the southern part of the Lofoten margin, and is characterized by continuous high amplitude reflector character.

Seismic sequence S8

A slightly more proximal environment has been proposed for the late Cretaceous, Campanian-Maastrichtian time (Hansen et al., 2012). Shallow boreholes indicate increased sand influx, interpreted as offshore deposits below storm wave-base (Smelror et al., 2001). Significant similarities between sequences S7 and S8 are evident. However, the internal reflections observed in sequence S8 are more continuous and are composed of stronger amplitude reflections. The sequence is subcropping close to the sea floor, and the wavy geometry towards the WLBF is enhanced (Fig. 4.7).

4.3.4 Paleogene reflector and sequence

Base Tertiary unconformity (BTU) reflector

The BTU reflector has been tied to well 6610/3-01 R2, and interpreted as top Tang Formation (NPD, 2016b) (Fig. 4.1). The reflector is interpreted as an unconformity because it overlies both Lower and Upper Cretaceous strata. The seismic character is seen as discontinuous and with low seismic amplitude. Hence, the pick of the reflector has often been recognized due to downlaping reflections (Fig. 4.12).

Seismic sequence S9

The BTU reflector forms the lower boundary of sequence S9, where erosional truncation by the seafloor represents its upper boundary (Fig. 4.3 and Table 4.1). The sequence is interpreted to consist of Paleogene sediments, and is only observed in the southernmost parts of the study area. The lower part of the sequence is interpreted as the Tang Formation, consisting of claystones with minor sandstones and limestones layers at a deep marine depositional environment during Danian to late Paleocene (NPD, 2016b). Gently dipping clinoterms, with toplap truncation, make up the internal configuration of the sequence (Fig. 4.11). The clinoterms are to a large extent transparent, and difficult to pick, however a westerly propagation is observed. Furthermore, this sequence exhibits the wavy/folded configuration also seen in Upper Cretaceous successions (Fig. 4.7).

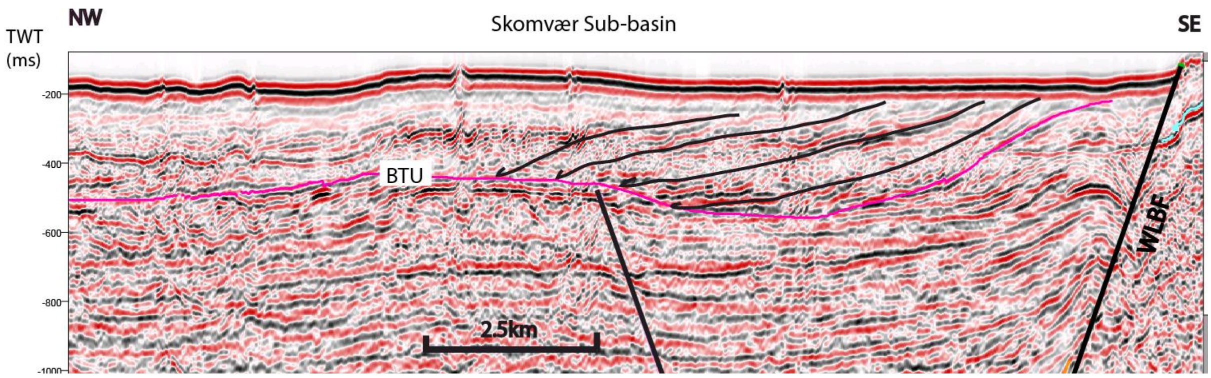


Fig. 4.11: Part of seismic example from regional profile LO-02-87 (profile location in Fig. 4.20). The Base Tertiary Unconformity (BTU) horizon is recognized by diffuse downlaping clinoterms in the Skomvær Sub-basin.

4.4 Time-structure surfaces

In order to better illustrate the structural elements within the Lofoten-Vesterålen margin, time-structure maps have been generated from the interpreted horizons. A total of seven time-structure maps are described in this sub-chapter, and have been considered to better illustrate the regional geological events. These time-structure maps enhance the main structural elements at different depths. The present-day relief seen in the deep, and older in time time-structure maps is a cumulative result of all geological events that have taken place. Hence, the time-structure maps do not give a direct indication of the topographical relief associated to the interpreted time period. The majority of horizons are restricted in lateral distribution by topography and faults. BCU and T-LJ are the only horizons that generate continuous time-structure maps across the entire study area, and give a good representation of the interpreted structural elements.

4.4.1 Pre-Cretaceous

The *Triassic-Lower Jurassic (T-LJ) time-structure surface* visualizes the deepest recorded topographic outline of the Lofoten-Vesterålen margin. The overall impression is that the time-structure map indicates that all present-day structural elements are evident (Fig. 4.12). In general, the time-structure map is dominated by NNE-SSW trending faults and the major basin bounding faults are emphasized by the abrupt depth variation, seen by the densely spaced contour lines. The major highs and ridges can be easily depicted and are associated with the basin bounding faults, as described in sub-chapter 2.2.1. The depth to the horizon varies considerably throughout the entire study area, ranging from ~6000 ms in the deepest part of northern Træna Basin to subaerial exposure on the Lofoten Ridge. Gradual elevation of the horizon towards northwest is observed, representing the Utrøst Ridge, while an abrupt elevation of the horizon is evident towards southeast along the Lofoten Ridge. A general shallowing trend towards north is observed, and the deepest part of the Vesterålen margin only reaches a depth of 1500-2000 ms. Furthermore, the northern Træna Basin, Skomvær and Havbåen sub-basins are noticeable, and the structural high separating the Skomvær and Havbåen sub-basins is possible to be detected. Elongated elevated structures are observed within the Skomvær and Havbåen sub-basins, and may represent rotated fault-blocks (Fig. 4.12).

The *Middle Jurassic (MJ) time-structure surface* is of limited lateral extent, and contributes with little additional information to the margin architecture evolution. Hence, the MJ time-structure surface is not included, as seismic profiles used in this study depict and visualize better the basin topography during this time period.

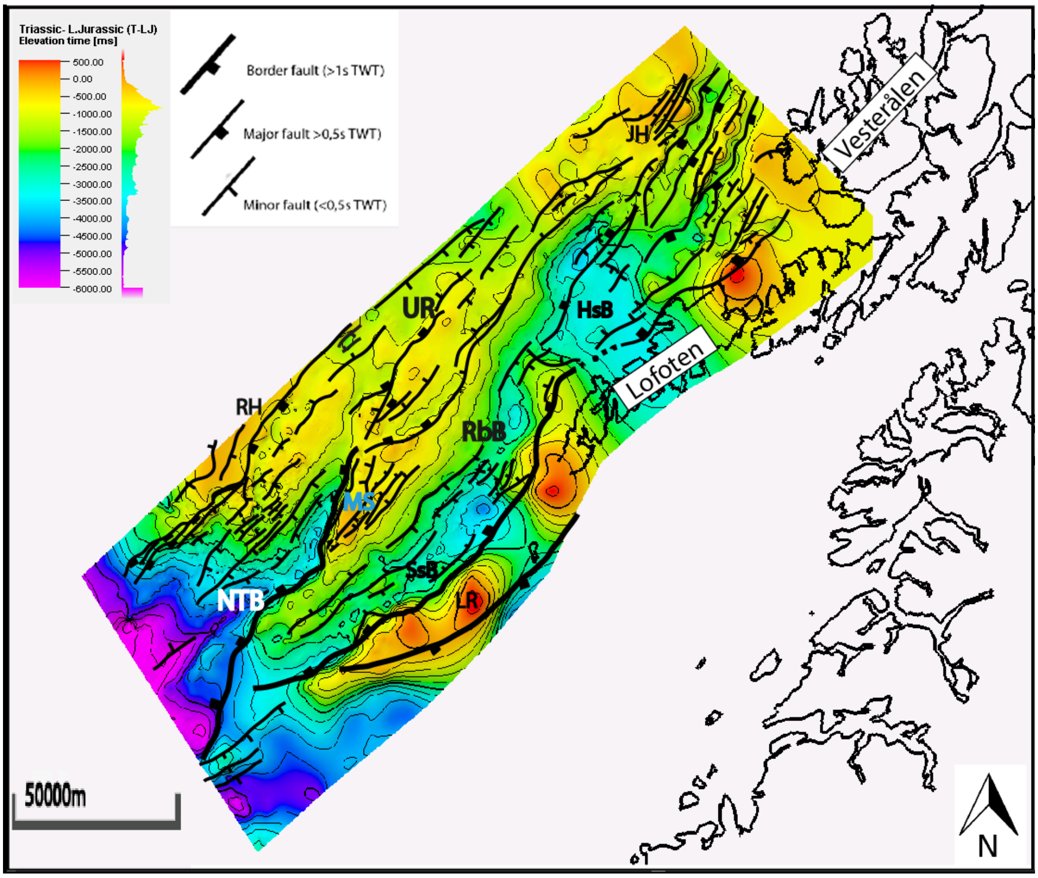


Fig. 4.12: Time-structure surface of the T-LJ horizon (contour interval 500 ms). All mapped faults are draped above the surface.

4.4.2 Lower Cretaceous

The *BCU time-structure surface* illustrates all the present-day structural elements, and defines the base of the Cretaceous basins shown as local depressions, ranging from 3000 to 3500 ms (Fig. 4.13). Hence, a good indication of the general basin outline is provided. The generated time-structure surface differs slightly compared to the T-LJ time-structure surface. This is possibly due to reactivation of faults, and lower confidence in the T-LJ time-structure surface, as it is located at a greater depth. Still, the general NNW-SSE faulting trend is also dominant in this time-structure surface. The elevated area observed in the Skomvær Sub-basin (Fig. 4.12) is no longer evident in the *BCU time-structure surface* (Fig. 4.13). In general, the horizon ranges in depth from ~5000 ms in the deepest part of the basins to ~50 ms towards the structural highs. Local depth variations across the Utrøst Ridge are evident, with depth differences in the order of ~250 ms. In the central part of the Utrøst Ridge, the contour lines illustrate larger closures of approximately the same depth. The East Røst High and the Jennegga High are more dominated by local-scale and frequent alteration of the contour line interval. It is further observed that these areas are associated with major faults, separating the ridge from the northern Træna Basin and the Havbåen Sub-basin, respectively. Limited seismic coverage hampers detailed interpretation along the Lofoten Ridge proper, but the current seismic coverage provides a good interpretation of the area.

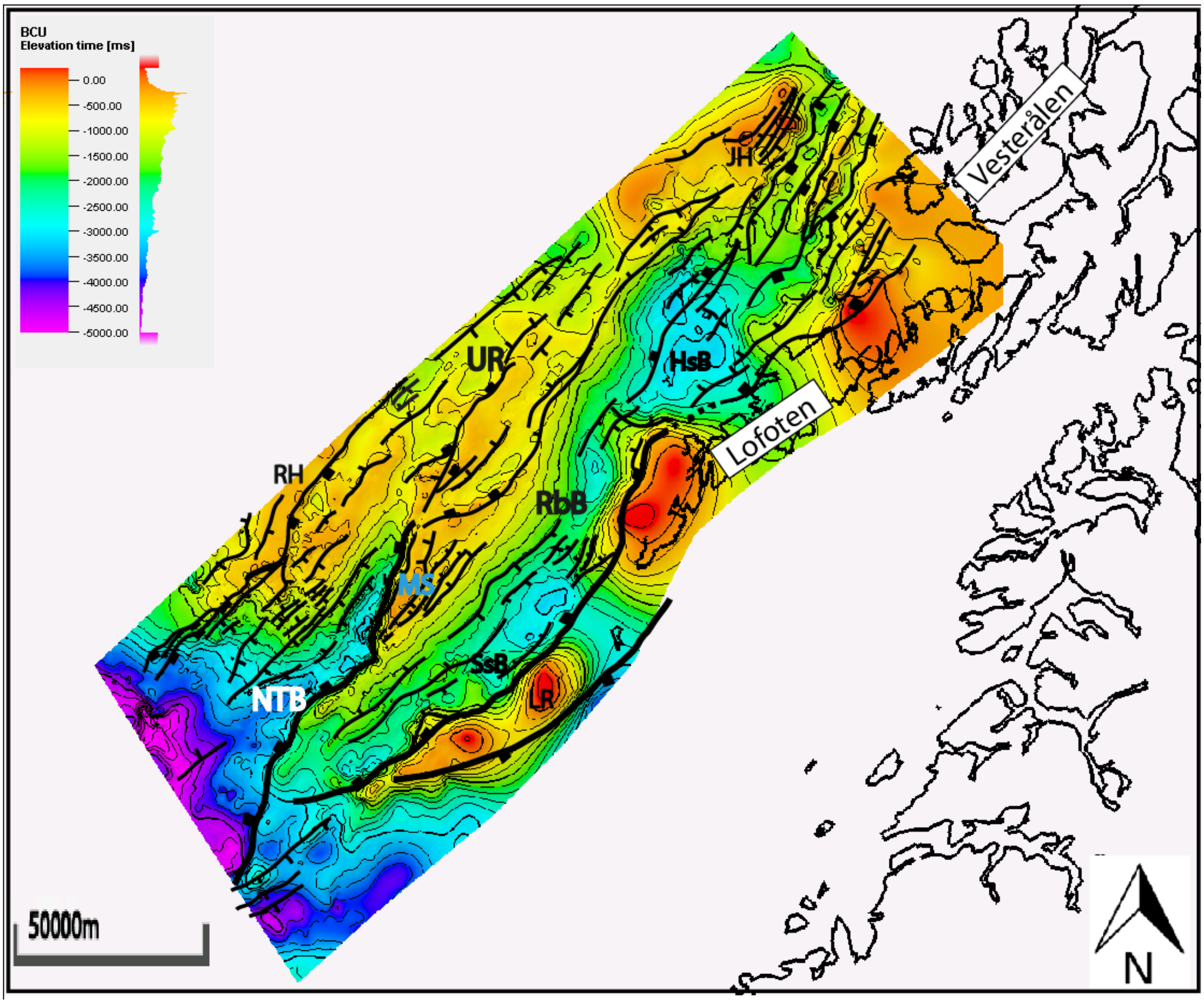


Fig. 4.13: Time-structure surface of the BCU reflector (contour interval 300 ms). All mapped faults are draped above the surface.

Three time-structure surfaces were constructed to represent the Lower Cretaceous basin-infill: Intra Lower Cretaceous (ILC), Intra Aptian (Apt), and Intra Albian (Alb). Lateral distribution of all three time-structure surfaces is limited to the West Lofoten Border Fault (WLBF) and Vesterdjupet Fault Zone (VFZ) hanging-wall. A widening of the basins with time is demonstrated by the upward increasing lateral extent of the time-structure surface, with greatest distribution of the Intra Albian horizon (Figs. 4.14-4.16).

The *ILC time-structure surface* ranges in depth from 2500 ms at the most, to 1000 ms in the Ribban Basin (Fig. 4.14). In contrast to the BCU time-structure surface, two structural highs are evident in the transition from the Skomvær to Havbåen the sub-basins in the ILC time-structure surface (Fig. 4.14). This relief is partly apparent in the *Intra Aptian time-structure surface* (Fig. 4.15), and absent in the *Intra Albian time-structure surface* where only one structural high is again evident (Fig. 4.16). All three time-structure surfaces show a characteristic northward narrowing of the northern Træna Basin with final termination within the partly segmented Utrøst Ridge. Only the Intra Albian time-structure surface is present in the Skomvær Sub-basin, which illustrates greater depth of the Havbåen Sub-basin compared to the Skomvær Sub-basin (Fig. 4.16). Furthermore, the *Intra Albian time-structure surface* is observed to be restricted in distribution by the West Lofoten Border Fault (WLBF). Here it is noted that the time-structure surface exhibits a rather constant depth within the Havbåen Sub-basin (~1700 ms) towards the fault-plane. In the northern portion of the WLBF, a gradual elevation of the time-structure surface is observed towards the fault-plane, in the order of 1500 to 1000 ms (Fig. 4.16).

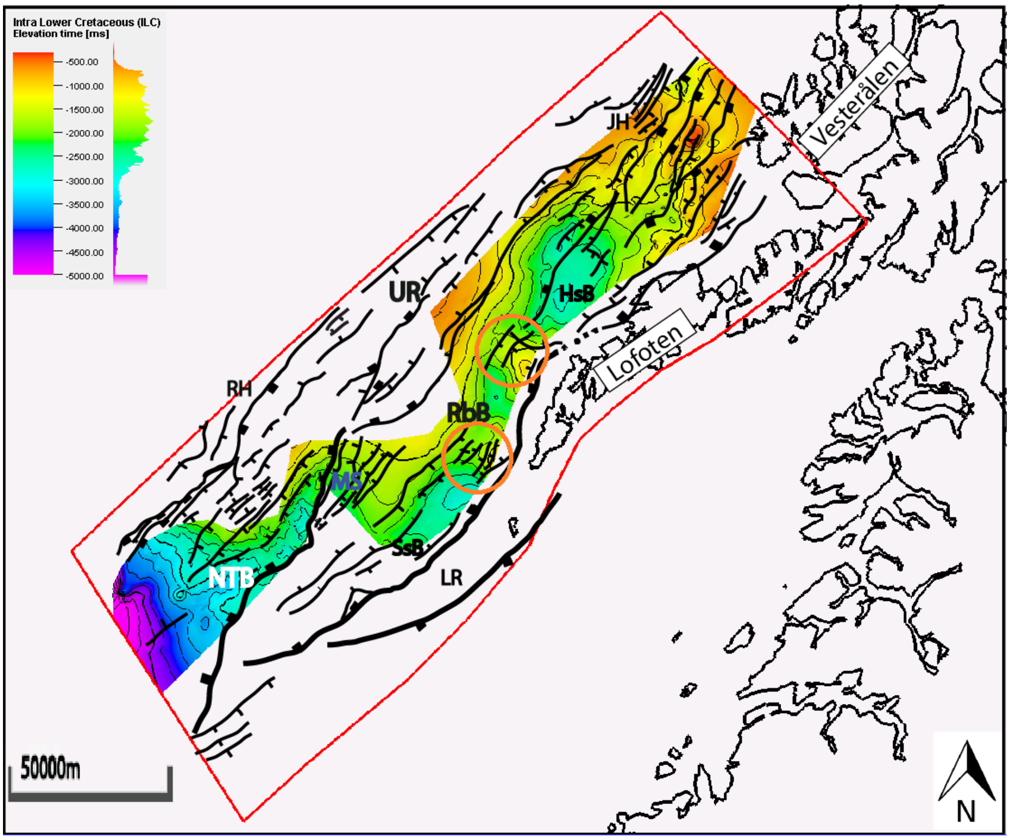


Fig. 4.14. Time-structure surface of the Intra Lower Cretaceous (ILC) reflector (contour interval 300 ms), exhibiting lateral extent restricted to the basins. All mapped faults are draped above the surface.

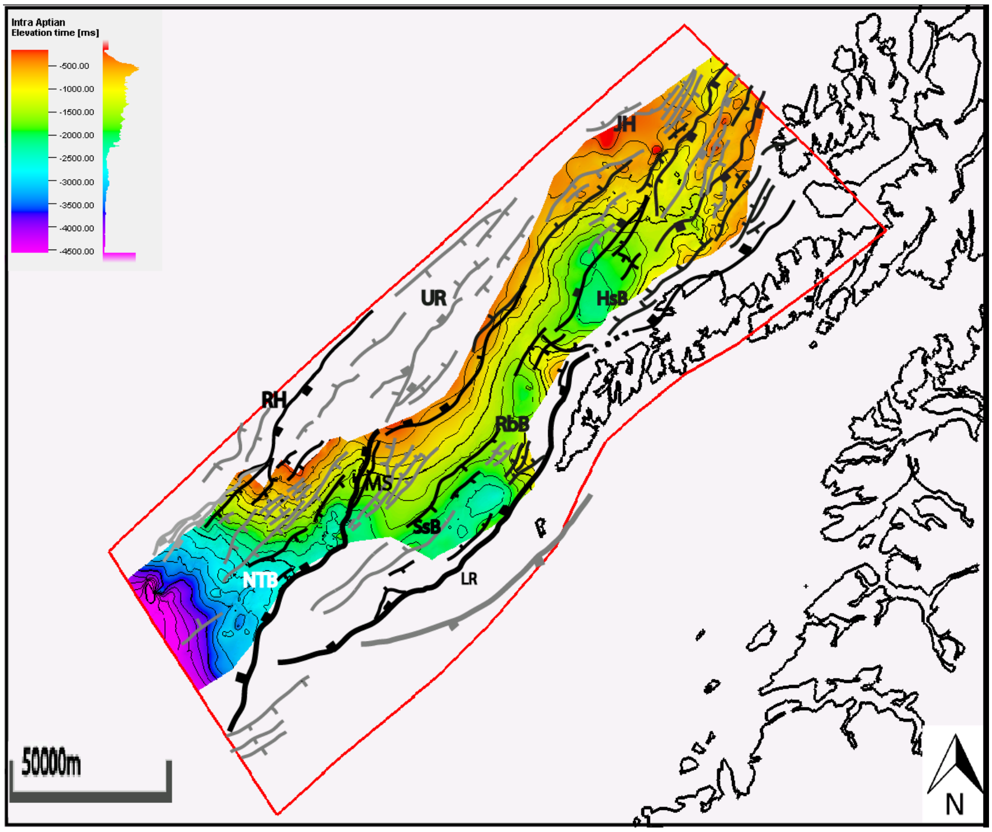


Fig. 4.15: Intra Aptian (Apt) reflector time-structure surface (contour interval 250 ms). Aptian fault activity is illustrated as black faults, while inactive faults are displayed as grey.

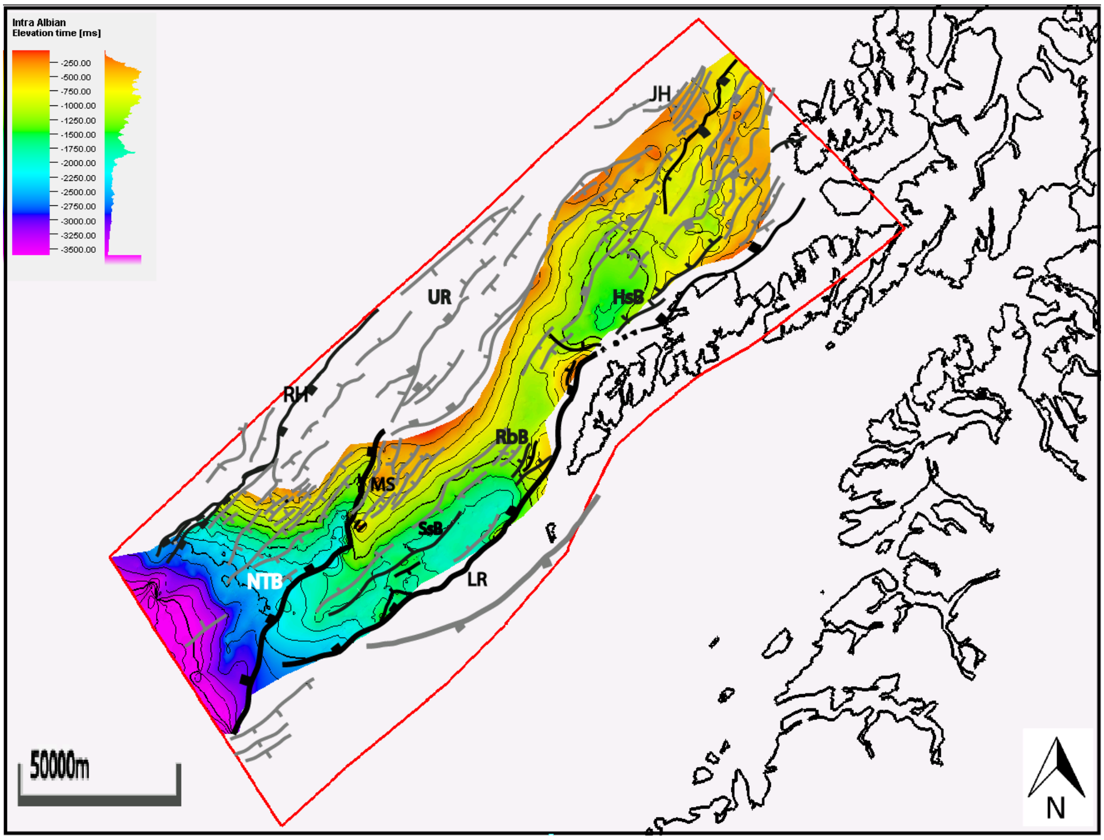


Fig. 4.16: Intra Albian (Alb) reflector time-structure surface (contour interval 250 ms). Albian fault activity is illustrated as black faults, while inactive faults are displayed as grey. Note the consistent depth towards the West Lofoten Border Fault (WLBF) in the southern part, while a more diffuse shallowing trend in the southern part is evident.

4.4.3 Upper Cretaceous

The generated *Top Cenomanian (TC) time-structure surface* display a relative even depth distribution in NW-SE direction and provides only little evidence of the structural elements. However, the Marmæle Spur is still evident as an elongated high, separating the northern Træna Basin from the Skomvær Sub-basin. A slightly depth increase from the Skomvær Sub-basin (~1300 ms) to the northern Træna Basin (~1500 ms) is also observed (Fig. 4.17). Furthermore, the time-structure surface indicates the presence of the ridges, as an apparent elevation towards the ridges occurs. The apparent deepening trend towards south is also observed in the time-structure surface (Fig. 4.17).

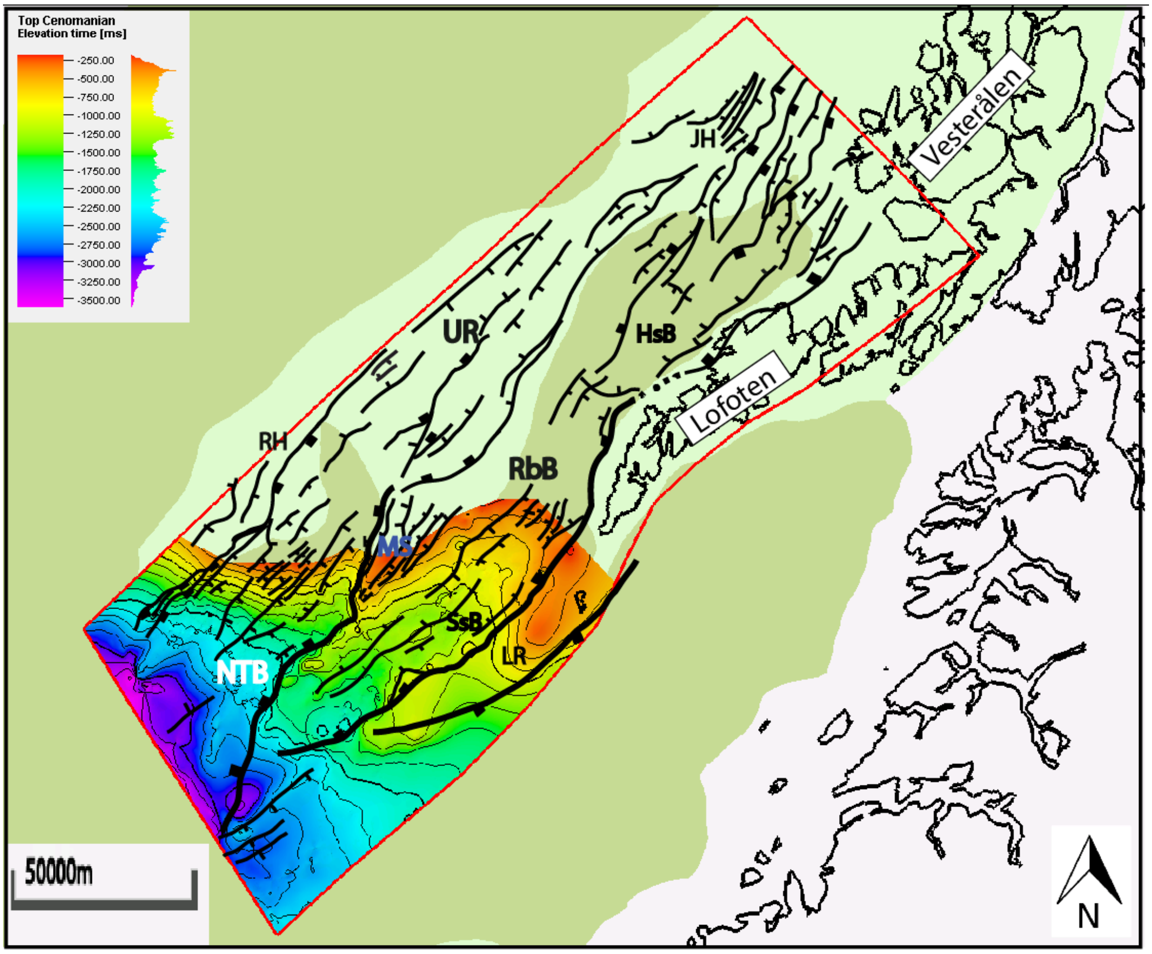


Fig. 4.17: Time-structure surface of the Top Cenomanian (TC) horizon (contour interval 200 ms). The horizon drapes above the Marmæle Spur in the northern part. The NPD structural element outlines are included in the background to illustrate elevation of the sequence in relation to the structural highs.

4.4.4 Paleocene

The *Base Tertiary unconformity (BTU) time-structure* surface exhibits a general uniform depth change in NW-SE direction. The average depth is ~500 ms in the northern part of the study area and reaches to ~1500 ms in the south (Fig. 4.18). Still, some local depth variations are observed in close vicinity to the Lofoten Ridge, and there is no clear distinction between the northern Træna Basin and the Skomvær Sub-basin, due to the limited expression of the Marmæle Spur.

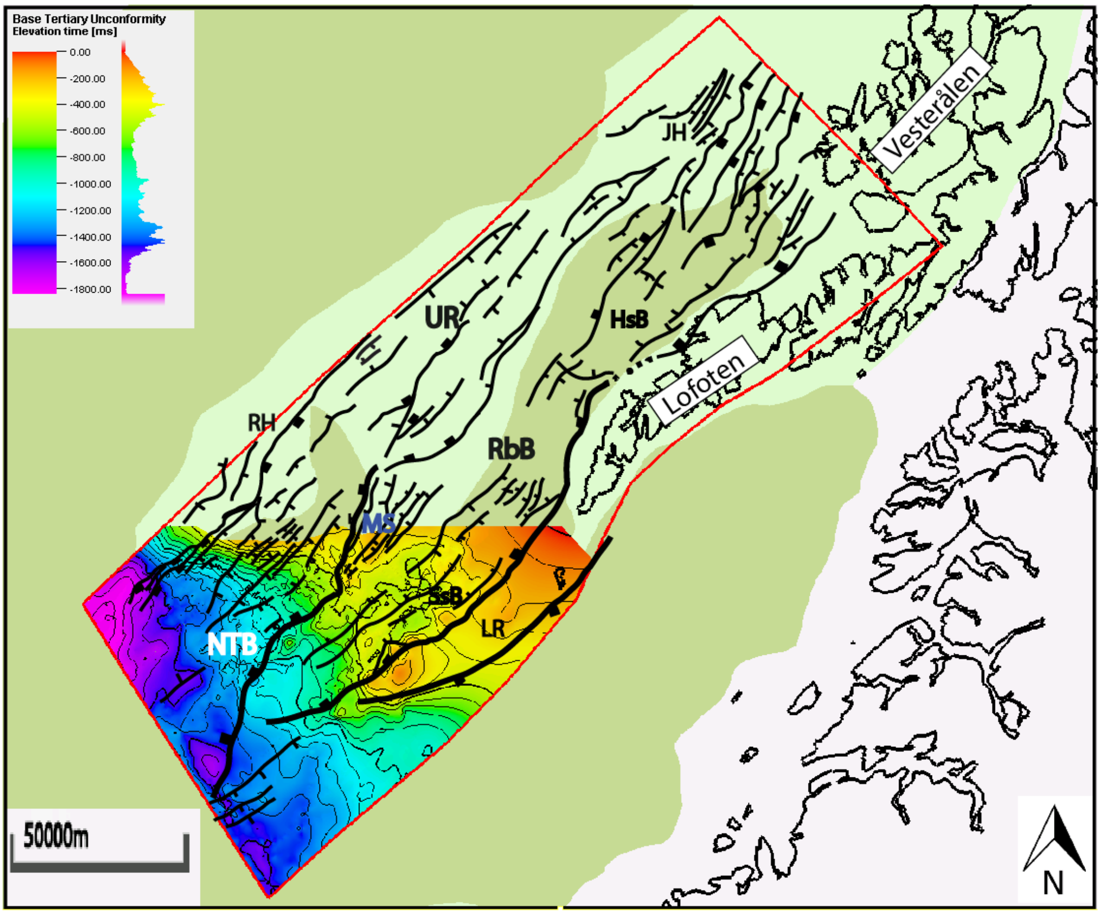


Fig. 4.18: Time-structure surface of the Base Tertiary Unconformity (BTU) reflector (contour interval 100 ms). The NPD structural element outlines are included as background to illustrate elevation of the sequence in relation to the structural highs.

4.5 Structural interpretation

4.5.1 Structural framework

The Lofoten-Vesterålen margin (LVM) is mainly dominated by extensional fault systems, generated from multiple phases of rifting. Fault distribution and structural features are summarized in the BCU time-structure surface (Fig. 4.19). This fault distribution is further enhanced from the magnetic and gravity anomaly data, where it is observed that border faults coincide well with the edges/sides of strong positive elongated anomalies (Figs. 4.21 and 4.22). Five regional seismic profiles (Figs. 4.23-4.27) were used when naming the faults, and a classification into border, major, and minor faults has been established (Table 4.2 and Fig. 4.19).

The majority of the faults seem to have been active at several stages during the formation of the extensional basins. The exact timing of faulting activity is difficult to determine due to the observed large erosion on the footwall, which hampers the precise correlation. From literature, some disagreements regarding the exact faulting activity exist. Nevertheless, there is evidence of four tectonic events within the Lofoten-Vesterålen margin, including:

1. Permo-Triassic
2. Late Jurassic-earliest Cretaceous
3. mid Cretaceous
4. Late Cretaceous-Early Tertiary (lithospheric break-up and seafloor spreading initiation at Eocene time)

The above tectonic events have affected the margin to a different degree, and the lowest confidence is associated with the Permo-Triassic rifting. In addition, there is limited evidence of Late Cretaceous-Early Tertiary deformation, as the main part of this deformation was located west of the Utrøst Ridge (Bergh et al., 2007). An analysis of the faults regarding throw, orientation and shape has been performed and summarized in Table 4.2. The general trend of the faults are NNE-SSW and they show an almost perpendicular orientation to the assumed extension direction (Bergh et al., 2007). The extent of the faults has been further emphasised in the structural map (Fig. 4.19), where border faults are intonated. Several less prominent faults are present in connection with the major faults and towards the basement highs. The smallest recorded/mapped faults (minor faults) only reach a throw of ~50 ms, and occur in arrays of multiple faults (named *H-group*).

In general, the border faults are seen as curvilinear faults segments, linking the Ribban and northern Træna basins. The oblique/bend shape is also clearly reflected in the shape of the basement ridges (Figs. 4.19, 4.21 and 4.22). The West Lofoten Border Fault (WLBF) is the longest border fault within the Lofoten-Vesterålen margin extending ~250 km, followed by the Vesterdjupet Fault Zone (VFZ) with an extent of ~100 km (Fig. 4.19). The greatest throw is observed within these two border faults, with Vesterdjupet Fault Zone exceeding a throw of ~3000 ms (~4-5 km) and West Lofoten Border Fault exhibiting a throw of ~2000 ms (~3-4 km) (Fig. 4.23). The Utrøst Ridge lacks a prominent border fault separating it from the basins (Fig. 4.23). Hence, several 50-70 km long faults connect and make a continuous pattern along the eastern flank of the Utrøst Ridge (faults *N5* and *N12*) (Table 4.2). The ~60 km in extent East Røst Fault Zone (ERFZ) and ~40 km in extent East Jennegga High Fault (EJHF) are interpreted as the main border faults separating the Utrøst Ridge from the northern Træna Basin and the Havbåen Sub-basin, respectively (Fig. 4.19).

The shape of the faults can give an indication of the magnitude and origin of the extensional or compressional events that have taken place. Listric faults are steeply dipping in the upper portions and become progressively less steep with depth, resulting in a curved shape with depth. The dip often flattens into a sub-horizontal detachment fault, with synthetic or antithetic faults detaching at a certain level (Fig 4.25). Synthetic faults have the same dip as the main fault, while antithetic faults dip in the opposite direction. Listric faults are associated with large-scale extensional tectonics and great displacements, often indicating long and continuous faulting activity (Twiss and Moores, 2007). There are two possible ways for the generation of a detachment, either as an initially low-angle fault, or by the rotation of an initially high-angle normal fault. The latter is proposed for the Lofoten-Vesterålen margin, where the Late Jurassic-earlies Cretaceous tectonism resulted in maximum rotation of the fault-blocks (Færseth, 2012).

The faults that define the northern Træna and Ribban basins will be presented below, along with the important fault complexes of the study area. Due to the observed along-strike fault polarity change within the Lofoten-Vesterålen margin, the structural segmentation into the Lofoten and Vesterålen margin segments is further presented.

Table 4.2: Summary of all interpreted faults. N: independent faults. H: represents an array of minor faults, interpreted to represent the same distribution/shape/age/displacement. WLBF= West Lofoten Border Fault, VFZ= Vesterdjupet Fault Zone, ERFZ= East Røst Fault Zone, EJHF= East Jennegga High Fault. Border fault (throw >1s), major fault (throw >0.5s) and minor fault (throw <0.5s).

Name	Geometry	Dip	Trend	Throw (ms TWT)	Significance	Comment
WLBF	**Listric**	**West**	**NE-SW**	**750-2000**	**Regional**	**Border fault. Decreasing towards north.**
H1	Planar	West	NNE-SSW	50-100	Local	Normal fault array, generating rollover-structure
H2	Planar to listric	west	NNE-SSW	50-100	Local	Small scale normal faults
Pyramiden	**Listric**	**East**	**NNE-SSW**	**1500**	**Semi**	**Terminates within the Jennegga Transfer Zone.**
N1	Listric	East	NNE-SSW	500	Semi	
EJHF	**Listric**	**East**	**NNE-SSW**	**1500**	**Semi**	
N2*	**Listric**	**West**	**NNE-SSW**	**600**	**semi**	
N25	Listric	East	NNE-SSW	50	local	Generates rotated Jurassic fault-blocks
N26	Listric	East	NNE-SSW	100	local	Generates rotated Jurassic fault-blocks
H3	Planar	West	NE-SW	100	Local	Detach onto WLBFZ at a depth of ~4000ms
N3	Planar	East	NNE-SSW	50	Local	
N4	Listric	West	NNE-SSW	50	Local	Connected to N2* at ca 4500ms
H4	Planar	East	NE-SW	100	Local	Antithetic faults, terminated by N2*
N5	Planar	West	NNE-SSW	250	Semi	
N6	Planar	East	NE-SW	150	Semi	
N7	Planar	West (slightly)	NE-SW	50	Local	
N8	Listric	West	NE-SW	50	Semi	
N9, N11	Planar	West	NE-SW	150-200	local	
N10	Planar	East	NE-SW	150	Local	
N12	Planar	West	NE-SW	500	Semi	
N13	Planar	West	NE-SW	500	Semi	
H6	Planar	West East	NE-SW	50-100	Local	Local small offset faults, between N13 and ERFZ
ERBF	Listric	East	NE-SW	1200	Regional	
N14	planar	East	?	50	Local	
N15	Planar to listric,	East	NE-SW	150	Local	
N16-N17	Planar	West	NNE-SSW	100	Local	
VFZ	**Listric**	**West**	**NNE-SSW**	**1500-3000**	**Regional**	**Strongly listric, follows internal basement configuration**
N19	Listric	West	NE-SW	100	Semi	
H7	Planar	East/west	NE-SW	50-100	Local	
N20	Planar	East	NE-SW	200	Local	
N21	Slightly listric	East	NE-SW	400		
ERFZ	**Planar to Listric**	**East**	**NNE-SSW**	**550-800**	**Regional**	**Footwall eroded**
N22	Planar	East	NE-SW	50	Local	
N23	Planar (slightly listric)	West	NE-SW	100	semi	
N24	Planar (slightly listric)	West	NE-SW	150	Local	
H8	Planar	perpendicular		50	Local	

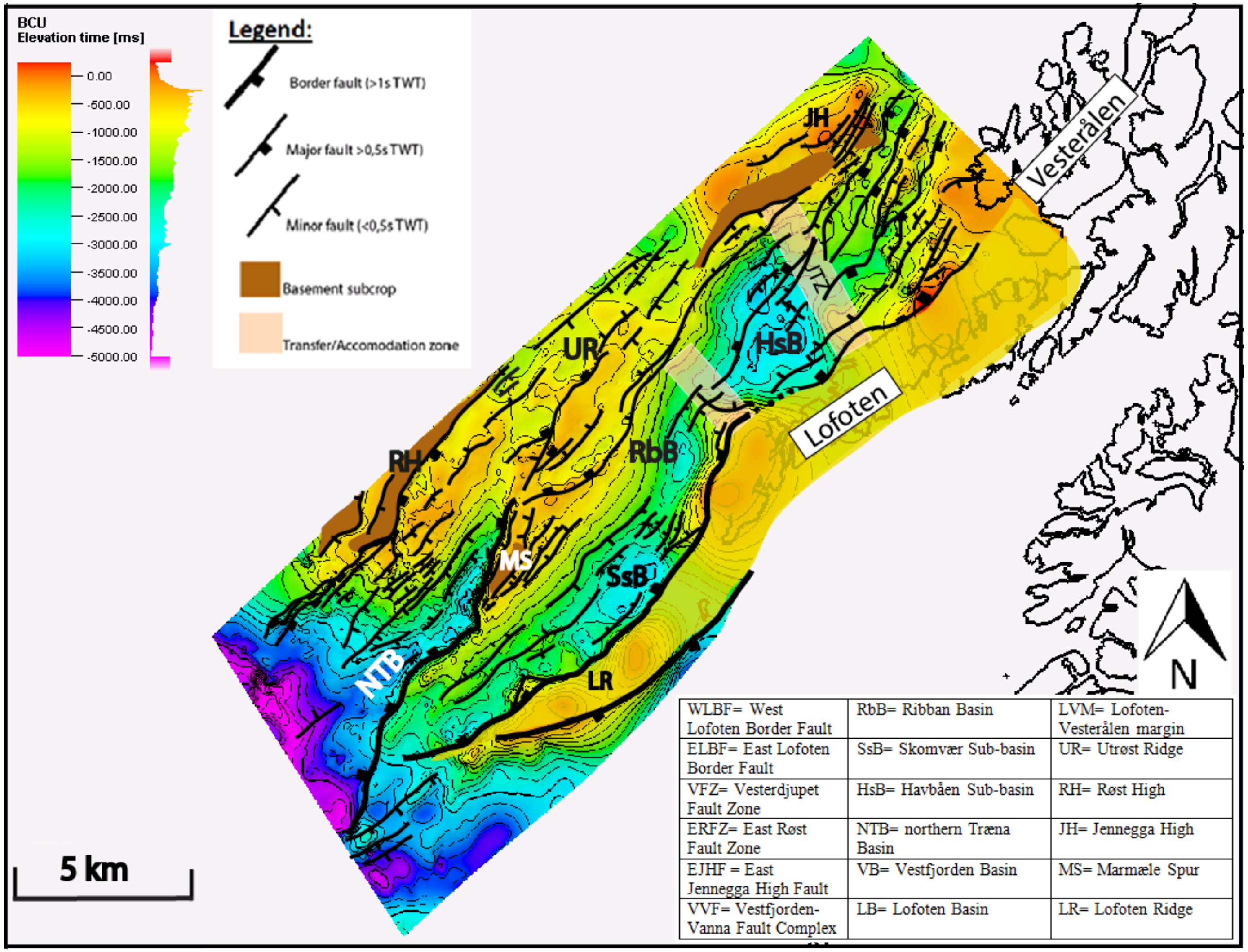


Fig. 4.19: BCU time-structure map used to establish the structural framework within the study area, providing cumulative records of strain both in Late Jurassic and in the Early Cretaceous rifting episodes. Structural observations are also based on earlier studies (Blystad et al., 1995; Tsikalas et al., 2001; Bergh et al., 2007; Færseth, 2012; Hansen et al., 2012).

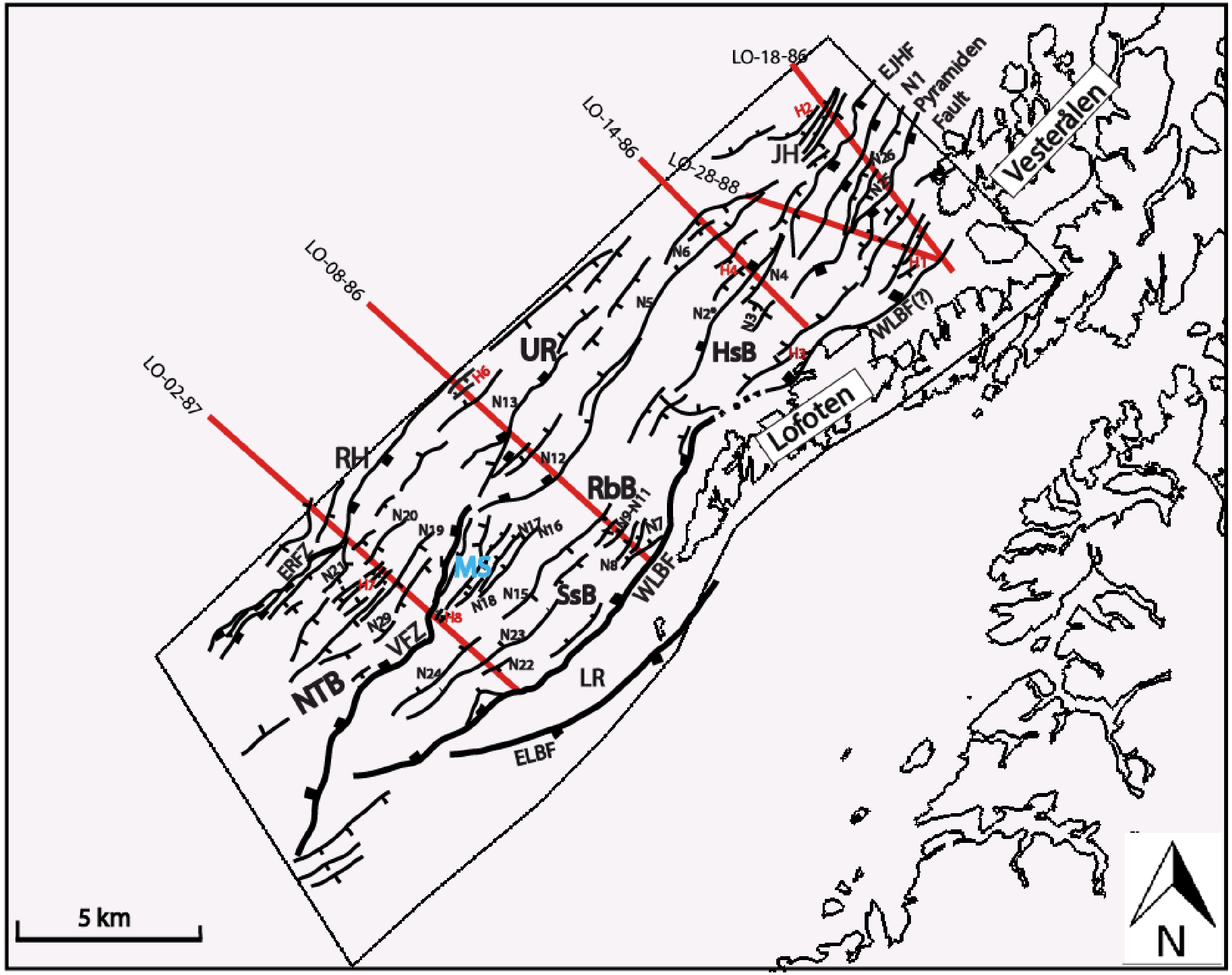


Fig. 4.20: Overview of interpreted fault-pattern distribution with corresponding names (additional information in Table 4.2). Locations of the five regional profiles presented in Figs. 4.23-4.27 are included.

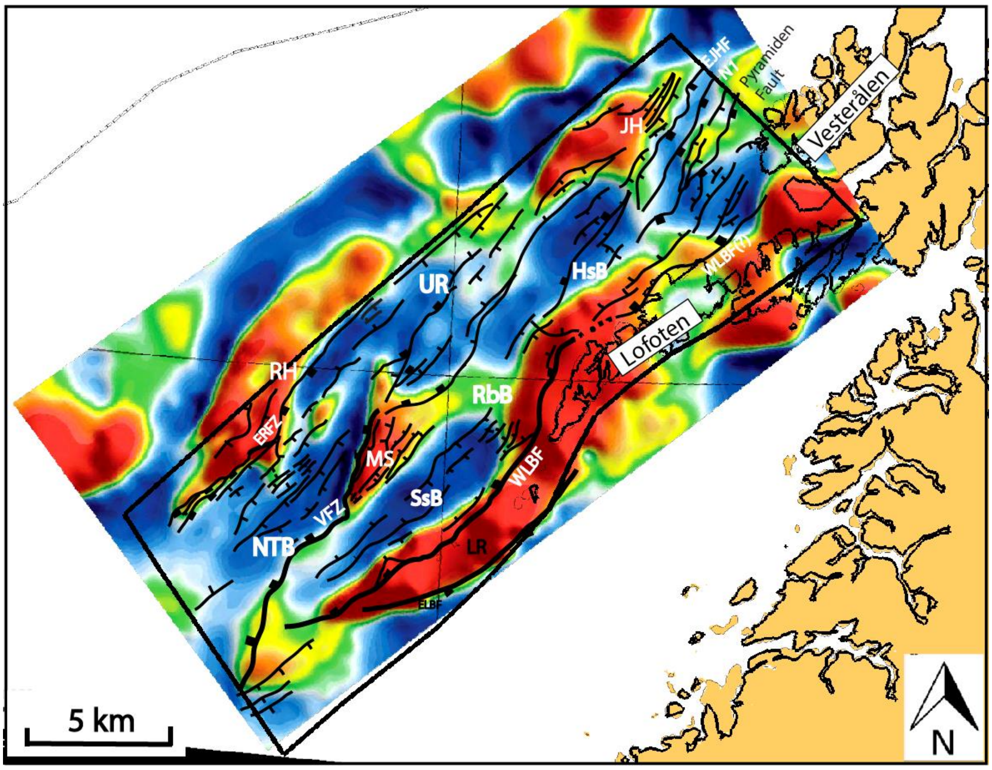


Fig. 4.21: 50-km high-pass filtered gravity anomaly data, with all interpreted faults draped above. Gravity data curtesy of TGS.

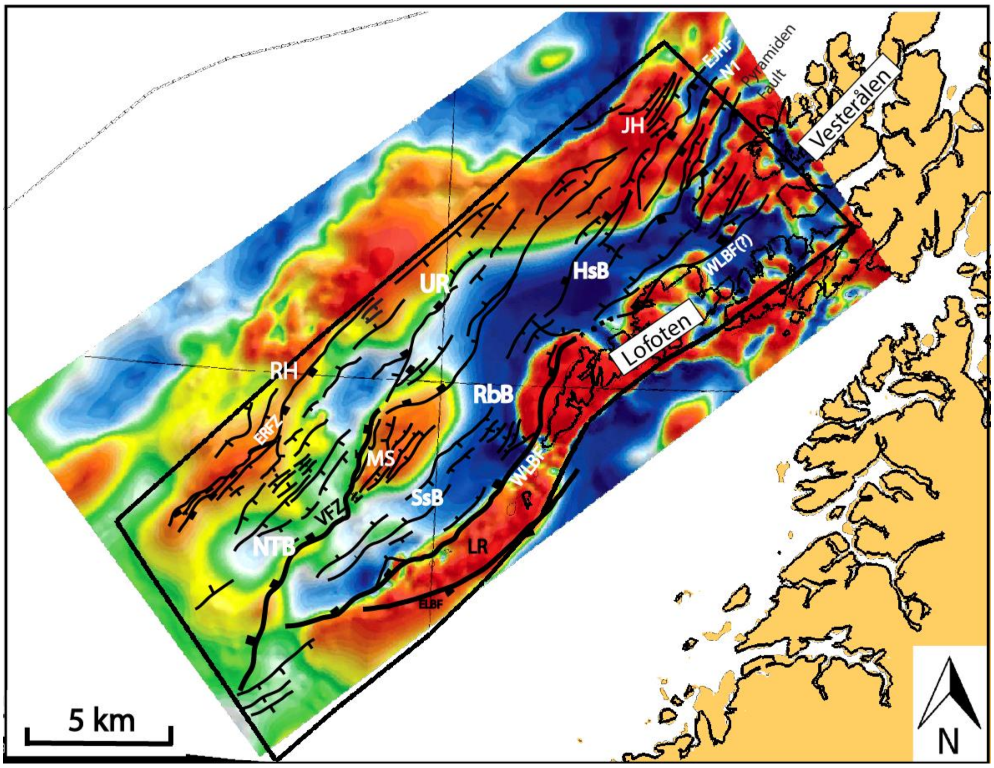


Fig. 4.22: 100-km high-pass filtered magnetic anomaly data, with all interpreted faults draped above. Magnetic data curtesy of TGS.

4.5.2 Main structural elements

Vesterdjupet Fault Zone (VFZ)

The Vesterdjupet Fault Zone is mainly represented by a westerly-dipping, NNE-SSW oriented fault, with some smaller parallel faults on the footwall (Fig. 4.23). A zig-zag trending outline of the fault is observed, and further enhanced by the morphology of the Mærmæle Spur (Fig. 4.19). From the magnetic and gravity data, it is observed that the fault coincides with a positive high anomaly pattern (Figs. 4.21 and 4.22). The fault exhibits a planar shape in the upper portions, and becomes low-angle with depth. It soles out at ~6000 ms (16-19 km) in the basement. It appears that the fault-plane follows internal basement fabrics, and this can be an indication of easier pathways for fault propagation. The maximum throw of VFZ is observed in the central part of its extent, exceeding ~3000 ms (4-5 km). The fault-throw displacement decreases towards north, and the fault branches into a series of splays over the Utrøst Ridge (Fig. 4.19).

The interpreted BCU reflector is seen as an erosional surface on both the footwall and hanging-wall of the Vesterdjupet Fault Zone (Fig. 4.23). The severe erosion observed in the Marmæle Spur indicates fault activity, and perhaps footwall uplift during and after the Late Jurassic-earlies Cretaceous rifting event leading to subaerial exposure. Several small-scale antithetic normal faults terminate in the Vesterdjupet Fault Zone, and generate parallel terraces along the fault-plane (Fig. 4.7).

East Røst Fault Zone (ERFZ)

The highly tectonized East Røst Fault Zone (ERFZ) is situated in the southeastern part the Røst High. The zone is best viewed in the T-LJ and BCU time-structure surface, and illustrates local offset of the horizons towards the Røst High. In general, the zone is comprised of E-dipping major faults, with minor synthetic and antithetic faults in the hanging-wall (Fig. 4.23). There are some ambiguities regarding the lateral extent of the East Røst Fault Zone towards south, as it seems like it is distributed along a splays of faults. However, one major fault separating the Røst High from the northern Træna Basin has been interpreted as the East Røst Fault Zone (Fig. 4.19). The fault exhibits more planar geometries compared to the adjacent border faults. Largest throw is observed in the southern part, ~850 ms (1.5-2 km), and decreases toward north ~340 ms (0.5-0.8 km). The central part of the fault exhibits a throw of ~600 ms (1-1.5 km), and soles out at depth of ~4000-5000 ms (13-15 km) in the basement, with limited evidence of fault propagation along internal basement reflectivity (Fig. 4.24). The East Røst Fault Zone forms the western boundary of the northern Træna Basin, and a terrace resembling structure has been generated in the hanging-wall (Fig. 4.23).

West Lofoten Border Fault (WLBF)

The deep and listric West Lofoten Border Fault marks the west flank of the Lofoten Ridge, and is traceable along the Loften-Vesterålen archipelago. The fault penetrates almost the entire crust, and soles out at ~6500 ms (17-20 km). It is evident from the gravity and magnetic anomaly data, that the fault propagates along the western edge/side of a positive anomaly, and separates the Lofoten Ridge from the Ribban Basin (Figs. 4.21 and 4.22). The largest throw is observed in the southern part exceeding 2000 ms (5-6 km) (Fig. 4.23). Noticeable decrease of throw is evident towards north, where a reduction to ~750 ms (1-2 km) is evident in the Vesterålen margin (Fig. 26). A general shift of the fault character occurs, as the southern parts of WLBF are dominated by planar geometries (Fig. 4.24), while the central and northern parts exhibit a low-angle geometry where it seems like the Lower Cretaceous strata are dragged along the fault-plane and a vague up-doming/lifting of the BCU reflector is observed (Fig. 4.10c and 4.25). This is further enhanced by the absence of a prominent positive gravity anomaly at this location (Fig. 4.21).

Due to the general character shift of the West Lofoten Border Fault towards north, it can be debatable whether the fault continues past the Jennegga Transfer Zone (Fig. 4.19). Tsikalas et al. (2001) proposed a termination of the West Lofoten Border Fault near the Jennegga Transfer Zone, where it branched onshore into fault zones within the Vestfjorden-Vanna Fault Complex (Fig. 2.3). The absence of a prominent border faults is evident towards the Vesterålen basement high. However, the West Lofoten Border Fault has been interpreted to continue north of the Jennegga transfer zone in this study, but with a significant reduction in throw (Fig. 4.19). The general geometry of the West Lofoten Border Fault also experiences a change towards north. In the southern part of the study area, the fault is seen as planar with throws of ~2000 ms, while a decrease down to throws of ~500 ms are observed in the northernmost part (Fig. 4.27).

4.5.3 Structural segmentation

Lofoten margin

The Lofoten margin is dominated by west-dipping normal faults, and listric border faults separate the Lofoten Ridge and Utrøst Ridge from the offshore rift basins. The border faults (WLBF, VFZ and ERFZ) extend from the basement and upwards until they terminate within the Cretaceous succession or by the sea floor. Intra-basement reflection detachment zones are observed onto the major fault surfaces/planes. Left stepping, westerly detachment is dominant (Fig. 4.25), however some exceptions are observed regarding the western margin of the northern Træna Basin (Fig. 4.23). It is difficult to detect the upper termination of the faults in the Lofoten margin. This is mainly due to the lack of traceable reflectors which can be used for correlation, and the varying quality of the seismic data.

The southern part of the margin is highly dominated by NE-SW trending faults. Fault linking appears and it is often associated with termination of major/border faults, which branches into a splay of faults. The majority of border faults have been interpreted as active during the Late Jurassic-earliest Cretaceous rifting event (Blystad et al., 1995), and the seismic profiles indicate that the majority of faults offset the BCU horizon (Figs. 4.23-4.27). Small-scale planar faulting is dominant on the structural highs and along the western part of the northern Træna Basin (Figs. 4.19 and 4.23). Furthermore, evidence of Late Cretaceous fault activity is observed in the vicinity of the Vesterdjupet Fault Zone and West Lofoten Border Fault (Fig. 4.23, 4.24). Planar faults (*H8*, *N7* and *N22*) sole out in the mid Cretaceous successions and are subcropping close to the sea floor. Small-offsets are connected to these faults, and a wavy configuration of the reflections is generated above the Vesterdjupet Fault Zone (Fig. 4.23).

Between the East Røst Fault Zone and Vesterdjupet Fault Zone a prominent roll-over/up-doming structure of the sedimentary strata is observed (Fig. 4.24). The structure seems to be generated from several antithetic and synthetic planar faults (*H7*), which cross-cut the T-LJ, MJ and BCU horizons. The faulting caused fault-block rotation of the Jurassic successions. The displacement is rather small (~50 ms), and the faulting terminates in the potential Permo-Triassic sediments at ~1700 ms depth. The array of partly rotated fault-blocks located in the southern part of the Skomvær Sub-basin (Fig 4.23) exhibit fault rotation that is observed to progressively increase in the basin towards West Lofoten Border Fault. Faults *N23* and *N24* depict the largest throws of the pre-Cretaceous successions, and a termination close to the

Intra Albian (Alb) horizon is observed (Fig. 4.23). Further north in the Skomvær Sub-basin, it is observed that the central part of the basin is situated above an array of normal faults (*N10-N8*) (Fig. 4.24). Towards the West Lofoten Border Fault fault-plane several fault-blocks are uplifted (Fig. 4.24).

The transition from Skomvær to Havbåen sub-basins is marked by a structural high, resembling an anticline shape (Fig. 4.19). Several perpendicular trending normal faults are observed, and interpreted as transfer faults. It is also observed that the normal faults partly overlap and they are comprised of opposite dip polarity (Fig. 4.19). This is often associated with a "low relief accommodation zone" (Gawthorpe and Hurst, 1993).

The southern part of Havbåen Sub-basin is dominated by west-dipping normal faults, which progressively detach onto the West Lofoten Border Fault (WLBF) with depth, in a westerly-direction (Fig 4.25). As previously indicated, the WLBF endured a reduction in throw towards north. Hence, a shift of the major fault from the WLBF to fault *N2** is considered. Fault *N2** terminates in the Intra Aptian (Apt) horizon, and exhibits a throw of ~600 ms (1-2 km). It propagates into the basement and detaches onto the WLBF at ~6000 ms (~15-16 km). Antithetic and synthetic (*H2* and *N4*) faults detach onto fault *N2** and only one single strand continues into the basement (Fig. 4.25).

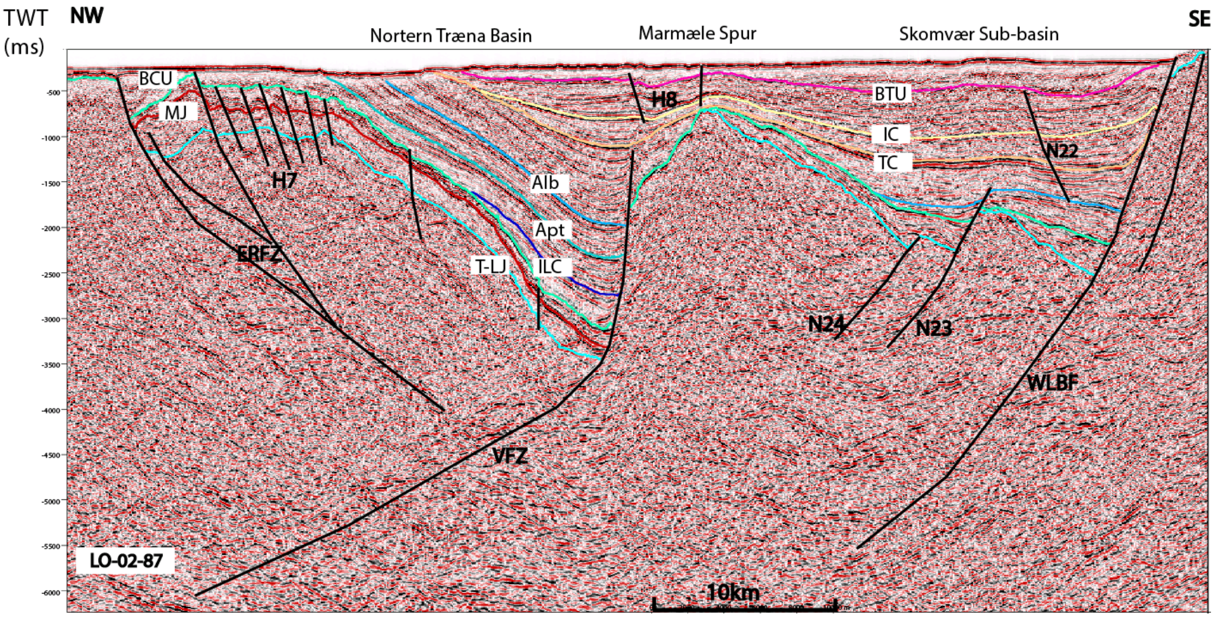


Fig. 4.23: Seismic profile illustrating the listric shape of the prominent West Lofoten Border Fault (WLBF), Vesterdjupet Fault Zone (VFZ) and East Røst Fault Zone (ERFZ), with associated smaller-scale planar faults. The severely eroded Marmæle Spur separates the Skomvær Sub-basin from the northern Træna Basin. Profile location in Fig. 4.20.

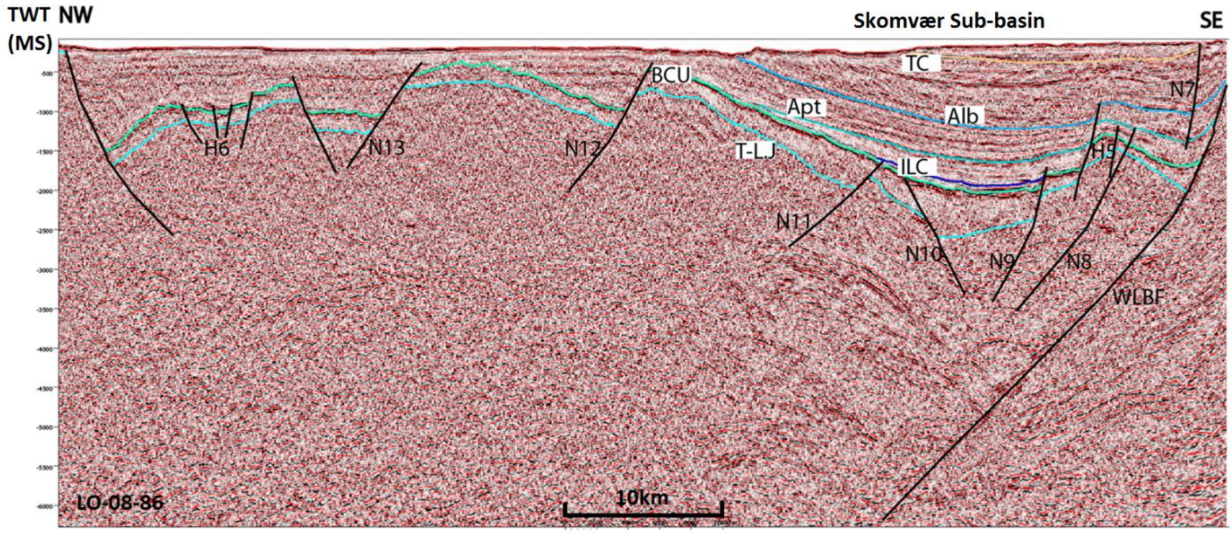


Fig. 4.24: Seismic profile illustrating the Skomvær Sub-basin located above an array of normal faults. Note the considerable reduction in throw of the West Lofoten Border Fault (WLBF) from Fig. 4.25. Profile location in Fig. 4.20.

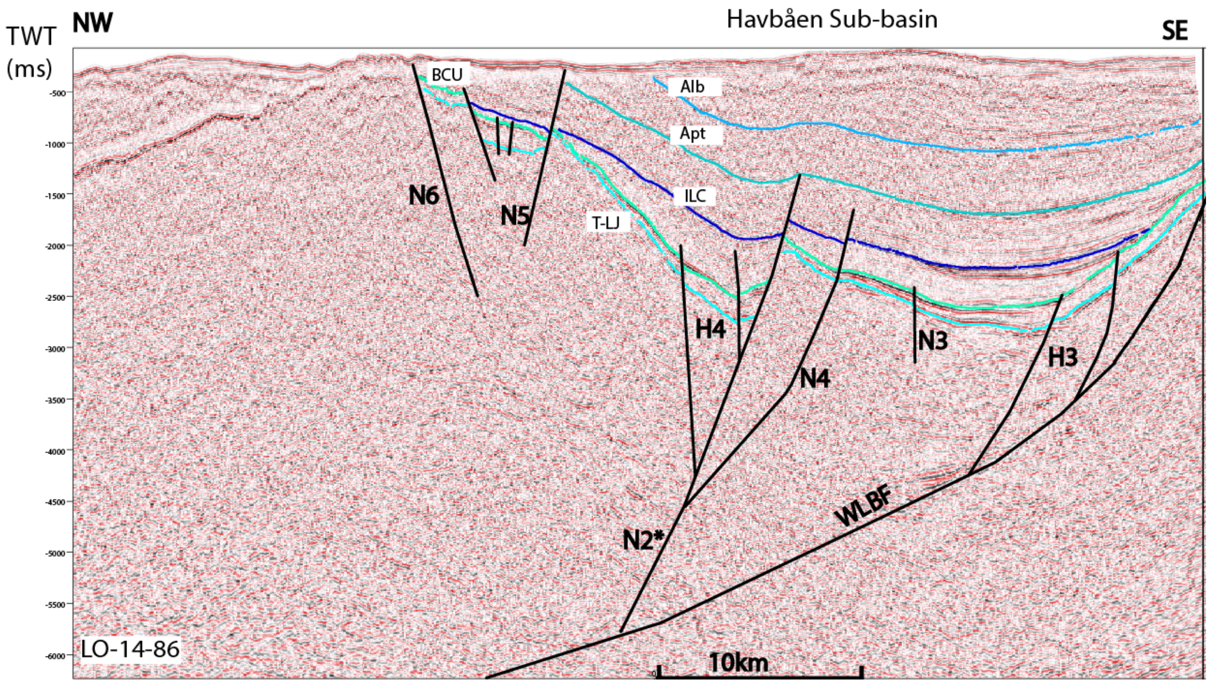


Fig. 4.25: Seismic profile displaying the northern part of Havbåen Sub-basin. Left stepping detachment onto the West Lofoten Border Fault (WLBF) is evident. Profile location in Fig. 4.20.

Jennegga Transfer Zone

A NNW-SSE oriented transfer zone is located east of the Jennegga High (Fig. 4.19) called the Jennegga Transfer Zone (Tsikalas et al., 2001). The location of the transfer zone coincides with a NW-SE striking positive gravity anomaly (Fig. 4.21). The fault polarity changes from a westerly to easterly dip direction across the transfer zone, and large Jurassic faults (*N1*, *N2**, East Jennegga High Fault and *Pyramiden*) terminate close to or within the zone. It is observed that the major *N2** and East Jennegga High Fault faults terminate in close vicinity, and are represented by opposite dip polarities on each side of the transfer zone (Fig. 4.19). The transfer zone might also act as a rift propagation barrier, and faults may be linked together in a left/right stepping detachment pattern (Færseth, 2012). This is also observed for the Lofoten and Vesterålen margin segments. In particular, local W-E trending transfer faults are present in the southern margin of the transfer zone. It is also observed that the general strike of the faults is more NE-SW orientated in the Lofoten margin, compared to the dominant NNE-SSW trending faults in the Vesterålen margin (Fig. 4.19).

Vesterålen margin

Figures 4.26 and 4.27 provide a good indication of the structural configuration of the northern part of the Havbåen Sub-basin within the western East Jennegga High Fault and the eastern West Lofoten Border Fault(?) border faults. A shift in fault polarity is evident, and the Vesterålen margin is mainly dominated by east-dipping Late Jurassic-earliest Cretaceous faults. General observations of fault displacement range between 50-1200 ms (0.5-3 km), and the faults affect mainly the BCU and T-LJ horizons, with some minor offsets of the mid Cretaceous horizons. The major faults tend to propagate deeper into the basement, and detach at a certain level between 4000-5000 ms.

North of the Jennegga Transfer Zone, four partly rotated fault-blocks are observed and are thought to be generated as a result of the low-angle east-dipping detachment structure. The detachment occurs at ~3500 ms where three synthetic faults detach in a right stepping manner onto the deeply listric East Jennegga High Fault (Fig. 4.26). A thin layer of the S1 seismic sequence is observed above the rotated fault blocks. The seismic succession is truncated by the BCU horizon and pinches out up-flank the paleo-highs, resembling wedge-shaped geometries. The East Jennagga High Fault and *Pyramiden* fault exhibit the greatest throw, with the *Pyramiden* hanging-wall indicating the most suppressed area. Planar faults combined with a gently curved shape of the basin are observed towards the eastern margin of the Havbåen Sub-basin (Fig. 4.26).

The three east-dipping listric faults, *Pyramiden*, East Jennegga High Fault (EJHF) and *N1*, are observed to exhibit a steeper fault-plane in the northern part of Havbåen Sub-basin where the strong low-angle detachment structure is reduced (Fig. 4.27). Hence, the Havbåen Sub-basin is no longer characterized by rotated fault-blocks, and instead these are replaced by one prominent WNW-tilted rotated fault-block between the *N1* and *Pyramiden* faults. The faults can be traced from the basement upward until fault *N1* terminates in the Intra Aptian (Apt) reflector, and *Pyramiden* and East Jennegga High Fault by the sea floor. There are some limitations in the confidence of fault timing due to the *N1* and *Pyramiden* faults being subcropping to the sea floor. However, the observed displacements of T-LJ and ILC reflectors confirm faulting activity within the Late Jurassic-earliest Cretaceous rifting event (Fig. 4.27).

Several west-dipping planar to slightly listric faults (*H1* and *H2*) are present on each side of the rotated fault block (Fig. 4.27). The largest displacement is observed in the T-LJ horizon, and several terraces are generated towards west. The *Pyramiden* fault hanging-wall is affected by an array of narrow east- and west-dipping shallow intra-basement involved faults (*H1*). The fault array, situated between two major faults with opposite polarities, generates a roll-over structure towards southeast (Fig 4.27). The Cretaceous succession is only limited affected, as only the faults exceeding throws larger than ~100 ms affect the BCU horizon. A pre-Cretaceous origin is proposed for the fault array.

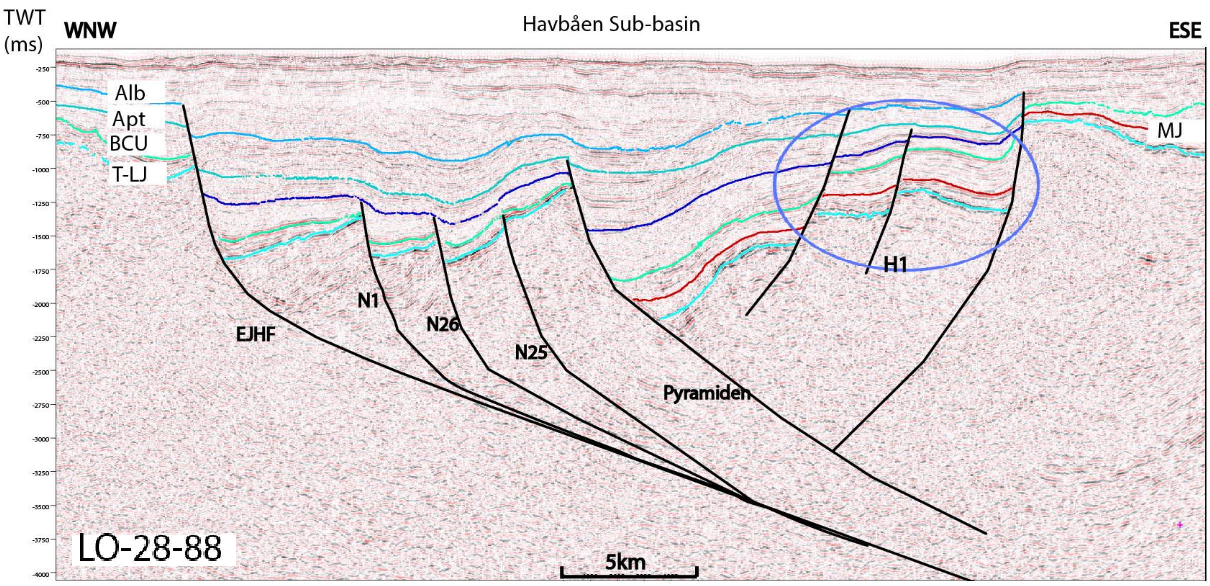


Fig. 4.26: Seismic profile illustrating rotated fault-blocks and a progressively right-stepping detachment with depth. Profile location in Fig. 4.20.

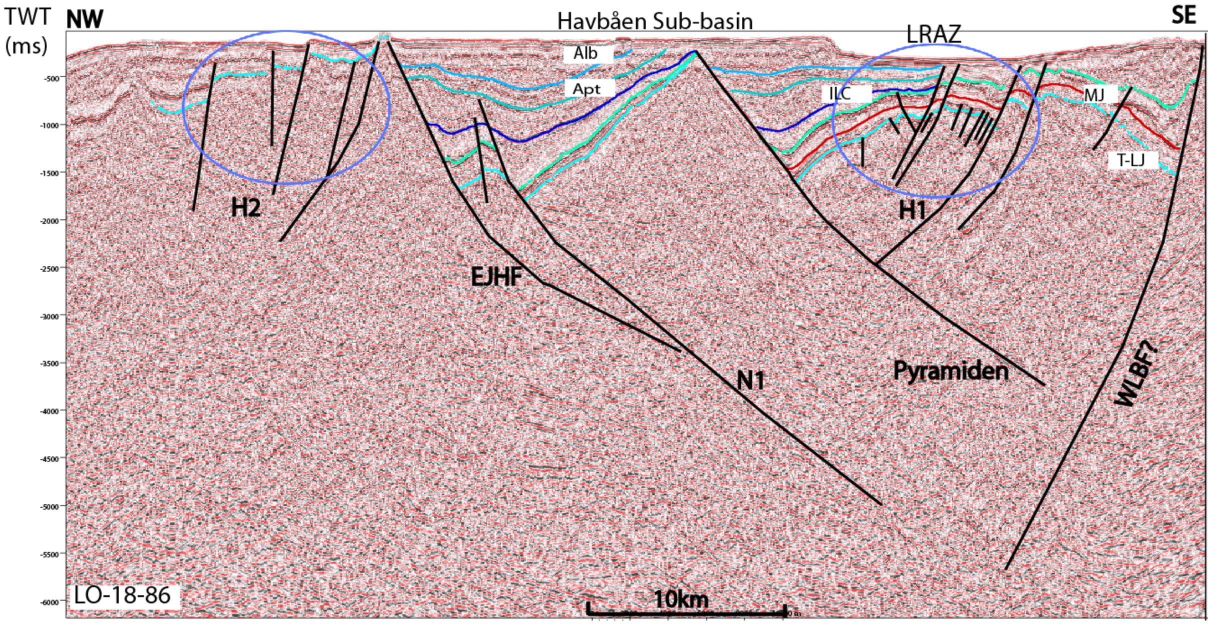


Fig. 4.27: Seismic profile illustrating prominent WNW-tilted fault-block. Note the roll-over shape generated between the *Pyramiden* fault and WLBF(?) of opposite polarities. Profile location in Fig. 4.20.

5 Discussion

5.1 Tectono-stratigraphic evolution

There are large uncertainties concerning the exact timing and the importance of the different tectonic events. Following earlier studies (Blystad et al., 1995; Tsikalas et al., 2001; Bergh et al., 2007; Færseth, 2012) the most dominant post-Caledonian tectonic events considered in the thesis (cfr. sub-chapter 4.5.1) took place during: Permo-Triassic, Late Jurassic-earliest Cretaceous, mid Cretaceous, and Late Cretaceous-Early Tertiary.

The following sub-chapter will focus on the interaction between fault activity and sedimentary deposition, in order to further describe the geological evolution of the study area. Thickness variations across faults with the largest sedimentary accumulations on the hanging-walls can be used to associate fault activity to a given time-period. Selected time-thickness maps have been utilized to illustrate and discuss the lateral variation of the sediment infill and tectonic evolution through time. Seismic examples mainly derived from parts and details on the five regional seismic profiles (Figs. 4.23-4.27), are used to better exemplify the observations and to achieve a more detailed understanding.

5.1.1 Permo-Triassic tectonism

Seismic sequence S1

A widespread Permo-Triassic rifting event is well-documented onshore East Greenland (Surlyk, 1990). However, claiming a distinct Permo-Triassic rifting event within the Lofoten-Vesterålen margin is difficult, due to limited stratigraphic control and locally severe erosion removing significant quantities of the sedimentary successions, mainly in the vicinity of the defined structural highs. Bergh et al. (2007) interpreted a N-S fault-trend for the Permo-Triassic rifting event, but no remarkable indication of this faulting-trend is observed within the study area. Thus, the possibility of younger tectonic events overprinting older structural elements is reasonable.

The best indication of a Permo-Triassic tectonic event is within the internal basement configuration. Here, it is observed that Mesozoic border faults often exhibit the same orientation as internal basement reflections (Fig. 4.23). In addition, the presence of the wedge shaped Paleozoic (Permo-Triassic) successions within the East Røst Fault Zone hanging-wall indicates older extensional events prior to the Middle Jurassic-earliest Cretaceous extension. Henstra et al. (2015) speculated that the Paleozoic sediments could provide areas of lower rheological strength compared to the crystalline basement, and hence create pathways of easier fault propagation. This could explain the highly tectonized zone, represented by the East Røst Fault Zone and the *H7* fault array, situated above the assumed Paleozoic successions (Fig. 5.1). Thickness increase of the S1 sequence is evident towards the East Røst Fault Zone, indicating the possibility of fault activity along this fault zone during the Triassic-Late Jurassic time-period. In addition, the faulting could have been driven by uneven compaction of the underlying Paleozoic sediments (Henstra et al., 2015).

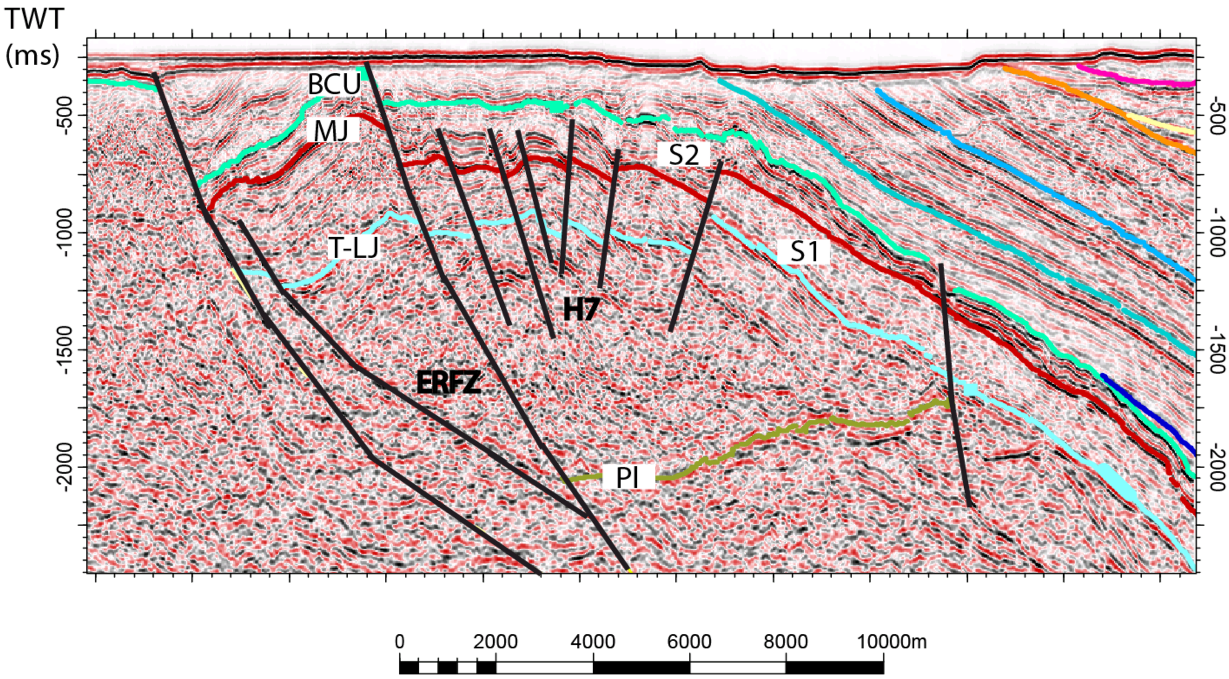


Fig. 5.1: Seismic example illustrating details from the regional profile 1 (LO-02-87). A highly tectonized zone (ERFZ and *H7*) is situated above the possible Paleozoic successions. Profile location in Fig. 5.2.

The Triassic-Early Jurassic period has been interpreted as a relatively tectonic quiet period (Faleide et al., 2010). The sequence is penetrated by the majority of faults within the study area, and abrupt thickness variations can be related to more recent rifting events. A combined time-thickness map have been generated for the S1 and S2 sequences, revealing greatest thickness variations in the southern and northern part of the study area (Fig. 5.2). Limited accommodation space during the Early Triassic resulted in the deposition of only a thin S1 sequence that often pinches out towards paleo-highs (Figs. 4.26 and 4.27). Tsikalas et al. (2001) interpreted this as possibly long-lived topography and the development of only local basins, compared to the adjacent shelves, e.g. Vestfjorden Basin and Trøndelag Platform, where greater successions of pre-Cretaceous sediments have been mapped (Spencer et al., 1990; Blystad et al., 1995).

Younger tectonic events and erosion have strongly affected the S1 sequence, and large uncertainties are associated with it. The greatest accumulation of the S1 sequence is detected across a series of normal faults beneath the Ribban Basin (Figs. 4.24). Differential subsidence within the Havbåen Sub-basin is observed across the *N2** fault, where antithetic faults (*H4*) gradually increases the sequence thickness towards the *N2** fault-plane (Fig. 5.3). At this locality, a limited internal configuration can be determined, and a thickening of the successions toward the fault-plane is apparent. This can be interpreted as deposition coeval with rifting, as the majority of syn-and post-rift successions are deposited on the hanging-wall.

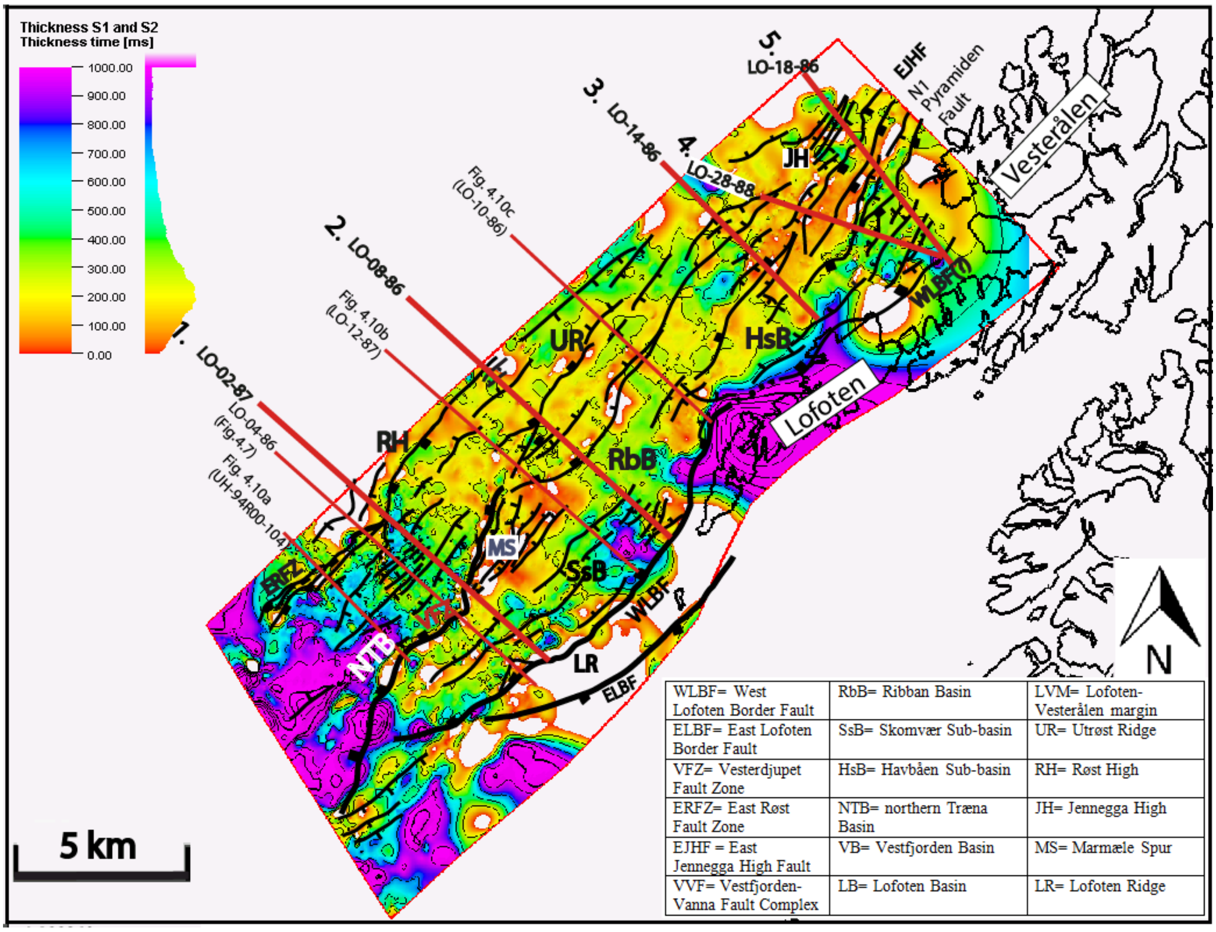


Fig. 5.2: Time-thickness map of the pre-Cretaceous successions (S1 and S2), with the location of the utilized key seismic profiles.

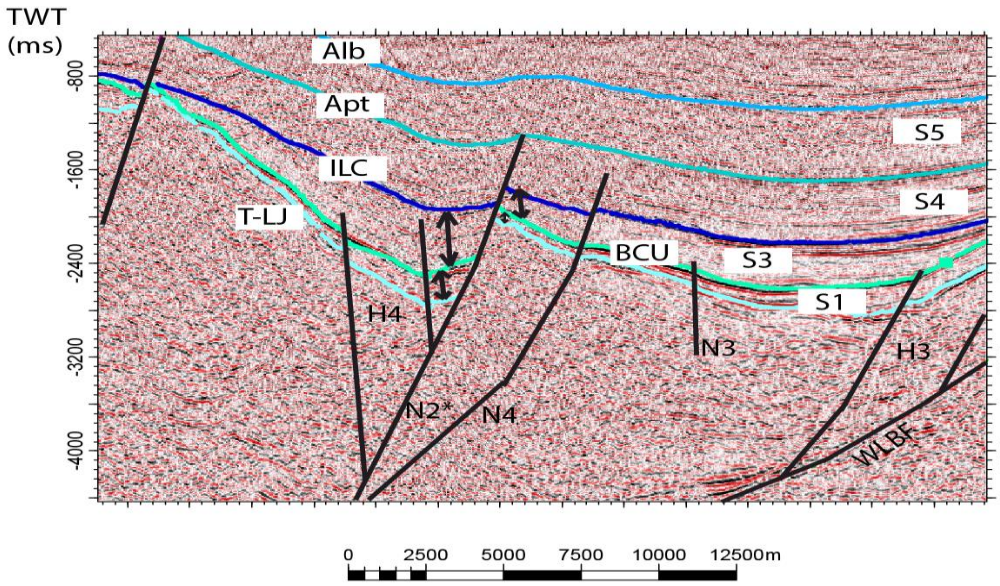


Fig. 5.3: Seismic example illustrating details from regional profile 3 (LO-14-86). The *N2** fault is interpreted as the most prominent, and thickness variations of the S1 and S3 sequences are evident across the fault. Profile location in Fig. 5.2.

5.1.2 Late Jurassic-earliest Cretaceous tectonic episode

Seismic sequence S2

Seismic sequence S2 represents the onset of a new period of rifting, the Late Jurassic-Early Cretaceous (Faleide et al., 2010). The initial fault activity within the northern Træna Basin is revealed by the wedge-shaped growth strata of the S2 sequence towards the Vesterdjupet Fault Zone, in the central parts of the fault-plane (Fig. 5.4). No apparent onlap of the reflections are observed towards the fault-plane, and the chaotic and transparent reflections indicate syn-rift deposition (Fig. 5.4). No record of growth strata is observed within the S2 sequence in the northernmost portions of the fault. Hence, the initial stage of rifting was probably not pronounced enough to produce a continuous fault towards north.

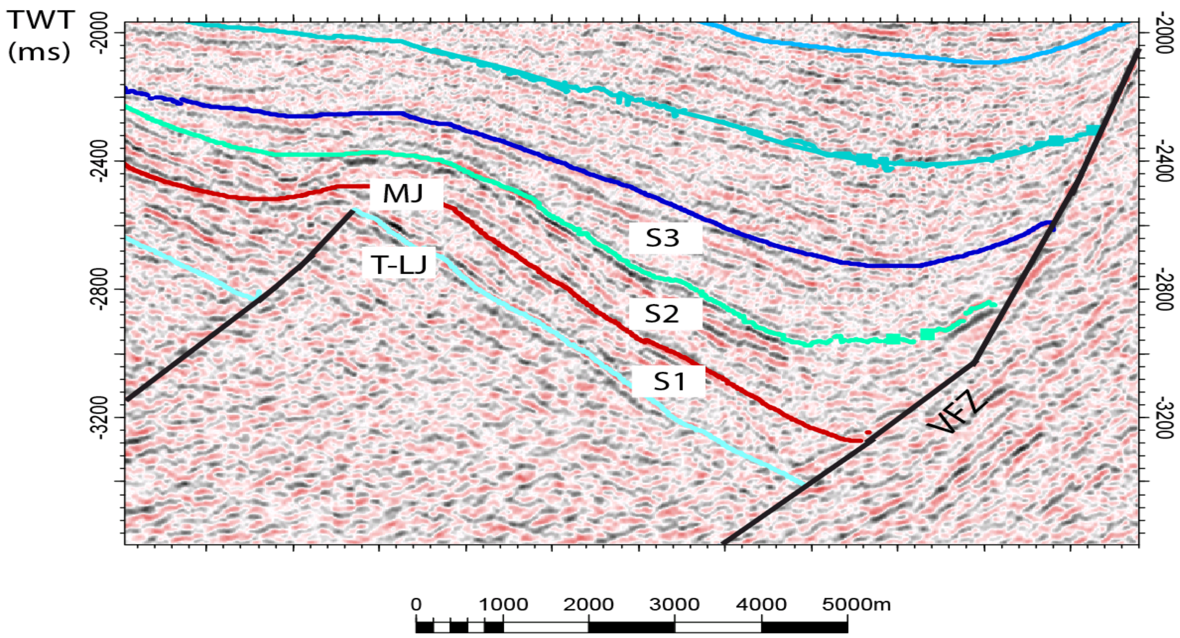


Fig. 5.4: Seismic example illustrating details from seismic line LO-02-88 that indicates growth of the S2 sequence towards the Vesterdjupet Fault Zone. Profile location in Fig. 5.5.

The Late Jurassic-earliest Cretaceous tectonic episode resulted in maximum rotation of the fault-blocks (Færseth, 2012), and the S2 sequence is located on rotated fault-blocks towards the East Røst Fault Zone (Fig. 5.1). This fault activity has been correlated to Late Jurassic rifting as the majority of faults terminate within the S2 sequence. As mentioned above, the Paleozoic successions could have generated zones of weaker strength, and hence generated the dense fault array (*H7*). Nevertheless, fault-block rotation is most prominent in the

Havbåen Sub-basin, where also the greatest accumulations of the S2 sequence are observed (Figs. 4.26 and 4.27). A gradual thickness increase across the *H1* fault array towards southeast is evident from the regional seismic profiles (Figs. 4.26 and 4.27). This is further enhanced in Figure 5.5, where partly overlapping faults (*H1*) with opposite polarities generate a low relief accommodation zone (Gawthorpe and Leeder, 2000). The generation of the low relief accommodation zone appears to have been developed through several rifting-events as the majority of small scale-faults terminate within the S1 sequence, larger scale faults offset the S2 sequence, and finally the sequence displays local thickness variations across the faults (Fig. 5.5).

The accumulation of the S2 sequence in the *Pyramiden* fault hanging-wall indicates fault activity during the Late Jurassic, creating a local depocentre. Wedge-shaped geometries are observed, but the reflections exhibit a sub-parallel character which onlap the fault-plane with tendency of being dragged along (Fig. 5.5). Furthermore, the absence of the sequence on the *Pyramiden* fault foot-wall could be an indication of extensive fault activity that was followed by erosion (Figs. 4.26, 4.27 and 5.5).

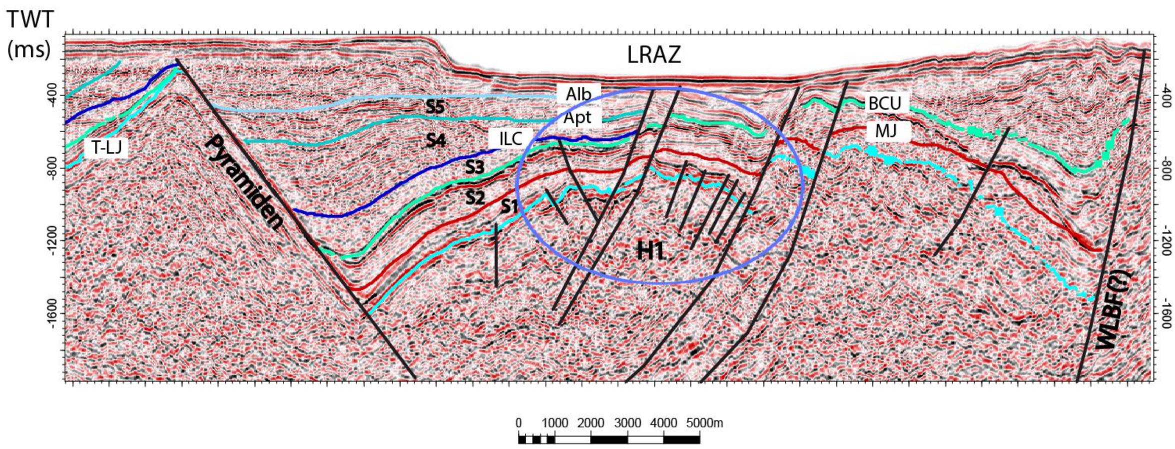


Fig. 5.5: Seismic example illustrating details from regional profile 5 (LO-18-86). Note the highly tectonized zone generated in the *Pyramiden* fault hanging-wall, creating a low relief accommodation zone (LRAZ).

Rift propagation and margin segmentation

The Ribban Basin is shallower and wider compared to the northern Træna Basin, which may be a result of the Marmæle Spur working as a rift propagation barrier during the Late Jurassic-earliest Cretaceous rifting event (Fig. 4.23). However, the best indication of a rift propagation barrier is the cross-margin Jennegga Transfer zone that could imply structural inheritance from earlier rifting episodes (Tsikalas et al., 2001). The zone is associated with polarity change and fault termination, and apparent left- and right-stepping detachment structures on each side of the zone (Figs. 4.25 and 4.26). The detachment structures are often associated with synthetic faults which extend up to BCU or ILC horizons, and these are believed to originate from the Late Jurassic-earliest Cretaceous tectonic episode. Furthermore, detachment structures often develop as a result of fault-reactivation, and their presence could be an indication of structural inheritance from earlier tectonic episodes (Twiss and Moores, 2007).

In general, northward decreasing fault activity is evident. This is illustrated by the apparent northwards decrease in throw of the East Røst Fault Zone and the Vesterdjupet Fault Zone, and the resulting narrowing and shallowing trend of the northern Træna Basin, before it terminates within the Utrøst Ridge. The time-thickness map of Lower Cretaceous successions (S3, S4 and S5) displays greatest differential subsidence within the Ribban Basin, with the dominant infilling pattern resembling the S3 distribution (Figs. 5.6 and 5.7). The S3, S4 and S5 sequences illustrate a gradual thickness increase towards south which could indicate a northward fault propagation within the Ribban Basin, and the Havbåen Sub-basin developed as the main depocenter (Figs. 5.7 and 4.25). However, an abrupt sediment reduction is evident across the Jennegga Transfer Zone (Figs. 4.19 and 5.7). This may imply a northward decrease in fault activity across the Jennegga Transfer Zone, while the Vesterålen margin seems to be more dominated by local depocenters, created in the hanging-wall of rotated fault-blocks (Figs. 4.27 and 4.28). The northward decrease in fault activity within the Vesterålen margin is confirmed by increased fault-block rotation and decreasing width. In addition, the characteristic low-angle listric faults (East Jennegga High Fault, *Pyramiden and N1*) exhibit steeper and less listric geometries towards south.

5.1.3 Lower Cretaceous basin infill

The Lower Cretaceous successions, comprising the S3, S4 and S5 sequences, represent the main part of the syn-rift infill within the northern Træna Basin and the Ribban Basin. This is better revealed by the generated Lower Cretaceous time-thickness map, which illustrates significant growth towards the Vesterdjupet Fault Zone and the West Lofoten Fault Zone

(Fig. 5.7). The border faults within the Lofoten-Vesterålen Margin, in particular Vesterdjupet Fault Zone, has been interpreted to develop from fault-linkage during the Early Cretaceous (Blystad et al., 1995; Hansen et al., 2012). Gradual variation of throw along the border faults is believed to affect the filling pattern, and local depocenters are possible to depict along the Veserdjupet Fault Zone (Fig. 5.7). Gawthorpe and Leeder (2000) indicated that this could be used to detect fault-linkage within extensional basins. Their model proposed growth of border faults as a result of along-strike propagation and by linkage of faults during the development of the basin, and hence affect the location and thickness of syn-rift deposits. Fault-linkage and lack of continuous faulting activity along the entire fault could explain the zig-zag trending geometry of the Vesterdjupet Fault Zone (Fig. 4.19).

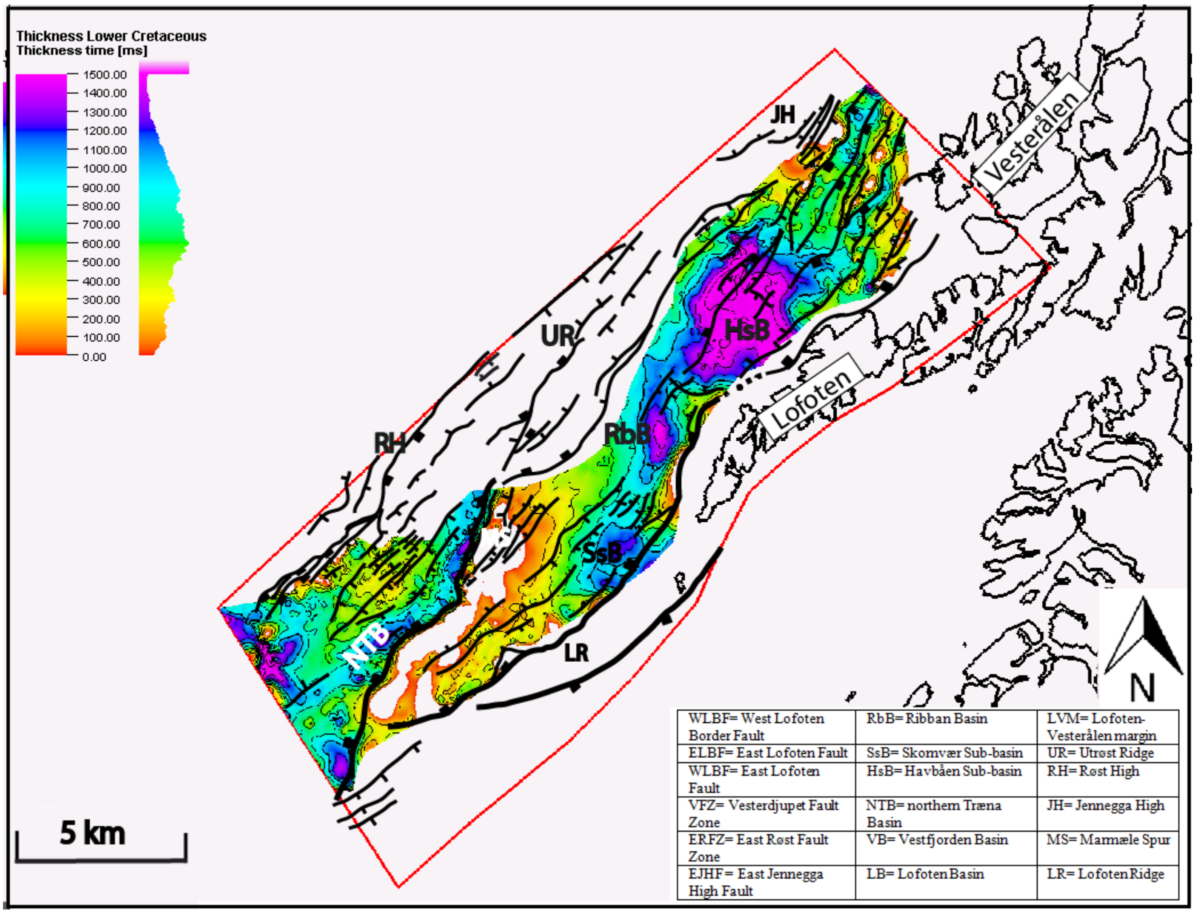


Fig. 5.6: Time-thickness map of the Lower Cretaceous succession (S3, S4 and S5 sequences), with the location of the utilized key seismic profiles.

Seismic sequence S3

The Late Jurassic rifting event has been interpreted to continue into the earliest Cretaceous. This is due to the wedge-shaped geometries of the S3 sequence in the hanging-walls, and the apparent syn-rift character (Fig. 5.8). Færseth (2012) argued that the earliest Cretaceous sedimentation resembles passive infill, with progressive onlap due to the increased accommodation space created during the Late Jurassic rifting. However, the S3 sequence is mainly dominated by transparent and discontinuous reflections and gives little indication of onlap within the northern Træna Basin.

The time-thickness map of the S3 sequence illustrates an early rift-basin infill (Fig. 5.7). The majority of deposits accumulated along the border faults, illustrating that the sequence is restricted to fault-bounded depocentres. The S3 sequence is gradually thinning towards the edges, generating a fan resembling structure (Fig. 5.7). Differential subsidence is evident, and an early development of the northern Træna Basin, Skomvær and Havbåen sub-basins is possible to detect.

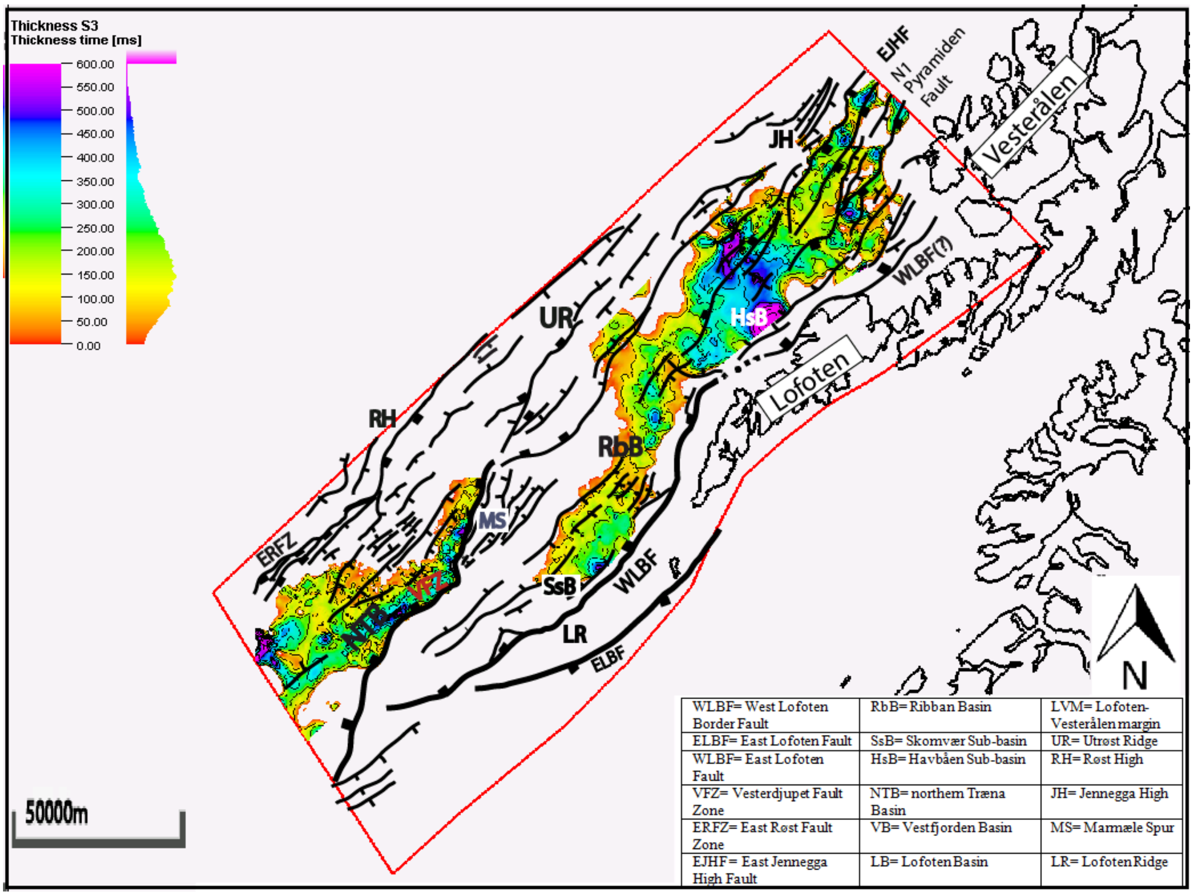


Fig. 5.7: Time-thickness map of the S3 sequence (earliest Cretaceous).

The Havbåen Sub-basin exhibits the greatest accumulations of the S3 sequence, and abrupt thickness variations are evident (Fig. 5.7). The time-thickness map reveals differential subsidence within the sub-basin, and a possible transfer of fault activity towards northwest is evident. This is further enhanced in regional profile 3 (Fig. 4.25), which illustrates the greatest thickness variation of the S3 sequence across fault *N2** (Fig. 5.3), and little evidence of fault activity along the West Lofoten Border Fault. Hence, the *N2** fault has been interpreted to represent the majority of fault activity at the time (Fig. 4.25). The extent of the S3 sequence up-flank the Utrøst Ridge varies possibly as a result of different degree of erosion and preservation of the sequence. The best up-flank preservation of the sequence is within the Havbåen Sub-basin (Fig. 4.25). This coincides with the observed character shift of the West Lofoten Border Fault (Fig. 5.19), including a decreasing throw and listric geometries together with an up-doming shape of the BCU horizon (Fig. 4.10c and 4.25). This enhances the belief of limited tectonic activity along the West Lofoten Border Fault.

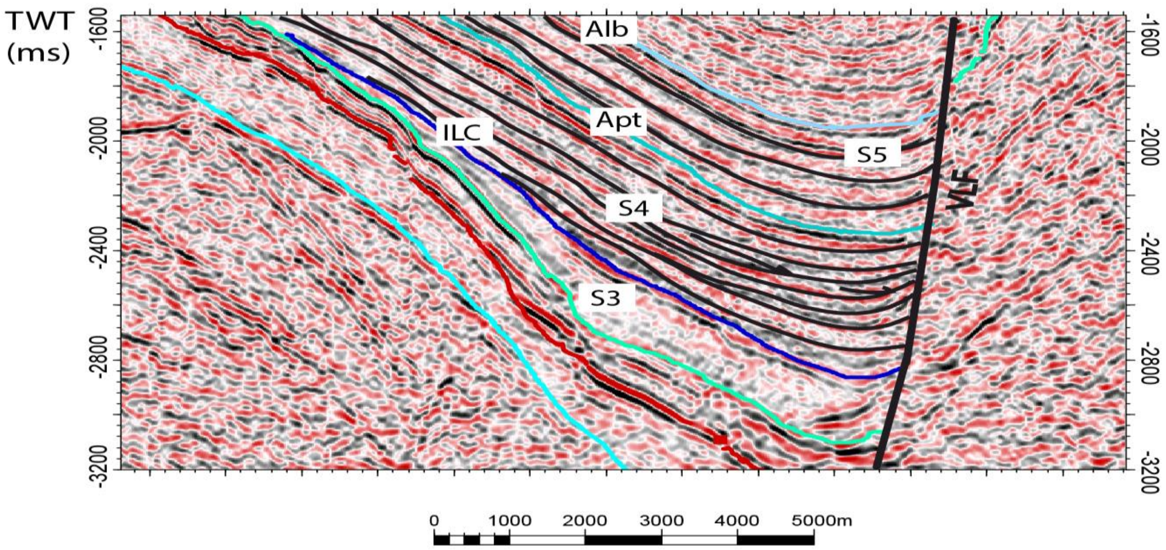


Fig. 5.8: Seismic example illustrating details from regional profile 1 (LO-02-87). Transparent and chaotic configuration of the S3 sequence is revealed, while the S4 and S5 sequences indicate more sub-parallel reflections towards the Vesterdjupet Fault Zone.

The Vesterålen margin exhibits similarly evidence of considerable tectonism. Regional profile 4 depicts greatest accumulations of the S3 sequence towards the *Pyramiden* fault hanging-wall, but significant deposits of the S3 sequence are also evident in relation to the East Jennegga High Fault (EJHF). The ILC horizon drapes the *N1*, *N26* and *N25* faults, indicating ceasing fault activity within the earliest Cretaceous (Fig. 4.26). However, regional profile 5 illustrates a northwards shift of main fault activity from the *Pyramiden* fault to the *N1* fault (Fig. 4.27). The fault-block between the East Jennegga High Fault and the *N1* has been uplifted and eroded, indicating syn-rift tectonism of the S3 sequence (Fig. 4.27). Regional profiles 4 and 5 illustrate the dominance of low-angle listric faults. These faults have been interpreted to represent massive and continuous fault activity, confirmed by the considerable erosion of the sequence along the *Pyramiden* fault foot-wall. The continuous activity along the fault is further intonated by the progressively younger seismic sequences (S1, S2, S3 and S4 sequences), exhibiting thickness increase towards the fault (Fig. 4.27).

Seismic sequence S4

The Valanginian deposits of the S3 sequence were followed by a major transgression as it can be seen in the deepening upward depositional system of shallow marine sandstones into offshore/shelf deposits during Aptian times of sequence S4 (Fig. 4.3) (Hansen et al., 2012). A mid Cretaceous rifting event, lasting from Aptian to Cenomanian times has been interpreted. The S4 sequence shows indication of a separate Aptian rifting event, followed by continuous post-rift subsidence.

Little thickness variations are observed within the S4 sequence in the northern Træna Basin, except the slightly indication of growth towards the Vesterdjupet Fault Zone (Fig 5.9 and 4.23). The S4 sequence indicates a westward onlaping trend onto the BCU horizon, which reflects fault activity and renewed accommodation space within Aptian times (Fig. 5.9). Less confidence exists in the fault timing of the East Røst Fault Zone. However, a slight thickness increase of the S4 sequence is observed (Fig. 5.9), indicating some activity during the Early Cretaceous. The southern part of the northern Træna Basin displays an almost horizontal basin floor between the East Røst High and the Vesterdjupet Fault Zone (Fig. 4.10a). In addition, the majority of the deposited sequences display a more homogenous thickness distribution, with the exception of the S1 sequence (Fig. 4.10a). This could imply simultaneous fault activity of the Vesterdjupet Fault Zone and the East Røst Fault Zone, and that the northern Træna Basin started to develop into a full-graben at its southern parts (Henstra et al., 2015).

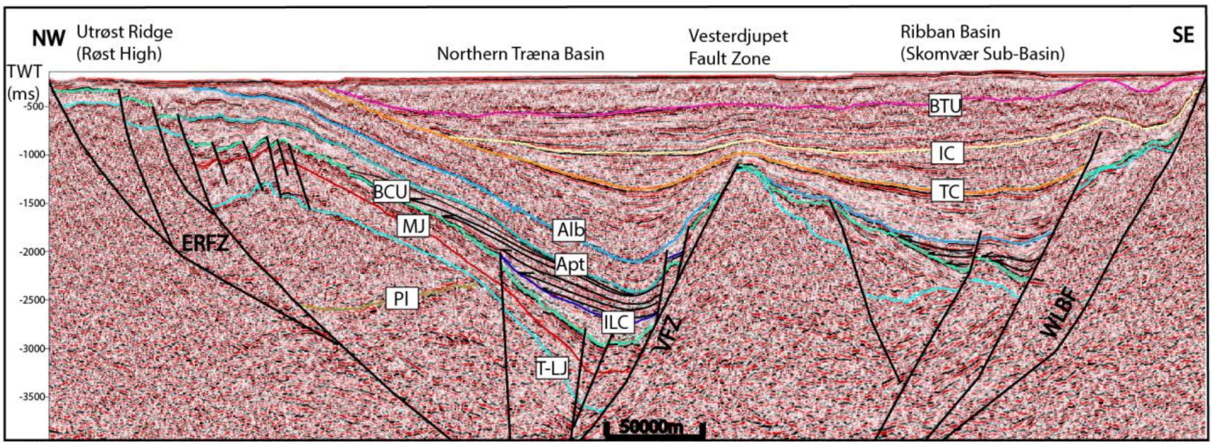


Fig. 5.9: Seismic example illustrating details of the seismic line LO-04.86. An onlaping trend of the S4 sequence in the northern Træna Basin and the S5 sequence in the Skomvær Sub-basin are evident.

Filling patterns within the Ribban Basin are mainly controlled by the West Lofoten Border Fault. Thickness variations of the sequence are gradual, and few indications of abrupt changes across faults are evident. The Skomvær Sub-basin is affected by limited tectonism, except for some fault activity in relation to the West Lofoten Border Fault (Figs. 5.9 and 5.10). The S4 sequence is pinching out towards the Utrøst Ridge, and a progradational onlaping trend is observed in the Skomvær Sub-basin, with younger sediments progressively overstepping each other (Fig. 5.10). The S4 sequence is increasing in thickness towards south, and reveals local zones of strong subparallel reflections in relation to the West Lofoten Border Fault (Figs. 4.10b,c and 4.25). The strong reflections were interpreted by Tsikalas et al. (2001) to represent a local supply of sandstones. This is called mass-gravity deposits on an early rift relief plane, and interpreted as syn-rift deposits. Possible sources could be local topographic highs or stronger footwall erosion, related to footwall uplift. Løseth and Tveten (1996) suggested that the Lofoten Ridge developed into a major source of clastic sediments at that time. Hence, the prominent seismic amplitude reflections could be a result of uneven erosion along the Lofoten Ridge.

The northern part of the Havbåen Sub-basin gives the best indication of rifting, with wedge-shaped geometries created along the *Pyramiden* fault and the East Jennegga High Fault (Figs. 4.26 and 4.27). The in-fill is chaotic, with little internal configuration, and a vague wavy and divergent shape of the reflections is observed towards the *Pyramiden* fault-plane (Fig. 5.5). The largest accumulations of the S4 sequence are observed in regional profile 4, towards the

Pyramiden fault-plane (Fig. 4.26). Regional profile 5 indicates a shift of fault activity towards the East Jennegga High Fault, as the greatest successions are located there.

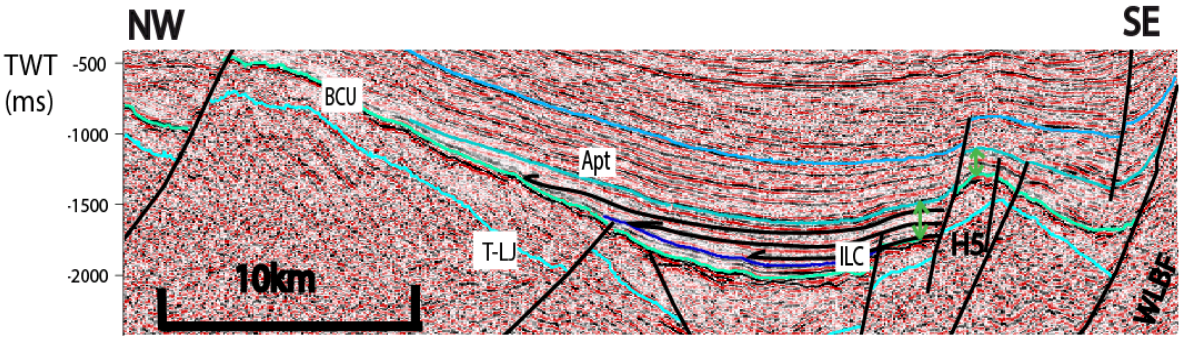


Fig. 5.10: Seismic example illustrating details of regional profile 2 (LO-08-86). A northwest onlaping trend of the S4 sequence filling in the earlier relief is observed.

Seismic sequence S5

The S5 sequence is characterized by parallel bedding with relatively uniform thickness, except for the gradual northward increase (Figs. 4.23-4.27). Minor local thickness variations are observed in the northern Træna Basin, while the Skomvær and Havbåen sub-basins exhibit some local thickness variations (Figs. 4.23 and 4.24). The upper boundary of the sequence, the intra Albian horizon, drapes or truncates the majority of intra-basin faults within the Lofoten-Vesterålen margin. This is further enhanced in the Intra Albian (Alb) time-structure surface (Fig. 4.16), where it is illustrated that the limited fault activity at the time is located close to the West Lofoten Border Fault, or in close vicinity to structural highs. In general, possible wedge-shaped geometries lack the indication of growth strata, and the period has been interpreted as tectonically stable. The absence of growth strata and prominent parallel bedding, gives little indication of syn-rift deposition (Figs. 4.7, 4.26 and 4.27). In addition, the laminar bedding could indicate slow sedimentation, probably from a low relief provenance. Furthermore, it is also possible that the sand influx has decreased, and the deposits are more dominated by siltstones in a low-energy environment. Hence, the sequence has been interpreted to be dominated by post-rift subsidence.

The regional seismic profiles (Figs. 4.23-4.27) illustrate that the S5 sequence mainly fills the earlier generated rift topography, enhanced by the westward onlap of the sequence onto the rotated fault-blocks within the Skomvær Sub-basin. However, no major down-throw of the

Intra Albian (Alb) horizon is observed, and the sequence is interpreted as passive infill due to the uneven relief (Fig. 5.8). Along the West Lofoten Border Fault it is still possible to detect fault activity as the sequence exhibits the largest accumulations towards the fault and gradually pinches out towards the Marmæle Spur (Fig. 5.9). The best indication of subsidence-driven accommodation space is observed within the northern Træna Basin, due to the apparent dragged shape of the sequence along the Vesterdjupet Fault Zone. In addition, two antithetic small-scale faults along the Vesterdjupet Fault Zone terminate within the S5 sequence, and could demonstrate some renewed fault activity of the Vesterdjupet Fault Zone (Fig. 5.9).

The East Jennegga High Fault offsets the Intra Albian (Alb) horizon and provides an indication of mid Cretaceous fault reactivation. The sequence increases in thickness toward the fault-plane, and a notable thickness increase above the rotated fault-blocks are observed. This could be connected to reactivation of the *N1, N26, N25* faults and hence generation of increased accommodation space (Fig. 4.26).

5.1.4 Late Cretaceous: subsidence and renewed tectonism

Seismic sequence S6

The S6 sequence marks the transition into the Upper Cretaceous successions. The time-thickness map of sequence S6 illustrates rather gradual thickness variations, except for the abrupt variations associated with the Vesterdjupet Fault Zone and the West Lofoten Border Fault (Fig. 5.11). Differential subsidence along the faults is evident, where the northern parts of the sequence exhibit the largest accumulations and may reflect mid Cretaceous deformation. The time-thickness map illustrates an apparent thickness increase from the Skomvær Sub-basin (~400 ms) to the northern Træna Basin (~600-700 ms) (Figs. 4.24 and 5.11). The Lofoten Ridge has been interpreted as the main source of clastic sediments (Løseth and Tveten, 1996), and the thickness variations could be a result of sediment bypass in the Skomvær Sub-basin and deposition in the northern Træna Basin (Fig. 5.9). However, the major fault activity at the time seems to have occurred along the West Lofoten Border fault (Fig. 5.11). At this location, large throw of the West Lofoten Border Fault is observed, and the sequence is characterized by sub-parallel reflections with a divergent geometry towards the fault-plane. This could indicate deposition coeval with rifting (Fig. 4.10b).

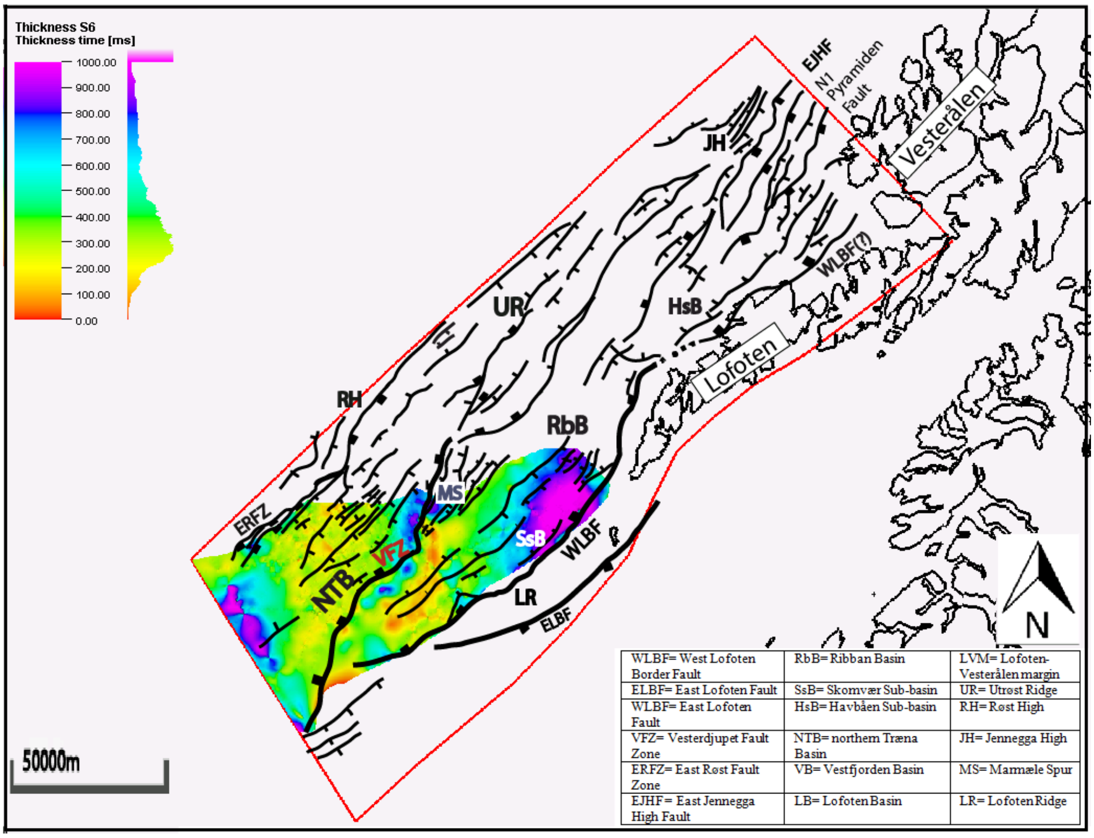


Fig. 5.11: Time-thickness map of the S6 (Albian-Cenomanian) sequence.

Seismic sequence S7

The Top Cenomanian (TC) horizon exhibits a prominent seismic amplitude character both along the northern Træna Basin and the Skomvær Sub-basin and drapes over the Vesterdjupet Fault Zone (Figs. 4.7 and 4.23). The wide extension of the horizon and strong reflection can be explained by a regional transgression combined with a basal shale layer (Tsikalas et al., 2001). The horizon marks a change in filling pattern of the basins, as the majority of rift topography has been filled in by the S6 sequence, and the S7 sequence displays less variations from the Skomvær Sub-basin to the northern Træna Basin (Fig. 5.9). The S7 seismic sequence is located above the deepest depocenters within the northern Træna Basin and the Skomvær sub-basin and exhibits sag geometry. The lack of sediment accumulation directly towards the border fault-planes indicates increased accommodation space due to subsidence. The sequence is interpreted to have developed during a post-rift setting as revealed by the westward onlaping trend of younger strata onto the Top Cenomanian (Fig. 5.9). The Lower Cretaceous successions are mainly composed by mudstones and siltstones, which exhibit a high initial compaction potential (Fig. 4.3). Hence, minor thickness variations within the

Upper Cretaceous sequence S7 are interpreted to be related to compaction driven effects of the underlying sequences rather than faulting (Hansen et al., 2012).

Seismic sequence S8

The onset of the Late Cretaceous-Early Tertiary rifting event is difficult to claim within the study area, as the majority of structures revealing this deformation are located west of the Utrøst Ridge (Blystad et al., 1995; Tsikalas et al., 2001; Bergh et al., 2007). The base reflector of seismic sequence S8 is strong and continuous, and indicates a marked lithological boundary. This has been interpreted as increased sand supply (Fig. 4.3), which could be a result of rifting. Furthermore, this boundary corresponds to the onset of a Late Cretaceous rift phase in the Vøring Basin, where correlations to commercial wells were possible (Tsikalas et al., 2001). Sequence S8 comprises of strong and continuous reflections and no abrupt thickness variations are observed. However, some local thickness variation above the Marmæle Spur is possible to detect, and is interpreted to be of Late Cretaceous age as the *H8* fault array terminates within the BTU reflector (Fig. 4.23). The geometry of the S8 sequence is lens-shaped compared to the sag geometry of the S7 sequence. This could be an indication of limited subsidence, and hence increased accommodation space created as a result of rifting.

The combined time-thickness map for all the Upper Cretaceous successions (S6, S7 and S8 sequences) illustrates a gradual northwards thickness decrease (Fig. 5.12). Compared to the prominent growth towards the border fault within the Lower Cretaceous, Figure 5.10 depicts that the Upper Cretaceous exhibits less differential accommodation space along the major faults. Few thickness variations are observed in the Vesterålen margin, and the Upper Cretaceous successions are mainly deposited in depressions generated from earlier rifting events (Figs. 4.26 and 4.27).

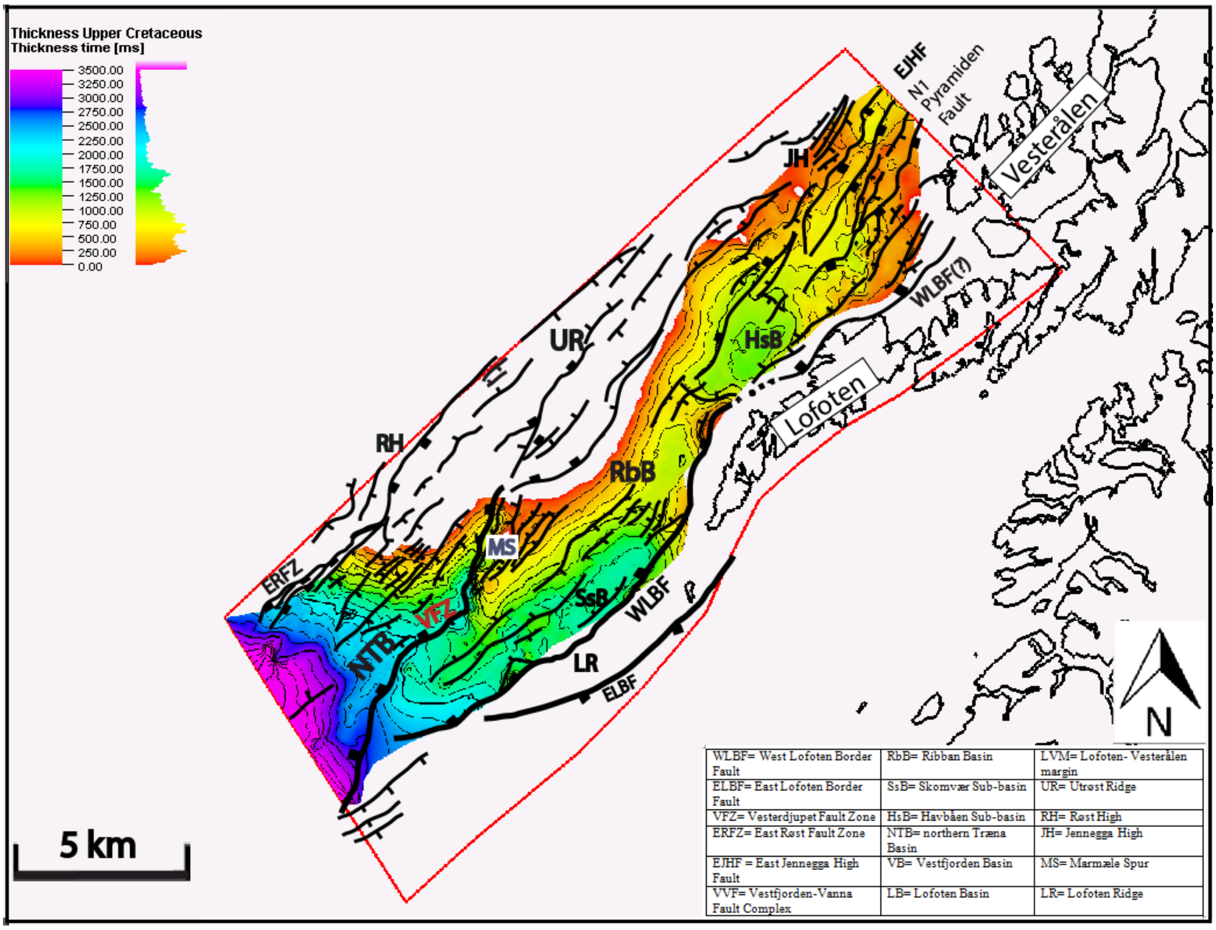


Fig. 5.12: Upper Cretaceous time-thickness map between the Intra Albian (Alb) horizon and the seafloor. The time-thickness map does not give an entirely representative thickness distribution of the Upper Cretaceous successions, as the seafloor has been utilized as the upper boundary. Hence, the Paleogene (S9 sequence) has been included in the southern parts. Also, Cenozoic uplift and erosion have affected the unit, leading to a northward thinning resulting in subcrop close to the seafloor.

5.1.5 Early Cenozoic margin evolution

Seismic sequence S9

The Late Cretaceous-Early Tertiary tectonism culminated at the Paleocene-Eocene transition (~55 Ma) and resulted in lithospheric break-up and the development into a passive margin (Eldholm et al., 2002). Seismic sequence S9 has been interpreted to be deposited in a more continental setting. The sequence is mainly dominated by sandstone deposits which emphasize the continental setting facies. Evidenced of the westward propagation of diffuse character downlaping clinothems, indicates large amount of sediment loading associated with the margin opening (Fig. 4.12).

Several small-scale faults are observed in close vicinity to the West Lofoten Border Fault which extends all the way to the sea-floor and terminates in depth within Lower Cretaceous levels (Fig. 4.24, fault *N7*). No prominent thickness variations are observed. The best indication of tectonism is revealed by the reactivation of the southern portion of the West Lofoten Border Fault. At this location, a fold has developed in the S8 and S9 sequences (Fig. 5.9). Hansen et al. (2012) interpreted this as a reverse drag fold or possibly a forced fold. This means that the fold could have developed as a result of both the extensional phase, and the slight compressional setting followed by the breakup-related tectonism and the initial seafloor spreading. Following the breakup, the margin developed into a passive margin in the transition Eocen-Oligocen, and evolved in response to the subsequent subsidence and sediment loading. The Cenozoic period is characterized by several phases of uplift, and considerable erosion is associated with the Late Pliocene glaciation of the Northern Hemisphere (Faleide et al., 2008).

5.2 Lofoten margin segment in a regional and conjugate setting

In order to complement the understanding of the rift-dominated architecture of the Lofoten-Vesterålen margin, a comparison with adjacent parts of the Norwegian continental margin and the conjugate Northeast Greenland continental margin is conducted. In this context, recent plate reconstructions (Fig. 5.13) and conjugate crustal transects between the Northeast Greenland and the Vøring/Lofoten-Vesterålen margins combined with additional seismic profiles are utilized to fit this purpose (Figs. 5.14-5.18).

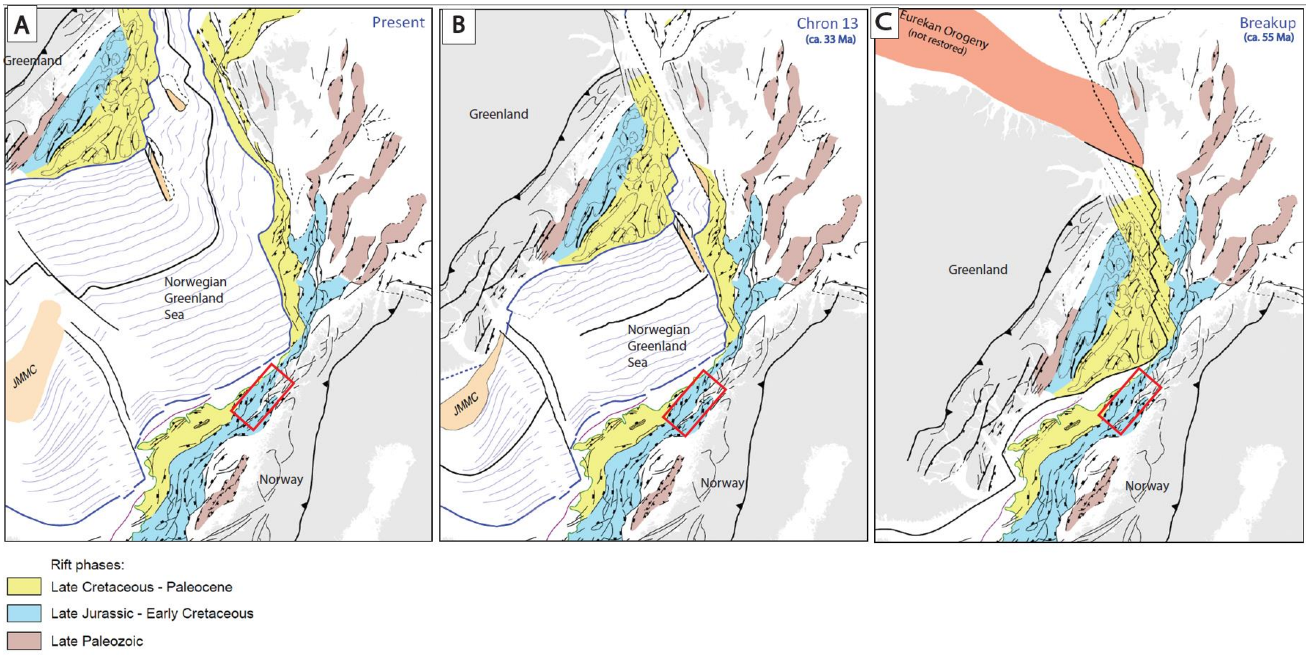


Fig. 5.13: NE Atlantic structural setting and framework: **(a)** present time, **(b)** plate reconstruction to Chron 13 (~33 Ma), and **(c)** plate reconstruction at time of breakup (~55 Ma). JMMC= Jan Mayen micro-continent (modified from Faleide et al., 2010).

5.2.1 Crustal structure

In contrast to the greatly extended crust of the Vøring and Barents Sea margins, it seems that the Lofoten-Vesterålen margin (LVM) was only moderately exposed to pre-breakup extension (Fig. 5.14) (Faleide et al., 2010). The crustal thickness of the Lofoten margin segment reaches a maximum of ~26 km beneath the slope, and the crust increases in thickness towards mainland Norway reaching ~35-38 km (Fig. 5.15). The northern part of the Lofoten margin segment is dominated by homogenous and thick crust and at this location a distinct continent-ocean boundary is possible to detect together with a rapid thinning of the crust beneath the slope (Fig. 5.14a). A general southwards thickness decrease of the crust is apparent along the LVM and Vøring margins, and the crust becomes more subject to across-margin thickness variations (Fig. 5.15).

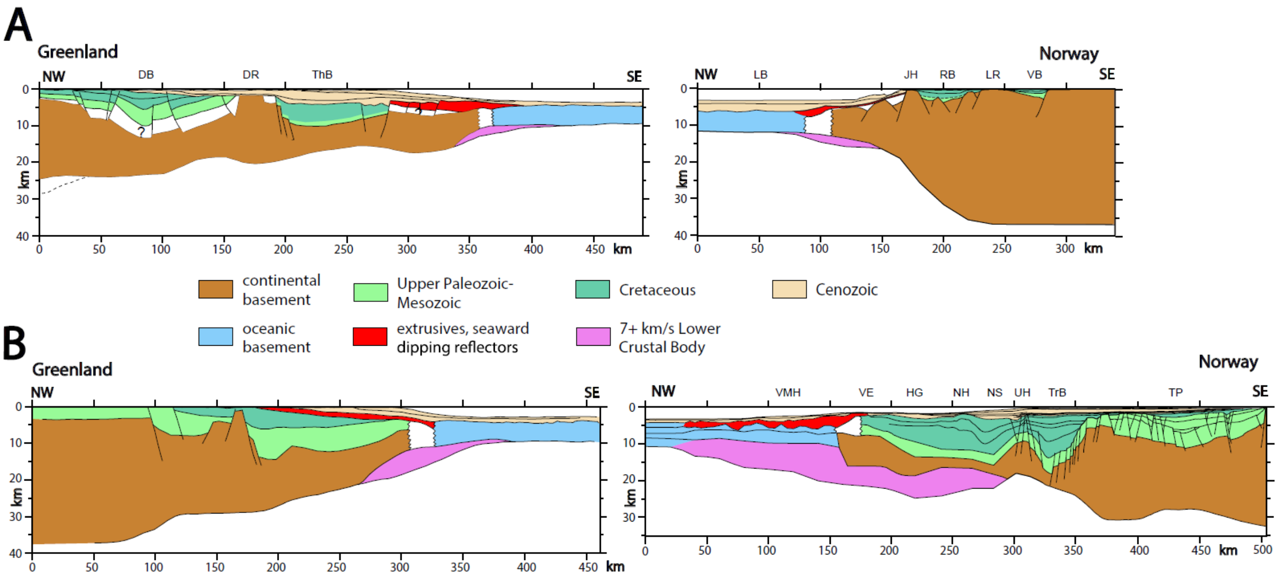


Fig. 5.14: (a) Conjugate crustal transects across the northern Lofoten margin segment and the Northeast Greenland margin. **(b)** Conjugate crustal transects across the northern Vøring and Northeast Greenland margins. Location of profiles in Fig. 5.17. DB: Danmarkshavn Basin, DR: Danmarkshavn Ridge, 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: Træna Basin, UH: Utgard High, VB: Vestfjorden Basin, VE: Vøring Escarpment, VMH: Vøring Marginal High (modified from Tsikalas et al., 2012).

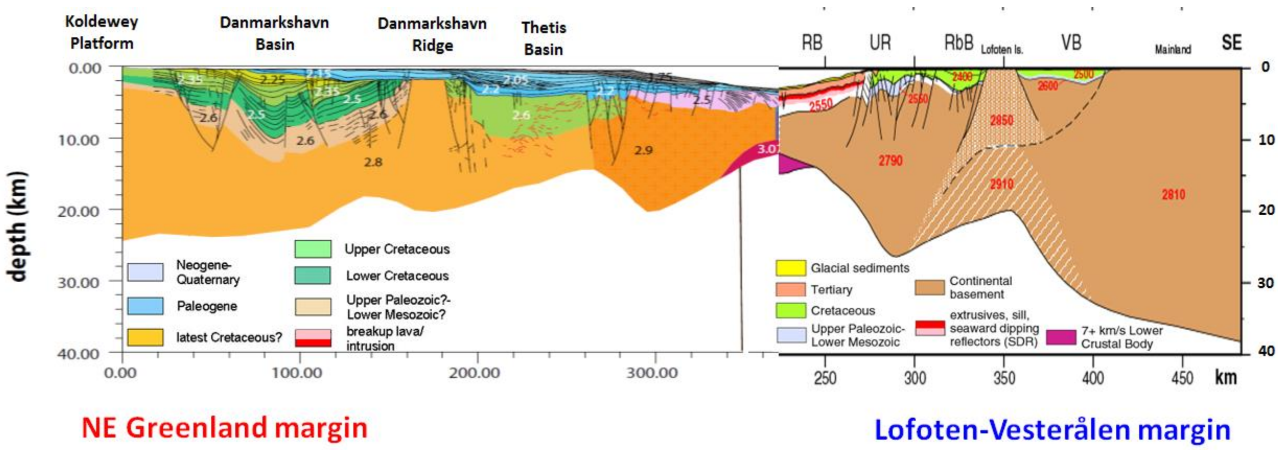


Fig. 5.15: Conjugate crustal transect across the Lofoten margin segment and Northeast Greenland margin. Note the local crustal thickness variations, and the presence of deeper Mesozoic basins within Northeast Greenland (modified from Tsikalas et al., 2005 and Faleide, 2016, pers. comm.).

The Lofoten-Vesterålen margin (LVM) is separated to the south from the Vøring margin by the Bivrost Lineament (Fig. 1.1). The Bivrost Lineament is interpreted to represent an across-margin transfer system, and can be related to the apparent crustal changes along the margin, together with distinct changes related to the extent of lithospheric stretching and emplacement of break-up related magmatism (Tsikalas et al., 2005). In this context, the Vøring margin is composed by highly extended crust and is more affected by break-up related magmatism, indicating greater lithospheric stretching in comparison to LVM (Fig. 5.14b). Furthermore, compared to the Vøring margin, well-defined lateral segmentation is evident for the Lofoten-Vesterålen margin. This lateral segmentation has been correlated to the pre-existing structural configuration and long-lived transfer zones, implying structural inheritance (Tsikalas et al., 2005).

In a regional sense, the plate reconstructions (Fig. 5.13) show that south of 70ºN, the line of breakup is oblique to the Cretaceous basin trend resulting in breakup at different locations with respect to the pre-existing rift systems on either side of the Bivrost transfer system. In this context, the “wide” Vøring margin is conjugate to a “narrow” East Greenland margin counterpart, while the “narrow” Lofoten-Vesterålen margin is conjugate to a “wide” Northeast Greenland margin counterpart (Fig. 5.13c). Furthermore, the oblique position of the line of breakup is similarly intonated in the apparent asymmetrical crustal architecture between the conjugate Northeast Greenland and the mid-Norwegian margins shown in the conjugate crustal transects (Figs. 5.14 and 5.15). In particular, the transects illustrate a northwards decreasing crustal thickness along the Northeast Greenland margin, while a crustal thickness increase is evident for the Norwegian margin at the same direction. This trend coincides with the oblique line of breakup, where the northern part of the Northeast Greenland and the Vøring margins experienced stretching phases with the highest extension (Figs. 5.13-5.15).

5.2.2 Pre-breakup basin evolution with emphasis on Late Jurassic-Cretaceous development

The basin architecture of the Northeast Greenland continental shelf depicts great resemblance to the architecture of the Lofoten-Vesterålen margin, as both margins are dominated by prominent NNE-trending basins and highs (Fig. 5.13) (Faleide et al., 2008). Results from earlier studies, exemplified with plate reconstructions and conjugate crustal transects, reveal the progressive lateral focus of several post-Caledonian rift events towards the line of eventual opening (Figs. 5.13-5.15). Similarly, earlier studies and current work on the thesis reveal evidence for widespread Permo-Triassic tectonism on the conjugate Lofoten-Vesterålen and Northeast Greenland margins, and that the structural margin configuration mainly evolved in response to the Late Jurassic-earliest Cretaceous rift episode. The deep basins situated within the Northeast Greenland continental shelf can be correlated to the Mesozoic basins of the mid-Norwegian shelf (Figs. 5.13c and 5.15). Furthermore, structural and stratigraphic relations also indicate a mid-Cretaceous rift phase at both margins. The subsequent Late Cretaceous-Early Tertiary rifting, with onset in Campanian time (as revealed at the NW Vøring Basin; (Ren et al., 2003), is characterised by prominent low-angle detachment structures at the outer parts of the conjugate margins (Figs. 5.15 and 5.16). The rift may have reached a cross-margin width of 200-250 km and led to breakup with prodigious extrusive and intrusive magmatic activity at the Paleocene-Eocene transition (Figs. 5.14-5.16).

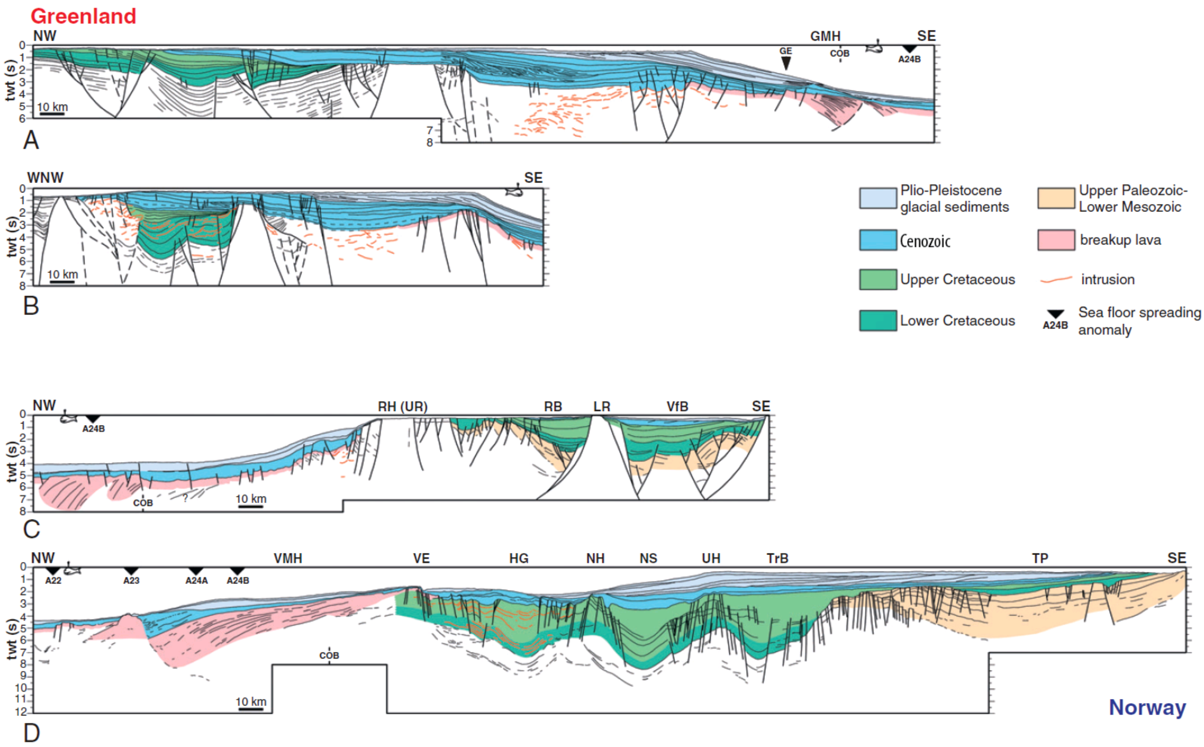


Fig. 5.16: Seismic profiles across the conjugate Northeast Greenland and mid-Norwegian margins. **(a)** Profile situated within the northern part of the Northeast Greenland continental shelf. **(b)** Profile situated within the southern part of the Northeast Greenland continental shelf. **(c)** Profile across the Lofoten margin segment **(d)** Profile across the Vøring margin. 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. See Fig. 5.17 for profile locations (modified from Tsikalas et al., 2012).

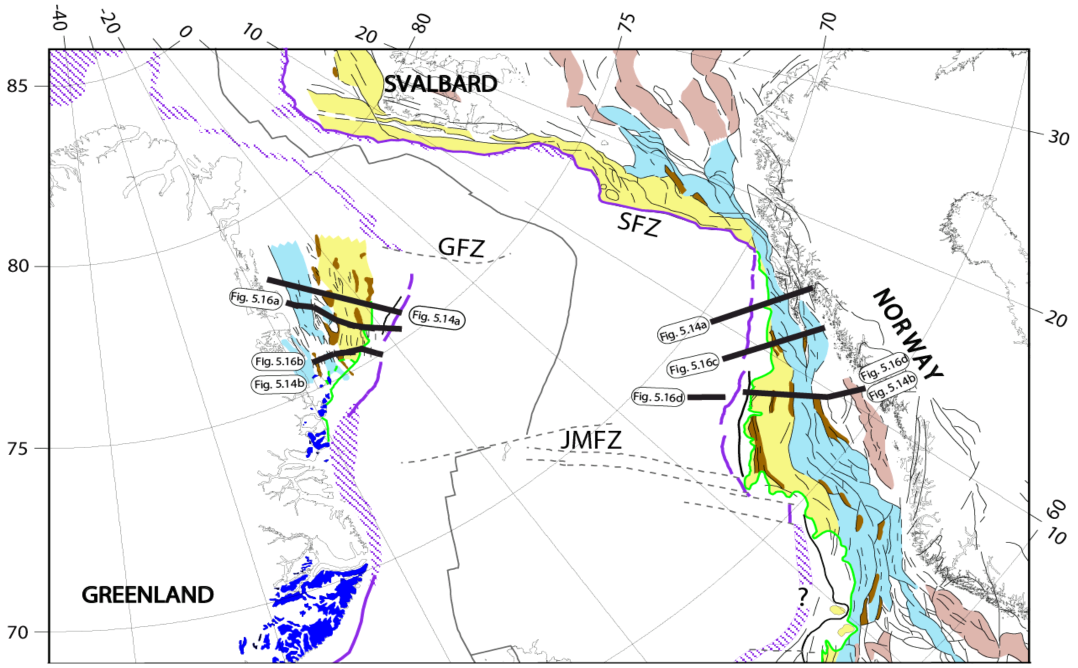


Fig. 5.17: The NE Atlantic rift province, with the conjugate Northeast Greenland and Norwegian passive margins. GFZ: Greenland Fracture Zone, JMFZ: Jan Mayen Fracture Zone, SFZ: Senja Fracture Zone (modified from Tsikalas et al., 2012).

Comparison of sequences along the conjugate margins

The basin architecture and infilling patterns of the basins along the Norwegian continental shelf, and in particular along the Lofoten-Vesterålen margin, are related to the northward propagation of the North Atlantic seafloor spreading, which had a progressive lateral focus towards the eventual line of breakup in the Paleocene-Eocene transition (Tsikalas et al., 2012). Each rift episode ranging from Permian to Cenozoic is related to this northward propagation, and the generated intra-continental sedimentary basins reflect rifting phases of varying intensity. First a comparison between the Ribban and Vestfjorden basins is conducted, followed by a comparison on details of basin configuration between the conjugate margins derived from the regional available seismic profiles (Fig. 5.16). The main focus lies within the Late Mesozoic to Cenozoic basin evolution. However, the Permo-Triassic rift event represents an important precursor for further rift propagation, and has been included when comparing the Vestfjorden and Ribban Basins.

Significant Permo-Triassic faulting activity has been recorded within the Vøring margin, Trøndelag Platform, and further northwards into the Vestfjorden Basin (Faleide et al., 2008). This is evident by the large thickness of the Triassic-Lower Jurassic successions underneath the Trøndelag Platform (Fig. 5.16d), and in the Vestfjorden Basin (Fig. 5.18). The north-

northeastward continuation of thick Triassic-Lower Jurassic successions into the Vestfjorden Basin has been interpreted to represent a progressive similar direction propagation of the rifting. This corresponds to the interpreted WNW-ESE oriented extension during the Permo-Triassic rift event, resulting in mainly NNE-SSW fault trends (Figs. 4.7 and 5.2). Further northward propagation of the Permo-Triassic rifting activity is interpreted to continue partly onshore mainland Norway in major fault complexes, as the Vestfjorden-Vanna Fault Complex (Fig. 2.3), and has resulted in the generation of prominent Permo-Triassic basins in the SW Barents Sea (Fig. 5.13a) (Faleide et al., 2010; Indrevær et al., 2014). Still, the best evidence of Permo-Triassic rifting is observed onshore Eastern Greenland margin (Surlyk, 1990). The Lofoten-Vesterålen margin has been interpreted to consist of peneplained basement highs in the Triassic period (Færseth, 2012), and the thin Triassic-Lower Jurassic successions within the Ribban Basin provides less evidence of accommodation space generated as a result of Permo-Triassic rifting.

Similarly, the Lower Cretaceous successions are significantly thicker within the Vestfjorden Basin compared to the Ribbain Basin (Fig. 5.18). Both basins give the overall impression of thickness increase towards the Lofoten Ridge, with some thickness variations across faults. The Late Jurassic-earliest Cretaceous extension is well documented within the Ribban Basin, and the apparent increase of Lower Cretaceous successions east of the Lofoten Ridge could imply an eastward propagation of faulting activity. In contrast to the Vestfjorden Basin, the Ribban Basin is more dominated by Upper Cretaceous successions. The Upper Cretaceous successions are associated with subsidence generated accommodation space prior to the onset of Late Cretaceous rifting (cfr. sub-chapter 5.1.4). The Upper Cretaceous successions within the Vestfjorden Basin exhibit a homogenous thickness, and could be associated with subsidence driven increase of accommodation space. Little evidence of activity along the Eastern Lofoten Border Fault (ELBF) exists during the Late Cretaceous (Figs. 4.19 and 5.18), which contrasts in comparison to the evolution of the Ribban Basin. At this location within the Ribban Basin, the Upper Cretaceous successions increase in thickness towards the West Lofoten Border Fault (WLBF) and indicate greater influence of Late Cretaceous-Early Tertiary rifting (Figs. 4.19 and 5.18).

The main Cenozoic depocenter is situated in the Vestfjorden Basin, and is almost absent in the Ribban Basin (Fig. 5.18). This could be a result of more severe erosion and uplift on the margin west of the Lofoten Ridge. Nevertheless, the possibility of the Lofoten Ridge acting as a sediment barrier could explain the apparent westward decrease of the Cenozoic successions

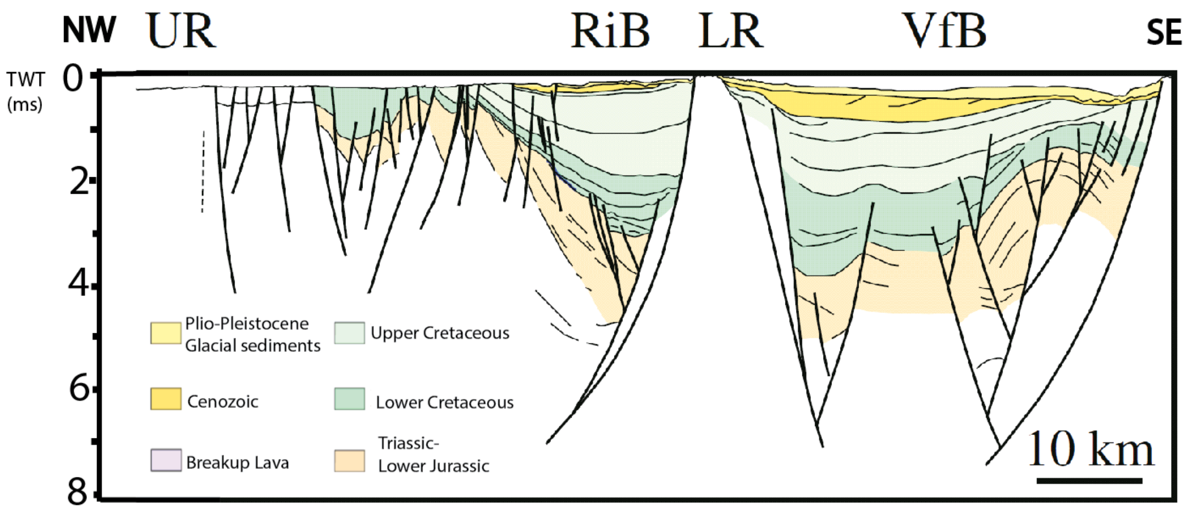


Fig. 5.18: Detail of seismic profile Fig. 5.16c, illustrating the basin architecture and infilling patterns of the Vestfjorden Basin (VfB) and the Ribban Basin (RiB) across the Lofoten Ridge (LR). UR: Utrøst Ridge. Profile location in Fig. 5.17 (equivalent to the Fig. 5.16c location).

The breakup and early opening of the Central Atlantic during the Late Jurassic-earliest Cretaceous generated pronounced tectonism along the Norwegian and Northeast Greenland conjugate margins (Tsikalas et al., 2012). It is considered a precursor to the eventual lithospheric breakup, and considerable thinning of the crust is evident (Tsikalas et al., 2012). The extensional stress field has been interpreted as NW-SE oriented, reflected in the overall NE-SW trending faults within the Lofoten-Vesterålen margin. The Cretaceous sedimentary basins of the Lofoten margin segment are narrower and shallower compared to the Vøring margin (Fig. 5.16). The deepest part of the basins exceeds a depth of ~8 s, compared to the Ribban and Vestfjorden basins which only reach a depth of ~4 s. In particular, the Vøring Basin is displayed as a wide sag basin located above greatly extended crust, reflecting stretching phases of higher intensity compared to the Lofoten-Vesterålen margin (Fig. 5.16). The Lofoten margin segment depicts basins consisting of thick Lower Cretaceous successions. Lateral thickness variations in the lowermost part of the sequence are evident, and imply that rifting has continued into the earliest Cretaceous (Fig. 5.16c). The Vøring Basin is dominated by Upper Cretaceous successions, and only a relatively thin Lower Cretaceous sequence is observed. That exhibits homogenous thickness with limited variations

(Fig. 5.16d). Hence, less evidence of Early Cretaceous rifting exists for the Vøring margin. The sag geometry has been correlated to differential subsidence during Late Cretaceous and stretching phases with high extension during Late Cretaceous-Early Tertiary (Faleide et al., 2010).

In general, the relatively narrow basins of the mid-Norwegian and Northeast Greenland continental shelf are more dominated by Lower Cretaceous successions compared to the wider basins at both margins (Fig. 5.16). Similarly to the mid-Norwegian margin, the two Northeast Greenland profiles also display evidence of Lower Cretaceous thickness variations, and a possible continuation of the rifting into earliest Cretaceous. The Lower Cretaceous sequence thins towards north, and emphasizes the northward propagation of fault activity (Fig. 5.16a, b). The northernmost profiles of the Northeast Greenland and the mid-Norwegian margin give the best evidence of rifting continuing into the earliest Cretaceous (Fig. 5.16a, c). This is interpreted due to observed greater thickness variations and the fact that depocenters mainly developed directly in the vicinity of the fault-plane. The seismic profiles in the Vøring Basin and its conjugate counterpart in Northeast Greenland are dominated by deeper basins, with sag geometries (Fig. 5.16b, d). In contrast to the Vøring Basin, the southern Northeast Greenland profile is dominated by Lower Cretaceous successions, with only a thin wedge of Upper Cretaceous sequences above (Fig. 5.16b).

A modest extension in mid Cretaceous time has been observed within the Lofoten-Vesterålen and the Vøring margins (Tsikalas et al., 2012). The thesis work has further confirmed renewed rifting during Aptian in the Lofoten-Vesterålen margin, evidenced by syn-rift thickness variations and shallow borehole data indicating an upward deepening depositional system. This is further enhanced by the change from neritic to bathyal conditions within the Vøring margin during Aptian-Albian times, reflecting eustatic sea-level change and regional tectonism (Ren et al., 2003; Tsikalas et al., 2012). Structural and stratigraphic relations could indicate a similar rifting event within the Northeast Greenland. Aptian-Albian coarse clastic submarine fans related to deep-water shales deposited along the border faults onshore East Greenland suggest fault activity at the time (Surlyk, 1990). In particular, Figure 5.16a indicates an apparent pinch out of the upper part of the Lower Cretaceous sequence along the SE-tilted rotated fault-block, and the largest sediment accumulations lie within the hanging-wall. This apparent syn-rift thickness variation indicates at least activity along the western major faults during mid Cretaceous times.

Along the mid-Norwegian margin regional subsidence is observed at the onset of the Late Cretaceous rifting during Campanian (Tsikalas et al., 2012), and this is best illustrated in the Vøring Basin, where the sub-basins are filled by thick layers of Upper Cretaceous sediments, reflecting phases of high extension and generation of increased accommodation space (Fig. 5.16d). It was possible to correlate the Late Cretaceous-Paleocene rift-related subsidence at the Vøring Basin to the Lofoten margin segment, although at the latter a lower magnitude extension is aasumed due to the observed northwards thinning of the Upper Cretaceous sequence. At the Lofoten margin, Upper Cretaceous successions display consistent and gradual thickness increase towards the western and eastern side of the Lofoten Ridge (Fig. 5.16c). This is in contrast to the Vøring Basin where the Upper Cretaceous succession shows thickness variations across faults (Fig. 5.16d). Tsikalas et al. (2012) interpreted the initiation of Late Cretaceous rifting at the conjugate Northeast Greenland margin to have taken place simultaneous with that of the mid-Norwegian margin. This was based on observations of normal faulting of middle Campanian age, and the generation of low-angle detachment faults similar to the ones along the mid-Norwegian margin. Furthermore, the southern Northeast Greenland profile only exhibits a thin wedge of Upper Cretaceous sequences (Fig. 5.16b), reflecting less accommodation space created during the Late Cretaceous-Early Tertiary rifting event. Northward increase of the Upper Cretaceous successions within the Northeast Greenland margin is evident, and confirms that the extension was greatest towards north. At this location, a syn-rift character of the sequence is observed across the two major faults generating a horst structure in the western part of the profile (Fig. 5.16a). The Late Cretaceous extension continued into the Paleocene, with little evidence of tectonism along the SW part of the line of breakup. The lateral extent of the Late Cretaceous-Early Tertiary deformation varies along the conjugate mid-Norwegian and Northeast Greenland margins and a great part the deformation leading to lithospheric breakup is masked seaward along the conjugate margins by breakup lavas (Tsikalas et al., 2012).

Finally, Cenozoic successions are evident along the conjugate margins (Figs. 5.16 and 5.17), with an apparent thickness decrease. The Cretaceous successions are truncated by the Cenozoic successions, implying uplift and erosion, possibly during the Paleocene rifting

(Tsikalas et al., 2012). The general northward decrease of the Cenozoic sequence (excluding the glacial-related part) implies increasing northward uplift and erosion along both margins, with the greatest erosion of pre-Cenozoic sequences observed within the Lofoten margin segment, as the Cenozoic sequence is almost absent there.

6 Summary and conclusions

The tectono-stratigraphic evolution of the eastern part of the Lofoten rifted margin segment, comprising the northern Træna and Ribban basins, has been studied in detail utilizing several datasets. These include: available 2D multi-channel seismic reflection profiles; well-to-seismic ties and stratigraphic information from one exploration well and published information from all IKU shallow boreholes in the area together with the Andøya onshore outcrop; and gravity and magnetic data. Within the regional structural context, the main focus of the conducted work has been on seismic and structural interpretations by integrating the available datasets in order to reveal the structural styles of the northern Træna and Ribban basins, with main emphasis on fault evolution and the Cretaceous basin infill history. Furthermore, in order to complement the understanding of the rift-dominated architecture of the Lofoten margin segment, a comparison with adjacent parts of the Norwegian continental margin and the conjugate Northeast Greenland continental margin has been conducted.

The northern Træna Basin and the Ribban Basin (further sub-divided into Skomvær and Havbåen sub-basins) mainly evolved as a result of the Late Jurassic-earliest Cretaceous tectonic episode that coincides with the most pronounced extension event along the North Atlantic margins. However, structural inheritance from the Permo-Triassic rift event is observed in the internal basement configuration and is interpreted to have been susceptible to later fault reactivation. This is reflected in the strongly listric character of the Vesterdjupet Fault Zone and the West Lofoten Border Fault, which exhibit fault-plane orientations that coincide with internal basement fabrics.

The onset of Late Jurassic rifting is best depicted in the central part of the northern Træna Basin and the northern Havbåen Sub-basin. However, the lack of continuous growth strata indicates that the initial phase of rifting was not pronounced enough to generate continuous and elongate faults. The Upper Jurassic succession is overlaid by thick Lower Cretaceous successions, and the apparent syn-rift character of the lowermost Cretaceous strata indicates that the rifting continued into the earliest Cretaceous. The border faults continued to develop through fault-segment linking and the Lofoten Ridge, the Utrøst Ridge and the Marmæle Spur developed into prominent structural highs at the time.

Progressive northward fault propagation has been proposed for the Lofoten margin segment during the Late Jurassic-earliest Cretaceous rifting as it is evidenced by the apparent fault-throw reduction and the slight decrease in thickness of the Lower Cretaceous successions towards north. This is best evidenced by the observed narrowing and shallowing trend of the northern Træna Basin before it terminates within the Utrøst Ridge. Prominent Late Jurassic-earliest Cretaceous faulting continued into the Ribban Basin, and the lateral gradual variation of fault-throw along the West Lofoten Border Fault has resulted in the development of the Skomvær and Havbåen sub-basins as prominent depocenters. The two sub-basins are separated by a "low relief accommodation zone" that coincides with an apparent change in fault direction and fault-throw reduction towards north associated with the West Lofoten Border Fault. There is limited evidence of the "low relief accommodation zone" acting as a rift propagation barrier, and the Havbåen Sub-basin has developed into the main Lower Cretaceous depocenter. Farther north, the abrupt thickness decrease of the Lower Cretaceous successions across the Jennegga Transfer Zone has been interpreted to be a result of the zone acting as rift propagation barrier. In addition, across the transfer zone opposite fault polarities, in left- and right-stepping detachment structures, of the major Late Jurassic-earliest Cretaceous faults are observed. The rifting ceased in the earliest Barremian, but reactivation along the border faults during the Aptian is evident. The Aptian rifting was followed by subsidence, which marks the transition into the Upper Cretaceous successions. Late Cretaceous is characterized by post-rift subsidence with little evidence of prominent deformation. The structural highs and rotated fault-blocks generated during Late Jurassic-earliest Cretaceous are draped by Upper Cretaceous successions. The distinct Upper Cretaceous thickness increase between the Skomvær Sub-basin and the northern Træna Basin has been interpreted as sediment bypass from the Skomvær Sub-basin and deposition within the northern Træna Basin.

Late Cretaceous-Paleocene rifting has preceded the lithospheric breakup at the Paleocene-Eocene transition (~55 Ma), and has generated low-angle detachment structures west of the Utrøst Ridge, however only minor reactivation along the West Lofoten Border Fault is observed within the Lofoten margin segment. The Cretaceous successions are truncated by a relatively thin Cenozoic sequence within the study area, implying uplift and erosion, possibly as a result of the Paleocene rifting and subsequent lithospheric breakup.

The first-order tectono-stratigraphic evolution of the Lofoten margin has been compared with the Vøring margin and the conjugate Northeast Greenland margin, in order to better understand the development of the extensional basins in a regional and conjugate context. The comparison has revealed that the Lofoten margin experienced only moderate pre-breakup extension compared to the Vøring margin and the northern part of the Northeast Greenland margin. Furthermore, the conjugate mid-Norwegian and Northeast Greenland continental margins show an asymmetrical crustal architecture with “wide”/”narrow” margin counterparts, and distinct changes related to the extent of lithospheric stretching. In this context, the line of breakup is oblique to the Cretaceous basin trend and resulting in breakup at different locations with respect to the pre-existing rift systems on either side of the Bivrost transfer system.

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