University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Petroleum Geosciences Engineering	Spring, 2013 Open
Writer: Riki Tasrianto	(Writer's signature)

Faculty supervisor: Alejandro Escalona

External supervisor(s): Michael J. Young and Colin D.Hirning

Title of thesis:

Rift Segmentation and Domain Architecture of Lofoten-Vesterålen Margin, Offshore Norway

Credits (ECTS): 30

Keywords: Extensional tectonic Hyper-extended vs. non hyper-extended margin Lofoten-Vesterålen Margin Rift segmentation Rift domain architecture Rift evolution	Pages: 73 Stavanger, June 15th 2013

Rift Segmentation and Domain Architecture of Lofoten-Vesterålen Margin, Offshore Norway

ACKNOWLEDGEMENT

This thesis report is submitted as a partial fulfillment of the Master Degree of Science in Petroleum Engineering with specialization in Petroleum Geosciences. The research is mainly carried out at ConocoPhillips Norge office in Tananger, Norway.

The author would acknowledge ConocoPhillips Norge for providing all of seismic, well and potential data used within this study. Special thanks is giving to Guy Flanangan (ConocoPhillips technology centre, Houston USA) for processing the potential data, to Duncan Ferguson (ConocoPhillips UK) for balancing several key seismic line, to Neil Grant (ConocoPhillips UK) for assisting the structural restoration, to Alfred Austboe (ConocoPhillips Norge) for assisting the plate reconstruction, and to Willy Fjeldskaar (University of Stavanger/Tectonor) for providing the latest study of the Plio-Pleistocene glaciation within Scandinavia.

The author would express the gratitude to Alejandro Escalona (University of Stavanger) for guiding through this project and providing idea - motivation to accomplish this study.

Thanks to Michael Young (ConocoPhillips Norge) and Colin D Hirning (ConocoPhillips Norge) as the external supervisor for this study, also to Chris Parry, Joern Hauer, Matteo Gennaro and Peter Bornmann in ConocoPhillips Norge for the discussion and feedback.

Finally, the author would thanks to Petroleum Geosciences department of University Stavanger, for awarding the COREC (Center for Oil Recovery) scholarship during the two years study in the university.

ABSTRACT

The Lofoten-Vesterålen margin (LVM) is located in the offshore northern Norway. It is the least explored and understood margin within the Norwegian passive margin due to the authority's restriction, which closed this margin for petroleum exploration. Several published geologic studies for the LVM, proposed different models for margin architecture of the LVM. The first model by Tsikalas et al. (2001), divided the LVM margin into three rift segments: Lofoten, Vesterålen and Andøya segment separated by transfer zones. The second model by Bergh et al. (2007) questioned the existence of lateral segmentation by the transfer zones and proposed that the lateral segmentation was caused by a temporal and spatial initiation of the faults families. The third model was suggested by Færseth (2012), proposed that the LVM consists of two rift segments bounded by an accommodation zone without any strike-slip motion.

This study utilize 2D seismic, well data, onshore outcrop and a set of gravity-magnetic data in order to further investigate the rift segmentation, rift evolution and domain architecture across the margin.

In this study, three rift segments are defined (South Lofoten, North Lofoten and Vesterålen-Andøya) and a model called progressive rift segmentation is proposed, whereby segmentation occurred during Early Cretaceous and Late Cretaceous within the LVM. The first segmentation is marked by the opposing fault polarity between each rift segments, while the second segmentation is characterized by a unique type of deformation consisting of Jurassic-Late Cretaceous fault decoupling. This later type of deformation does not appear to have observed within the other area in the Norwegian passive margin.

The rift evolution of LVM consist of pre-rifting/marginal rifting event during Triassic and Jurassic, shown by the localize distribution of wedge shape sedimentary package, main-rifting event during Early Cretaceous and post-rifting event during Late Cretaceous to present.

Furthermore, in this study the LVM is classified into three distinct rift domains: Proximal, Necking and Oceanic. Each of these domains consistently shows prominent structural similarities across the margin. The observation also reveals the difference of the rift domain architecture between lower-plate (hyper-extended) margins to the upper-plate (non-hyper-extended) margins. The lower-plate (hyper-extended) margins is characterized by the presence of Proximal, Necking, Distal, Outer and Oceanic domain, while within the upper-plate (non-hyper-extended), no Outer and Oceanic domain are observed.

Finally, a remarkable correlation of the Necking domain to the petroleum province within the Vøring margin hints the significance of rift domain characterization within passive margin setting. The Necking domain in the Vøring margin is interpreted to be favored by all of petroleum system element to work and preserve the hydrocarbon. The different characteristic of the Necking domain in the LVM to the Vøring margin degrade the likely-hood of the same petroleum play may exist (e.g., Jurassic play). Although, seismic interpretation and well data observation reveal that the Lower and Upper Cretaceous play may have greater potential for the LVM.

Rift Segmentation and Domain Architecture of Lofoten-Vesterålen Margin, Offshore Norway

List of figures

1 Introduction

1.1 Location

The Lofoten-Vesterålen margin (LVM) is located offshore northern Norway, it lies in between mid-Norwegian Sea and Barents Sea. Physio-graphically, it is situated between the Vøring margin and Barents Sea margins, both of which contain multiple hydrocarbon discoveries. The LVM segment is approximately 400 km long and is characterized by a narrow continental shelf with a steep offshore slope. In contrast to the rest of the Norwegian continental margins (e.g., Vøring margin and Barents Sea margin), the LVM is marked by the exposed of Lofoten-Vesterålen Islands (*Figure 1.1*).

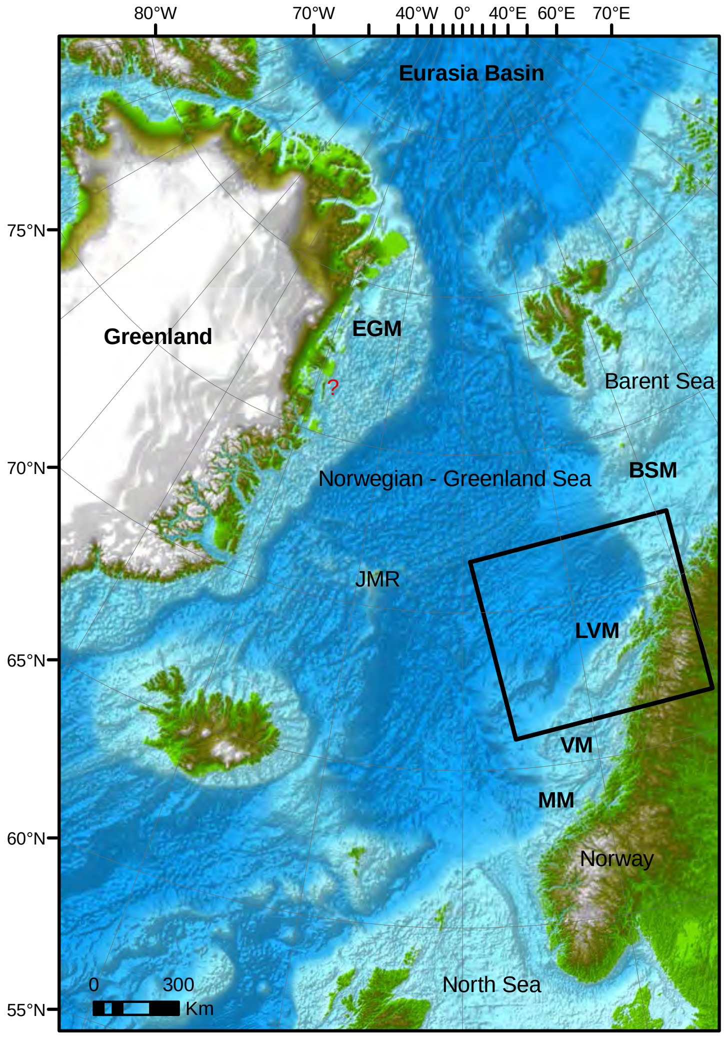

Figure 1.1 The location of Lofoten - Vesterålen margin. *This map shows the location of the Lofoten-Vesterålen margin (in the black square) relative to the Vøring margin (VM), Barents Sea margins (BSM) and the East Greenland margin (EGM). MM: Møre margin, JMR: Jan Mayen ridge.*
The bathymetry data refers to the International Bathymetric Chart of the Arctic Ocean (2012)

1.2 Background and Objectives

The Lofoten-Vesterålen Margin (LVM) has been classified as an upper-plate (non hyper-extended) rift segment of the conjugate Norway-Greenland passive margin (Faleide et al., 2008; Parry, 2012). In contrast to the Vøring margin, no published study has specifically characterized the rift margin architecture and rift domain arrangement along the LVM. However, there are several published studies that discuss specifically the tectonic evolution of this area (Tsikalas et al., 2001; Bergh et al., 2007; Færseth, 2012). These authors proposed different models for the tectono-magmatic evolution of the LVM, mainly concerning the lateral segmentation along the margin (Figure 1.2).

1. Tsikalas et al. (2001) divided the LVM margin into three rift segments: Lofoten, Vesterålen and Andøya segments. Each of these rift segments are separated by transfer zones named Jennengga and Vesterålen transfer zones. Tsikalas et al. (2001) argued the presence of these transfer zones based on evidence of flipping of fault polarity between the rift segments and also by a correlation with oceanic fracture zones mapped using gravity and magnetic data (Figure 1.2A).
2. Bergh et al. (2007) questioned the existence of the lateral segmentation by NW-SE trending transfer zones proposed by Tsikalas et al. (2001). Based on cross-cutting relationships and kinematic variations between different fault populations (offshore and onshore), they argued the reason for the lateral segmentation is a temporal and spatial initiation of offshore faults and corresponding fault-fracture evolution onshore. They also proposed the rifting mechanism of the conjugate margin Norway-Greenland during Early-Late Cretaceous was oblique rather than the conventional orthogonal extension proposed by Tsikalas et al. (2001) (Figure 1.2B).
3. Finally, Færseth (2012) suggested the LVM consist of two rift segments bounding by an accommodation zone. The change in the structural pattern within the LVM takes place across an accommodation zone and this zone acted as a rift propagation barrier during Jurassic crustal stretching. The change in dip direction of the Jurassic faults across this zone took place without any evidence of strike-slip motion (Figure 1.2C).

This study will integrate all available subsurface and surface data, including the newest 2D seismic surveys acquired by Norwegian Petroleum Directorate (NPD) within 2007-2008 and

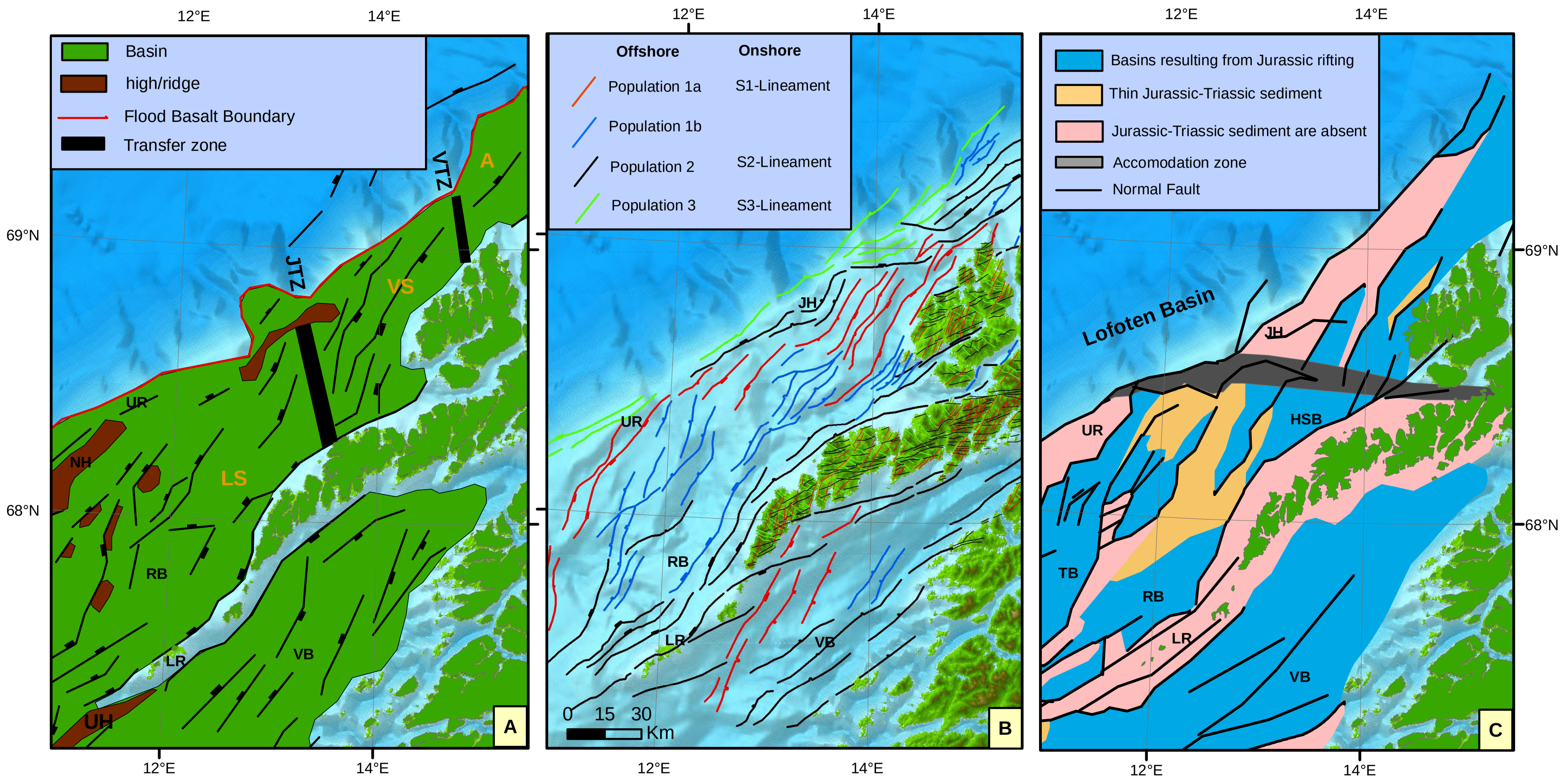

Figure 1.2 Three published models of the LVM margin segmentation. *A). Tsikalas et al. (2001). JTZ: Jennengga transfer zone; VTZ: Vesterålen transfer zone; LS: Lofoten segment; VS: Vesterålen segment; AS: Andøya segment; UR: Ultrøst ridge; RB: Ribban basin; VB: Vestfjørden basin; UH: Utgard high; NH: Nyk high.*

B. Bergh et al. (2007) mapped and linked the offshore faults with the onshore lineaments then proposed the existence of four fault families within the LVM. Each of these fault families is related to distinct rifting events and rifting orientation starting in the Permo-Jurassic (proto-rift), lasting through the Cretaceous (syn-rift) and ending in the Palaeogene (post-rift).

C. Færseth (2012) divided the LVM into 2 segments, separating by an accommodation zone trending East-West.

several vintage 2D seismic surveys (acquired within 1978-1998) which have been reprocessed in 2000. The aims of this study are:

- to define the lateral variation of tectonic evolution within the LVM in relation to the rift segmentation occurred, with emphasize to characterize the Vesterålen-Andøya deformation.
- to propose a model of rifting evolution and rift domain arrangement within the LVM.
- to review published extensional mechanism models for the LVM.
- to define the rift domain architecture within the LVM and to make a comparison of rift domain architecture between the upper-plate (non hyper-extended) LVM with the lower-plate (hyper-extended) Vøring margin.
- to define the rift domain architecture within the conjugate East Greenland margin.
- to discuss the implication of rift domain architecture on the Petroleum exploration activity.

2 Current Geological Knowledge

Based on numerous published studies, this section will discuss the current geological knowledge related to;

i. the passive rift margins architecture including key terminologies and concepts.
ii. the geological setting of the Lofoten-Vesterålen margin and its relevant regional geology (e.g: Vøring margin and East Greenland margin).

2.1 Review of Passive Margin Architecture

2.1.1 Lower-plate and Upper-plate of an Asymmetry Conjugate Passive Margin

Lister et al. (1986) introduced the concept of upper-plate and lower-plate passive margins, as the complementary asymmetry of opposing margins after continental breakup. They concluded that symmetrical/pure shear extension proposed by McKenzine (1978) have limited applicability, while structural asymmetry may be a general feature of passive margin. The upper-plate and lower-plate margin mainly differ in their rift stage structure and in their uplift/subsidence characteristics (Figure 2.1).

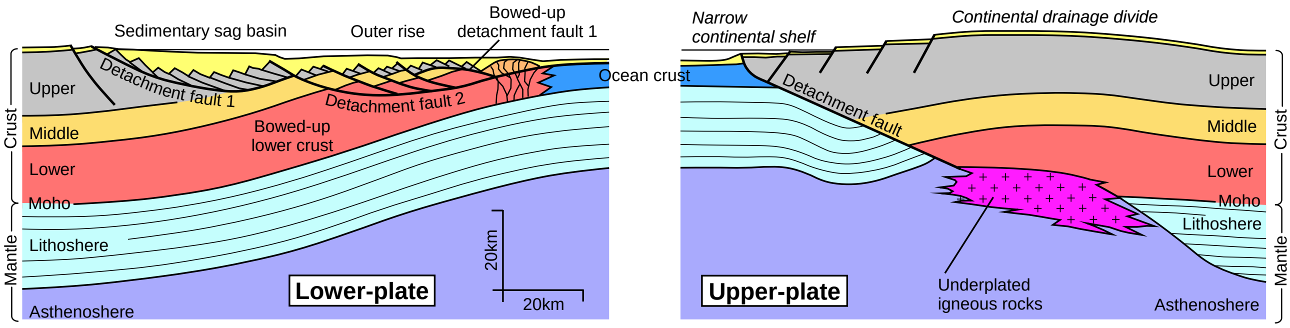

Figure 2.1 Detachment-fault model of passive continental margin. *The asymmetry passive contínetal margin in this model shows the lower-plate and upper-plate characteristics (simplified after Lister et al., 1986)*

The upper crust of a lower-plate margin is generally highly structured. It typically has rotational normal faults, detachment faults and tilt fault blocks of the rift phase of passive margin development. By contrast, the structure of an upper-plate margin is relatively simple by comparison. The upper-plate margin is characterised by graben-half graben structures and high angle normal fault which is generally only weakly rotational (Lister et al., 1986) (Figure 2.1).

The lower-plate is subjected to hyper extension meaning it experienced approximately 400% extension from its original crust length, while the upper-plate is not considered to experienced the same amount of extension. Furthermore, transfer zones offset marginal features and allow the margin to switch from the upper-plate to the lower-plate characteristics along the strike (Miller et al., 1983).

2.1.2 Rift Domain Architecture

In contrast to the model of Lister et al. (1986) model which generalized structural feature of passive margins, Pinvidic et al. (2012) proposed a distinctive division within each rift segment of passive margins. Their model mainly derived from first order structural similarity between three pairs of conjugate rift margins bordering the Atlantic Ocean: Iberia-Newfoundland, Mid Norway-Greenland, and Angola-Brazil. Furthermore, they proposed a seaward arrangement of distinct domains: proximal, necking, distal and outer, each of which exhibits distinct structural characteristics. They concluded that each domain represents a distinct stage in the evolution of the rift margin: stretching, thinning, hyper-extension and magmatic oceanization, respectively (Figure 2.2).

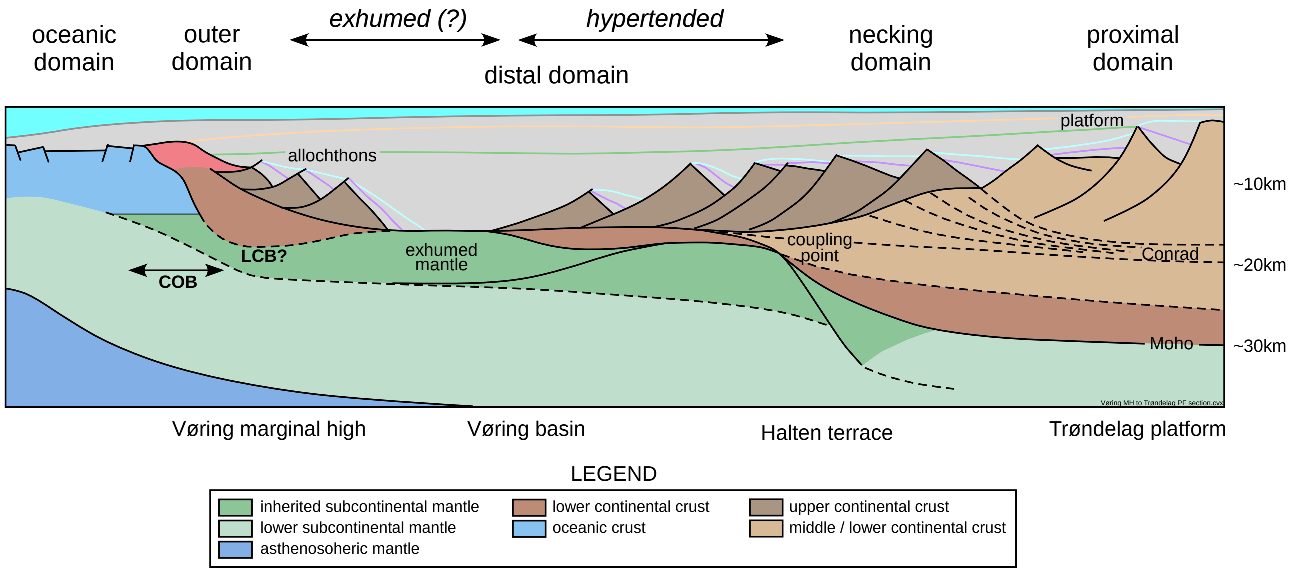

Figure 2.2 Schematic section of a typical rifted margin domain architecture. *This section represents one rift segment of a conjugate passive margin.*
The associated Mid-Norway structural elements from Trøndelag platform, Halten Terrace, Vøring Basin and Vøring Marginal High are also presented.
COB: Continent ocean boundary, LCB: Lower crustal bodies (simplified and modified after Pinvidic et al., 2012).

The proximal domain corresponds to the inboard continental crust that has been stretched at a low grade of extension and is characterised by classic graben and half-graben structures filled with wedge shape syn-tectonic sedimentary units (Figure 2.2).

The necking domain relates primarily to a specific wedge shape of the crust, where the crust experienced drastic crustal thinning from approximately 30 km to less than 10 km. It is marked by basin-ward increase in total accommodation space. It is a transition domain between the continental-ward proximal domain, where deformation is decoupled at the crustal scale, and the ocean-ward distal domain, where it is coupled and no ductile layers prevailed in the crust (Figure 2.2).

The distal domain is regularly referenced as a hyper-extended domain where the crust has been thinned down to less than 10 km. The expression of this domain within the upper crust is a sag-type basin (Figure 2.2).

The outer domain is located between the poorly-defined basement of the distal domain and the unambiguous oceanic crust. The ocean-ward limit ideally corresponds to the COB (Continent-Ocean Boundary). The continent-ward limit in some settings corresponds to the ocean-ward closure of the sag-type basin where the top basement rises. Within magma-rich margins such as Vøring margin, this domain is referred to the marginal high (e.g., Vøring Marginal High) (Figure 2.2).

The oceanic domain corresponds to oceanic crust accretion. The continent-ward limit of this domain is the Continent Ocean Boundary (COB) (Figure 2.2).

2.2 Geological Setting of Lofoten-Vesterålen Margin

The Lofoten-Vesterålen margin (LVM) is a narrow rift margin (~150 km in the south Lofoten and ~35 km in the Andøya) that has been classified as an upper-plate (non hyper-extended) margin (Faleide et al., 2008; Parry, 2012). The width of the margin is defined from the coastline to the continental slope. The LVM is bounded to the south by a lineament named Bivrost lineament (BL) which separates it from the lower-plate (hyper-extended) Vøring margin and to the north by the Senja Fault Zone (SFZ), which separates it from the Barents Sea margin. Furthermore, the LVM has been linked to its conjugate margin named the East Greenland margin (Tsikalas et al., 2001; Faleide et al., 2008; Hansen et al., 2012). The East Greenland is a wide margin (~250 km) which is situated opposite to the LVM, and was interpreted as a lower-plate margin (Parry, 2012). The rift basins of the LVM preserve mainly Mesozoic sediment (Hansen et al., 2012; Dore et al., 2012) (Figure 2.3).

The Lofoten-Vesterålen margin (LVM) comprises a series of grabens and half grabens structure striking NE-SW: Vestfjorden, Ribban, Skomvær and Kvalnesdjup, bounded by a series of complex normal fault systems and flanked by basement horsts (Utrøst ridge, Røst ridge, Lofoten ridges and the islands of Vesterålen) (Figure 2.4A). The LVM present structural configuration was closely influenced by the episodic Mesozoic rifting (Hansen et al., 2012; Dore et al., 2012).

The onshore geology of the Lofoten-Vesterålen islands is dominated by the Precambrian basement (Protorezoic to Archean) consisting of mangeritic, charnockitic and high-grade migmatic gneiss which is highly fractured (Bergh et al., 2007) (Figure 2.4B-C). The only Mesozoic outcrop found within the LVM is on northeast Andøya Island, specifically around the Ramså-Skarstein-Andenes area. The Mesozoic outcrop comprises approximately 700 m Middle Jurassic to Lower Cretaceous sequences. The existence of Mesozoic sequence within Ramså-Skarstein-Andenes was related to the opening of Triassic-Early Jurassic Andfjørden basin, east of Andøya (Dalland, 1961) (Figure 2.4C).

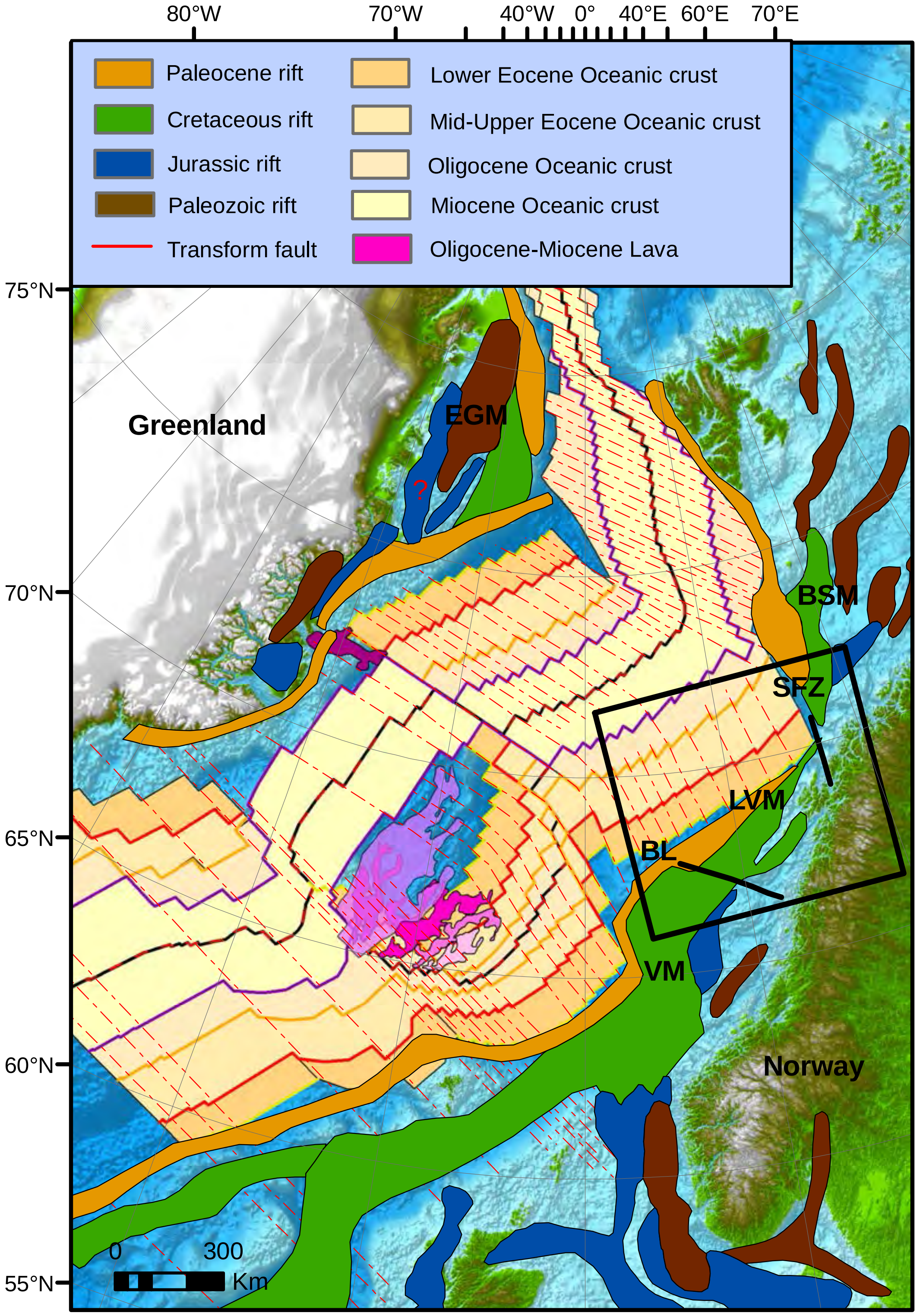

Figure 2.3 The LVM geological setting. *This map shows the setting of the LVM relative to the Norway-Greenland conjugate margins. In contrast to the upper-plate (non hyper-extended) margin, the lower-plate (hyper-extended)margin is characterized by a relative wider margin (e.g., Vøring and East Greenland margin).*
Dore et al. (2012) suggested the LVM is dominated by Cretaceous basins while the Upper Palezoic and Jurassic basin are not prominent.
The Cenozoic oceanic crust, transfrom fault and Oligocene-Miocene lava refer to Parry (2012).
MM: Møre margin, VM: Vøring margin, LVM: Lofoten-Vesterålen margin, BL: Bivrøst Lineament SFZ: Senja Fault zone, BSM: Barent Sea margin, EGM: East Greenland margin.

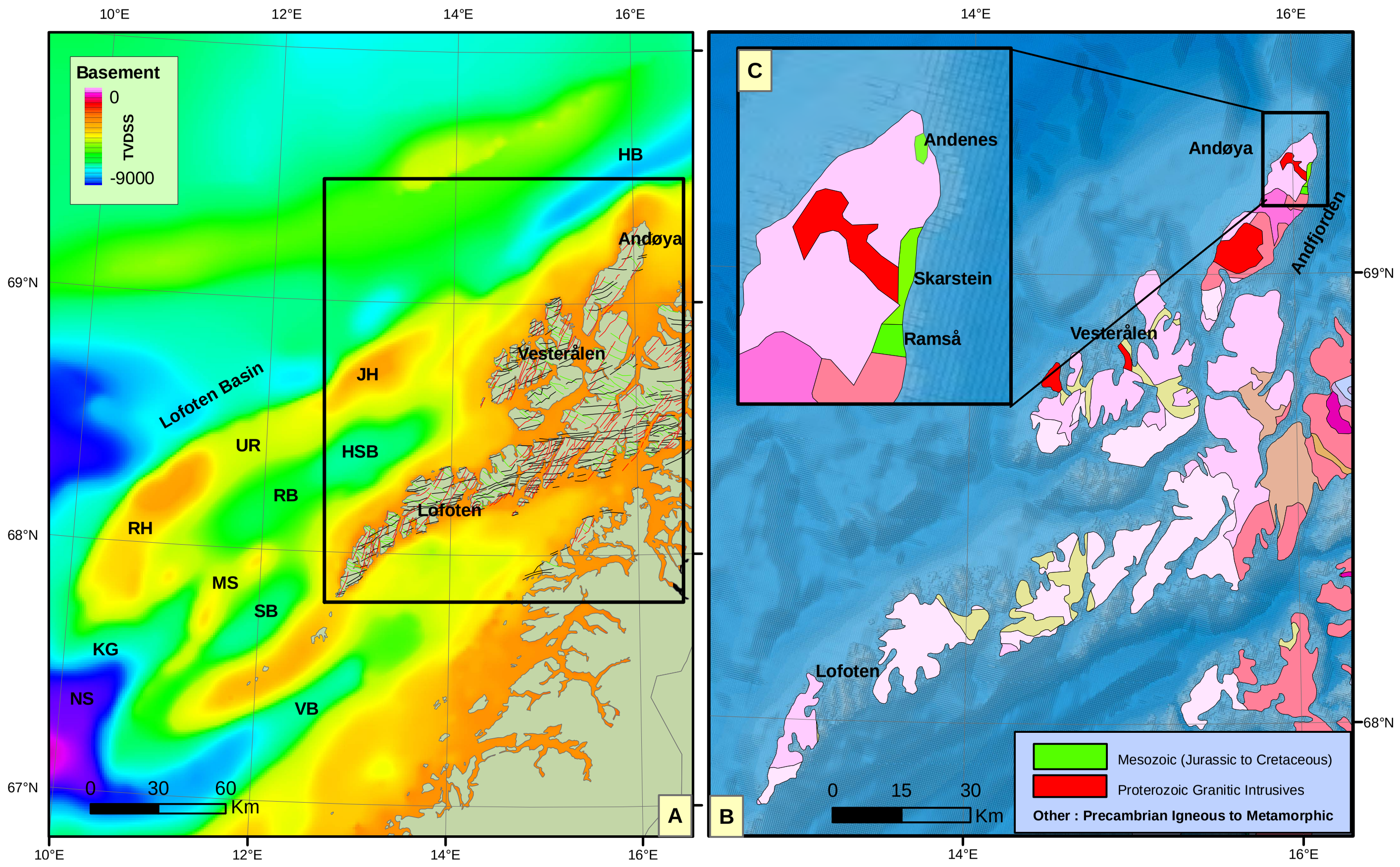

Figure 2.4 The LVM structural elements and onshore geology. *A. The NGU basement map shows a series of grabens-half grabens and basement horsts within the LVM. This map also shows the onhore lineament mapped by Bergh et al. (2007).*
UR: Ultrøst Ridge; JH: Jennengga High; RH: Røst High; RB: Ribban Basin; VB: Vestfjørden Basin; HSB: Havbåen sub Basin; MS: Marmæle Spur; SB: Skomvær sub Basin; KG: Kvalnesdjup Graben; NS: Någrind Syncline HB: Harstad Basin.

B. The LVM onshore geology shows that the Lofoten-Vesterålen onshore is dominated by the Precambrian basement.

C. The Andøya onshore geology shows the existence of Mesozoic sediment in the northeastern part of the island.

2.3 The Evolution of Lofoten-Vesterålen Margin

For the period of Meso-Archean (~2890 Ma) to present, two periods of the opening and closure of ocean basins have been documented within the Norway-Greenland continent (Henriksen and Higgins, 2008; Faleide et al., 2008; Bergh et al., 2012; Parry, 2012) (Figure 2.5).

- **Meso-Archean to Paleo-Proterozoic** (~2890 Ma - 1970 Ma). This episode is marked by the continental crust accretion/amalgamation of smaller Archean terranes that formed the earliest super-continent (Bergh et al., 2012) (Figure 2.5A).

- **Meso Proterozoic to NeoProterozoic** (~1250 Ma - ~980 Ma). This period is characterized by the continent to continent collision named Sveconorwegian orogeny, when the Baltica collided with Laurentia (Figure 2.5B).

- **Neo Proterozoic to Ordovician** (~600 Ma - ~460 Ma). This episode is represented by the rifting phase and the opening of the Iapetus Ocean. During this period, the Sveconorwegian suture zone reversed to become a detachment fault (Parry, 2012) (Figure 2.5C).

- **Ordovician to Early Devonian** (~460 Ma - ~390 Ma). During the Ordovician to Early Devonian, the second continental collision occurred (Caledonian Orogeny). This orogeny re-used the Iapetus Ocean crustal-scale detachment weakness as a suture zone (Parry, 2012) (Figure 2.5D).

- **Late Paleozoic to Late Paleocene** (~300 Ma - 55 Ma). The last episode of the margin opening within the Norway-Greenland margin occurred starting from Late Paleozoic to Early Mesozoic culminating by the opening of the North Atlantic Ocean at Eocene time (Faleide et al., 2008; Dore et al., 2012; Færseth, 2012). The margin opening occurred during a period of multi-stage rifting, followed by subsequent uplift and erosion (Hansen et al., 2012). Dore (2012) divided the margin opening into four episodes of rifting; i) Late Paleozoic-Early Mesozoic, ii) Jurassic, iii) Cretaceous and iv) Paleocene rifting. Furthermore, it was suggested that there was a change of the extension direction between Norway and Greenland. From Early Triassic to Early Cretaceous the extension direction of Norway and Greenland was oriented WNW-ESE, while during Late Cretaceous it shifted to NW-SE. The NW-SE extension lasted until the breakup of Norway-Greenland in the Eocene (Hansen et al., 2012; ConocoPhillips, 2013) (Figure 2.6).

- **Early Eocene to present** (55 Ma - 0 Ma). After the continental breakup, the Norwegian passive margin was set in to a light compressional tectonic regime due to the sea-floor spreading (Blystad et al., 1995). Another prominent geological event during this period was the glaciation. The Plio-Pleistocene glaciation was a regional event across Scandinavia, consisting of several cycles, with the last glaciation occurring at approximately 20,000 years ago. As the consequence of this glaciation, isostatic rebound caused regional uplift of the entire Scandinavia (Riis and Fjeldskaar, 1992; Fjeldskaar, 1997; Fjledskaar, 2012). There are two mechanisms for uplifting that have been identified by Fjeldskaar et al. (2012). The first mechanism is isostatic rebound due to ice melting, while the other one is isostatic rebound due to glacial erosion. Fjeldskaar et al. (2012) estimated that the amount of ice thickness within the Lofoten-Vesterålen margin (LVM) was about 600 m at 20,000 years ago (Figure 2.7A). Subsequent removal of the ice load caused isostasy uplifting of approximately 150 m during the last glaciation (Figure 2.7B). Furthermore, Fjeldskaar et al. (2012) estimated another 200 m uplifting happened within the LVM caused by isostatic rebound due to the erosion of 450 m of sediment by glacials between 3.5 Ma and 20.000 years ago (Figure 2.7C).

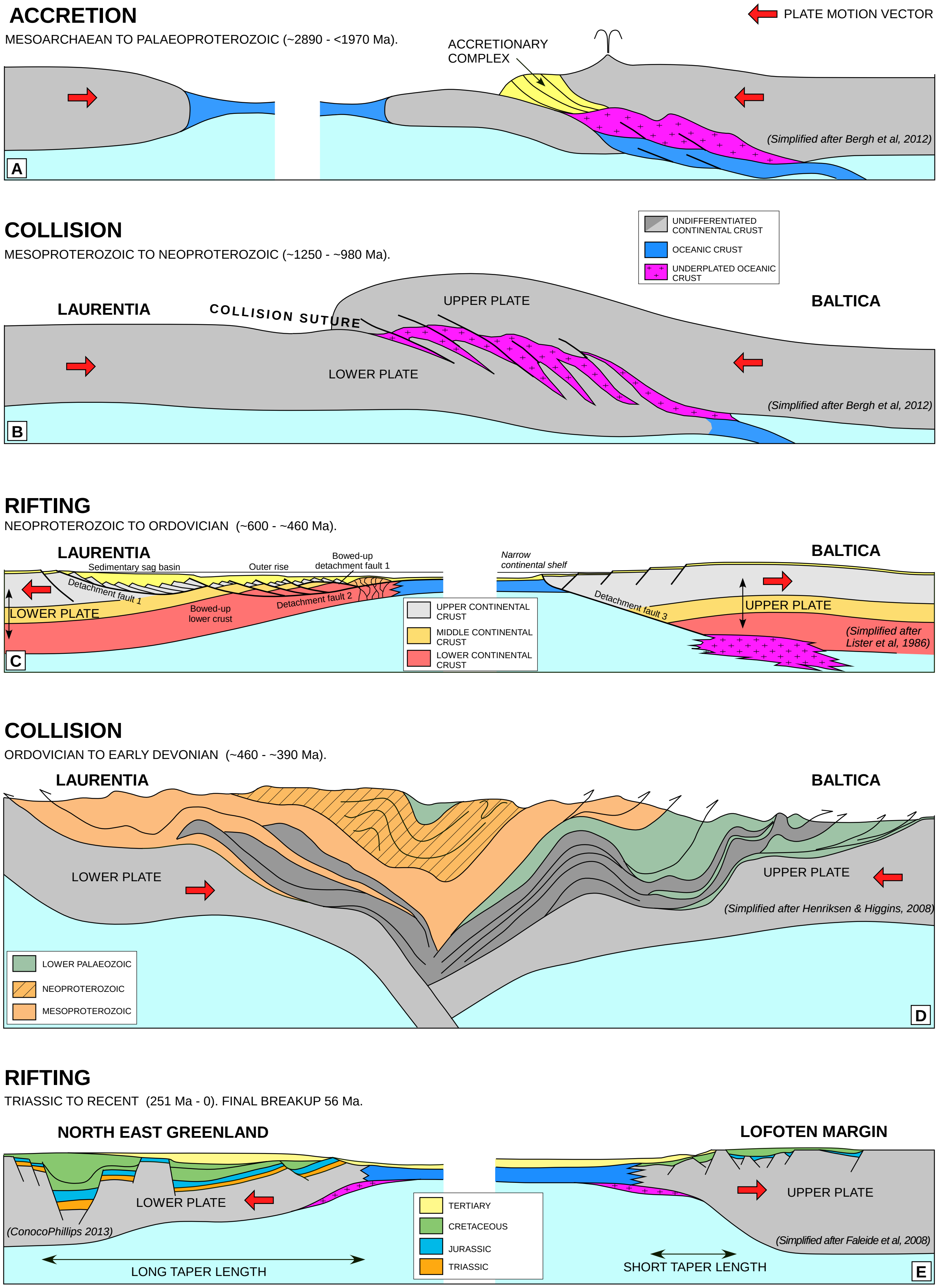

Figure 2.5 Reconstructions of the Lofoten-Greenland conjugate margin. *Wilson Cycles and Tectonic inheritance (periodic opening and closure of ocean basins) since Meso-Archean to recent (modified from Parry, 2012).*

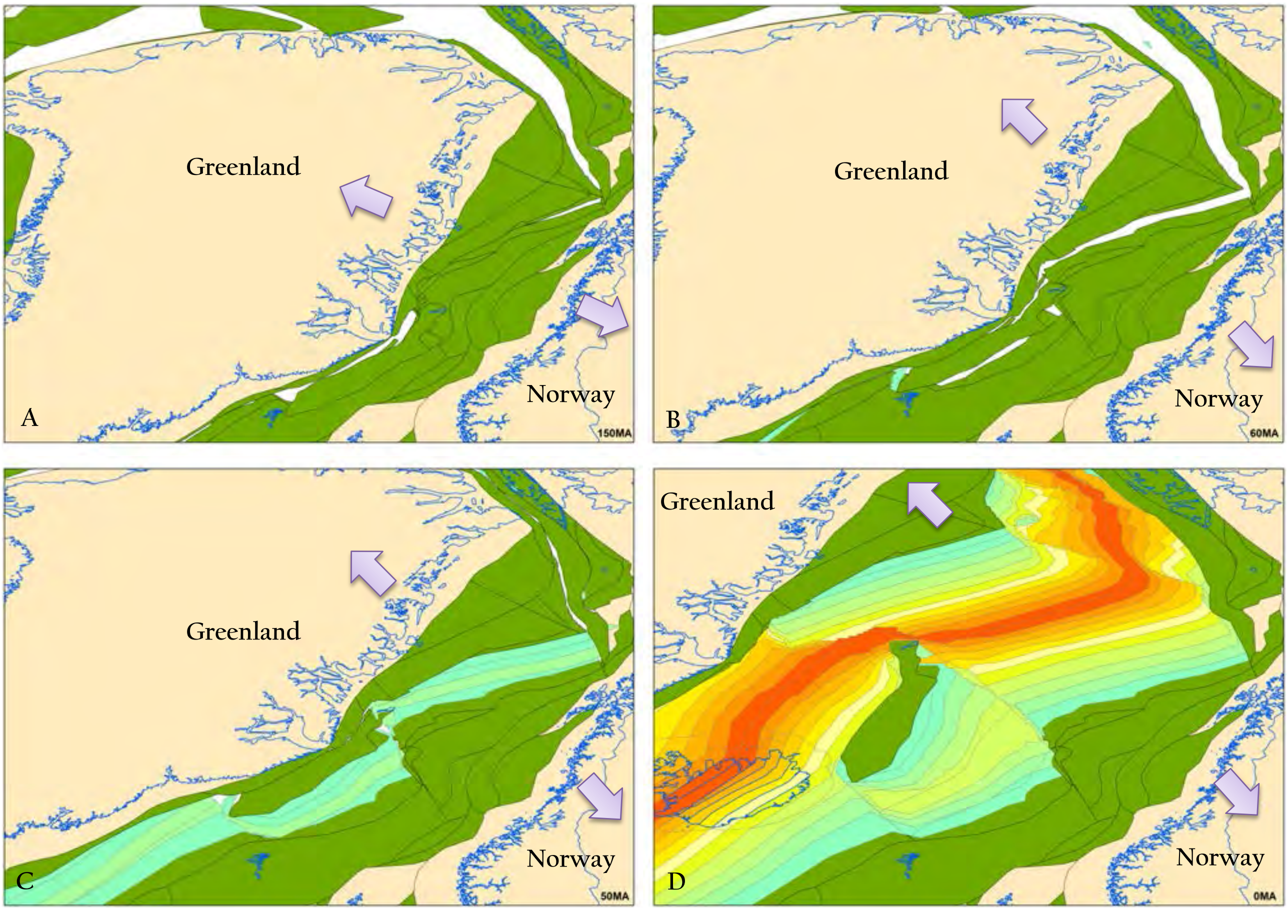

Figure 2.6 Norway-Greenland plate reconstruction 150Ma-present. *A). Plate Reconstruction back to 150Ma B). 60Ma C). 50Ma D). present.*
The plate reconstruction shows the separation of Norway-Greenland continent culminating with the continental break up in Early Eocene (50Ma, Figure C).
The plate wizard model used in this reconstruction originally developed by Fugro Roberston and further modified by ConocoPhillips (2012).

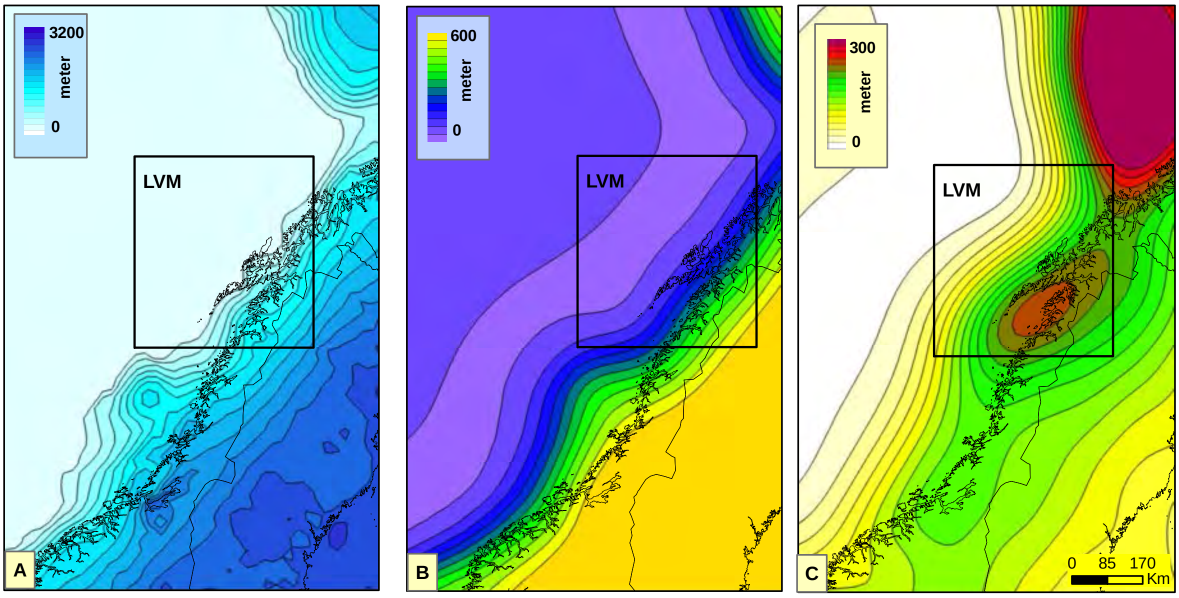

Figure 2.7 Plio-Pleistocene glacial. *A). Ice thickness during the last glaciation (20.000 years ago) B). Isostacy uplift caused by ice melting C). Isostacy uplift caused by glacial erosion (Fjeldskaar, 2012)*

3 Data and Methodology

Database

In order to achieve the objective of this study, several subsurface and surface data are used, which are summarized as follows:

Wells and Outcrop data

The wells and outcrop data used in this study mainly consist of (Figure 3.1):

- Two Exploration wells: 6710/10-1 and 7019/1-1.
- Five IKU shallow wells: 6711/04-U-01, 6710/03-U-01, 6710/03-U-03, 6814/04-U-02 and 6811/04-U-01
- One onshore outcrop within northeast Andøya which refer to Dalland (1981) and Hansen et al. (2012)

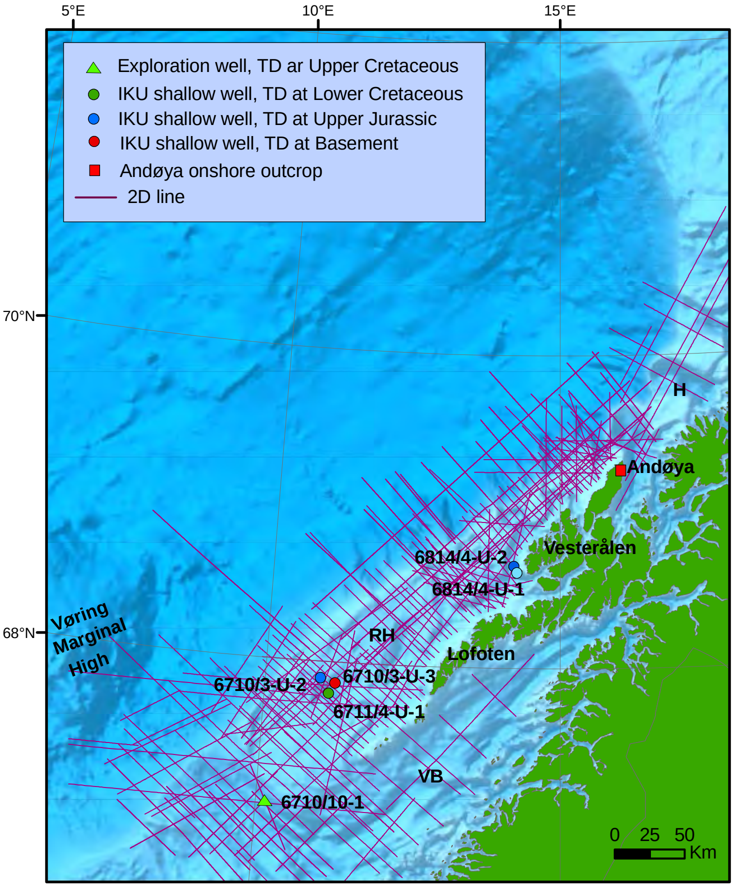

Figure 3.1 Basemap of well and seismic data. *RH:Røst high; VB:Vestfjørden basin; HB: Harstad basin*

2D seismic data

The seismic data set includes 10,000 kms of 2D multi-channel seismic which were chosen as the basis for this study. The 2D seismic data used in this study generally consist of three main vintages (Figure 3.1)

- Publically available heritage data acquired by several different companies from 1974-1998.
- A subset of the above data that was reprocessed in 2000. The reprocessing was subjected to eliminate the multiples reflections (Water bottom, Peg-leg and Inter-bedded multiple) by employing several seismic processing modules such as: SRME (Surface related multiple attenuation) and Radon de-multiple.
- Recent Norwegian Petroleum Directorate (NPD) data acquired in 2007 and 2008, which then partially reprocessed from 2008-2012.

The average spacing between the seismic lines is about 5 km. The seismic data quality is moderate to good except below the basalt covered areas where the top of the basalt has reflected most of the seismic energy, with limited energy transmitted through. The 2D seismic data extends to a depth of 7-8 s TWT which is sufficient to identify the top basement reflection.

Gravity and magnetic data

The gravity and magnetic data available from ConocoPhillips Norge database are employed in order to delineate the margin morphology as well as to identify and trace structural lineaments. Both gravity and magnetic data were processed by ConocoPhillips technology centre, in Houston, USA.

The magnetic data used in this study has been corrected to the Earth's inclined magnetic field. The correction applied to the magnetic data to correct the anomalies such that the anomalies appear over their source bodies, without any inclination (Figure 3.2B).

The Bougeur gravity used in this study is also subjected to a correction. The correction is employed in order to remove the thermal related anomaly caused by the variation in

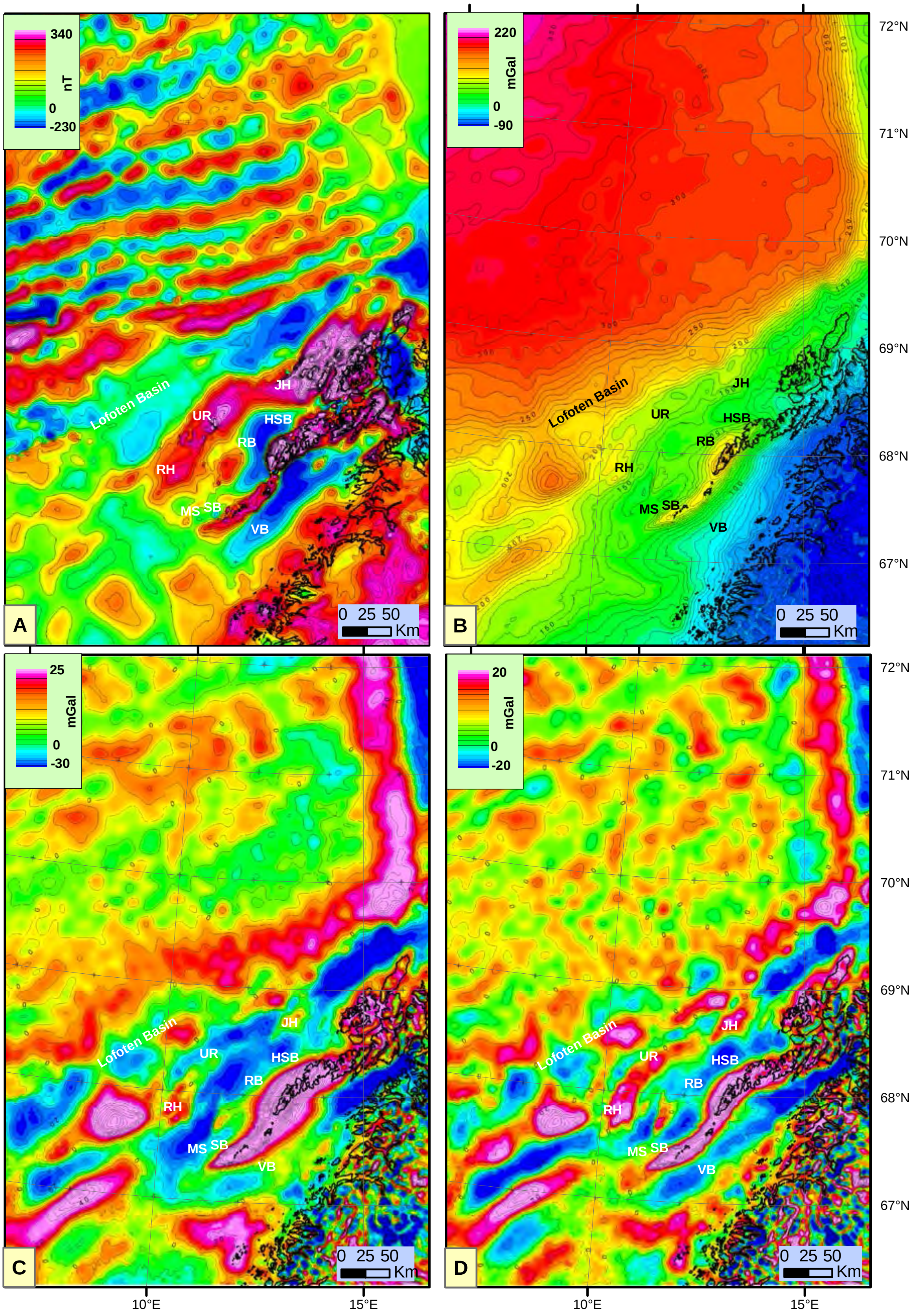

Figure 3.2 Potential data. *A: Magnetic anomaly*
B: Thermal corrected Bougeur anomaly
C: 200km high pass filter Bougeur Gravity anomaly
D: 100 km high pass filter Bougeur Gravity anomaly

UR: Ultrøst Ridge; JH: Jennengga High; RH: Røst High; RB: Ribban Basin; VB: Vestfjørden Basin; HSB: Havbåen sub Basin; MS: Marmæle Spur; SB: Skomvær sub Basin. All of magnetic and gravity datas refer to Flanagan (2013).

temperature between the hot oceanic-rifted continental margin with the cool un-stretched lithosphere (Greenhalgh and Kusznir, 2006). The Bougeur correction used a correction density of 2.20 g/cm^3 offshore and 2.67 g/cm^3 onshore (Figure 3.2A).

Finally, 100 km high pass filter and 200 km high pass filter thermal corrected Bougeur Gravity data were incorporated in this study, in order to highlight more local anomalies that may be associated with structure at the basement surface or within the sedimentary section (Figure 3.2C-D).

Methodology

All of the available well data (exploration and IKU shallow wells) were tied to the seismic using available time depth data (check shot or VSP) in order to constraint the seismic reflectors. The following key seismic horizons were interpreted on all chosen 2D lines: top basement (TB), Base Jurassic Unconformity (BJU), Base Cretaceous Unconformity (BCU), Base Lower Cretaceous, Base Cenozoic and Base Quaternary. The seismic interpretation was integrated with the available gravity-magnetic data to better constrain the margin structural morphology.

In order to investigate the evolution of structural pattern of the LVM through time, a structural restoration was carried out. The structural restoration mainly was used to validate the seismic interpretation and thus better allow a comparison between different geological structure within the LVM. The vertical shear methods of Gibbs (1983, 1984) was used for the structural restoration by employing the GLS Lithotect software.

4 Subsurface Geology of the Lofoten-Vesterålen Margin based on Seismic, Well and Potential Field data

4.1 Geologic Province of the Lofoten-Vesterålen Margin

South Lofoten Province

The South Lofoten province of the Lofoten-Vesterålen margin is characterized by the graben-half graben structures named: Vestfjorden Basin, Skomvær sub Basin, Ribban Basin, Kvalnesdjups Graben and Lofoten Basin. These structures are bounded by the structural highs named: Røst High and Lofoten Ridge. The width and shape of the graben-half graben is varying along the strike of the South Lofoten province (Figure 4.1).

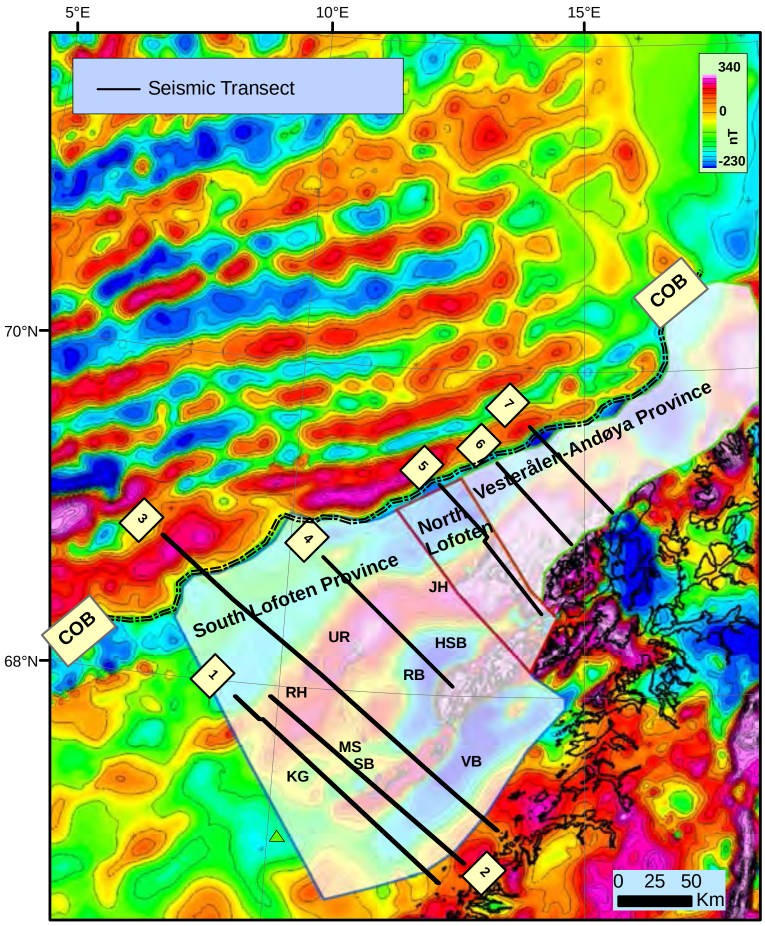

Figure 4.1 Basemap of seismic transect. *The seismic transect is presented with the Magnetic map in order to show the structural elements across the margin.*

UR: Ultrøst Ridge; JH: Jennengga High; RH: Røst High; RB: Ribban Basin; VB: Vestfjørden Basin; HSB: Havbåen sub Basin; MS: Marmæle Spur; SB: Skomvær sub Basin; KG: Kvalnesdjup Graben;

The graben-half graben structures within the shelf area of the South Lofoten province is closely controlled by the planar normal faults. No prominent fault rotation was observed. Seismic interpretation revealed these planar normal faults consist of two main faults: the Triassic-Jurassic normal faults and the Early Cretaceous faults. Generally, the Triassic-Jurassic faults is dipping to the East, in contrast, the Early Cretaceous faults is dipping to the West (Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5).

The slope area of the South Lofoten province is characterized by a different style of faulting. This fault system bound the Røst High to the deep Lofoten Basin. A series of high-dip Lower Cretaceous seismic reflectors within these faults block indicating that these fault blocks experienced rotation during the faulting. In general, this fault system are dipping to the West, they are basement involved meaning that it is a thick skinned deformation and they are down throwing the basement to the deep Lofoten Basin (Figure 4.2 - Figure 4.5).

The deep Lofoten Basin within the South Lofoten province is marked by a distinct high reflector body on-lapping to the Early Cretaceous fault blocks, interpreted as the basalt. This basalt has been dated as Early Eocene (Tsikalas et al., 2001) (Figure 4.2 - Figure 4.5). No distinct geological feature was observed below the top Basalt reflection. Furthermore, an integrated observation of seismic transect-4 and the Magnetic data revealed the transition of the crust within the Lofoten Basin, from the continental crust to the oceanic crust. The crust transition which named as Continent Ocean Boundary (COB) is characterized by an abrupt change of the magnetic anomaly from relative low magnetic (deep and old continental crust) to very high magnetic anomaly (young oceanic crust) (Figure 4.1 and Figure 4.4).

North Lofoten Province

The North Lofoten province of the Lofoten-Vesterålen margin is marked by the Lofoten ridge, Havbåen sub-Basin, Jennegga high and Lofoten Basin, respectively from the coastline to the deep North Atlantic ocean (Figure 4.1 and Figure 4.6). Identical to the South Lofoten province, the shelf area within the North Lofoten province is characterized by the half graben structures which are controlled by the planar normal faults. However, the Early Cretaceous faults within this province shows different characteristic to the South Lofoten province. In this province, the Early Cretaceous faults are mainly dipping to the East.

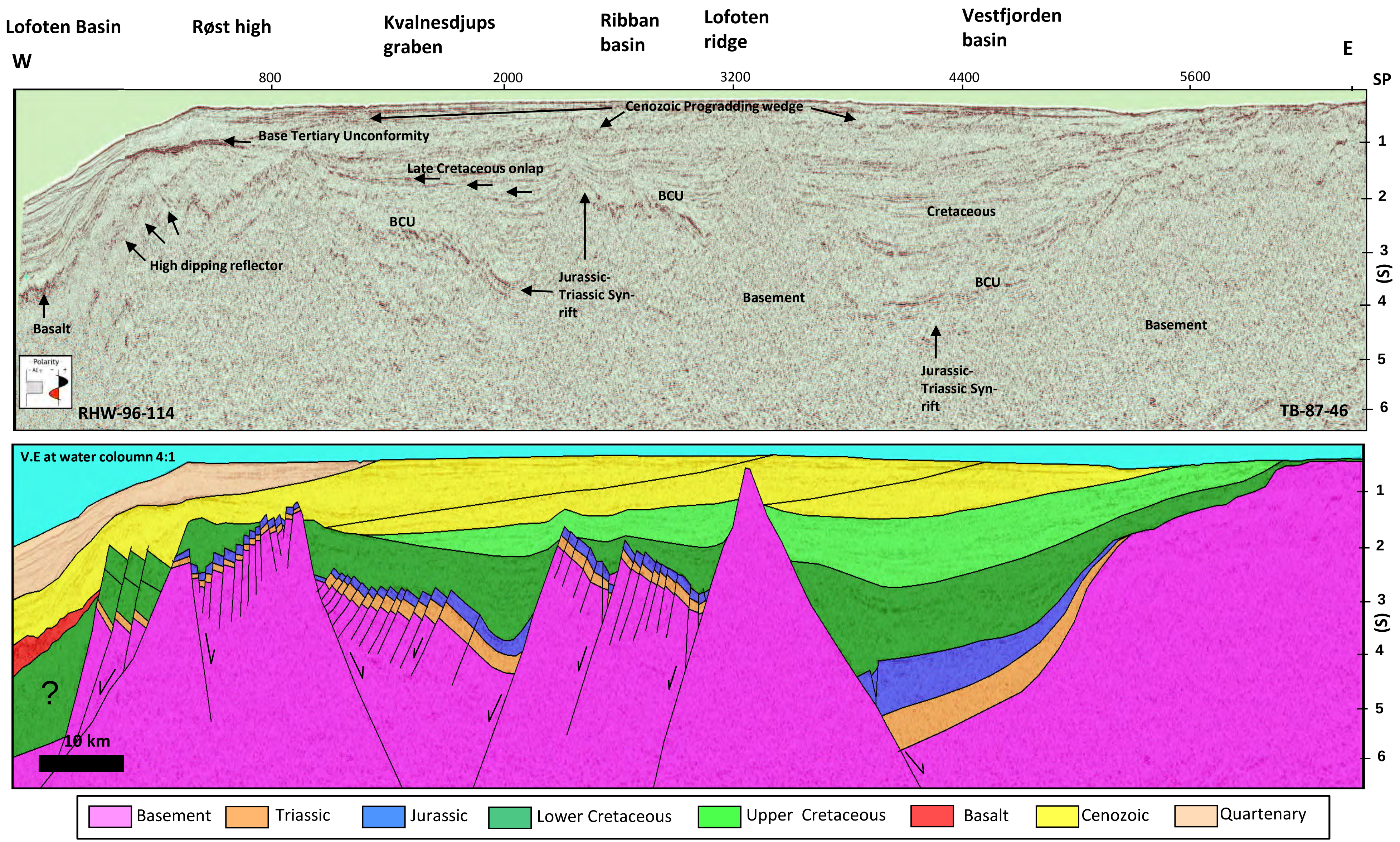

Figure 4.2 Seismic transect-1. *This seismic transect is the southernmost seismic transect located at the south Lofoten province. The shelf are is characterized by graben-half graben structures, while the slope area is marked by a series of rotated fault blocks detach to a border fault.*

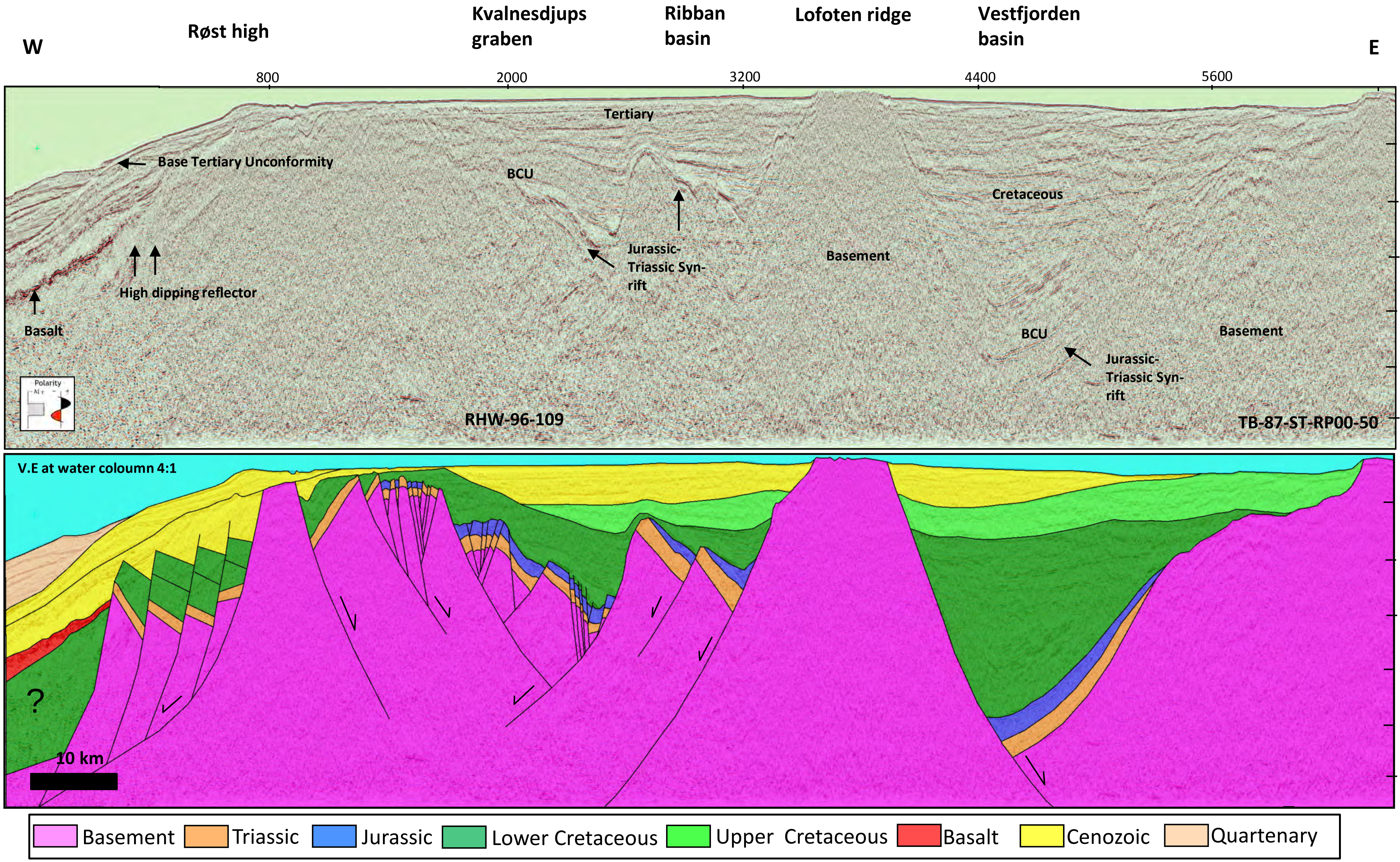

Figure 4.3 Seismic transect-2. *This seismic transect is located at the south Lofoten province. The structural style within this area is identical to seismic transect-1: the shelf are is characterized by graben-half graben structures, while the slope area is marked by a series of rotated fault blocks detach to a border fault.*

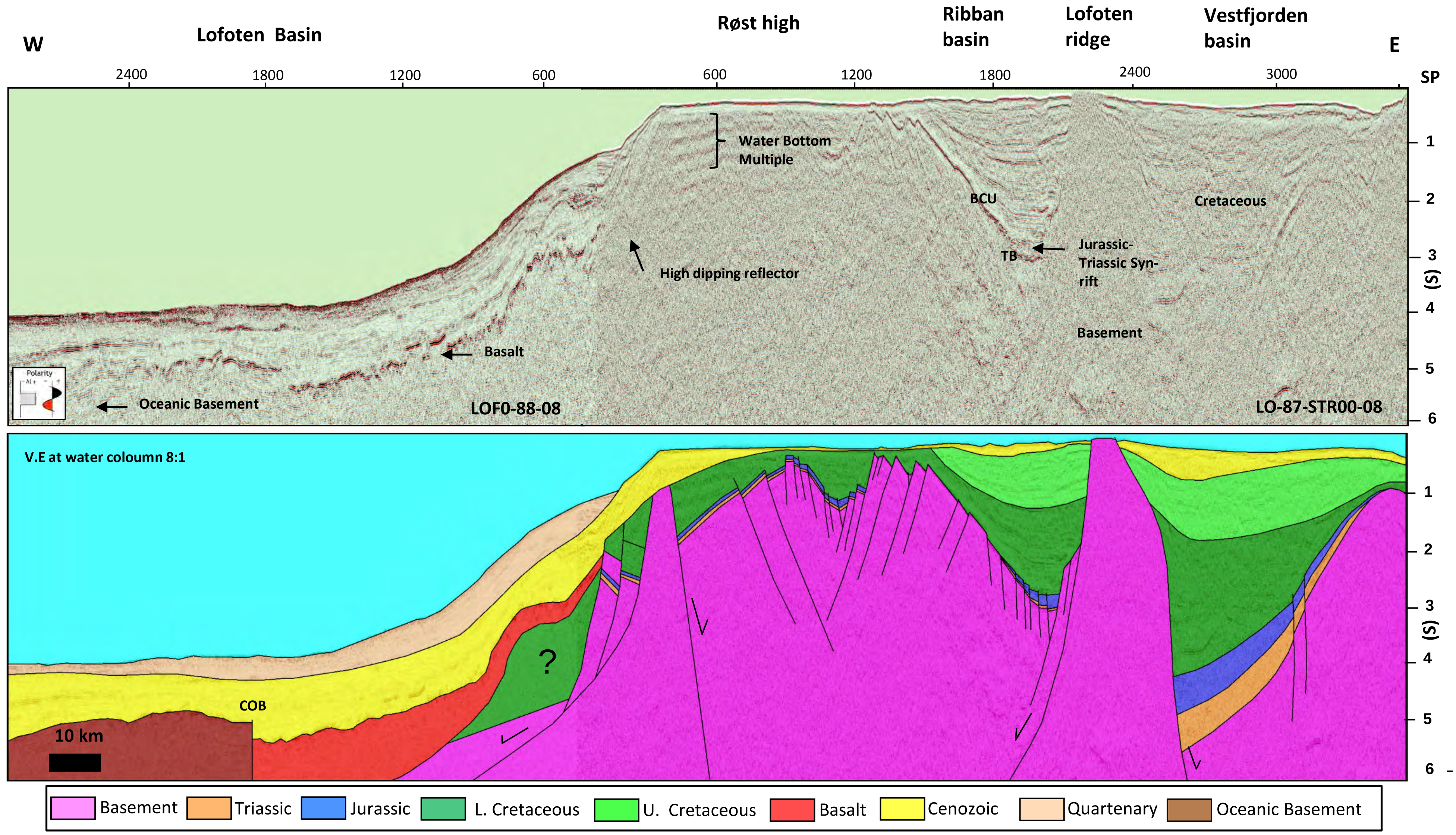

Figure 4.4 Seismic transect-3. *This seismic transect is located at the central part of the south Lofoten province. Notice the transition of the crust from continent to oceanic revealed by this seismic transect.*

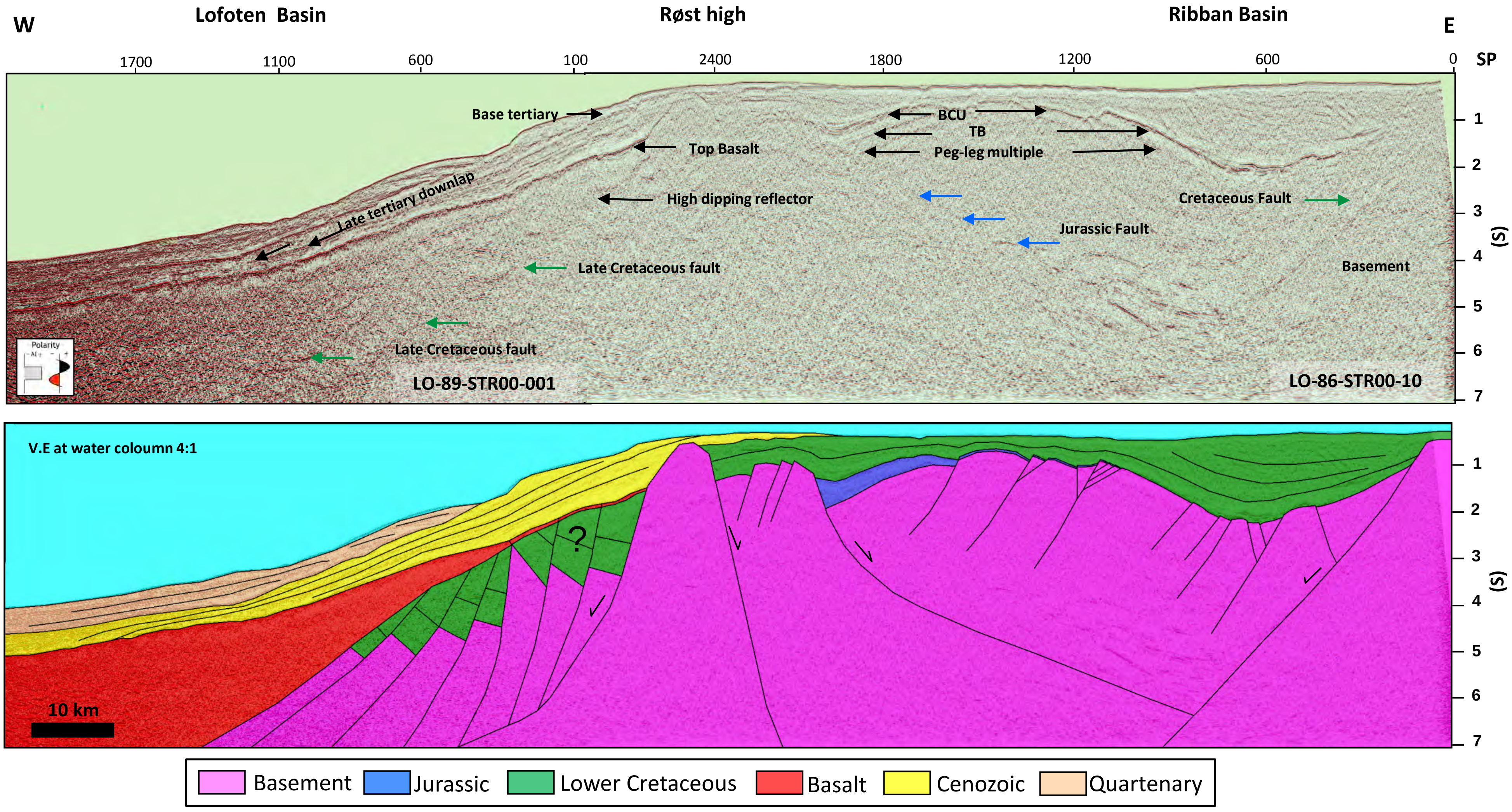

Figure 4.5 Seismic transect-4. *This seismic transect is located at the northernmost of south Lofoten province. Notice the absence of the Late Cretaceous sequence within this seismic transect.*

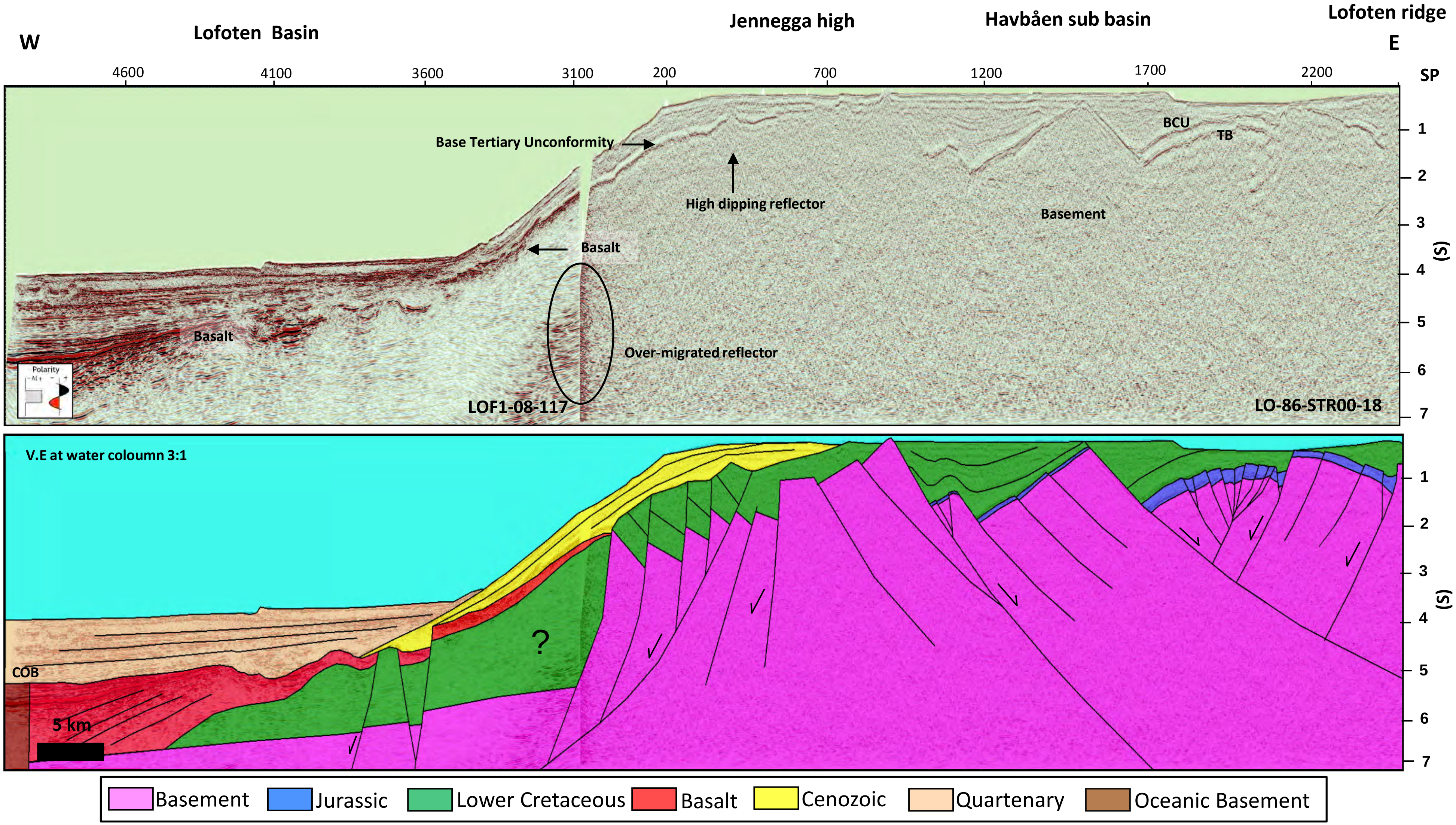

Figure 4.6 Seismic transect-5. *This seismic transect is located at the north Lofoten province. The Early Cretaceous faults in this seismic transect is generally dipping to the east, which is the opposite polarity to the equivalent structures in the south Lofoten province.*

The slope and the deep basin area of the North Lofoten province shows identical characteristic with the South Lofoten province. The slope area is characterized by the rotated Early Cretaceous faults which mainly dipping to the west, while the deep basin is represented by the Basalt and the Continent Ocean Boundary (Figure 4.6).

The Vesterålen-Andøya province

The Vesterålen-Andøya province is mainly marked by the extension of the Jennengga High stucture to the north (Figure 4.1). Fundamentally, a unique type of structural style occurs within this province. The shelf to slope area is characterized by the Jurassic and the Late Cretaceous-Early Cenozoic fault decoupling. This type of structure has not been observed within the South and North Lofoten provinces (Figure 4.7 and Figure 4.8).

Within the fault decoupling system, a series of Jurassic normal faults were observed dipping to the East in the Vesterålen-Andøya province. Remarkably, these normal faults appear to have a different geometry to the typical normal faults observed in the South and North Lofoten provinces (Figure 4.2 - Figure 4.6). These Jurassic faults appear to be planar but they have a low dip angle.

The low dip angle of the Jurassic normal faults within the Vesterålen-Andøya province is interpreted cause by the fault rotation after the faulting happen. Seismic interpretation revealed that the Jurasssic fault rotation was only occurred within the Vesterålen-Andøya province and they were progressively developed, starting from the southernmost of the Vesterålen-Andøya province to the northernmost of the province. In contrast, no indication of the Jurassic faults rotation observed within the South and North Lofoten province (Figure 4.9).

Within the same fault decoupling system, the Late Cretaceous-Early Cenozoic faults were observed detaching on the Lower Cretaceous sequence. These faults are dipping to the west, they appears to experienced rotation, and they are suggested to detach to a sub horizontal detachment zone. These observation led for the present of a thin-skinned deformation within the Vesterålen-Andøya province.

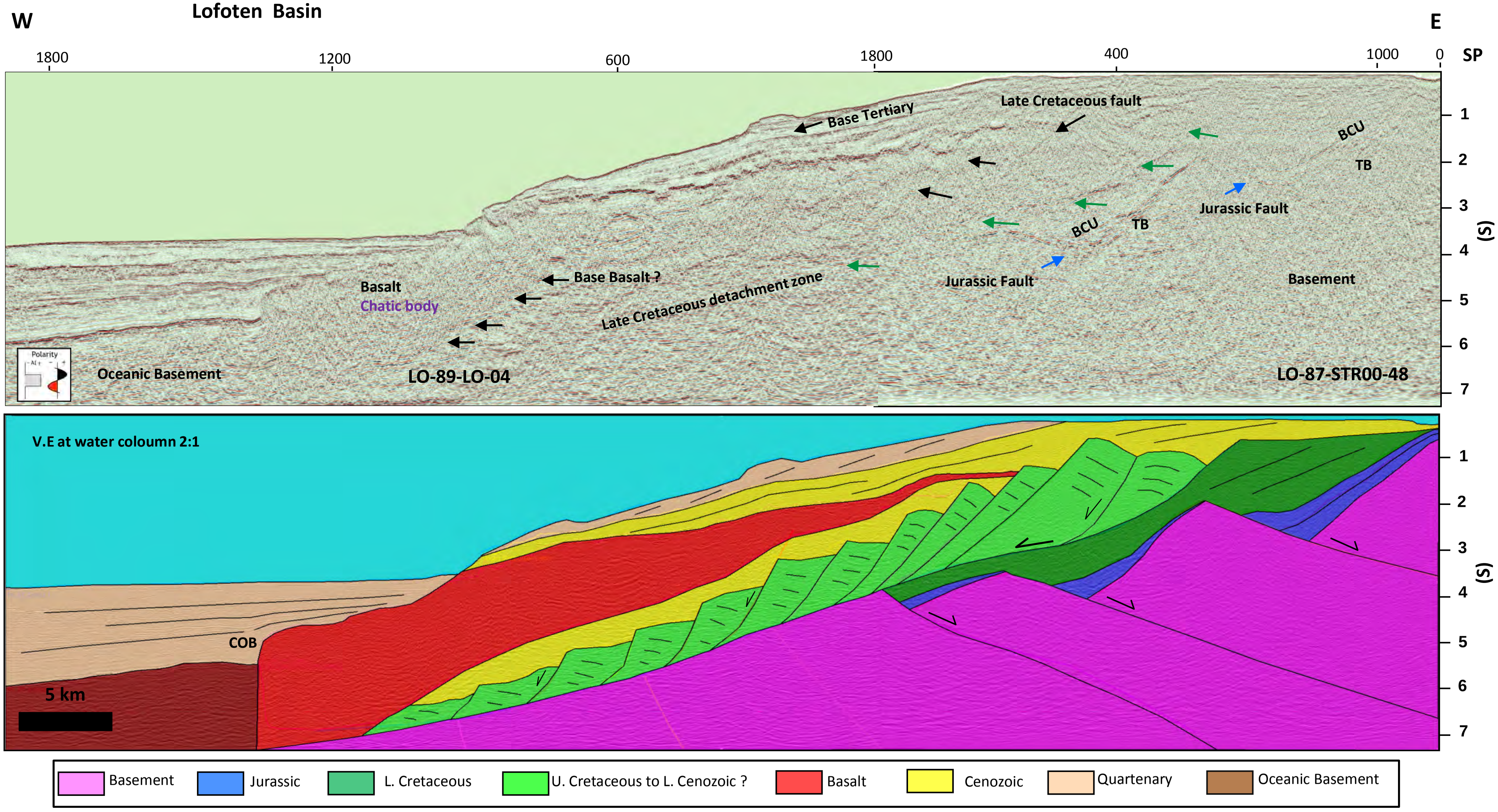

Figure 4.7 Seismic transect-6. *This seismic transect is located at the offshore Vesterålen. Jurassic and Late Cretaceous-Early Cenozoic fault decoupling is suggested as the main structural feature within this seismic transect.*

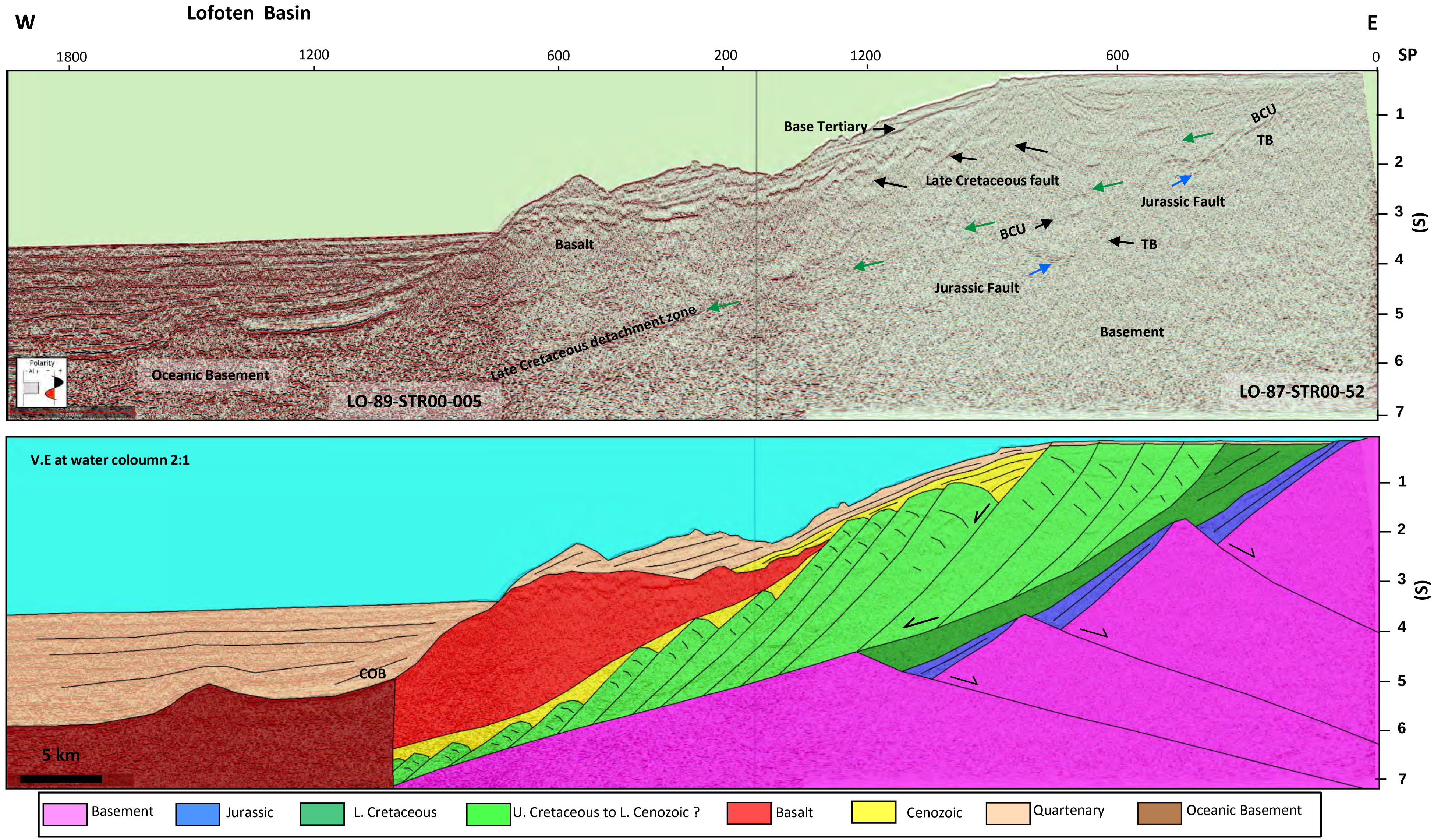

Figure 4.8 Seismic transect-7. *This seismic transect is located at the offshore Andøya. Identical to the seismic transect-6, the Jurassic and Late Cretaceous-Early Cenozoic fault decoupling is observed within this seismic transect.*

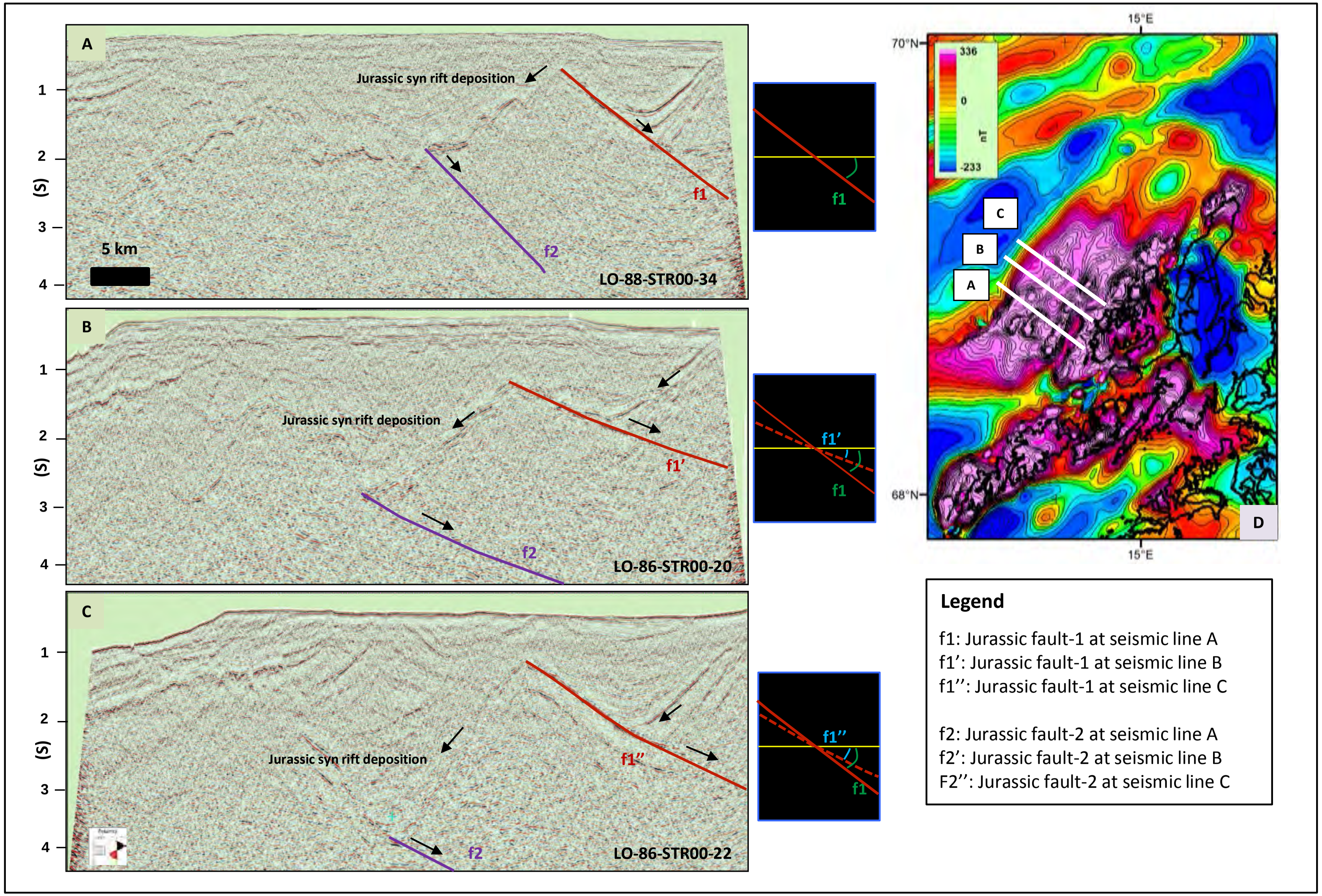

Figure 4.9 Progressive Jurassic fault rotation - South Vesterålen. *Seismic line A is located in the North Lofoten province while the seismic line B-C are located in the Vesterålen-Andøya province.*
These seismic line show a progressive development the Jurassic faults rotation. The seismic line A shows the Jurassic fault-1 has high angle indicating it did not experience any rotation, while within seismic line B and seismic line C the Jurassic fault-1 has low angle which indicates the fault rotation.

Identical to the South and North Lofoten provinces, the deep Lofoten Basin within the Vesterålen-Andøya province is marked by the presence of the basalt on-lapping to the Late Cretaceous-Early Cenozoic fault blocks and also characterized by the transition to the oceanic crust named Continent Ocean Boundary (COB).

4.2 Structural Restoration of the North Lofoten and the Vesterålen-Andøya Province

Seismic interpretation reveals the abrupt change of structural style in between the north Lofoten province and Vesterålen-Andøya province. The north Lofoten province is characterized by east-dipping Jurassic and Cretaceous faults (Figure 4.6) while the Vesterålen-Andøya province is marked by the Jurassic and Late Cretaceous-Early Cenozoic faults decoupling (Figure 4.7 and Figure 4.8). The Jurassic faults in Vesterålen-Andøya province are dipping to the east while the Late Cretaceous-Early Cenozoic fault detachment are dipping to the west (Figure 4.7 and Figure 4.8).

In order to define the ancient structural style of the North Lofoten province and the Vesterålen-Andøya province within Pre-Late Cretaceous, structural restorations were carried out. The restorations are carried for one of seismic transect within the North Lofoten province also for one seismic transect within the Vesterålen-Andøya province. The structural restorations were performed based on the vertical shear of Gibbs (1983, 1984) methods using the GLS Lithotect software (Figure 4.10 and Figure 4.11).

The structural restoration to the Base Cretaceous Unconformity for both of the seismic transects revealed the similarity of the structural style between the North Lofoten province and the Vesterålen-Andøya province within Pre-Late Cretaceous. Both of the provinces show graben-half graben structures which are controlled by the East-dipping normal faults, although the density of the faulting is different. This observation suggest the same type of deformation occurred within the North Lofoten province and the Vesterålen-Andøya Pre-Late Cretaceous, while Post-Late Cretaceous, each of province experienced different type of deformations (Figure 4.10 and Figure 4.11). Furthermore, the structural restoration also suggest that the Jurassic normal faults within the Vesterålen-Andøya province were originally high angle, then, due to the fault rotation, they were reformed to be low angle.

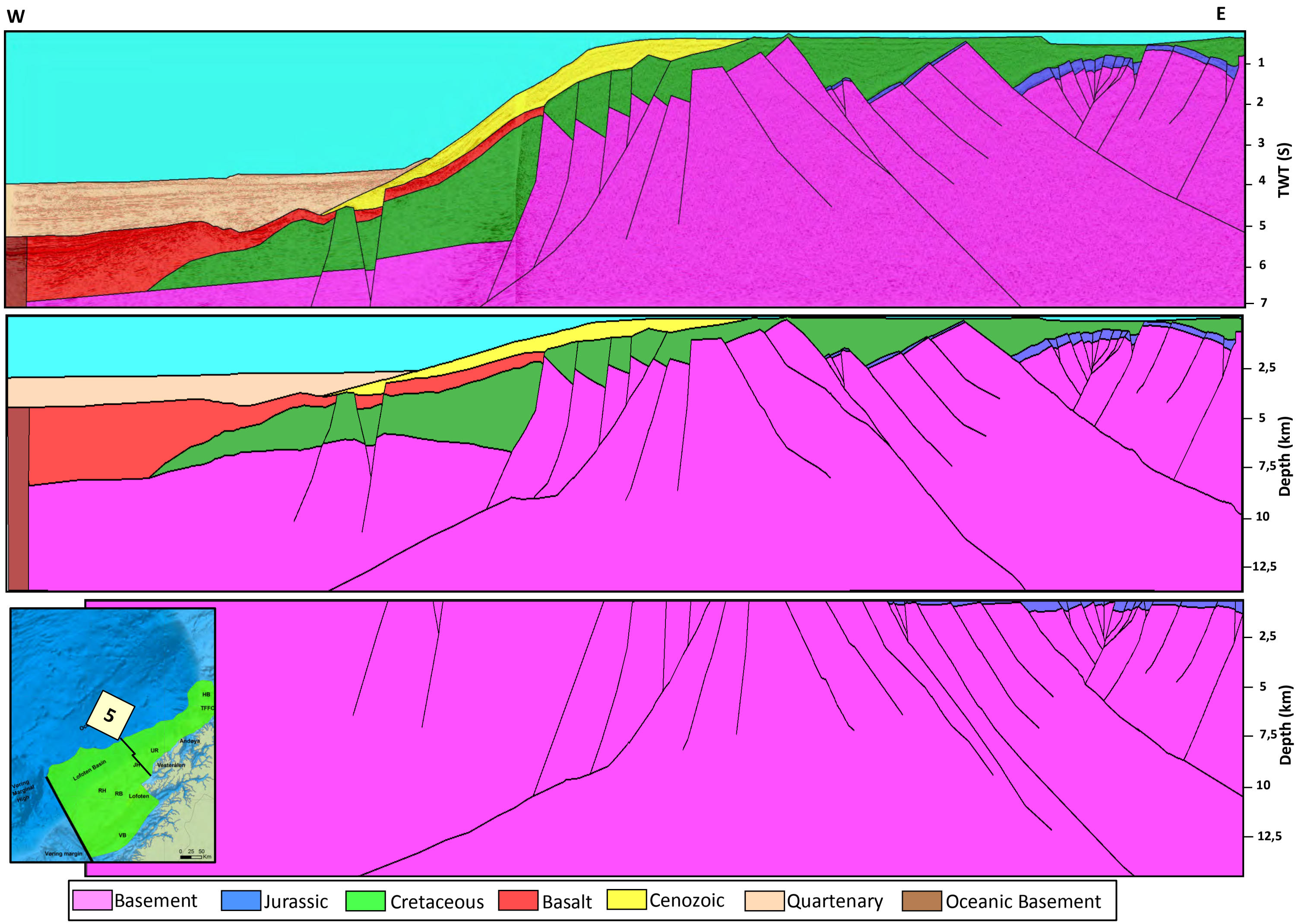

Figure 4.10 Vertical shear fault restoration of an interpreted seismic transect-5. *A) Interpeted seismic transect-5 in time domain B) Interpreted seismic transect-5 in depth domain C) BCU (Base Cretaceous Unconformity) restoration shows the ancient structural style of the North Lofoten province within Pre-Late Cretaceous.*

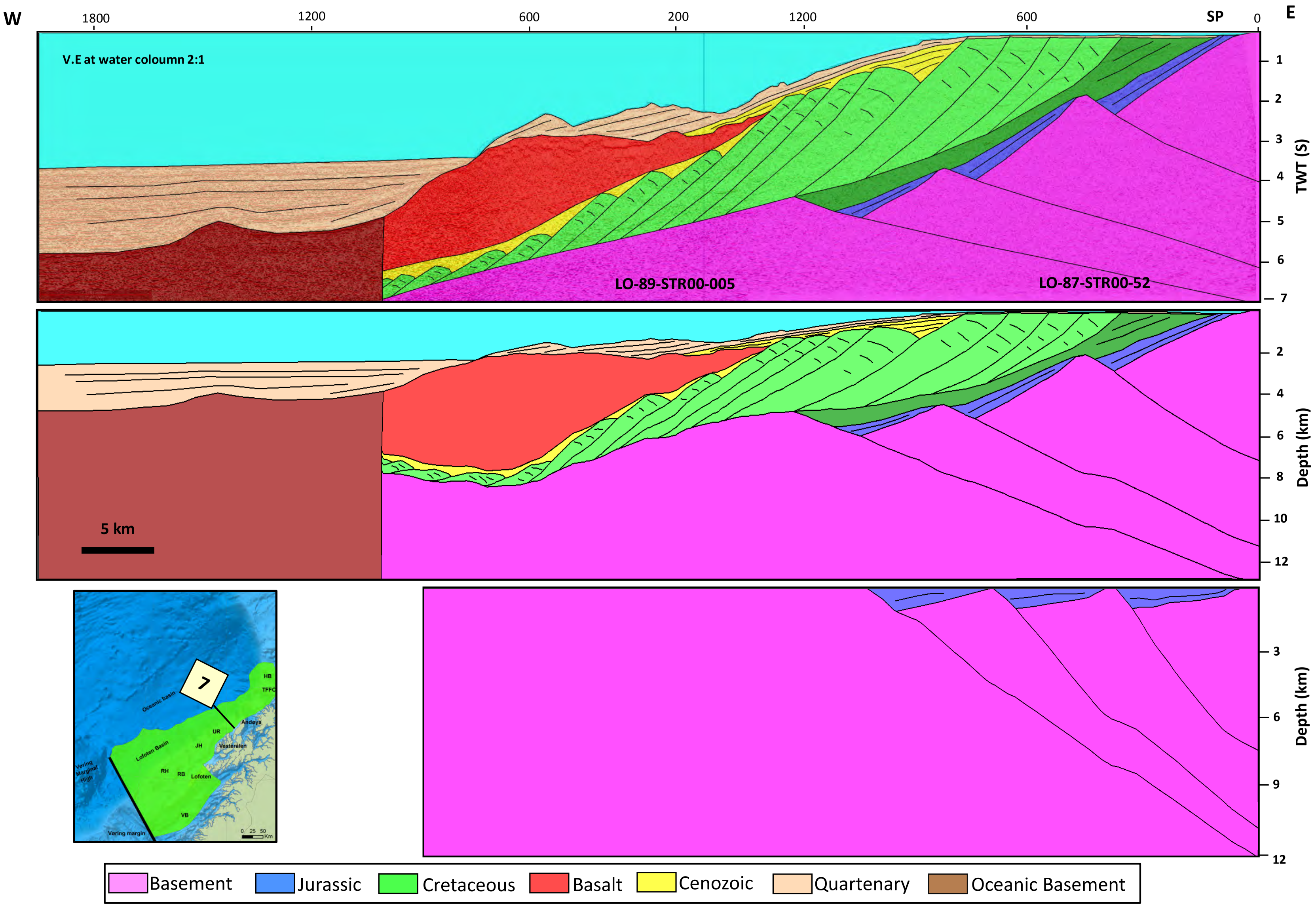

Figure 4.11 Vertical shear fault restoration of an interpreted seismic transect-7. *A) Interpeted seismic transect-7 in time domain B) Interpreted seismic transect-7 in depth domain C) BCU (Base Cretaceous Unconformity) restoration shows the ancient stuctural style of the Vesterålen-Andøya province within Pre-Late Cretaceous.*

4.3 Tectono-stratigraphic Development of Lofoten-Vesterålen Margin

Six distinct, Triassic to recent sequences overlie the Precambrian basement are observed within the Lofoten-Vesterålen margin (LVM). The understanding of the development of these sequences is based on seismic interpretation which constrained by the available well data across the margin (Figure 3.1 and Figure 4.12).

Precambrian basement

In the south Lofoten province, IKU well 6710/03-U-03 confirmed the presence of the Precambrian basement consisting of gneiss rock. Based on core description in IKU well 6710/03-U-03, no indication of weathering is observed experienced by this rock (Hansen et al., 2012). In contrast, the Precambrian basement found in the north Lofoten and Vesterålen province shows indication of weathering (Hansen et al., 2012) (Figure 4.12). Within the seismic data, the top Precambrian basement is characterized by high positive seismic reflector, while the basement body is defined by the chaotic internal configuration (Figure 4.2-Figure 4.8).

Triassic

The Triassic sequence has been suggested as the oldest sedimentary sequence penetrated by the available wells in south Lofoten province (e.g IKU well 6710/03-U-03) (Figure 4.12) (Hansen et al., 2012). It consists of conglomerate and sandstone sequence which interpreted as a proximal alluvial fan deposits (Hansen et al. 2012) (Figure 4.12). On the shelf area of the South Lofoten province, thin Triassic sequence (~ 0,25 seconds TWT) is observed lies on the top of the Precambrian basement (Figure 4.2-Figure 4.5). Seismic interpretation revealed that the Triassic sequence is thinning out toward the continental slope to the west, and also toward the northern part of the South Lofoten province. Due to the homogen thickness of the Triassic sequence within the south Lofoten province, it leads for indication of pre-rift stage or marginal rifting event within Triassic (Figure 4.2-Figure 4.5). The only area indicates the presence of syn-tectonic deposition during Triassic is at the Vestfjorden Basin (Figure 4.2-Figure 4.4). In contrast to the south Lofoten province, in north Lofoten and Vesterålen-Andøya province, Triassic sequence is absent (Figure 4.12 and Figure 4.6-Figure 4.8).

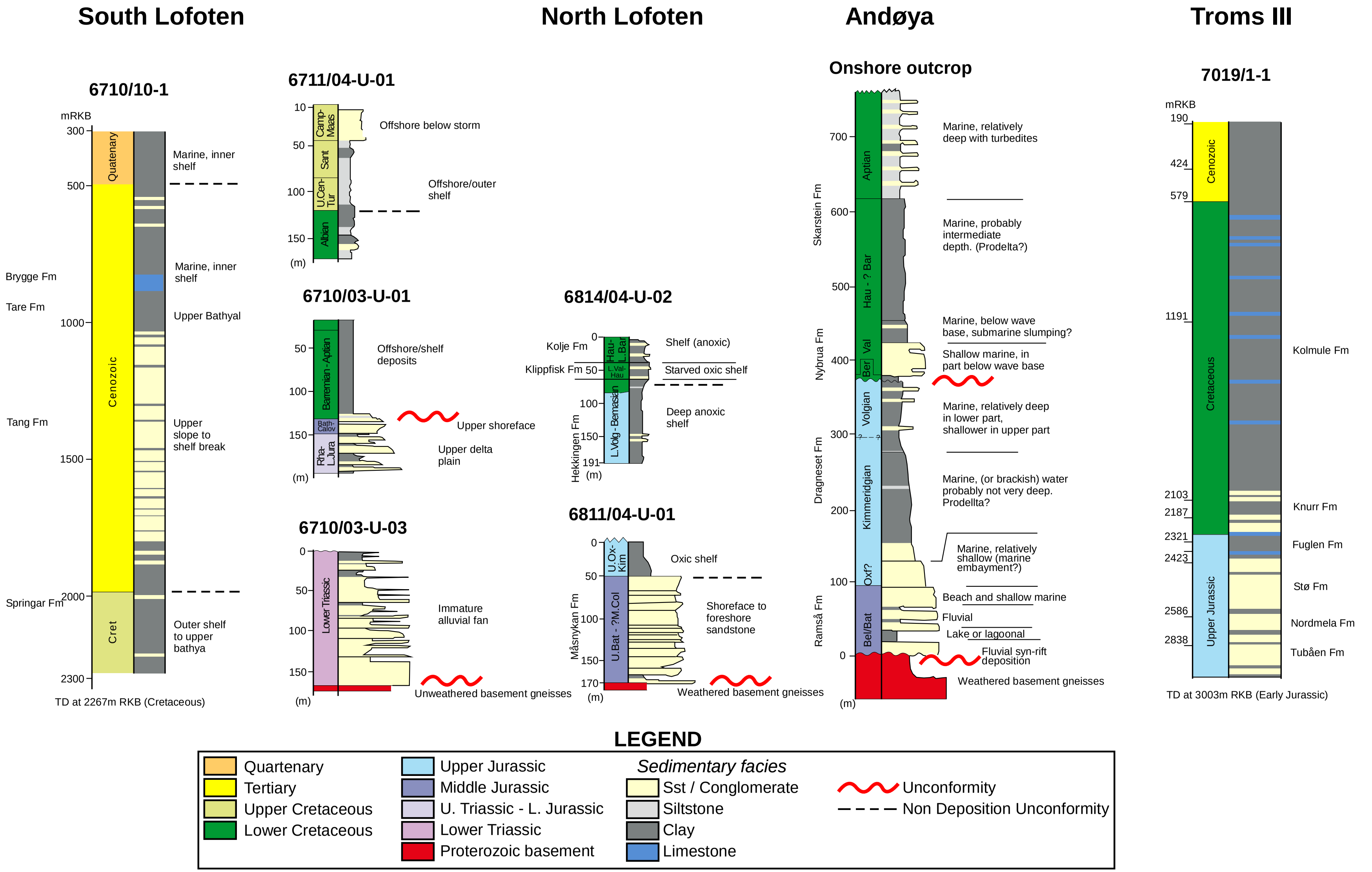

Figure 4.12 The LVM available well data. *Stratigraphy information for the well 6710/10-1 was summarized after Fawke et al. (2001) and for the well 7019/1-1 was compiled from Stensland and Austlid (2001). The IKU well stratigraphy information was simplified after Hansen et al., 2012*
Well 7019/1-1 (Troms III) is also employed in order to constraint the stratigraphy in the northernmost part of the LVM margin.

Jurassic

The IKU wells and Andøya outcrop has confirmed the existence of Jurassic sequence within the South Lofoten province (IKU well 6710/03-U-01), north Lofoten province (IKU wells 6811/04-U-01 and 6814/04-U-2) and Vesterålen-Andøya province (Figure 4.12). The Jurassic sequence is characterized by shallow marine to shelf deposition consisting of Sandstone, Siltstone and Claystone (Hansen et al., 2012). In the Vestfjorden Basin, Kvalnesdjups Graben and Skomver sub Basin, the Jurassic sequence is characterized by a wedge shape sedimentary package (~0.8 second TWT in Vestfjorden Basin) which interpreted as syn-tectonic deposition (Figure 4.3). While exclude those two areas, the Jurassic sequence is marked by a homogen sediment thickness indicating pre-rift stage or marginal rifting event. Seismic interpretation revealed that the Jurassic sequence is mostly developed within the shelf area and it is thinning out to the slope area (Figure 4.2-Figure 4.8).

Lower Cretaceous

The Lower Cretaceous sequence is marked mainly by a marine clay succession within the entire margin (Figure 4.12). Core description in IKU well 6710/03-U-01 and 6711/04-U-01 (south Lofoten), 6814/04-U-2 (north Lofoten) and Andøya outcrop reveals that this sequence mainly was deposited in the marine environments (shelf to deep marine) (Figure 4.12) (Hansen et al., 2012). An erosional unconformity marks the contact of the Lower Cretaceous sequence to the Upper Jurassic sequence which confirmed by well 6710/03-U-01 and the Andøya outcrop (Figure 4.12) (Hansen et al., 2012). Within the seismic data, the Lower Cretaceous sequence is characterized by thick wedge shape sedimentary package (up to 3 second TWT) indicating syn-tectonic deposition covering the province from the shelf to the slope as well as from the south Lofoten province to the Vesterålen-Andøya province.

Upper Cretaceous

In the South Lofoten province, the IKU well 6711/04-U-01 and exploration well 6710/10-1 has confirmed the presence of the Upper Cretaceous sequence (Figure 4.12). This sequence consists of Claystone and siltstone interpreted as an outer shelf sequence (Hansen et al., 2012). A non deposition unconformity was interpreted separating this sequence to the Lower Cretaceous sequence (Figure 4.12, well 6711/04-U-01) (Hansen et al., 2012). Seismic interpretation reveal that Upper Cretaceous sequence has homogen thickness, onlapping to the Lower Cretaceous sequence, indicating the post rift event (Figure 4.2 and Figure 4.3). In contrast, no well data has confirmed the present of Upper Cretaceous sequence within the north Lofoten and Vesterålen-Andøya province. Within the seismic data, the existing of Upper Cretaceous sequence within the north Lofoten province is questionable due to seismic interpretation reveals that the Lower Cretaceous sequence is interpreted present just below the seabed (Figure 4.6). In the Vesterålen-Andøya province, the existence of Upper Cretaceous sequence is justified from the characteristic difference of the seismic reflector package on top of the Lower Cretaceous sequence (Figure 4.7 and Figure 4.8). Different to the Lower Cretaceous, the Upper Cretaceous sequence is characterized by prominent deformation reflecting by the fault detachment.

Cenozoic to recent

Only within south Lofoten province the existence of the Cenozoic and Quaternary sequence has been confirmed in the LVM (Figure 4.12, well 6710/10-1 and 6711/04-U-01). The Cenozoic sequence within these wells consist of sandstone and Claystone that interpreted as the upper slope to inner shelf deposition, which indicating shallowing upward successions (Figure 4.12, well 6710/10-1 and 6711/04-U-01). Within the seismic data, the Cenozoic sequence appears as the progradding wedge sequence which down-lapping to the Upper Cretaceous sequence (Figure 4.2-Figure 4.8). The Quaternary sequence is mainly observed within the slope area and the deep Lofoten basin, down-lapping to the Cenozoic sequence (Figure 4.2-Figure 4.8).

5 Rift Segmentation and Evolution of Lofoten-Vesterålen Margin

5.1 Rift Margin Segmentation of the Lofoten-Vesterålen Margin

North and South Lofoten Segmentation

The opposing polarity of the Early Cretaceous faults between the South Lofoten province and the North Lofoten province indicates that rift segmentation occurred within the Lofoten-Vesterålen magin (LVM) during Early Cretaceous (Figure 4.5 and Figure 4.6). Pre-Early Cretaceous, the LVM is interpreted as one rift segment, due to no evidence of the opposing of Triassic-Jurassic faults polarity.

As rift system evolve, two rift segments commonly interact and connect within a region called as an accommodation/transfer zone (Gawthorpe et al., 1997). In this zone, a complex deformation may exists involving strike-slip, dip-slip and oblique-slip faulting. The strike slip fault within the accommodation/transfrer zone in theory, is a high angle fault or can be called as a vertical fault (Van der Pluim and Marshak, 2004), which is difficult to be detected using the 2D seismic.

The potential field data (Magnetic, Bougeur gravity anomaly, 200 km high pass filter Bougeur anomaly and 100 km high pass filter Bougeur anomaly) are employed in order to observed any evidence of a strike slip motion between the south Lofoten province and north Lofoten province (Figure 5.1). The observation is focused by observing any lateral offset of gravity-magnetic anomaly between these provinces. The observation suggest that no strong evidence of lateral offset within the gravity-magnetic anomaly in between south Lofoten province and north Lofoten province, that justify the accomodation/transfer zone in between these province does not associate with a strike slip fault (Figure 5.1).

Vesterålen-Andøya Segmentation

In the Vesterålen-Andøya province, the fault detachment system occurred during Late Cretaceous to Early Cenozoic suggest the second rift segmentation (Figure 4.7 and Figure

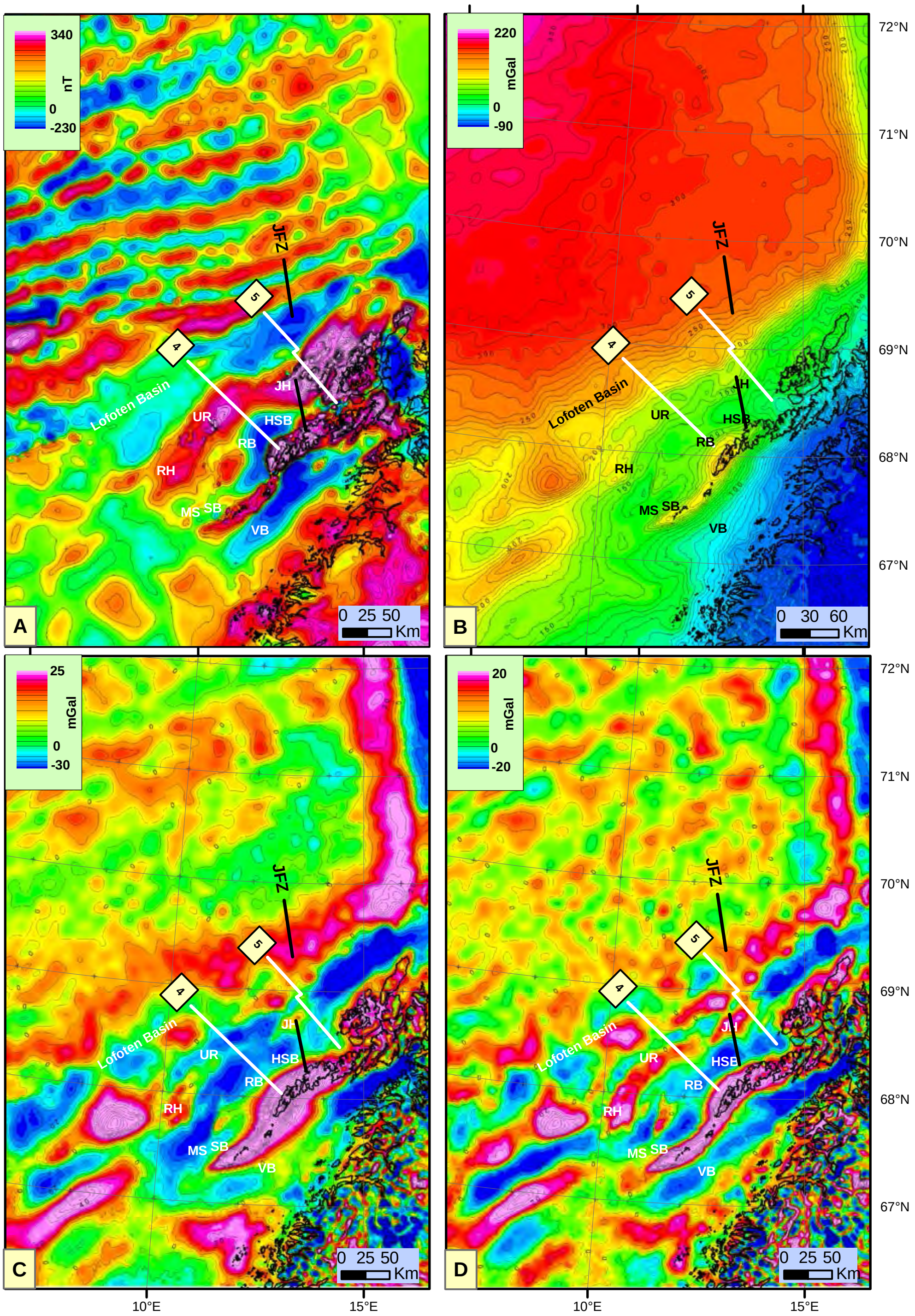

Figure 5.1 North Lofoten accommodation/transfer zone.. *Observation of the strike slip movement between the South and the North Lofoten provinces.*
The seismic transect-4 is the northermost seismic transect within the South Lofoten province and the seismic transect-5 is the southernmost seismic transect within the North Lofoten segment.
A). Magnetic B). Thermal corrected Bougeur anomaly, C). 200 km high pass filter Bougeur anomaly and D). 100 km high pass filter Bougeur anomaly.
The location of seismic transect-4, seismic transect-5 and Jennengga transfer zone proposed by Tsikalas et. al (2001) are also posted.
UR: Ultrøst Ridge; JH: Jennengga High; RH: Røst High; RB: Ribban Basin; VB: Vestfjørden Basin; HSB: Havbåen sub Basin; MS: Marmæle Spur; SB: Skomvær sub Basin.
The potential datas is referred to Flanagan (2013).

4.8). This segmentation restricted the type of deformation occurred within the Vesterålen-Andøya province to the North Lofoten province and South Lofoten province. However, Pre-Late Cretaceous, the Vesterålen-Andøya province appears to experienced the same type of deformation with the North Lofoten province, in other word, they were one rift segment (see section 4.2) (Figure 4.10 and Figure 4.11).

Time Progressive Segmentation of The Lofoten-Vesterålen Margin

The existence of the two subsequent rift segmentation within the Lofoten-Vesterålen Margin (LVM) during different time period, suggest that the LVM experienced time progressive segmentation. During Early Cretaceous, the LVM was segmented into two segments: the South and the North segment, bounded by a accommodation/transfer zone without any evidence of strike slip fault. The South segment is represent by the South Lofoten province while the North segment consist of the North Lofoten province and the Vesterålen-Andøya province. Furthermore, during Late Cretaceous-Early Cenozoic, the North segment of the LVM was subjected to another segmentation, restricted the North Lofoten province to the Vestrålen-Andøya province (Figure 5.2).

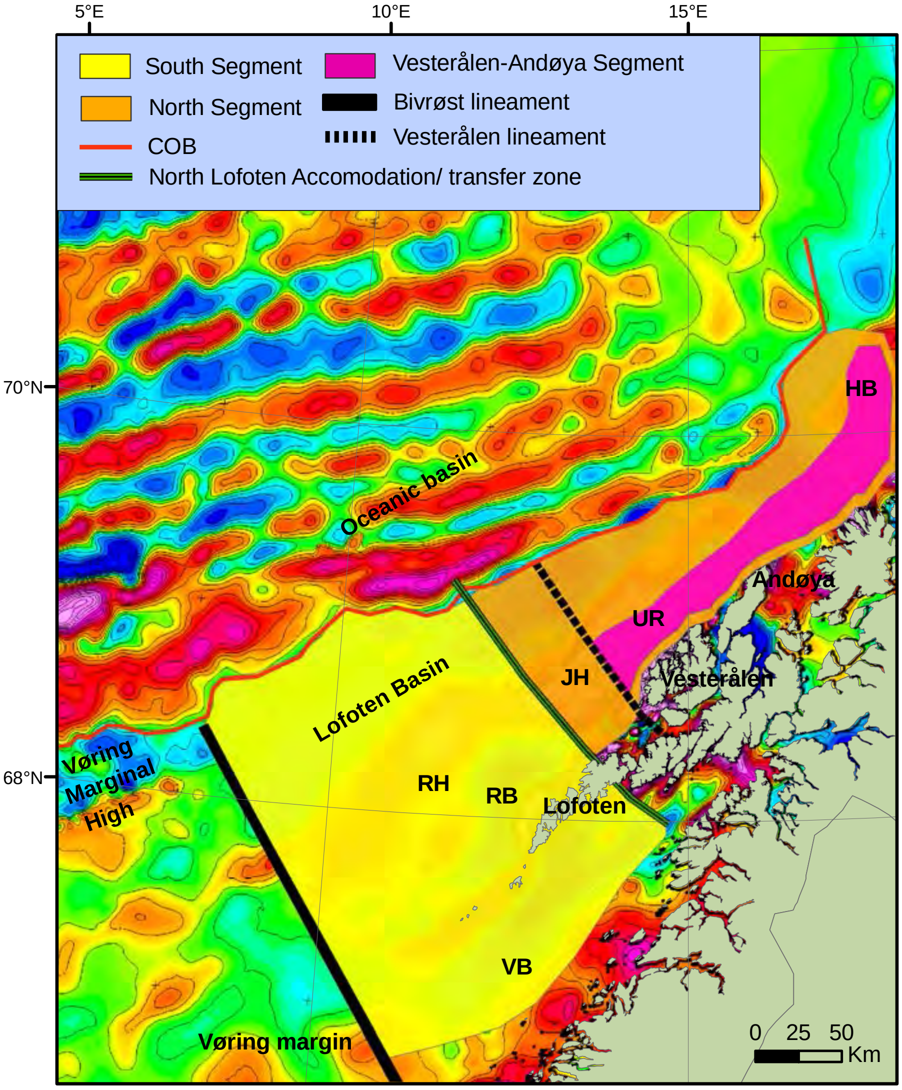

Figure 5.2 The LVM Rift segmentation. *An accomodation zone named North Lofoten accomodation zone is set bounding the South and the North Lofoten province. Furthermore, the Vesterålen lineament is placed restricting the Vesterålen-Andøya province to the North Lofoten province.*
UR: Ultrøst ridge; JH:Jennengga high; RH:Røst high; RB:Ribban basin; VB:Vestfjørden basin; HB: Harstad basin. The magnetic data is referred to Flanagan (2013)

5.2 Rift Evolution of the Lofoten-Vesterålen Margin

By integrating the seismic data, stratigraphy information from well data and potential data, a rift evolution model of the Lofoten-Vesterålen margin (LVM) will be proposed. The rift evolution model suggested in this study focus on the Mesozoic to recent rift evolution. Slightly different with the previous model (Hansen et al., 2012), the proposed rift evolution model is also taking in to account the rift segmentation explained within the previous section (Figure 5.3).

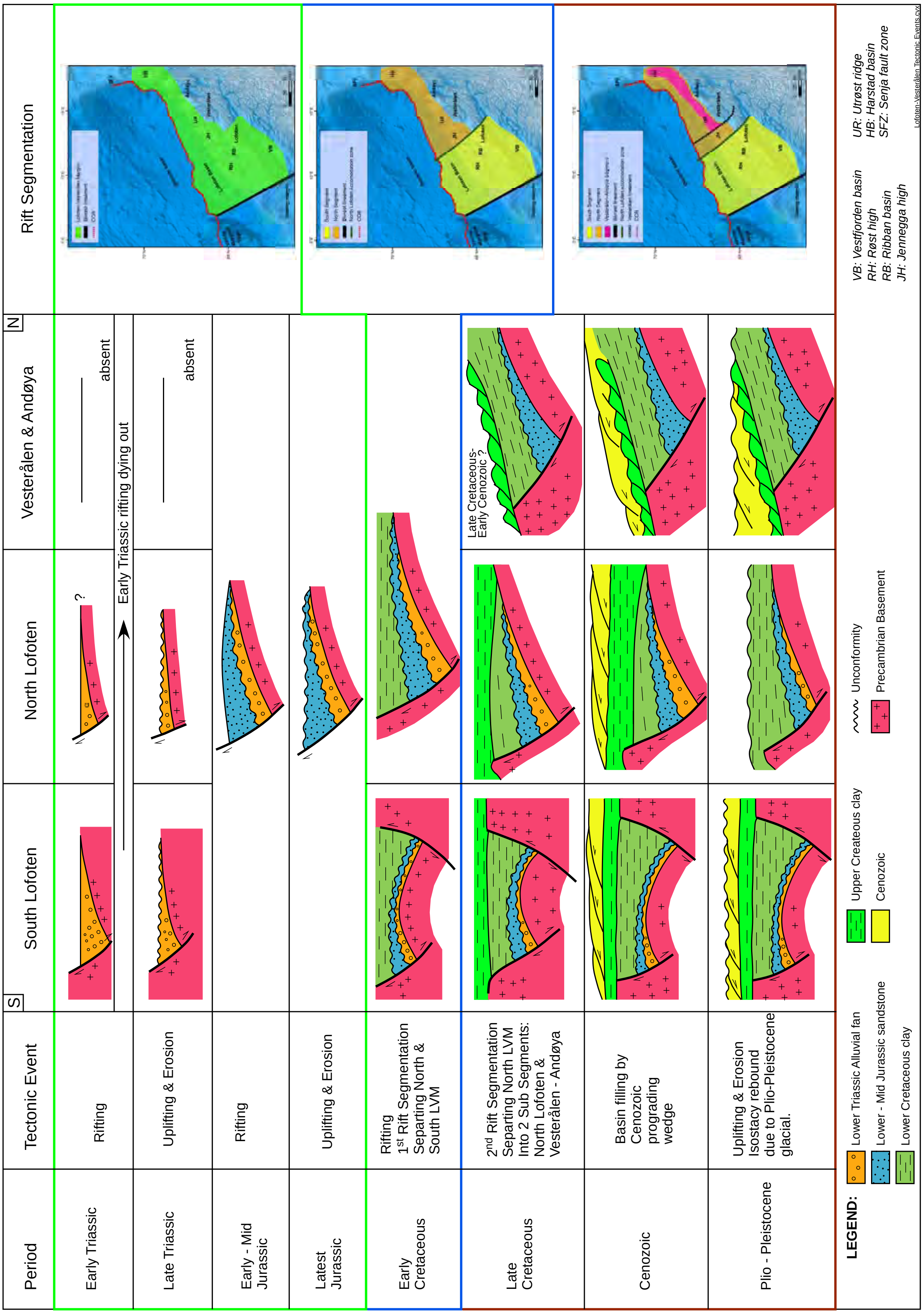

Figure 5.3 The LVM tectonic evolution from Mesozoic to recent.

Triassic

The abundance of the Triassic sequence within the LVM is limited. No distinct evidence for the Triassic sequence is found within the North Lofoten province and the Vesterålen-Andøya province (section 4.1) (Figure 4.12). This suggest that the Triassic rifting was dying out toward the North Lofoten province and the Vesterålen-Andøya province and hence limited tectonically generated accommodation space. Furthermore, during this period, the Lofoten-Vesterålen margin is suggested to be unsegmented (Figure 5.3).

Jurassic

During early to mid Jurassic, the LVM experienced a rifting event marked by the east dipping normal faults (Figure 4.2-Figure 4.8). The early to mid Jurassic syn rift package is observed within the entire LVM (Figure 4.12). During the Late Jurassic, an uplift and erosion event was occurred within the LVM indicated by the presence of erosional Unconformity (Figure 4.12, well 6710/03-U-01 and Andøya outcrop). No rift segmentation is observed within this period (Figure 5.3).

Early Cretaceous

The early Cretaceous is characterized by the major rifting event within the LVM. During this time the major faults and basement ridges became prominent structural element. Thick syn rift sequence (~3 second TWT) is observed within the entire margin (Figure 4.2-Figure 4.8). The first rift segmentation occurred within this period restricting the South Lofoten province to the North Lofoten and Vesterålen-Andøya province (Figure 5.3).

Late Cretaceous

Within the South Lofoten province, the Late Cretaceous is characterized by the subsequent post rift stages. The upper Cretaceous sequence is observed to be un-structure indicating no distinct deformation occurred. Furthermore, within the North Lofoten segment, most of the Upper Cretaceous sequence is observed to be absent which interpreted caused by erosion. In contrast, the upper Cretaceous sediment within the Vesterålen-Andøya province is observed to experienced prominent deformation, which led for the second rift segmentation (Figure 5.3).

Cenozoic

The Early Cenozoic sequence is marked by the presence of a sedimentary prograding wedge, down-lapping onto the Late Cretaceous sequence which consistently present along the margin. The vertical succession of the Cenozoic sequence observed on well 6710/10-1 indicates a shallowing upward of the Cenozoic succession reflected by the upper slope-shelf break to the inner shelf depositional environment (Figure 4.12). These observation indicate the LVM experienced major Regression during Cenozoic (Figure 5.3).

Plio-Pleistocene

During the Plio-Pleistocene, the LVM is subjected to experienced regional uplifting and erosion, indicates by the extensive Cenozoic erosion within the entire margin (Figure 4.2-Figure 4.8).

5.3 The Vesterålen and Andøya Deformation

The late Cretaceous-early Cenozoic fault detachment that occurred within the Vesterålen-Andøya province was suggested to be correlated to several prominent geological feature observed, as follows:

- The rotation of the East-dipping Jurassic fault and the Lower Cretaceous sequence (Figure 4.7 and Figure 4.8).
- The exposure of the Vesterålen-Andøya island (Figure 2.4).
- The presence of the high magnetic anomaly within the offshore Vesterålen-Andøya province (Figure 4.1). In comparison, the high magnetic anomaly within the Lofoten ridge and the Røst high coincide with shallow basement while within the offshore Vesterålen-Andøya province, the basement was interpreted to be 3 - 4 second TWT deep (Figure 4.3, Figure 4.7 and Figure 4.8).
- The lateral shifting of the Lofoten coastline to the Vesterålen coastline (Figure 2.4).

In order to explain this deformation, two geologic evolution models for the Vesterålen-Andøya province will be proposed, initiating this type of deformation:

1. Transform fault

Transform faults are a well known geological feature along the Mid Atlantic margin, while authors also believe transform faults also exist within the North Atlantic margin (e.g., West

UK, Mid Norway and Southeast Greenland) (Parry, 2012). Tsikalas et al. (2001) postulated the presence of a transfer fault in between the rift segments in the Lofoten-Vesterålen margin which is closely related to the oceanic fracture zone, although, the location of their transfer fault is slightly different with the one will be proposed in this study (Figure 1.2).

The main evidence for a transform fault within the Vesterålen and Andøya province are: i). The lateral shifting of the Vesterålen-Andøya coastline relative to the Lofoten coastline and ii). The lateral shifting of the high gravity anomaly between the offshore Lofoten and the offshore Vesterålen (Figure 5.4A) . The transform fault is suggested to have rotated the existing East-dipping Jurassic faults and the Lower Cretaceous sequence starting in Late Cretaceous. Furthermore, the rotation also created gravitational instability within the Upper Cretaceous-Lower Cenozoic sequences which then initiated the Upper Cretaceous-Lower Cenozoic sequences to slide on the Lower Cretaceous sequence, forming the fault detachment system (Figure 5.4).

2. The Mantle up-doming

The second model is explained by the presence of the mantle up-doming within the Vesterålen-Andøya province (Figure 5.5A). The existence of the mantle up-doming within the North Atlantic margin has been suggested by several authors (e.g., Rohrman and Van der Beek, 1996). One of the model suggested that the mantle up-doming initiates by an interaction of the hot (low viscosity) asthenosphere layer with the cold (higher viscosity) cratonic lithosphere, which caused a Rayleigh-Taylor instability. This model estimated the diameter of the dome range from 100-150 km (Rohrman and Van der Beek, 1996).

The main evidence of the mantle up-doming in the Vesterålen and Andøya province is the anomalous high magnetic within the offshore Vesterålen-Andøya province. The magnitude of this anomalous high magnetic within this province, is as high as the magnetic anomaly within the onshore Lofoten - Vesterålen island (Figure 5.5A). The second evidence which support this idea is the shape of this anomalous high magnetic which appears to be circular. In term of size, the mantle up-doming suggested in this study has ~75 km diameter.

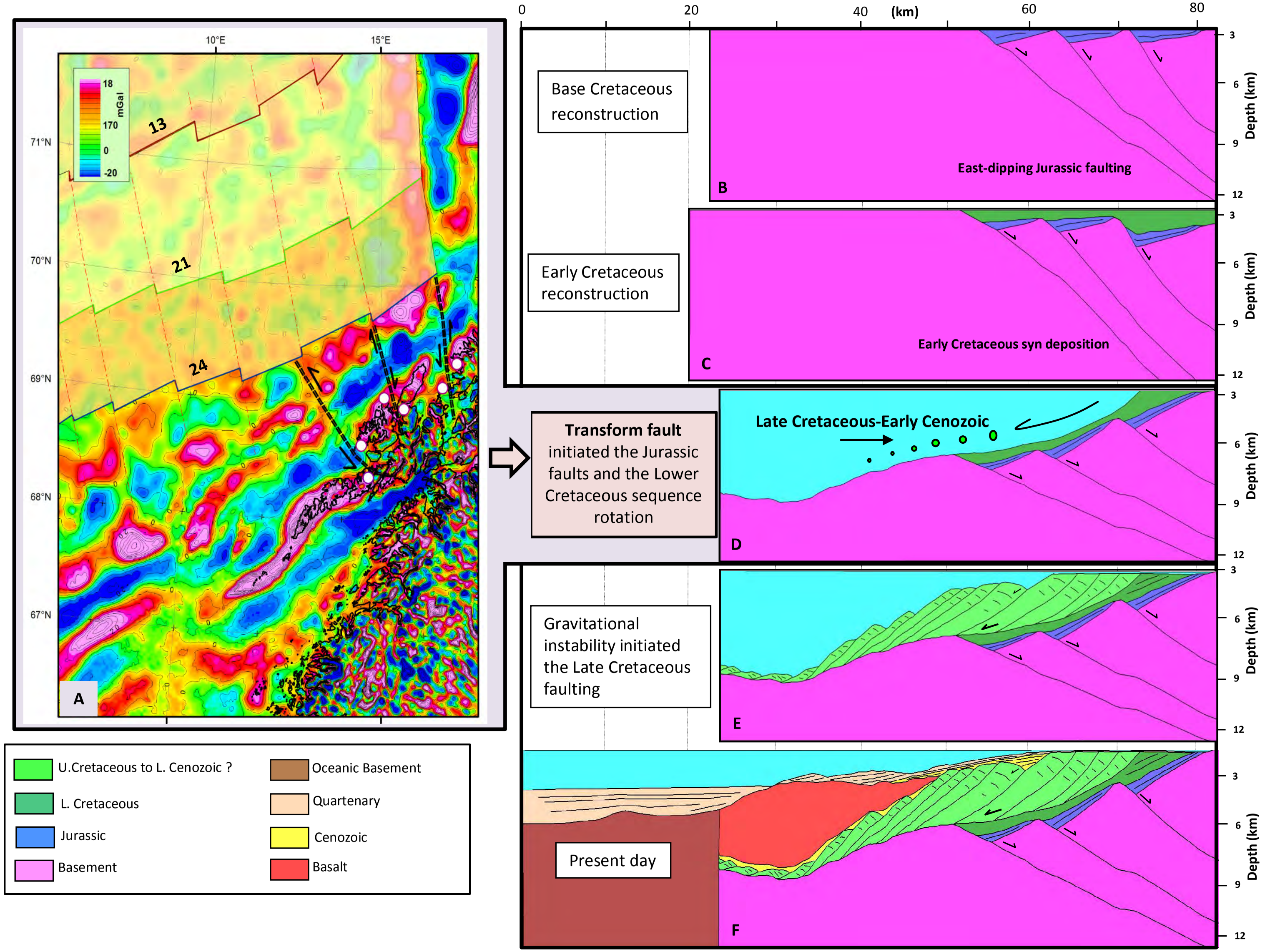

Figure 5.4 Vesterålen-Andøya stuctural evolution-1st model. *A). 100 km high pass filter gravity anomaly shows the proposed transform fault within the Vesterålen-Andøya province.*
B-F). explained within the figure.

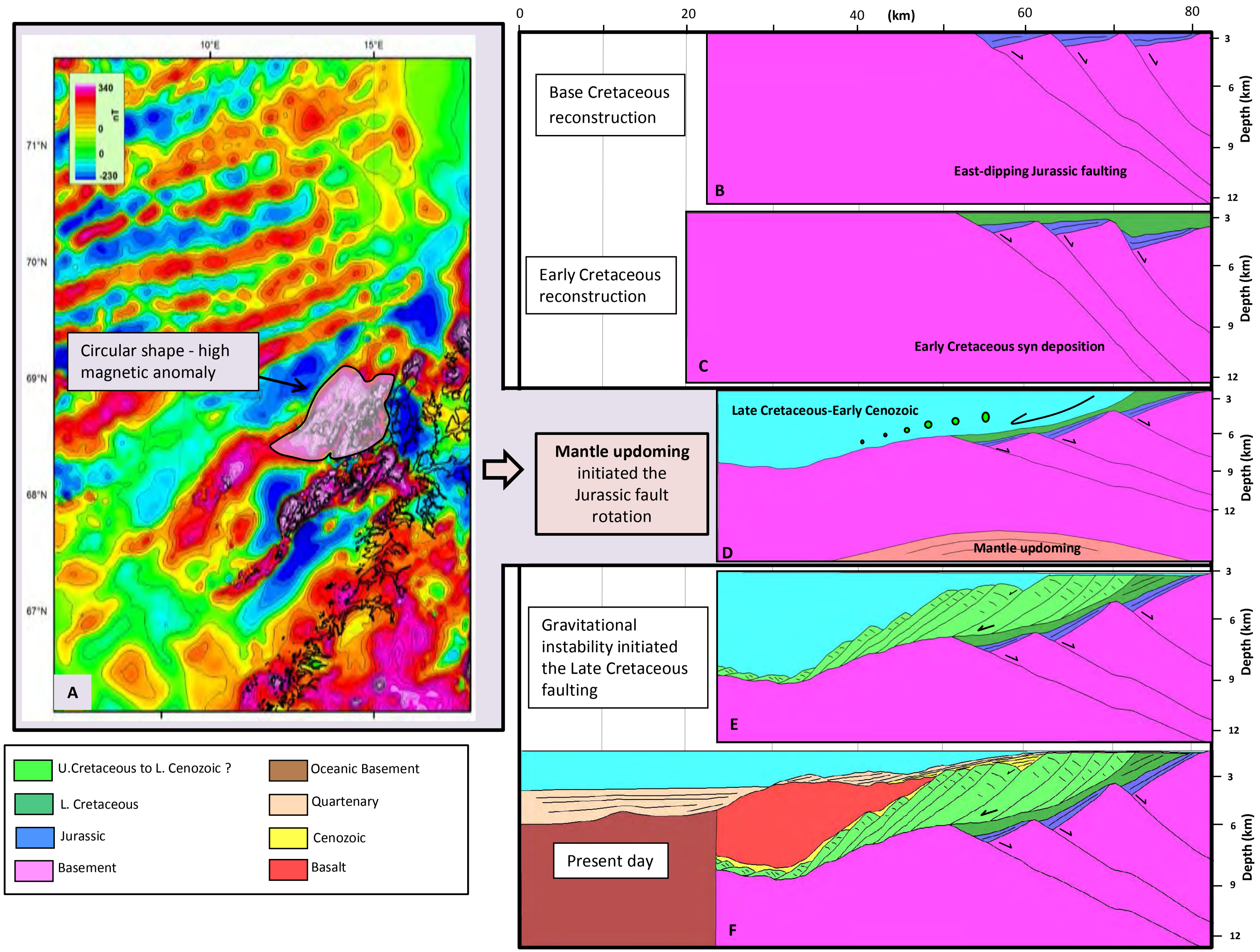

Figure 5.5 Vesterålen-Andøya stuctural evolution-2nd model. *A). Magnetic anomaly shows the proposed mantle upldoming within the Vesterålen-Andøya province. The diameter of the mantle up-doming proposed within this model is approximately 75 km. B-F). explained within the figure.*

Furthermore it is interpreted that intrusion of a high magnetic body coming from the deep mantle which further initiated the Jurassic faults and the Lower Cretaceous rotation. The rotation created gravitational instability which led for the development of the Late Cretaceous-Early Cenozoic fault detachment system (Figure 5.5).

6 Rift Domain Architecture of the Lofoten-Vesterålen margin

Examining the upper crust structural style using the 2D seismic and the potential data along the Lofoten-Vesterålen margin (LVM), which further incorporated with the crustal thickness, a first order structural similarity within the margin is determined. This similarity shows the seaward arrangement of the rift domain architecture:

- **Proximal domain**

The continental shelf area along the LVM shows identical graben-half graben structures filled with the wedge shape syn-tectonic sequences along the margin. The fault system is characterized by high angle planar normal faults without any indication of the fault detachment system. This area was subjected to a low amount of crustal thinning, indicating by thick continental crust, approximately 40 km. This area is categorized as the Proximal domain (Figure 6.1, Figure 6.2 and Figure 6.3).

- **Necking domain**

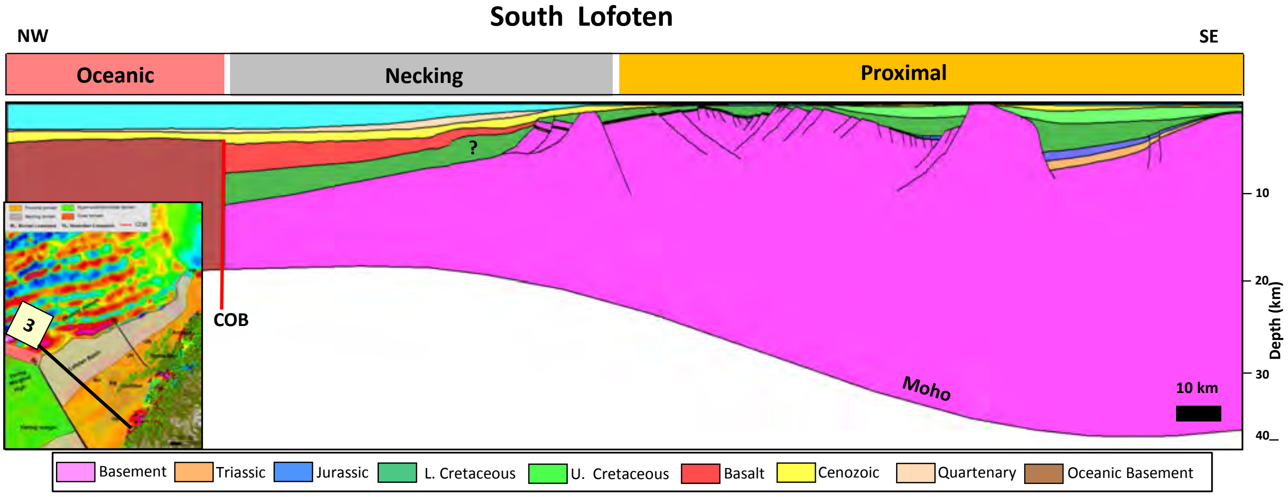

Figure 6.1 South Lofoten rift domain architecture. *Seaward arrangement of the south Lofoten rift domain: Proximal, Necking and Oceanic. Depth to Moho was determined by the gravity inversion, executed by Flanangan (2013).*

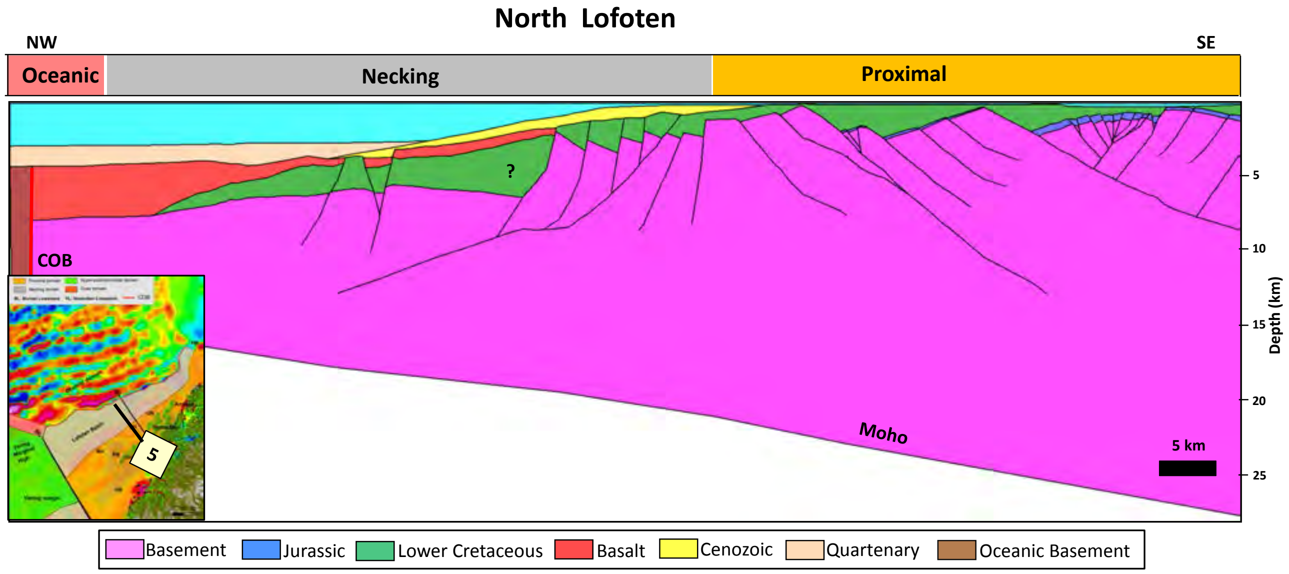

Figure 6.2 North Lofoten rift domain architecture. *Seaward arrangement of the north Lofoten rift domain: Proximal, Necking and Oceanic. Depth to Moho was determined by the gravity inversion, executed by Flanangan (2013).*

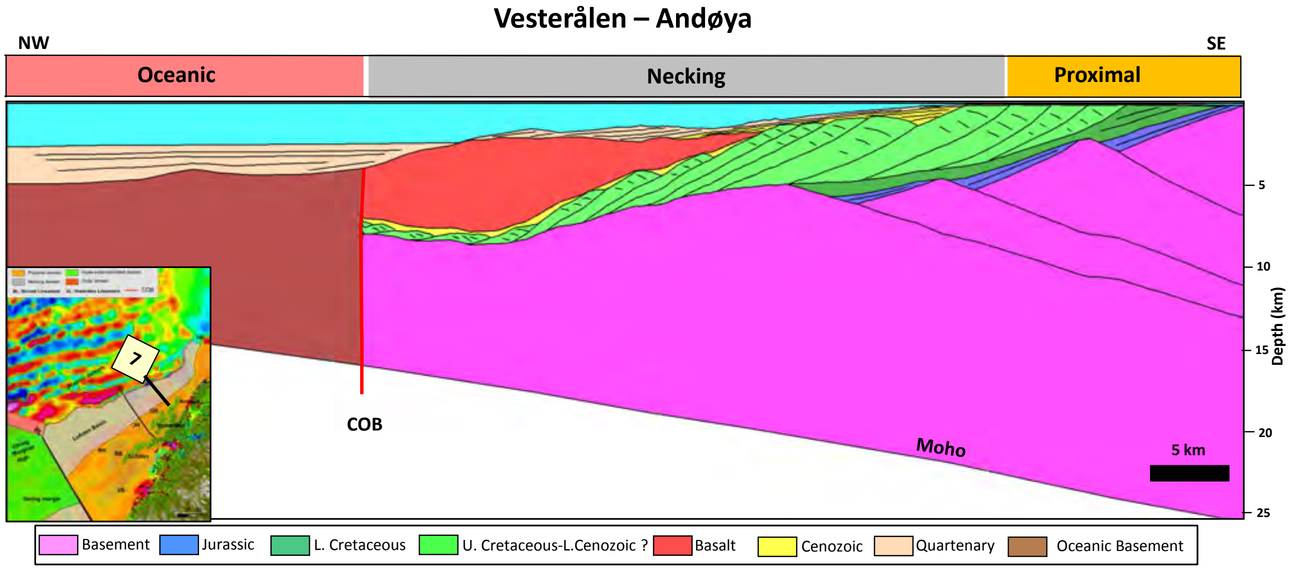

Figure 6.3 Vesterålen Andøya rift domain architecture. *Seaward arrangement of the Vesterålen-Andøya rift domain: Proximal, Necking and Oceanic. Depth to Moho was determined by the gravity inversion, executed by Flanangan (2013).*

Within the south Lofoten and north Lofoten province, this area is characterized by a series of rotated normal faults which detach into a major fault. This faults separates separated the inboard continental crust (Proximal domain) to the deep Lofoten basin (Figure 6.1 and Figure 6.2). In the Vesterålen-Andøya province this area is marked by the low angle fault detachment (Figure 6.3). The crust within this area shows a specific wedge shape defines as the inflection point associated with a drastic crustal thinning from approximately 30 km to 15 km. Within that observation, this area is classified as the Necking domain (Figure 6.1 - Figure 6.3).

- **Oceanic domain**

Within the deep basin, the most prominent feature is the existence of the COB (Continental Ocean Boundary) indicating the transition of the crust type, from the continental crust to the oceanic crust. Within the magnetic data, this domain is characterized by a distinct high magnetic anomaly stripes indicating the oceanic crust accretion (Figure 6.4). This domain is classified as the oceanic domain (Figure 6.1 - Figure 6.3).

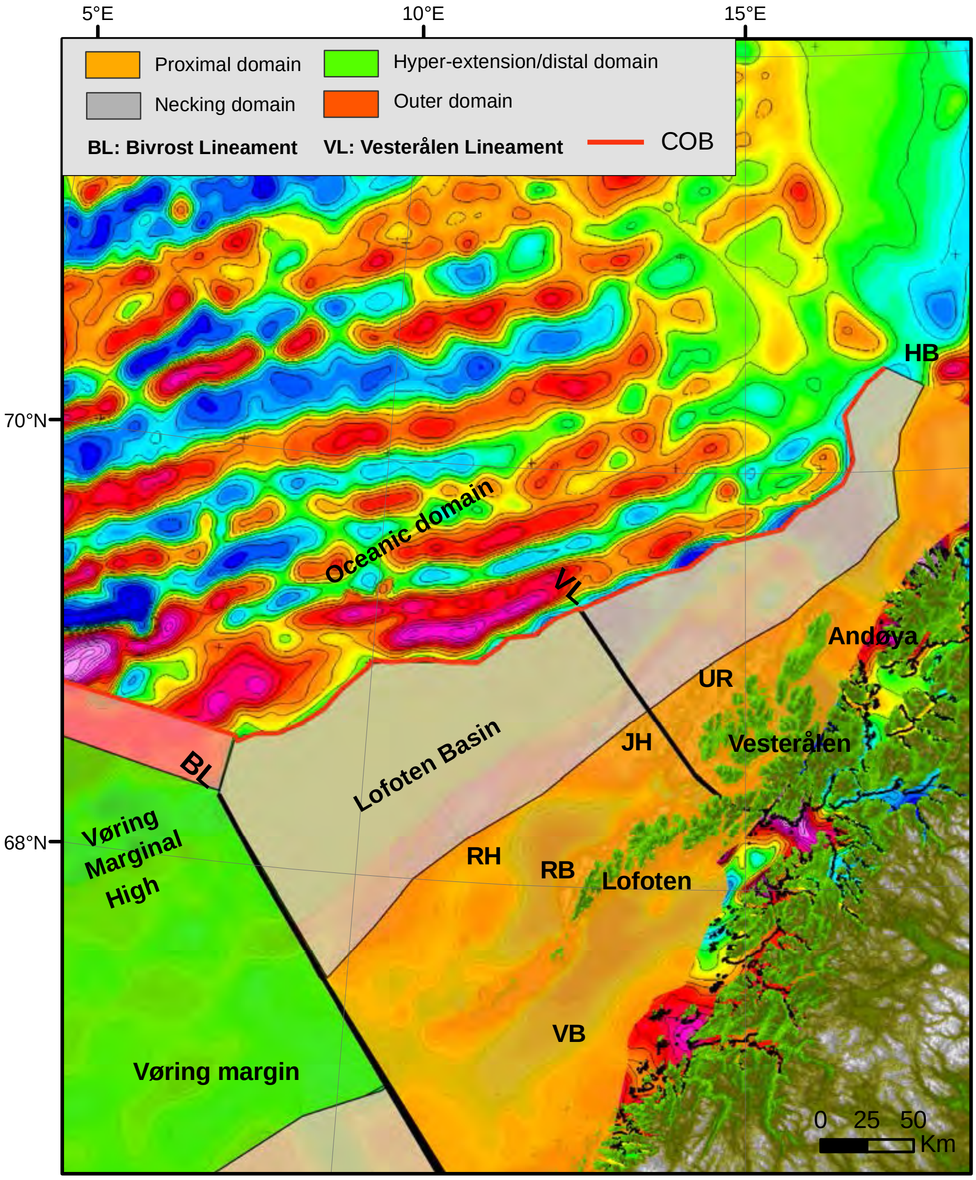

Figure 6.4 LVM rift domain architecture. *Seaward arrangement of the LVM domain: Proximal, Necking and Oceanic. Each of domain represent distinct comparable stuctural style and crust thickness.*
Notice the absent of the hyper-extension and Outer domain within the LVM, while within the Vøring margin both of those two domain present (see Figure 7.3 for more about Vøring rift domain).
UR: Ultrøst ridge; JH: Jennengga high; RH: Røst high; RB: Ribban basin; VB: Vestfjørden basin; HB: Harstad basin

The arrangement of the rift domain architecture across the LVM shows consistent seaward arrangement of Proximal, Necking and Oceanic domains (Figure 6.4). The observation of upper crust structural style and crust thickness suggest for the absence of Hyper-Extension/distal and Outer domain within this margin (Figure 6.1 - Figure 6.3).

7 Discussion

7.1 Review of the Rift Segmentation Models within the LVM

The Lofoten-Vesterålen (LVM) rift segmentation model proposed within this study is different to the previous published models (Figure 1.2). In thi study, a model called time progressive segmentation was proposed for the LVM, which reflect the subsequent rift segmentation during the Early Cretaceous and Late Cretaceous (Figure 5.2 and Figure 5.3). Furthermore, the observation through the potential field data revealed that no strong evidence for the presence of a strike slip fault within the North Lofoten accommodation zone, which restricting the South Lofoten to the North Lofoten province (Figure 5.1 and Figure 5.2). In contrast, the rift segmentation separating the North Lofoten province to Vesterålen-Andøya province is characterized by: i) the lateral shifting of the Lofoten coastline to the Vesterålen coastline (Figure 2.4) and ii) the lateral shifting of high magnetic anomaly within the offshore Vesterålen-Andøya province (Figure 4.1), which hint the existence of strike slip motion.

7.2 The LVM Extension Mechanism: Orthogonal vs. Oblique extension

Bergh et al. (2007) carried out extensive work on the onshore Lofoten-Vesterålen margin, mapping the onshore lineament and further linking them to the offshore faults (Figure 1.2B and Figure 2.4A). Then, based on his hypothesis on the fault kinematic arrangement, he suggested that the rifting mechanism of Norway-Greenland during Late Jurassic - Paleogene was oblique rather than the conventional orthogonal extension (Tsikalas et al., 2001).

The main issue which may disregard this hypothesis is the fact that the entire onshore Lofoten-Vesterålen island is represented by the Precambrian basement and metamorphic rocks (Figure 2.4). The justification of the age of these onshore lineament is uncertain, due to no Mesozoic rocks is preserved, except within Andøya (Figure 2.4). The onshore faults and lineaments may have been generated long time before the Mesozoic rifting and therefore are unrelated to the extension event.

In a different study, Gabrielsen et al. (2002) also mapped the onshore faults and lineaments for the entire Norway and Sweden, including the onshore Lofoten-Vesterålen margin. They grouped these faults and lineaments in to six groups based on their main orientation. They concluded that regardless of the local variation of fault orientation present, the main orientation of the onshore faults and lineaments within Norway and Sweden (including the onshore Lofoten-Vesteålen) is northwest-southeast (Figure 7.1). This orientation is the opposite to the Mesozoic offshore faults which are trending northeast-southwest (Tsikalas et al.,2001; Bergh et al., 2007; Færseth et al.,2012; Hansen et al., 2012). Gabrielsen et al. (2002) suggested that these onhsore fault and lineament represent the inherited structural grain, arising from a mega structure pattern imposed on the western Fennoscandian shield during Proterozoic time (Figure 2.5).

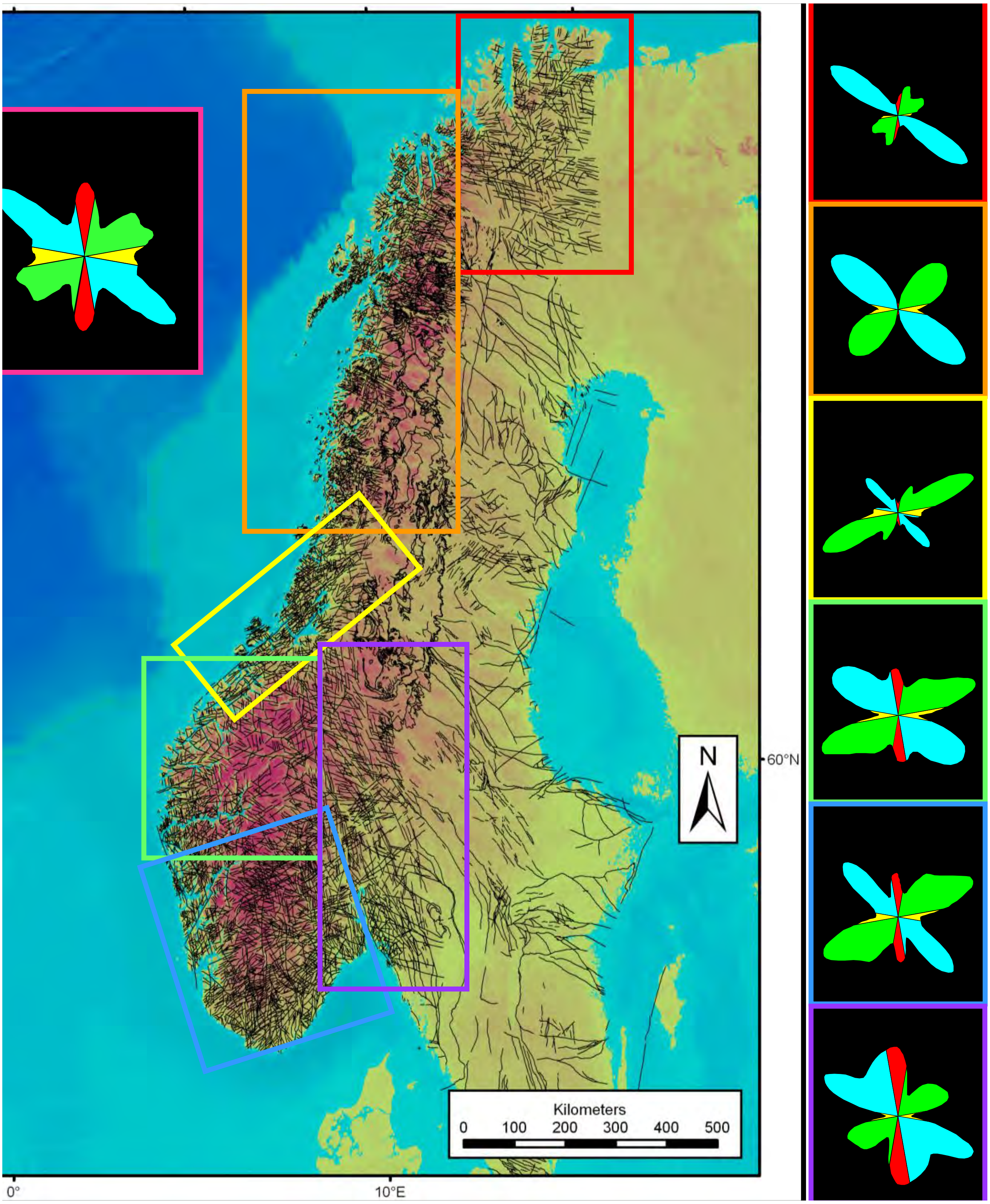

Figure 7.1 Tectonic Lineament of Norway and Sweden. *Northwest-Southeast to Westnorthwest-Eastsoutheast lineament populations (Gabrielsen et al., 2002)*

7.3 The Rift Domain Architecture of the Lower-plate vs. Upper-Plate Margin

The principal schematic model of the rift margin domain architecture, suggested by Pinvidic et al. (2013) was closely derived from a Lower plate (hyper-extended) passive margin. Within the Norwegian passive margin, their model was closely referred to the arrangement of the Vøring margin (Figure 2.2). Furthermore, Pinvidic et al. (2013) showed that the arrangement of the Lower plate (hyper-extended) margin is not as homogeneous as was proposed by Lister (1986) (Figure 2.1). Pinvidic et al. (2013) suggested five different rift domains existed within the passive margins, each of them has distinct structural style and specific crustal thickness and each of them relates to a particular rifting phase (Figure 2.2).

In this study, based on the observation through the Lofoten-Vesterålen margin (LVM), it is suggested that the seaward arrangement of the rift domain architecture within an upper-plate (non hyper-extended) passive margin, is different to the Lower plate margin. The main prominent difference are: i) The absence of the outer domain within the upper-plate margin ii)The absence of the distal/hyper-extension domain within the upper-plate margin (Figure 6.1-Figure 6.4). Furthermore, it is suggested that the rift domain architecture within an upper-plate passive margins is not as simple and homogeneous as was proposed by Lister (1986) (Figure 2.1).

7.4 Rift Domain Architecture of the East Greenland Margin

In order to complement the understanding of the rift domain architecture within the Norway-Greenland conjugate margin, a characterisation of the rift domain architecture within the East Greenland Margin (EGM) is presented. A crustal profile crossing the Koldewey Platform, Danmarkshavn Basin, Danmarkshavn Ridge and Thesis Basin is employed to fit this purpose (Figure 7.2). Regardless of the local variation that occurs, identical seaward arrangement of the rift domain architecture comprise proximal, necking and oceanic domain was observed. Each of these domains is characterised by a distinct upper crust structural cstule and specific crust thickness.

Previously, it was expected that the rift domain architecture of the EGM would be identical to the Vøring margin, because both of them appear as a wide-hyper extended margin (Figure 2.2). However, the crustal profile across the EGM revealed that, no specific style

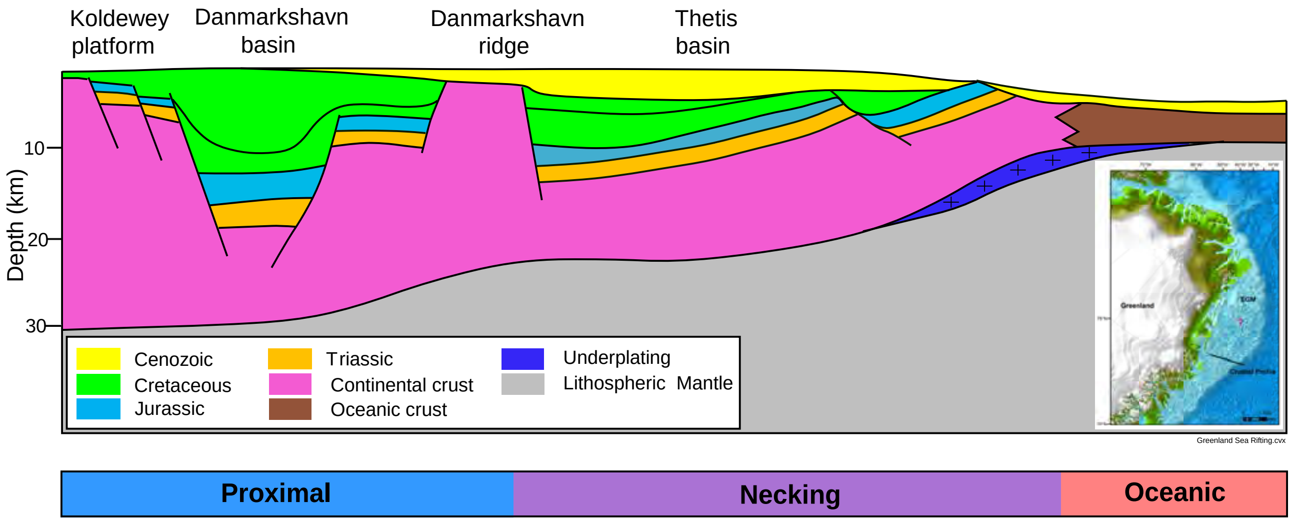

Figure 7.2 Crustal profile across East Greenland margin.. *The proximal domain is characterized by graben-half graben structures, high angle planar normal faults and thick continent crust, indicating this domain experienced stretching phase with low amount of extension. This domain is represented by the Koldewey platform and Danmarkshavn basin. The necking domain is corresponded to the Danmarkshavn ridge to the Thesis basin indicating by the wedge shape of the continental crust.*

which lead to the presence of an outer domain and a sag-type basin (hyper-extension domain) within the EGM. This observation indicates that a wide hyper-extended passive margin may have different structural arrangement.

However, the observation of the rift domain architecture within the EGM in this study is limited within the southern part of the margin, rising likely-hood that a lateral variation may also occur across the margin (Figure 7.2).

7.5 The Implication of Rift Domain Architecture to Petroleum Exploration

The Necking domain in the Vøring margin

In terms of petroleum exploration implications, a remarkable correlation between oil-gas field distribution in the Vøring margin and the Necking domain, hint the significance of the rift domain characterization within the passive margin. In the Vøring margin, several known giant oil-gas fields (e.g., Heidrun and Aasgard) and some other significant discoveries (e.g., Tyrihans, Kristin and Victoria) are situated within this domain (Figure 7.3). The necking domain within the Vøring margin appears to set the ideal condition for the entire petroleum system elements to work. Based on the observation of the geologic setting of several known

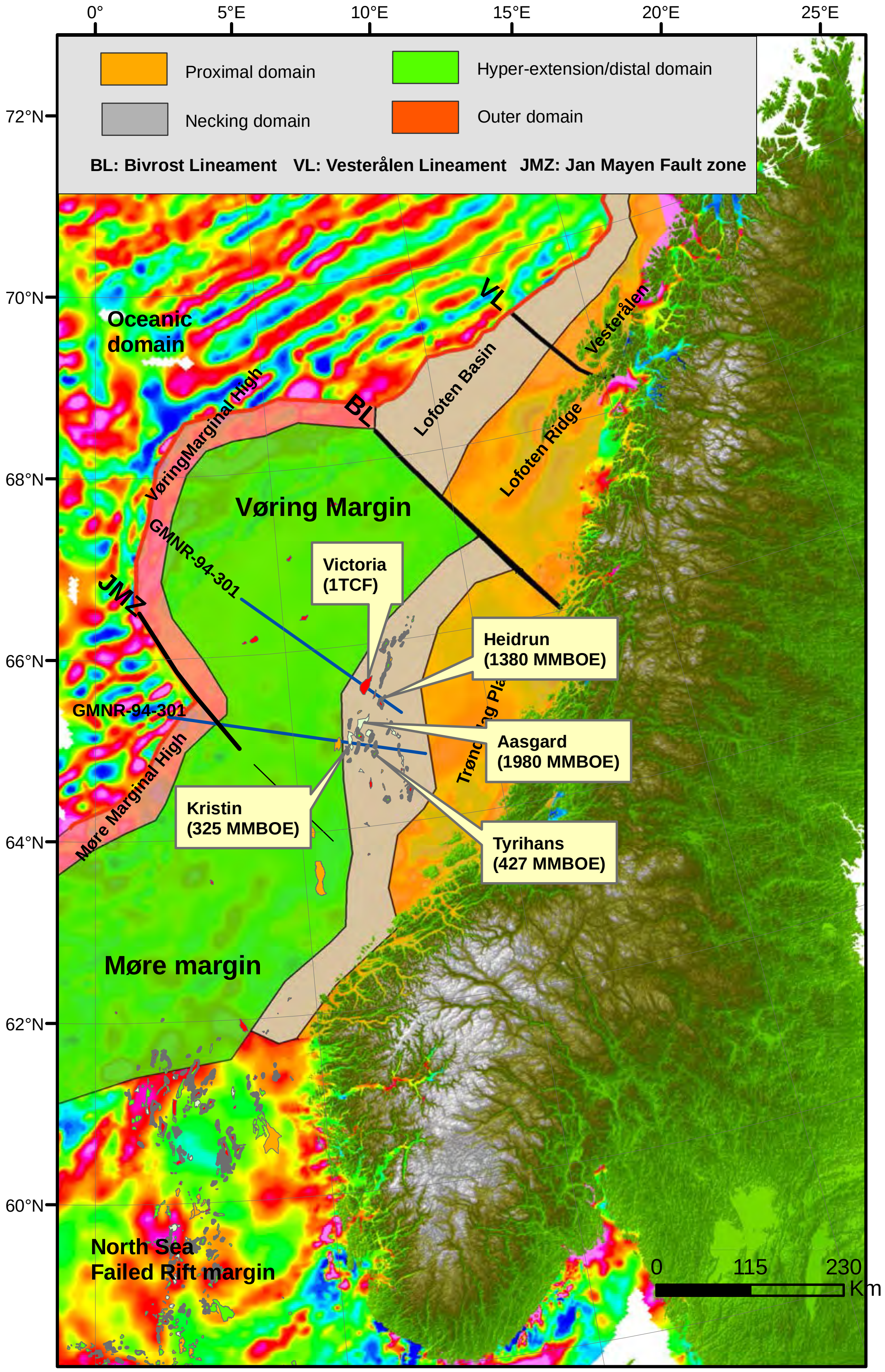

Figure 7.3 Rift domain architecture of Norwegian passive margin. *Norwegian oil-gas fields and the offshore magnetic data are also presented in the map.*
The magnetic data is referred to Flanangan (2005) and the rift domain architecture within Vøring and Møre margin is referred to Pinvidic et al. (2013)

hydrocarbon discoveries in the Halten terrace, several key factors are suggested to support this domain as the key petroleum province (Figure 7.3):

- **Trap**. The Necking domain in the Vøring margin is characterised by a series of rotated fault blocks consisting of Jurassic sequence. The uplifted footwall of rotated fault blocks is a favoured place for the hydrocarbon to be trapped (Figure 7.4).
- **Burial and Seal.** Within the Necking domain in the Vøring margin, the Lower to Middle reservoirs are covered by approximately 2.5 - 3 km Cretaceous and Cenozoic Shales, which further generate sufficient burial for maturing the hydrocarbon. The Cretaceous and Cenozoic Shales in this domain also acts as an regional seal (Figure 7.4).
- **Heat Flow**. Due to experienced thinning phase within the rift evolution, the Necking domain is marked by the wedge shape of the crust, with a thickness between 10-30 km (Figure 2.2). This crustal thickness appears to yield a suitable heat flow for maturing the hydrocarbon (Figure 7.4).
- **Reservoir quality**. The Lower-Middle Jurassic reservoirs within the Necking domain is situated within approximately 3 km depth. The amount of overburden experienced by the reservoir appear to be tolerable, preserving porosity (Figure 7.4). Furthermore, the Palaeogeographic reconstruction within the Norwegian passive margin back to the Early-Mid Jurassic revealed that the Necking domain within the Vøring margin was situated in deltaic-shallow marine environment (Torsvik et al. 2002), which is favoured environment for the coarse grain (high quality) reservoirs to be developed.

In comparison, for the same type of petroleum play (Jurassic play), the distal domain within the Vøring margin appears to have a greater challenge in order to preserve hydrocarbon accumulation. The greater challenge observed are the burial and the reservoir quality. The large thickness of the Cretaceous and Cenozoic sequence (approximately 6 km) present within the distal domain may have buried the Jurassic sequence much deeper than in the Necking domain, which may have resulted in source rock over-mature and poor reservoir quality (Figure 7.4).

The Necking domain within the Lofoten-Vesterålen margin

The likely-hood of the Necking domain within the Lofoten-Vesterålen margin (LVM) to be a petroleum province is questionable. As has been describe in the section 7.3, the characteristic

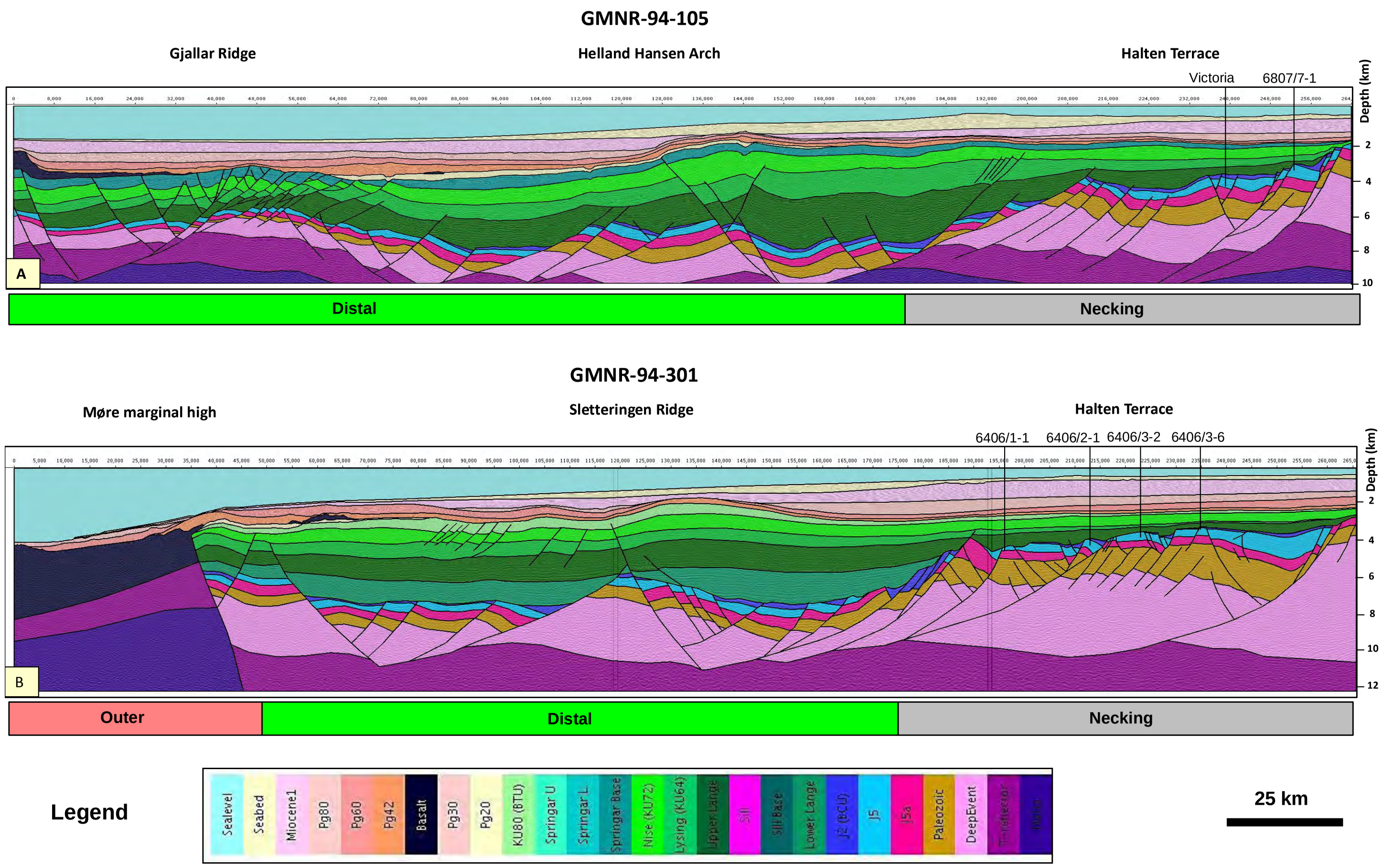

Figure 7.4 Vøring margin crustal profile. *A. GMNR-94-105 crustal profile shows the seaward arrangement of the rift domain architecture within the Vøring margin. Several oil-gas discoveries (e.g: Heidrun and Victoria) were found within the Halten Terrace. The Halten Terrace is suggested as the Necking domain within the Vøring margin.*
B. GMNR-94-301 crustal profile shows identical arrangement of rift domain architecture in the Vøring margin. The Necking domain within this area is also a prolific hydrocarbon province (e.g: Kristin, Tyrihans and Aasgard).
The petroleum system in Halten Terrace is understood to include: Lower and Middle Jurrasic sandstone as the reservoir, Lower and Upper Jurassic clay as the source rock intervals, Cretaceous clay as the regional seal and the rotated fault block as the trapping mechanism.
The crustal scale interpretation is referred to Grant (2011). See Figure 6.3 for the location of the crustal profiles,

of the Necking domain between the LVM is different to the Vøring margin. Several positive and negative factors which may influence the petroleum risk assessment of this area summarised as follow:

A. South and North Lofoten provinces

Negative indication:

- **Reservoir and Source rock..** The presence of the Lower-Middle Jurassic reservoir and Upper Jurrasic source rock within the Necking domain in the LVM is debatable. Seismic interpretation revealed that the Jurassic sequence is thinning out toward the Necking domain (Figure 6.1-Figure 6.2).
- **Seal.** Different than the Cretaceous sequence within the Necking in the Vøring margin which is un-faulted, the Cretaceous sequence within the Necking domain in the LVM is highly faulted. The faulting of Cretaceous shale may reduce the capability of this sequence to seal the hydrocarbon accumulation (Figure 6.1-Figure 6.2).

Positive indication:

- **Trap.** The Necking domain within the LVM is characterized by rotate fault blocks, which identical to the Vøring margin, is ideal for hydrocarbon trapping mechanism. Seismic interpretation revealed that this rotated fault manly consist of Lower Cretaceous sequence (Figure 6.1-Figure 6.2).
- **Heat gradient.** Similar to the Vøring margin, the Necking domain within the LVM also have a wedge shape of crust, which appears to be a positive indication for petroleum system (Figure 6.1-Figure 6.2).

Lower Cretaceous play in South and North Lofoten Province

Since, the Jurassic play within Necking domain in the South and North Lofoten provinces is not as promising as the Vøring margin, the alternative play which should be considered is the Lower Cretaceous play. Seismic interpretation revealed that the Lower Cretaceous sequence within this domain is experienced faulting. The rotated fault block within this domain may be favoured for the hydrocarbon to be accumulated (Figure 6.1-Figure 6.2).

B. Vesterålen-Andøya province

Similar to the South and Lofoten province, within the Necking domain in the Vesterålen and Andøya province, the Jurassic sequence does not appear to be a favourable play, due to the insignificance thickness of the Jurassic sequence within the uplifted footwall. The Upper Cretaceous-Lower Cenozoic sequence is considered to be alternative play within this province due to the fact that they are highly faulted which may a positive indication for trapping mechanism (Figure 4.7 and Figure 4.8). However, the understanding of the Upper Cretaceous-Lower Cenozoic sequence is poor in the Vesterålen-Andøya province, due to no well data and outcrop confirm the presence and the characteristics of this sequence.

In term of reservoir and source rock, a promising indication is observed within the Lower Cretaceous sequence in the Vesterålen-Andøya province. Sedimentary outcrop within northeast Andøya revealed the presence of 40 meter shallow marine sandstone which may a good candidate for reservoir in this province. This sandstone overly by 300 meter Claystone within the northeast Andøya (Figure 4.12).

8 Conclusion

Interpretation of the subsurface data integrated with the potential field data, onshore geology, plate tectonic reconstruction revealed the lateral variation of the tectono-magmatic style along the Lofoten-Vesterålen margin (LVM), which further summarised as follow:

1. The LVM is suggested to experienced time progressive rift segmentation. The first segmentation occurred during Early Cretaceous separating the South Lofoten province to the North Lofoten province by an accommodation/transfer zone. The transfer zone allowed a switch of the fault polarity between each rift segments. The second segmentation is proposed to be initiated during Late Cretaceous separating the Vesterålen-Andøya province to the North Lofoten province. This segmentation is marked by an unique type of deformation involving a thin skinned fault detachment system within the Vesterålen-Andøya province.

2. Two models are proposed to explain the distinctive deformation of the Vesterålen-Andøya province. The first model denote the presence of the transform fault arose with conjunction to the North Atlantic margin opening, which allowed the existing Jurassic fault to be rotated, and created gravitational instability during Late Cretaceous-Early Cenozoic. The gravitational instability cause the Upper Cretaceous-Lower Cenozoic sequence to slid on top of the Lower Cretaceous sequence forming a fault detachment system. The second model suggest the presence of the mantle up-doming within the offshore-onshore Vesterålen-Andøya province. Similar to the first model, the up-doming rotated the Jurassic fault block and induced gravitational instability which further controlled the presence of the fault detachment system.

3. The rift evolution within the LVM is suggested has strong correlation with the rift segmentation, which indicate that a variation of rift evolution may occur within each rift segments. Early Mesozoic to recent margin opening suggests that:

- The Triassic time is represented by the marginal rifting within the South Lofoten province, while no indication of the equivalent event is observed within the North Lofoten and the Vesterålen-Andøya province.
- The Early-Middle Jurassic is represented by a rifting event within the entire margin. Thin (~0,2 seconds TWT) and nearly constant thickness of Lower-Middle Jurassic sequence is

observed, although a wedge shape syn-tectonic deposition was found locally within the entire margin.

- The Early Cretaceous is marked by the main rifting event through the LVM. Thick Lower Cretaceous syn-tectonic deposition sequence (~3 seconds TWT) is observed within the entire margin.
- The Late Cretaceous is characterized by the post rift event within the South and the North Lofoten province, which no prominent deformation observed. However, within the Vesterålen-Andøya province, Late Cretaceous corresponds to the distinctive thin skinned deformation.
- The Cenozoic is suggested to be a major regression event. The Cenozoic prograding wedge indicates that the margin opening was loaded by a large amount of sediment.
- The Plio-Pleistocene is characterised by the glaciation which led to regional uplifting within the entire margin.

4. The extension mechanism of the LVM is still questionable due to the fact that each model (orthogonal vs. oblique rifting) is still plausible. The onshore-offshore fault families interpretation suggested by Bergh et al. (2007) was not able to convey the presence of an oblique rifting, due to the fact that there is an uncertainty within the timing of the onshore fault and lineament. The existing onshore lineament may have been initiated Pre-Mesozoic.

5. The identification of the rift domain architecture within the LVM revealed the difference of the rift domain architecture between the lower-plate (hyper-extended) and upper-plate (non-hyper extended) passive margin. The prominent difference are the absence of the Outer domain and Hyper-Extension/Distal domain within an upper-plate passive margin.

6. The available data used for the rift domain architecture characterization within the East Greenland margin shows identical 1st order domain architecture similarities, consisting: Proximal, necking and oceanic domain. No Outer and hyper-extended domain was observed within the East Greenland margin.

7. Finally, the characterization of the rift domain architecture within the Vøring margin suggest a remarkable correlation between the Necking domain and the distribution of petroleum accumulation. The Necking domain appear to be favourable for all of the

petroleum system elements, which further establish an outstanding petroleum province in the passive margin setting.

REFERENCES

Bergh, S. G., Eig, K., Kløvjan, O. S., Henningsen, T., Olesen, O. & Hansen, J.-A. 2007. The Lofoten-Vesterålen continental margin: a multiphase Mesozoic-Palaeogene rifted shelf as shown by offshoreonshore brittle fault-fracture analysis. *Norwegian Journal of Geology* 87, 29-58.

Bergh., S.G., Corfu., F., Myhre., P.I., Kullerud., K., Arnitage., P.E.B., Zwaan., K.B., Ravna., E.K.,Holdsworth., R.E., Chattopadhya, A.2012.Was the Precambrian Basement of Western Troms and Lofoten-Vesterålen in Northern Norway Linked to the Lewisian of Scotland? A Comparison of Crustal Components, Tectonic Evolution and Amalgamation History", Tectonics - Recent Advances, Prof. Evgenii Sharkov (Ed.), ISBN: 978-953-51-0675-3, InTech, DOI: 10.5772/48257. Available from: http://www.intechopen.com/books/tectonics-recent-advances/was-the-precambrian-basement-of-western-troms-and-lofoten-vester-len-in-northern-norway-linked-to-th

Blystad, P., Brekke, H., Færseth, R. B., Larsen, B. T., Skogseid, J. & Tørudbakken, B. 1995. Structural elements of the Norwegian continental shelf. Part II: The Norwegian Sea Region. *Norwegian Petroleum* Directorate Bulletin 8, 1-45.

Dalland, A. 1981. Mesozoic sedimentary succession at Andøya, Northern Norway, and relation to structural development of the North Atlantic area. In: *Geology of the North Atlantic borderlands.* (edited by Kerr, J. W. & Fergusson, A. J.). *Canadian Society of Petroleum* Geologist Memoir 7, 563-584.

Doré, A. G., Lundin, E.R., Wienecke., S. 2012, Hyperextension, weakening and crustal folding in the north Atlantic domain. Third Central & North Atlantic Conjugate Margins ConferenceTrinity College Dublin, 22-24 August

Faleide, J. I., Tsikalas, T., Breivik, A. J., Mjelde, R., Ritzmann, O., Engen, Ø., Wilson, J. & Eldholm, O. 2008. Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes* 31(1), 82-91.

Færseth, R. B. 2012. Structural development of the continental shelf offshore Lofoten-Vesterålen, northern Norway. *Norwegian Journal of Geology,* vol. 92., pp 19-40

Fawke, A., Aakre, J., Nygård., A. 2001. Final well report-well 6710/10-1. Statoil.

Fjeldskaar, W., 1997. The flexural rigidity of Fennoscandia inferred from the post-glacial uplift. Tectonics 16, 596-608.

Fjeldskaar, W., Amantov. A, Løtveit,I.F., Grunnaleite, I., Sydnes. M., Jensen, N.B., Gudmundsson,A., Christie, O.H.J., Riis., F. and Kollbotn, L. 2012. Final report: Neogene Uplift of the Barents sea. Tectonor.

Gawthorpe, R.L., Sharp, I., Underhill, J.R., Gupta, S., 1997. Linked sequence stratigraphic and structural evolution of propagating normal faults. Geology 25 (9),

Gibbs, A.D., 1983. Balanced cross-section construction from seismic sections in area of extensional tectonics. Journal of Structural Geology 5, 153-160.

Gibbs, A.D., 1984. Structural evolution of extensional basin margins. Journal of the Geological Society of London 141, 609-620.

Gabrielsen, R. H., Odinsen, T. & Grunnaleite, I. 1999. Structuring of the Northern Viking Graben and the Møre Basin; the influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex. *Marine and Petroleum Geology* 16, 443-465.

Henriksen, N., and Higgins, A.K, 2008. Geological research and mapping in the Caledonian orogen of East Greenland 70^0N-82^0N, in Higgins, A.K, Gilotti, J.A., and Smith, M.P., eds, The Greenland Caledonians: Evolutionof the Northeast Margin of Laurentia: Geological Society of America Memoir 202, doi: 10. 1130/2008.1202(01).

Lister, G.S., Etheridge, M. A. & Symonds, P. A. 1986. Detachment faulting and the evolution of passive continental margins. Geology 14, 246-250

Parry, C., 2012. Opening of the north Atlantic & Norwegian-Greenland sea: Lessons from the south & central Atlantic ocean. 30th Nordic Geological Winter Meeting

Peron-Pinvidic, G., Manatschal, G., Osmundsen, P.T., Structural comparison of archetypal atlantic rifted margins: A review of observations and concepts, Marine and Petroleum Geology (2013), doi: 10.1016/j.marpetgeo.2013.02.002

McKenzie, D., 1978. Some remarks on the development of sedimentary basins, *Earth* and Planet Sci. lett., v. 40, 25-32

Miller, E.L., Gans., P.B., and Garing,J. 1983. The snake range decollement: An exhumed mid-Tertiary brittle-ductile transition: Tectonics, v.2, p 239-263

Riis, F. and Fjeldskaar, W., 1992. On the magnitude of the Late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea. In: Larsen, R.M., Brekke, H., Larsen, B.T. and Talleraas, E. (eds.). Structural and tectonic moddeling and its application to petroleum geology. Norwegian Petroleum Society, pp. 163-185. Elsevier

Rohrman and Van der Beek, 1996. Cenozoic postrift domal uplift of North Atlantic margins: An asthenospheric diapirism model, *Geology* 1996;24;901-904

Stensland, D. & Austlid T. 2001. Final well report-well 7019/1-1. Norsk Agip A/S.

Torsvik, T.H., Carlos, D., Mosar, J., Cocks, L.R.M. & Malme, T., 2002. Global reconstructions and North Atlantic palaeogeography 400 Ma to Recent. In: Eide, E.A. (coord.). BATLAS - Mid

Norway plate reconstructions atlas with global and Atlantic perspectives. Geological Survey of Norway, pp. 18-39.

Tsikalas, F., Faleide, J. I. & Eldholm, O. 2001. Latteral variations in tectono- magmatic style along the Lofoten-Vesterålen volcanic margin off Norway. *Marine and Petroleum Geology* 18, 807-832.

Tsikalas, F., Faleide, J. I., Eldholm, O. & Wilson, J. 2005. Late Mesozoic-Cenozoic structural and stratigraphic correlations betweenthe conjugate mid-Norway and NE Greenland continental margins. In: *Petroleum Geology: North-West Europe and Global Perspectives* - Proceedings of the 6th Petroleum Geology Conference (edited by Doré, A. G. & Vining, B. A.). Geological Society, London, 785-801.

Van der Pluim, B. and Marshak, S., 2004. Earth structure 2nd edition, W.W.Norton & Company Inc, New York.