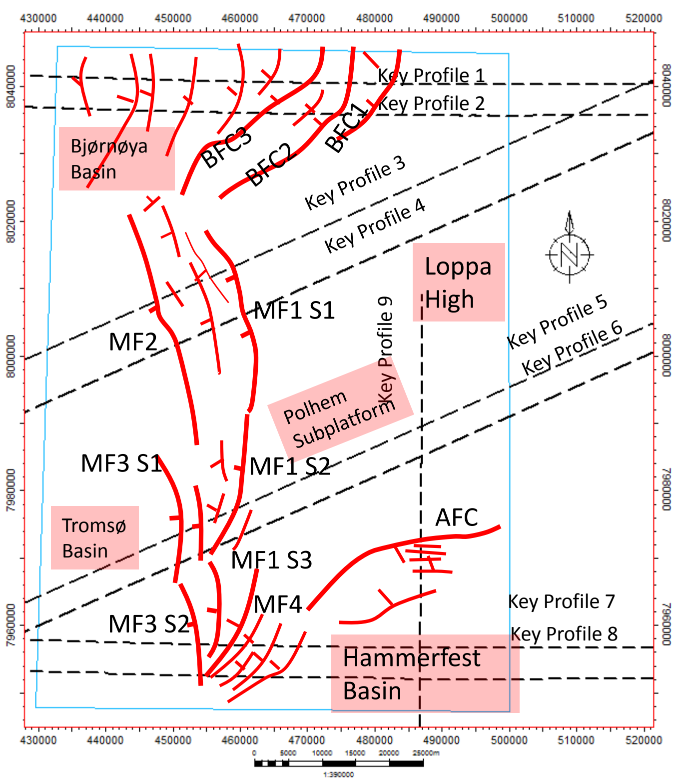
Master Thesis, Department of Geosciences

Structural Analysis of the Northern Ringvassøy-Loppa Fault Complex in the Southwestern Barents Sea

Tauqeer Ahmad Saadi



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Structural Analysis of the Northern Ringvassøy-Loppa Fault Complex in the Southwestern Barents Sea

Tauqeer Ahmad Saadi

Master Thesis in Geosciences

Discipline: Geology

Department of Geosciences

Faculty of Mathematics and Natural Sciences

University of Oslo

10.03.2014

Tutor (s): **Prof. Jan Inge Faleide, Dr. Michael Heeremans, and Dr. Sebastien Gac UiO**

This work is published digitally through DUO – Digitale Utgivelser ved UiO

http://www.duo.uio.no

It is also catalogued in BIBSYS (http://www.bibsys.no/english)

Abstract

The northern Ringvassøy-Loppa Fault Complex consists of extensional faults which separate the Tromsø and Hammerfest basins in south; the Loppa High and Tromsø Basin in center; and the Polhem Subplatform and Tromsø Basin in the northernmost part.

2D seismic interpretation has been carried out, to figure out general fault dips, location of fault nucleation, and detachment zones. In addition to this, basin modelling has been performed to investigate stretching factors.

The northern Ringvassøy-Loppa Fault Complex consists of normal listric faults which dip from 37° to 54° towards west. This fault complex may be classified as Class1 type of Gabrielsen (1984) as it is basement involved fault and has regionally tectonic influence.

Numbers of segments are found in fault complex which are synthetic and collectively have collateral relationship with each other. The fault segment between the Loppa High and Tromsø Basin shows maximum displacement along the strike and probably indicates location of fault nucleation.

Expansion growth index indicates that this fault complex remained active from Early Permian to Late Permian times and fault activity culminated from Middle Jurassic to Early Cretaceous times. Faults also reactivated in Early Aptian and Eocene times.

Probably there are three detachments which are approximately located between the Intra Permian and Top Permian, the Base Cretaceous and Intra Cretaceous, and the Intra Cretaceous and Base Tertiary.

Basin modelling of reveals that the Tromsø Basin has gone through great extension and stretching factor lies between 2.2 and 2.4. This model predicts oil and gas occurrence which coincide nicely with oil discovery in the area.

Acknowledgement

First of all, I would like to express my deep gratitude to my supervisor Jan Inge Faleide for his valuable guidance and help throughout the tenure of my thesis work. I am also grateful to Michael Heeremans for providing assistance in the project. And big thanks to Dr Sebastien Gac for providing me constant help in Basin Modelling part.

Thanks to TGS and Fugro for providing seismic lines for this project.

I am also thankful to department's IT staff, management and all those hands which remained involved in providing me assistance.

Words become shorter to say thanks to my family and brother who kept on encouraging me from outside Norway.

I am thankful to my thesis colleagues Tausif Ahmad and Peter Hansford. Discussion with these guys always remained a valuable asset. Muhammad Jamil and Arif Butt also helped me from time to time. I wish you guys all the best.

At the end, I want to express my deep gratitude to this beautiful country and its nice people to make my educational tenure, perhaps the most memorable time of my life. Wherever, I go and wherever I live, my love with this land will remain intact.

T. A. S

Contents

1. Introduction

The Barents Sea is an epicontinental sea surrounded from the north and west by passive continental margins. This sea is situated in the north of Norwegian mainland; and in the south of Franz Josef Land and Svalbard. From the eastern side, it is bounded by Novaya Zemlya which meets to Kola Peninsula in the south (Faleide, 1984). Study area is shown amid regional setting of the southwestern Barents Sea (Fig. 1.1).

Most of the basement rocks in Barents Sea are believed to belong to Caledonides which formed in response to collision between Laurentia and Baltic Shield (Roberts and Gee, 1985). This Caledonide framework influenced later structuring of the Barents Sea (Gudlaugsson et al, 1998; Ritzmann and Faleide, 2007). Because zones of weaknesses exist in the Barents Sea, some of these weak zones even belong to pre-Caledonian age which reactivated in geological pasts even after collapse of Caledonides (Gudlaugssonet al, 1998). Ringvassøy-Loppa Fault Complex is believed to develop along one of these weak zones and the northern part of this fault complex is situated in study area.

The main purpose of this study is to analyze Ringvassøy-Loppa Fault Complex in detail. Special emphasize has been put on determining the general geometry, segments linkage, evidence of possible detachments and timing of the faults. For this purpose 2D seismic lines have been mapped and all faults have been marked to deduce the general structure of the area. Horizons have been correlated with seismic sequences to see the relationship between faulting and deposition.

Basin modelling is also done to see how much stretching has been experienced by crust after rifting events.

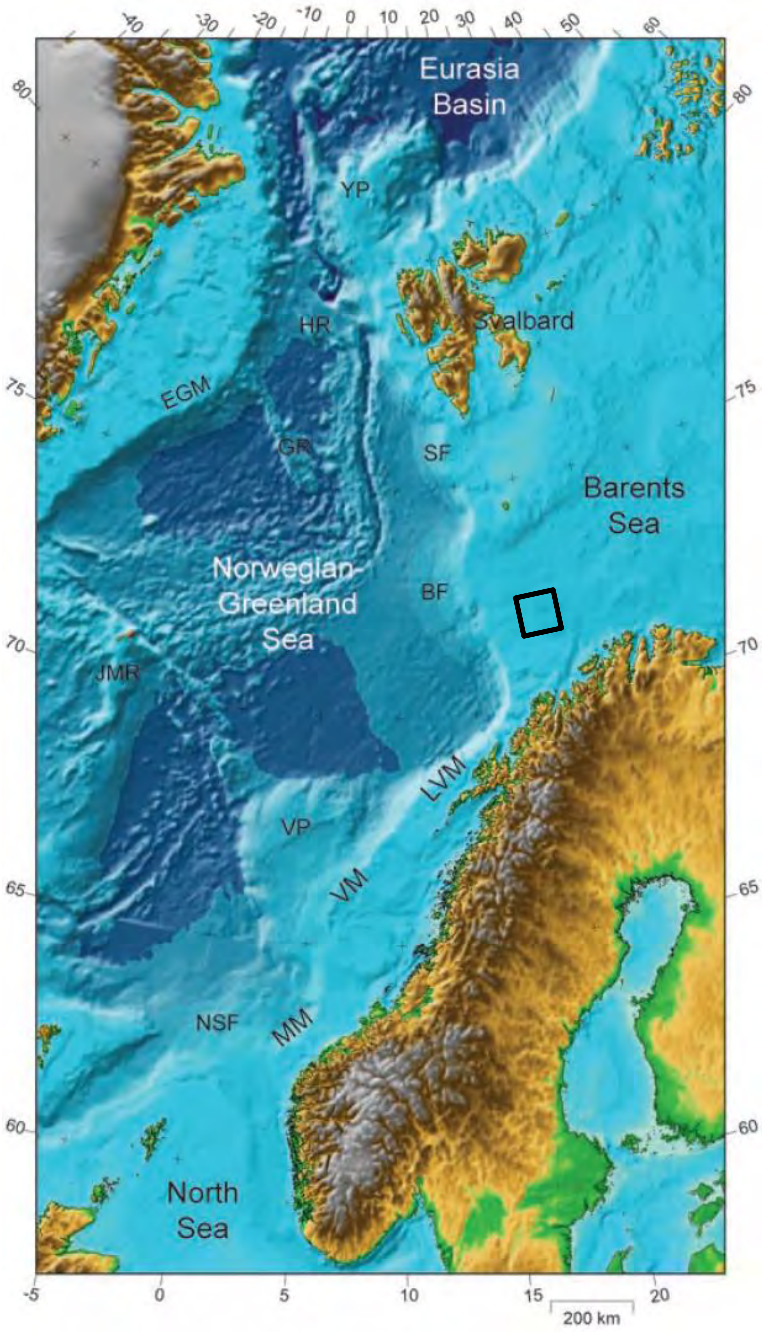


Figure 1.1: Regional setting of the southwestern Barents Sea. Study area has been indicated with black rectangle box (Modified from Faleide et al., 2008).

2. Geological Settings

The western Barents Sea is a part of the continental shelf of north-western Eurasia which was formed by two main continental collisions (Dore, 1995) and is bounded by the Eurasia Basin to the north and by younger passive margins to the west which were developed in response to Cenozoic opening of the Norwegian Greenland Sea (Fig. 2.1) (Faleide et al., 2010; Gabrielsen et al., 2011).

Based upon the sedimentary infill, tectonic style and crustal structure Faleide et al. (1993a and 2010) divided the western Barents Sea into distinct regions:

The Svalbard Platform which is stable since Late Paleozoic covered by relatively flat lying Upper Paleozoic and Mesozoic succession dominated by Triassic sediments.

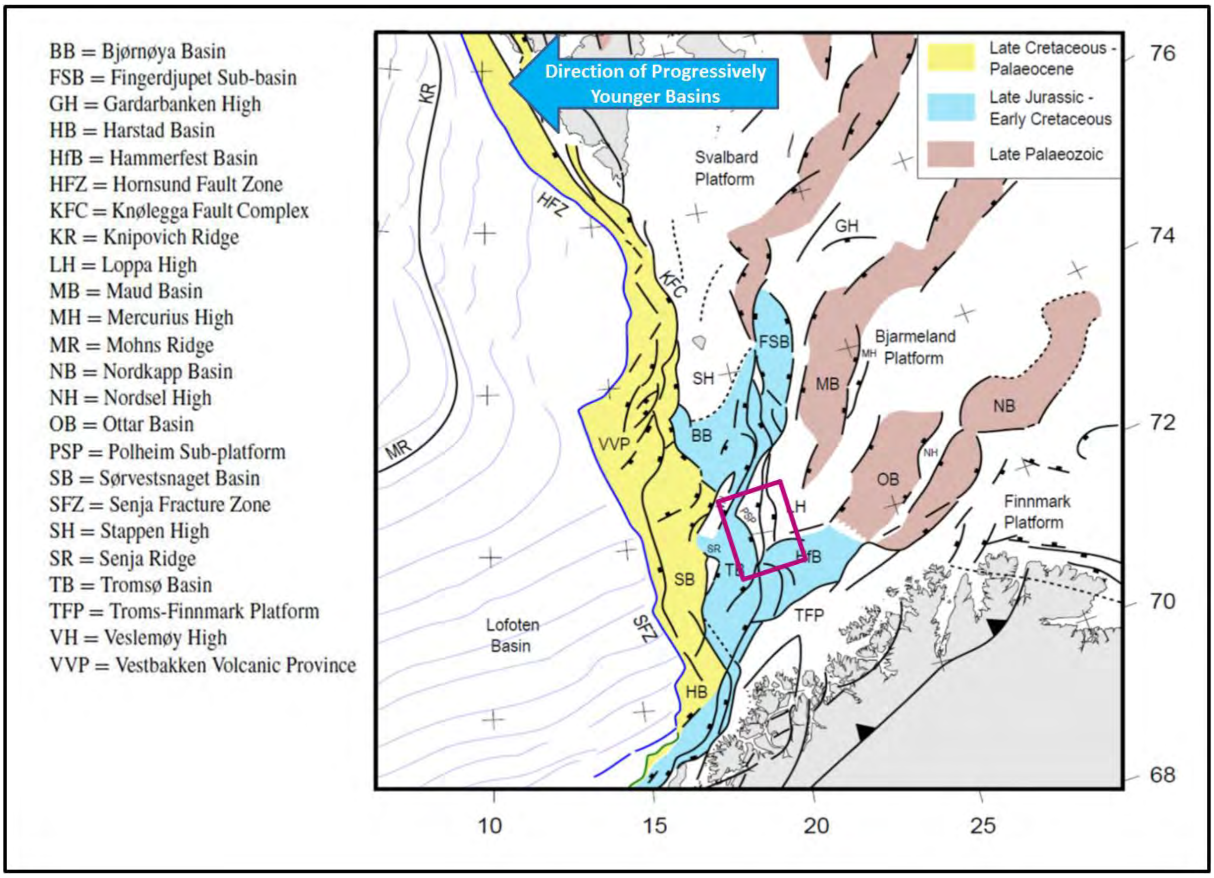


Figure 2.1Main structural elements of Barents Sea, basins become younger from east to west, red box points to the location of study area (modified from Faleide et al., 2010).

The Basin Province is characterized by number of sub basins and highs with increasing structural relief between Svalbard Platform and Norwegian Coast.

The western margin comprises of three major elements; Firstly, a southern sheared margin along the Senja Fracture Zone (SFZ). Secondly, a central rifted complex SW of Bjørnøya associated with volcanism. And thirdly, a northern, initially sheared and later rifted margin along the Hornsun Fault Zone (HFZ). Tertiary breakup encompasses the continent-ocean transition in the form of narrow zone and the margin is overlain by a thick upper Cenozoic sedimentary wedge.

The structural evolution of the South Western Barents Sea has been governed by several tectonic phases since Paleozoic time and culminates with seafloor spreading in the early Cenozoic time.Oceanic subduction and subsequent collision between the Precambrian Baltic Shield and Laurentia during Ordovician to Early Devonian resulted in the formation of the Caledonian Orogen (Roberts & Gee, 1985; Roberts, 2003) and this gain is believed to later control structural evolution of the area (Faleide et al., 1984; Gudlaugsson et al., 1998; Breivik et al., 2002; Ritzmann & Faleide, 2007).

The post-Caledonian geological evolution of the western Barents Sea is controlled by an extensional regime since at least Early Carboniferous times (Ziegler, 1988; Dore, 1991), culminating with seafloor spreading in the early Cenozoic (Faleide et al., 1993a, 2008) and can be divided into various episodes which are given below:

During the Late Palaeozoic two main extensional periods affected the area were Late Devonian to mid-Carboniferous and Late Carboniferous tolate Permian (Lippard and Roberts, 1987; Gabrielsen et al., 1990; Nøttvedt et al., 1990; Dengo & Røssland, 1992; Jensen & Sørensen, 1992; Gudlaugsson et al., 1998; Clark et al., 2013). While the dominant phase was of crustal extension which resulted in the formation of several interconnected basins separated by fault-bounded highs. Selis Ridge is one of the important Late-Paleozoic structured high (Glørstad-Clark et al., 2011). Tromsø, Nordkapp, Bjørnøya, Hammerfest, Fingerdjupet, Maud and other basins formed during this time and the dominant deformation mechanism was basement-involved normal faulting (Dengo & Røssland, 1992). The resulted basins served as depocenters for alluvial fan and floodplain clastic sediments together with the carbonates (Steel & Worsley, 1984; Gabrielsen et al., 1990; Dengo & Røssland, 1992). Hammerfest Basin is also believed to have been formed during this phase (Dengo &

Røssland, 1992; Jensen and Sørensen, 1992). Upper Carboniferous – lower Permian shallow-water carbonate platform with evaporitic sequence filled the structural relief (Faleide et al., 1984; Larssen et al., 2005). A transition to clastic deposition occurred in response to the Uralian orogeny in the southeast and landmasses to the south during latest Permian time (Johansen et al., 1993).

No major tectonic activity has been recorded in the region making latest Permian to Triassic relatively quiet period. However, tilting influenced the relief of the Selis Ridge (Gabrielsen et al., 1990; Johansen et al., 1993; Glørstad-Clark et al., 2010). Typical rift-related faulting is notably absent, however, Salts tectonics influenced depositional pattern in the Nordkapp and Maud basins during Triassic (Gabrielsen et al., 1990; Faleide et al., 1993a, b). Several phases of minor uplift during Early–Middle Triassic characterized sediment progradation while The Selis Ridge acted as a barrier (Glørstad-Clark et al., 2010).

Major rifting event between Norway and Greenland was initiated which led to the widespread rifting accompanied by strike-slip adjustments along old structural lineaments characterized the late Middle Jurassic–Early Cretaceous in the south-western Barents Sea. The main zone of deformation remained west of the Loppa High which was also inverted in latest Jurassic earliest Cretaceous times (Dengo & Røssland, 1992; Faleide et al., 1993a). In the Middle-Late Jurassic, the SW Barents Sea underwent block faulting with major faults trending east and northeast directions which provided accommodation space for relatively narrow, very deep basins, such as the Harstad, Tromsø and Bjørnøya basins and shales were deposited in the restricted basins (Faleide et al., 1993a, b; Breivik et al., 1998), which were developed along with highs marking the termination of block faulting during the period (Gabrielsen et al., 1990).

Early Cretaceous extreme subsidence resulted in the development of major depocentres in the Harstad, Tromsø and Bjønøya basins (Breivik et al., 1998). The structural development became more complicated by local inversion along Ringvassøy-Loppa Fault Complex and its junction with Asterias Fault Complex (Gabrielsen et al., 1990). Reverse faulting and folding along with the extensional faulting in some part of the region took place in the Late-Cretaceous period (Gabrielsen et al., 1990) and The Loppa High was an island throughout the Cretaceous (Faleide et al., 1993a).

Seafloor spreading in the Norwegian-Greenland Sea during in Eocene times culminated the ongoing rifting in the western Barents Sea since Late Cretaceous and resulted in the development of dextral sheared margin along de Geer mega-shear zone with tensional component on the western side of the Barents Sea during the Paleocene-Eocene transition (Faleide et al., 1993; Gabrielsen et al., 2011). Deformation mostly occurred west of the Loppa High and the Senja Ridge along the pre-existing zones of weakness, whereas stable conditions prevailed east of the Loppa High (Dengo & Røssland, 1992).

An event of peak folding and inversion occurred locally during the Eocene and Oligocene periods (Gabrielsen et al., 1990). The northern part of the basin experienced extensional faulting and the deposition of a relatively thick Paleogene succession located just to the south of the rifted segment. Faults of Early Tertiary age are mostly sub-parallel to the rifted or sheared margin segments. Faults of Early Tertiary age are mostly sub-parallel to the rifted or sheared margin segments. The margin became tectonically quiet during the Oligocene. Approximately 3 km of sediments of the Barents Sea were eroded due to regional subsidence, combined with widespread Neogene uplift, resulted in the de position of a huge sedimentary wedge of Pliocene– Pleistocene age at the margin and in the oceanic basin represents the last episode of the complex western Barents Sea (Nyland et al., 1992; Breivik et al., 1996; Faleide et al., 1996). The western Barents Shelf is experiencing a regional uplift since the mid Miocene to the present (Dengo & Røssland, 1992).

2.1 Structural Elements

The northern part of Ringvassøy-Loppa Fault Complex is the focus of this project and this section provides a brief review of the fault complex and adjacent structural elements is described below (Fig. 2.3).

2.1.1 Loppa High

The Loppa High is situated between 71°50´N, 20°E and 71°55´N, 22°40´E, and 72°55´N, 24°10´E and 73°20´N, 23°E and is believed to be developed as a result of Late Jurassic to Early Cretaceous and Late Cretaceous-Tertiary tectonism (Gabrielsen et al., 1990). Western part of the Loppa High is situated above a Late Paleozoic- Early Triassic paleo-high, termed as Selis Rigdge by Glørstad-Clark et al. (2011).

The Loppa High is being separated from the surrounding basinal areas by major fault complexs. The Asterias Fault Complex is the delineation to the Hammerfest Basin in the south while the Bjørnøyrenna Fault Complex and the Ringvassøy-Loppa Fault Complex are respectively separating the Loppa High Area from Bjørnøya Basin and Tromsø Basin in the west. A monocline towards the Bjarmeland Platform and the Hammerfest Basin respectively marks the eastern and southeastern limit of the Loppa High area while the northeastern boundary is marked by the Svans Dome, a salt structure, and the Maud Basin, the associated rim synclines of the salt (Gabrielsen et al., 1990). The extent of the Loppa High area has also been associated by positive gravity and magnetic anomalies (Barrére et al., 2009).

Several uplifts, subsidence, tilting and erosional events have affected the area since Devonian time. Selis Ridge (Paleo High), was a narrow N-S trending ridge located in the western part of present day Loppa High generated in Late Carboniferous time, but the first major uplift was in Late Permian (Dengo & Røssland, 1992). The Loppa High area remained a positive structural feature until Early to Mid-Triassic time and turned into a depocentre from Late Triassic to Mid Jurassic (Larssen et al., 2005). Due to footwall uplift along the fault complexes on the western margin in Late Jurassic to Cretaceous time, Loppa High area was again uplifted and eroded (Faleide et al., 1993a). It is evident from Early Tertiary onlaps that the high remained a part of a shallow Barents shelf until it was uplifted and eroded again in Neogen time (Wood et al., 1989; Faleide et al., 1993a, b). The lack of post Jurassic sediments in the Loppa High area is result of several uplifts (Gabrielsen et al., 1990; Faleide et al., 1993a; Gabrielsen et al., 1993; Gabrielsen et al., 1997; Glørstad-Clark et al., 2011).

2.1.2 Asterias Fault Complex

The E-W trending Asterias Fault Complex is located between 71°50′N, 20°E and 72°20′N, 24° E. The fault complex separates Hammerfest Basin from Loppa High and is believed to be extensional in origin (Gabrielsen et al., 1990) also known as Southern Loppa High Fault System (Gabrielsen., 1984; Faleide et al., 1984; Berglund et al., 1986). The Asterias Fault Complex was initiated between Triassic to Jurassic and is a basement involved first or second order structure (Gabrielsen et al., 1984).

Half flower structure and local doming associated with the western segment (west of 21o15'E) of Asterias Fault Complex are clues of inversion while its northeasterly segment (northeast of 22oE) developed as a flexure underlain by deep extensional fault (Berglund et al., 1986; Gabrielsen et al., 1990). This fault complex is associated with very complex pattern of southerly and northerly dipping faults (Berglund et al., 1986).

Triassic activity along the Asterias Fault Complex is evident from the increasing thickness of upper Triassic strata towards Loppa High across the fault complex marking it as an inverse structure and Loppa High area as depocentre (Gabrielsen et al., 1990). Strong uplift took place during Early Cretaceous along the fault complex reflected by Onlaps of Aptian- Albian reflectors on the eroded part of the Loppa High (Gabrielsen et al., 1990). Asterias Fault Complex is believed to be extensional in origin (Gabrielsen, 1984; Gabrielsen et al., 1990), however, it is suggested that this fault zone had experienced compressional strike-slip movement and this structure collapsed into normal fault at the beginning of Cretaceous time (Berglund et al., 1986).

2.1.3 Bjørnøyrenna Fault Complex

The Bjørnøyrenna Fault Complex has a general NE-SW trend separating the Loppa High to the south east and Bjørnøya Basin to the southwest and is situated between 72° N′ 19° E and 73° 15′ N, 22° E (Gabrielsen et al., 1990).

The Bjørnøyrenna Fault Complex exhibits very complex geometry and has undergone multiple phase of deformation with time and is considered to be the northeast extension of Ringsvassøy-Loppa Fault Complex. Generally the complex is defined by an extensional origin and differentiated by listric fault geometries which get flatten into detachment in Permian rocks (Faleide et al., 1993) and lies over crustal zone of weakness.

A vertical displacement of about 6 second (TWT) on the Upper Triassic level occurred across the Bjørnøyrenna Fault complex and the throw terminates to the North and South (Gabrielsen et al., 1990). In addition the faults have been experienced strong deformation of the footwall block, reverse faults and deformed fault planes (Gabrielsen et al., 1984) which led to the two episodes of inversion in the Bjørnøyrenna Fault Complex. The early cretaceous time is dominated by strike slip movement whereas the late Cretaceous- early Tertiary age experienced compressional inversion with orientation of NW-SE (Gabrielsen et al., 1997).

2.1.4 Polhem Subplatform

Polhem Subplatform consists of a block faulted subplatform and the faults blocks are rotated and the faults are listric normal faults with a detachment zone deeper than Base Triassic. The Subplatform lies between the Loppa High area to the east, and to the west bounding by Ringvassy-Loppa and Bjørnøyrenna Fault Complexes. The faults got the listric geometry in Late Jurassic to Early Cretaceous time, and reactivation has occurred at later stages. The Jurassic rocks have been eroded from the platform (Gabrielsen et al., 1990).
The N-S trending bounding faults between the subplatform and the Loppa High area have been given the name Jason Fault Complex by Glorstad-Clark et al. (2011) and these faults are dominantly extensional with down to west displacement.

2.1.5 Hammerfest Basin

The Hammerfest Basin is relatively shallow complex sedimentary basin with ENE-WSW orientation (Fig. 2.3). This 70 km wide and 150 km long basin was developed during the second (Mesozoic) phase in Barents shelf (Berglund et al., 1986) while the depth of the basement in the Hammerfest Basin is 6-7 km (Roufosse, 1987).

The basin is separated from the Loppa High in the north by Asterias Fault Complex and from Finnmark Platform in the south by Troms-Finnmark Fault Complex. Its eastern limit is developed as a flexure against the Bjarmeland Platform (Larssen et al., 1990) while presence of the southernmost segment of the Ringvassøy-Loppa Fault Complex marks its western margin where the western Hammerfest Basin dips towards the Tromsø Basin in the West. It can be divided into a western and eastern sub basin on the basis of NW-SE striking offshore extension of Trollfjord-Komagelv Fault (Ziegler et al., 1986; Gabrielsen & Færseth, 1989; Gabrielsen et al., 1990).

Gabrielsen (1984), named the internal fault system with E-W, ENE-WSW and WNW-ESE trending faults as the Hammerfest Basin fault system. Major structural evolution of Hammerfest Basin was result of extensional deformation and it includes both deep, high-angle faults along the basin margin and listric normal faults detached in Permian sequence, situated more centrally in the basin (Berglund et al., 1986; Gabrielsen et al., 1990; Faleide et al., 1993).

Hammerfest Basin separated from Finnmark Platform during Late Carboniferous although, the Hammerfest Basin can be identified as a distinct entity already during Late Scythian time the Tromsø and Hammerfest basins were probably inter-related parts of a border epeiorgenic depositional system in the Triassic to Early Jurassic. The present day boundaries of the basin were formed from the Mid Jurassic. The main subsidence of the basin happened during the Early Cretaceous (Berglund et al., 1986; Gabrielsen et al., 1990).

2.1.6 Tromsø Basin

The NNE-SSW trending Tromsø Basin containing a series of salt diapirs linked by a smooth flexure with this trend and is bounded by the Ringvassøy- Loppa Fault Complex in the east and the Senja Ridge on the western side. The Veslemøy High is an intra basinal high separates it from Bjørnøya Basin in the north and towards south; Troms-Finnmark Fault Complex separates it from Finnmark Platform (Fig. 2.3) (Gabrielsen et al., 1990).

Gabrielsen (1984), named the detached related fault system as Tromsø Basin Fault System. The basement depth has been estimated based on gravity data is 10-13 km (Roufosse, 1987;

Gabrielsen et al., 1990), while the depth of the basin floor can only be estimated in the northern segment of the basin corresponding to 7.5 s twt (Brekke &Riis, 1987; Gabrielsen et al., 1990).

In the north, Tromsø Basin may have existed as a separate basin during salt deposition in Late Paleozoic time suggested by the presence of the north-north-east trending salt diapirs of Tromsø Basin (Dengo & Rossland, 1992; Jensen & Sørensen, 1992; Faleide et al., 1993; Gudlaugsson et al., 1994; Breivik et al., 1995) but was united with the Bjørnøya Basin later on and was not separated again until the Late Cretaceous Faulting along the eastern margin of the basin started in the Middle Jurassic and separated the basin from the Hammerfest Basin in the Early Cretaceous (Gabrielsen et al., 1990).

2.1.7 Ringvassøy-Loppa Fault Complex

The Ringvassøy-Loppa Fault Complex can be followed between 70°50′ N, 19°30′ E and approximately 72°20′N, 19°30′ E. Ringvassøy-Loppa Fault Complex has a general NNE-SSW strike. The northern part of the fault complex develops into a narrower zone and makes the transition between the Tromsø Basin and the Loppa High, and farthest north the transition between the Tromsø Basin and Polhem subplatform (Gabrielsen et al., 1990). The fault complex defines the western boundary of the Loppa High to the north where it consists of several high-angle normal faults merging into detachment deeper than Triassic (Faleide et al., 1993).

To the south, the fault complex merges into the southern part of the Troms-Finnmark Fault Complex separating Mesozoic age Hammerfest Bain in the east from Tromsø Basin in the west that experienced extensive subsidence in Cretaceous to Tertiary time (Gabrielsen et al., 1990; Faleide et al., 1993) (Fig. 2.5). This southern part of the Ringvassøy-Loppa Fault Complex was refferred as the Tromsø Basin/Hammerfest Basin Transition Zone (THTZ) and NNE-SSW striking swarms of the faults cross-cutting the E-W system of the Hammerfest Basin characterizes this zone by(Fig. 2.3) (Gabrielsen, 1984).

It is suggested that the fault complex was initiated already in Late Paleozoic time, and that basement movements have caused the fault complex to work as a long lived hinge line, based on a deep seated zone of weakness (Gabrielsen, 1984; Berglund et al., 1986). The eastern limit of the Paleozoic salt in the Tromsø Basin appear to be coincident with the Ringvassøy-Loppa Fault Complex and other observations that support the activity along Ringvassøy-Loppa Fault Complex at this early stage include the Permian movement shown by the western boundary faults of Loppa High (Gudlaugsson et al., 1998) and a slightly positive gravity anomaly is also supporting the presence of a deep zone of weakness in the fault complex (Gabrielsen et al., 1990).

Significant subsidence of the Tromsø Basin to the west suggested by the main displacement along the fault complex was recorded at Mid Jurassic (Gabrielsen, 1984; Gabrielsen et al., 1990; Dengo & Røssland, 1992; Faleide et al., 1993; Gudlaugsson et al., 1998; Gudlaugsson et al., 1994; Gabrielsen et al., 1997).

3. Seismic Interpretation & Results

The aim of this study is to analyze the Ringvassøy-Loppa Fault Complex; reactivation of this fault complex within the framework of regional tectonics; identification of possible detachments reported by previous workers in this fault complex; linkage relationship between individual faults etc. This chapter is about available data, interpretation procedure and difficulties faced during interpretation. Key profiles will also be presented in this chapter.

This study has been accomplished in four phases. These phases are interlinked with each other but have overall different tasks. The work flow and different phases are shown in (Fig. 3.1). In the first phase of this study, seismic lines were uploaded and a grid was formed in the study area; wells were projected and tied with seismic lines; and interpretation of key reflections was carried out and faults were marked. The second phase dealt with the creation of fault maps, time-structure maps and time-thickness maps. The third phase dealt with the basin modeling using TecMod. In this phase stretching factors and thermal maturity are discussed.

In the fourth phase, detailed analysis of fault complexes was carried out; possible position of detachments was identified; linkage relationship between faults was studied; timing of faults and reactivation of faults were established; classification of faults was also determined.

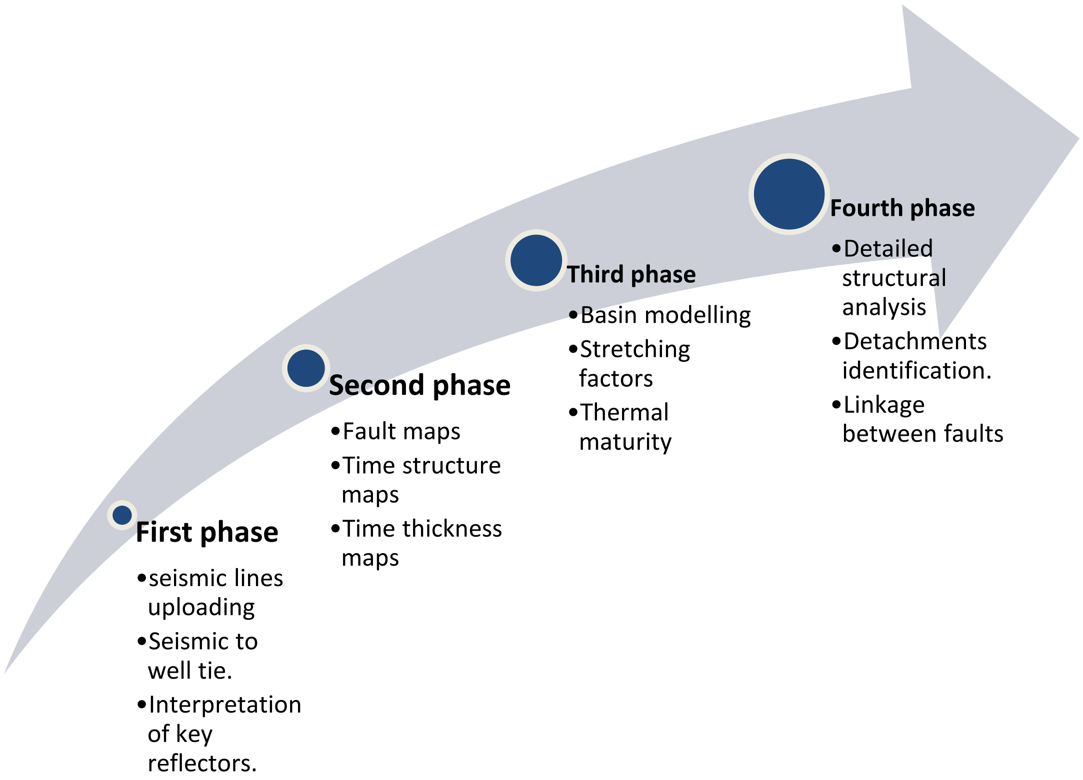


Figure 3.1: Work flow for this study.

3.1 Data

Seismic lines and six wells are the initial data through which this study is initiated. Wells were tied to seismic lines for stratigraphic calibration. Petrel software was used for seismic interpretation and fault analysis. Later marked surfaces in Petrel were exported into TecMod and basin modeling was carried out.

3.1.1 Seismic lines

There are two available seismic surveys. Both of these surveys consist of 2D seismic lines. But these surveys differ in terms of their orientation, coverage and resolution. One survey has NE-SW oriented seismic lines (Fig. 3.2). These lines have coverage up 12 s twt and have better resolution. But at certain places these seismic lines are not perpendicular to RLFC. That is why these are not solely used for fault interpretation. These provide better information about deeper reflectors in deeper basins. This survey has NBR06, NBR07 and NBR08 lines acquired by TGS and Fugro from 2006 to 2008 (www.npd.no).

The second survey has E-W and N-S lines (Fig. 3.2) and has coverage from 6 to 7 s twt. This survey was conducted by NPD between 1974 and 1984 (www.npd.no). These seismic lines do not provide information about deeper horizons (Base Cretaceous and Intra Jurassic) in Tromsø Basin and have poor resolution. But still these lines are useful when their orientation is perpendicular to faults.

3.1.2 Wells

A large number of wells have been drilled in study area but only six wells have been tied with seismic lines to confirm the position of reflectors intended to be interpreted. Well tops have been taken from Norwegian Petroleum Directorate as shown in Table 3.1. The position of these wells is shown in Fig. 3.2. Loppa High, Hammerfest Basin and Bjørnøya Basin contain two wells each. Lithologies of these structural elements vary greatly and the information we get from these wells is very diverse. For instance, that part of Loppa High which covers our study area is devoid of rocks younger than Triassic. But wells of Loppa High provide good control on the deeper reflectors. On the contrary, available wells in Hammerfest and Bjørnøya basins have not penetrated deeper than Intra Jurassic level (Table 3.1).

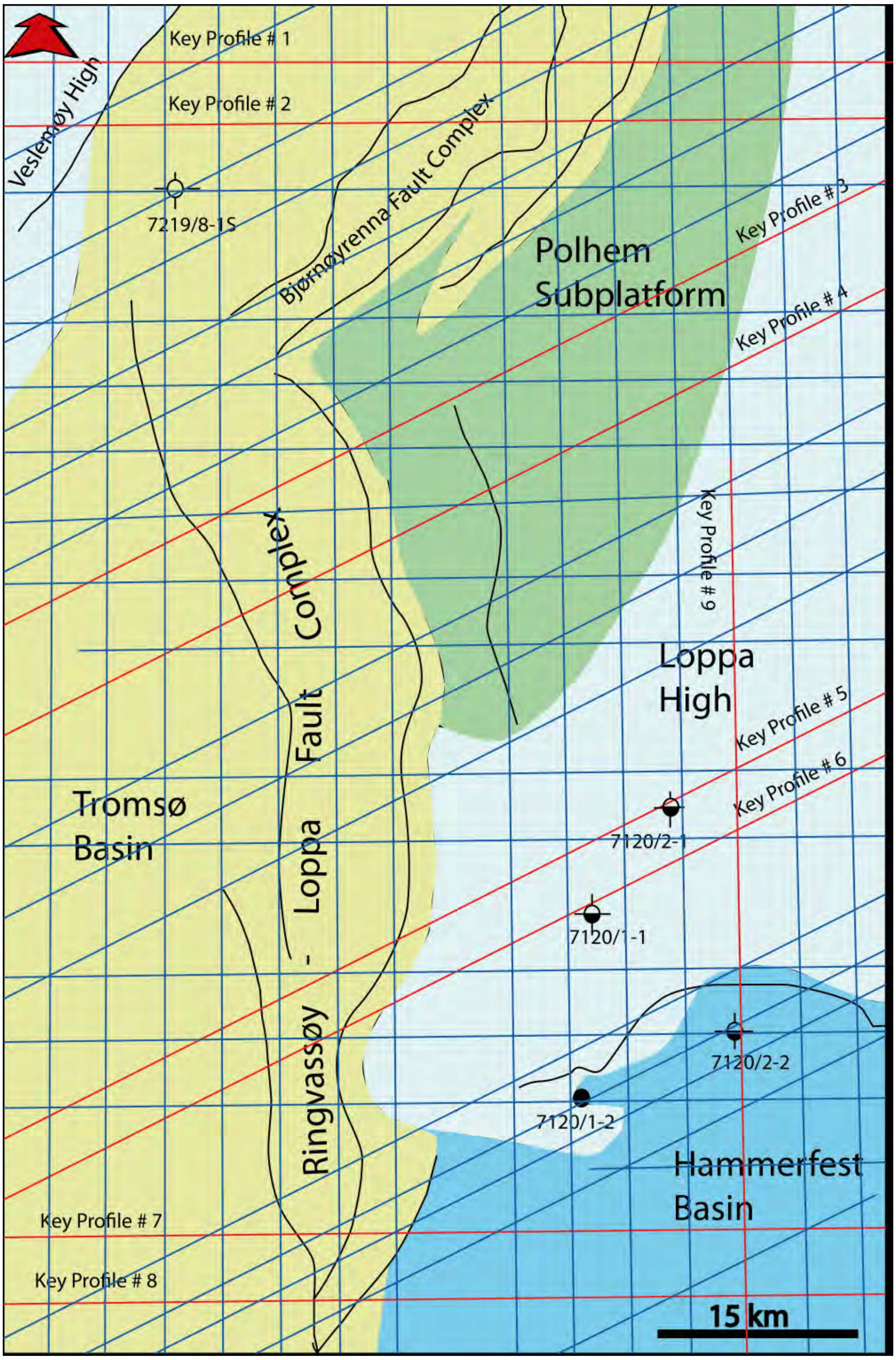


Figure 3.2: Study area with different geological provinces, seismic lines covering area and position of available wells for well-tie. Key profiles are shown in red color.

3.1.3 Wells Ties

Two wells (7120/1-1 and 7120/2-1) on the Loppa High have been tied for interpretation purpose (Fig. 3.3). Position of these wells is shown in Fig. 3.2. These wells are situated in the southwestern part of the Loppa High and provide control on the Top Permian and Intra Permian reflectors. Though Falk and Ugle formations of Carboniferous age, coincide reasonably well with the well tops of 7220/2-1 these reflectors have not been interpreted due to the fact that these reflectors are only resolved in the Loppa High and the do not provide information across the fault complexes. Data of these wells (Table 3.1) also indicates that these wells do not have rocks younger than Jurassic and Cretaceous. There is a thin unit of the Kapp Toscana Group but it is negligible. Torsk Formation of Oligocene age is directly overlying Triassic rocks of the Kapp Toscana Group. However in this study the youngest rock interpreted, in Loppa High, is Snadd Formation of Late Triassic age. Four reflectors have been tied with these wells (Fig. 3.3).

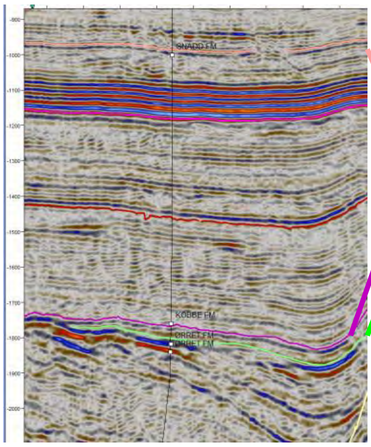
Another point which needs attention is that out of these two well, one well provides control on Intra Permian and other on Top Permian (Fig. 3.3). These two reflectors are the deepest reflectors which have been interpreted for this study.

After getting control on Loppa High, two wells (7120/1-2 & 7120/2-2) have been tied in the Hammerfest Basin, which provide good control on Base Tertiary, Intra Cretaceous, Base Cretaceous and Intra Jurassic. Position of these wells can be seen in Fig. 3.2 and well tie is shown in Fig. 3.4. Most of the older well tops of available wells, found in Loppa High, are not found in other geological elements of study area. And well tops of available wells (7120/1-2 & 7120/2-2) have not penetrated deeper than Jurassic age.

Table 3.1: Well tops of six wells. Selected horizons with their interpretive color scheme have been shown in this table. Well top taken from www.npd.no.

Age	Group/ Formation	7120/2-1	7120/1-1	7120/2-2	7120/1-2	7219/8-1S	7219/9-1
		Loppa High		Hammerfest Basin		Bjørnøya Basin	
Cenozoic	Sotbakken Gp	476	490	437	408	393	483
	Torsk Fm	476	490	437	408	554	483
Cretaceous	Nygrunnen Gp	Missing	Missing	1443	1560	Missing	Missing
	Kveite Fm	Missing	Missing	1443	1560	Missing	Missing
	Adventdalen Gp	Missing	Missing	1450	1585	1545	1468
	Kolmule Fm	Missing	Missing	1450	1585	1545	1468
	Kolje Fm	Missing	Missing	1948	1826	2080	
	Knurr Fm	Missing	Missing	2120	1878	2494	1836
Jurassic	Hekkingen Fm	Missing	Missing	2503	1984	3472	1893
	Fuglen Fm	Missing	Missing	2656	2158	4328	1919
	Kapp Toscana Gp	613	692	2692	2211	4521	1951
	Stø Fm	Missing	Missing	2692	2211	4521	1951
	Nordmela Fm	Missing	Missing	Not Penetrated	2365	Not Penetrated	2062
	Tubåen Fm	Missing	Missing	Not Penetrated	2452	Not Penetrated	2206
Triassic	Fruholmen Fm	Missing	692	Not Penetrated	2506	Not Penetrated	2305
	Snadd Fm	613	1106	Not Penetrated	Not Penetrated	Not Penetrated	2877
	Sassendalen Gp	1933	2285	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Kobbe Fm	1933	2285	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Klappmyss Fm	Missing	2315	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Havert Fm	Missing	2375	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
Permian	Tempelfjorden Gp	Missing	2403	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Ørret Fm	Missing	2403	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Røye Fm	Missing	2430	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Gipsdalen Gp	1945	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Ørn Fm	1945	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
Carboniferous	Falk Fm	2024	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Ugle Fm	2221	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Billefjorden Gp	2624	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Undifferentiated	2624	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated
	Basement	3471	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated

7120/1-1



Reflector	Formation	7120/1-1 Depth m	7120/2-1 Depth m
LT	Snadd	1106	613
MT	Kobbe	2285	1933
TP	Ørret	2403	
IP	Ørn		1945
ICar	Billefj-orden	2674	

7120/2-1

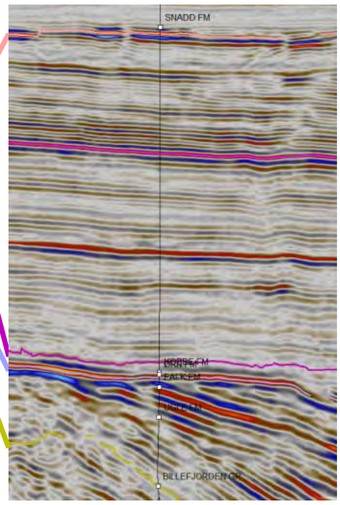
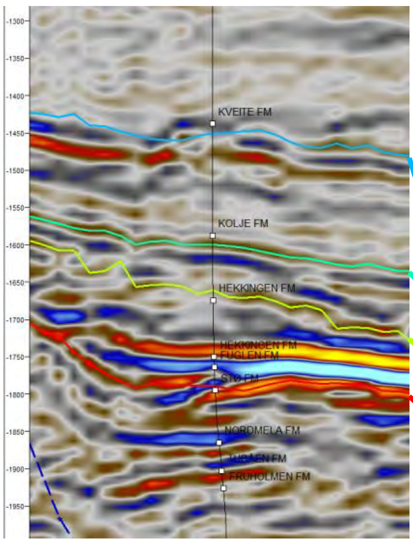


Figure 3.3: Wells of Loppa High are tied with seismic lines and their stratigraphy is calibrated.

Next wells, 7120/1-2 and 7120/2-2, have been drilled on the boundary between the Hammerfest Basin and Loppa High (Fig. 3.4). These wells provide well tops till Middle Jurassic age. Older horizons are not there for well tie.

7120/1-2



Reflector	Formation	7120/1-2 Depth m	7120/2-2 Depth m
BT	Kveite	1560	1443
IC	Kolje	1826	1948
BC	Hekkingen	1984	2503
IJ	Stø	2211	2692

7120/2-2

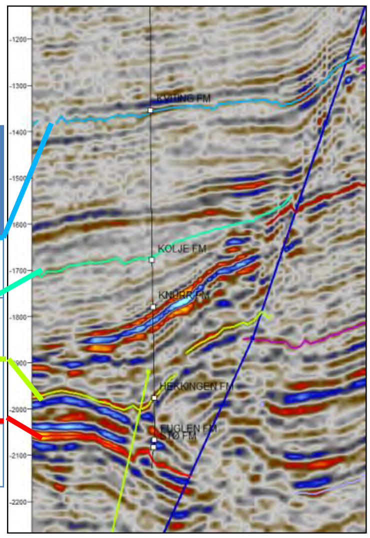
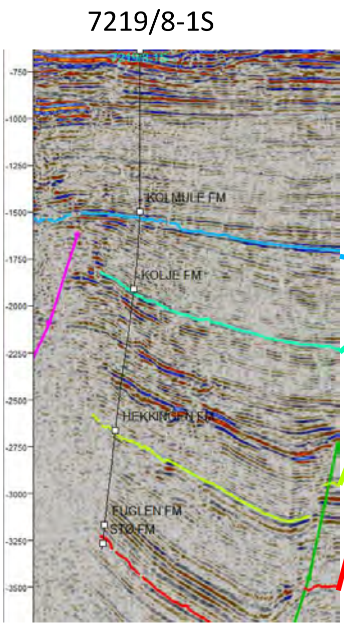


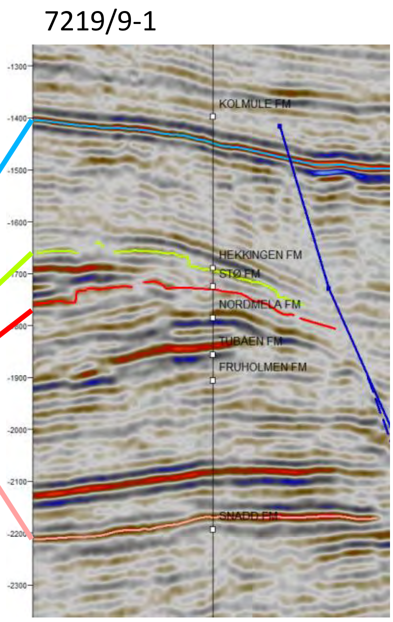
Figure 3.4: Wells of Hammerfest Basin have been tied and stratigraphy is calibrated.

Next two tied wells are present at the transition area between Tromsø Basin and Bjørnøya Basin as shown in Fig. 3.5. According to NPD’s fact pages, these wells have been considered in Bjørnøya Basin. Like Hammerfest Basin, these wells do not give information about reflectors older than Intra Jurassic time.

One interesting thing about these wells is that these wells do not have Kveite Formation which we considered for marking the Base Tertiary. In the absence of that, Top Kolmule Formation acts as the Base Tertiary (Fig. 3.5).



Reflector	Formation	7219/8-1S Depth (m)	7219/9-1 Depth (m)
BT	Kolmule	1545	1468
IC	Kolje	2080	
BC	Hekkingen	3472	1893
IJ	Stø	4521	1951
LT	Snadd		2877



.

Figure 3.5: Well ties from Bjørnøya Basin.

3.2 Interpretation

After well correlation interpretation was done. Eleven horizons were picked for interpretations which are given in Table. 3.2. Top Permian and Intra Permian reflectors provide useful information about Late Paleozoic rifting event. These reflectors are not easy to get control on in Tromsø Basin and have been marked only shallow basins or on Loppa High. Similarly Base Cretaceous and Intra Jurassic reflectors conclude Mesozoic rifting event. Base Tertiary has been marked to see activation of Mesozoic rifting.

Two extra reflectors have been picked at Polhem Subplatform. These reflectors do not coincide with any well top but these reflectors provide better control for lower level reflectors. These two reflectors have been named as Intra Triassic 1 and Intra Triassic 2 because these reflectors belong to Triassic age. These two reflectors belong to S4 sub-sequence of Glørstad-Clark (2011) and belong to Ladinian and Early Carnian age.

Table 3.2: Key reflectors with their respective color scheme and abbreviation.

Reflector	Formation/Group	Abbreviation	Colour Scheme
Base Tertiary	Top Kveite	BT	
Intra Cretaceous	Top Kolje	IC	
Base Cretaceous	Top Hekkingen	BC	
Intra Jurassic	Stø Formation	IJ	
Late Triassic	Snadd Formation	LT	
Intra Triassic 2	E. Carnian *	IT2	
Intra Triassic 1	Ladinian *	IT1	
Middle Triassic	Kobbe Formation	MT	
Top Permian	Ørret Formation	TP	
Intra Permian	Ørn Formation	IP	
Intra Carboniferous	Billefjorden Group	ICar	

* From Glørstad-Clark (2011)

3.2.1 Detail of Key Horizons

Billefjorden Group

Billefjorden Group at Loppa High contains arkosic breccias of varied colors, ignimbrites, conglomerates and other volcanic related clastic deposits (Larssen et al., 2002). This group has been found in well 7120/2-1. This group has been considered basement rock in basin modelling. Mapping below this group is difficultas seismic reflectors are really hard to map below that. No evidence of growth faulting has been found below that.

Age: Larssen et al. (2002) described its age between Famennian to Viséan. For basin modelling purpose, its age has been put to 318 Ma.

Seismic Sequence: Billefjorden Group has been correlated with SS1 of Glørstad-Clark (2011) which is part of megasequence MS1 (Larssen et al., 2005). The base of this sequence is associated with the basement rocks and bounded at the top by continuous reflector which is probably a flooding surface. Sub-parallel reflections with lower chaotic part; characterize this sequence (Glørstad-Clark, 2011).

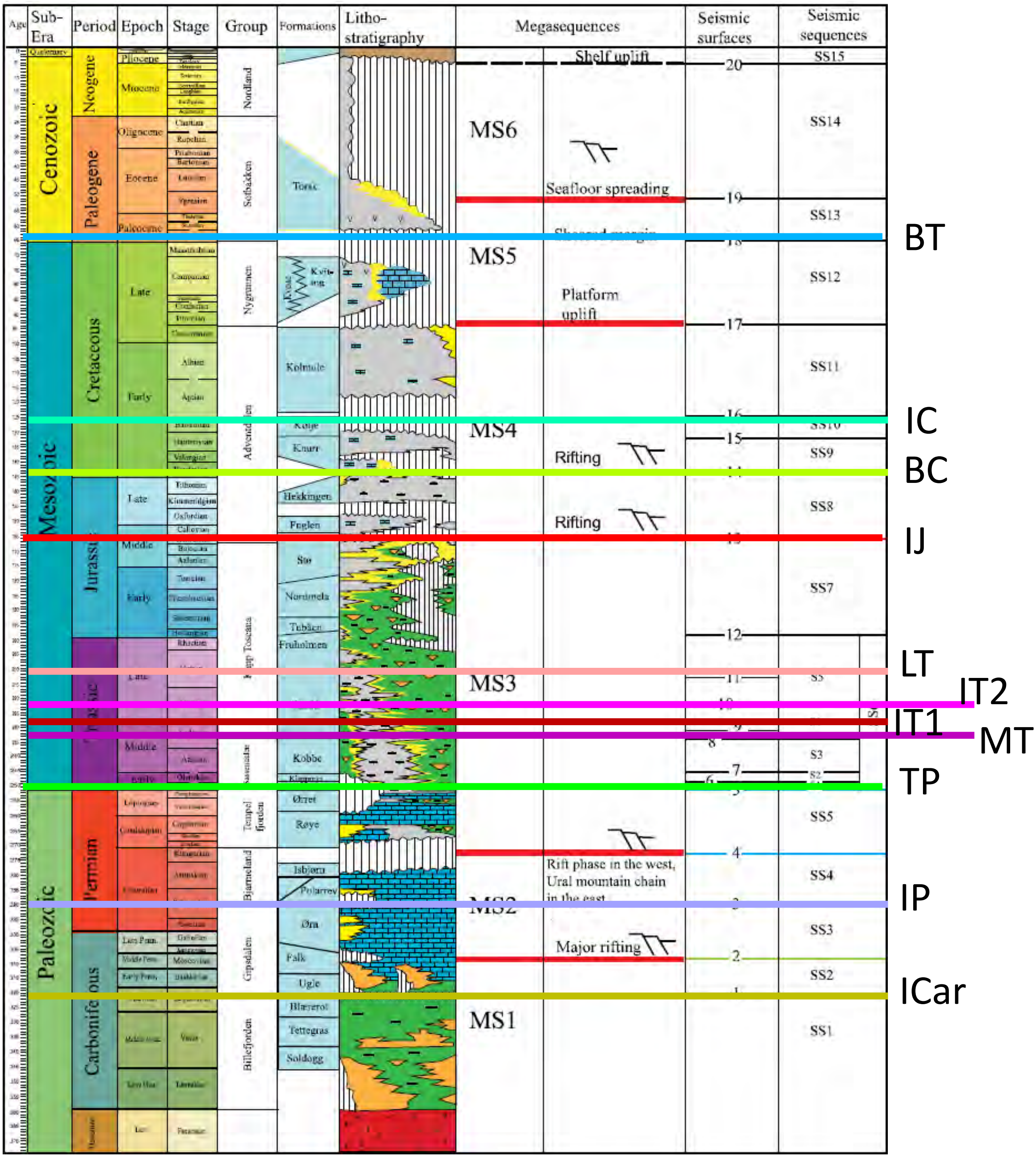


Figure 3.6: Interpreted horizons have been shown with their respective colors. Color scheme has been given in Table 3.3. (Modified from Glørstad-Clark, 2011)

Ørn Formation

This formation consists of marine carbonates of warm waters. It also contains evaporites and siliciclastic rocks in platform areas, while deeper part consists of halite (Larssen et al., 2005). Silica contents are not in that abundance in this formation, rather it is differentiated from underlying Falk Fm which contains abundant siliciclastic and carbonates rocks (Larssen et al., 2005).

Age: From well 7120/2-1 in the study area its age has been suggested from Late Moscovian to Early Sakmarian (Stemmerik et al., 1998 as cited in Larssen et al., 2005).

Seismic Sequence: Ørn Formation can be correlated with seismic sequence SS3, which is lower part of megasequence MS2 of Glørstad-Clark (2011) as shown in Fig. 3.6. Different sort of seismic facies are found in this sequence where lower part contains sub-parallel, transparent to chaotic seismic facies while the upper part can be characterized by high reflection, parallel units (Glørstad-Clark, 2011).

Ørret Formation

This formation is siliciclastic rock and contains sandstones, shales and siltstones, which belong to deep water facies (Larssen et al., 2005).

Age: Through correlation its age has been suggested from Kungurian? to Tatarian? (Larssen et al., 2005).

Seismic Sequence: Ørret Formation is part of Tempelfjorden Group and whole Tempelfjorden Group is correlated with seismic sequence SS5, which forms the lowermost part of megasequence MS3 of Glørstad-Clark (2011). Sub-parallel and normally transparent facies characterize this sequence (Fig. 3.6). This sequence is fairly thin in the Polhem Subplatform area (Glørstad-Clark, 2011).

Kobbe Formation

Basal part consists of shales while upper part consists of interbedded cemented sandstone, siltstone and shale (Dalland et al., 1988).

Age: Anisian age has been suggested though there are many depositional breaks within this formation (Dalland et al., 1998).

Seismic Sequence**:** Kobbe Formation can be correlated with subsequence S3; a part of seismic sequence SS6, which is part of megasequence MS3 (Glørstad-Clark, 2011).

Snadd Formation

Consists mostly of shales, upper part gradually changes into shales with interbedding of sandstones and siltstone. Lower and middle parts also contain calcareous beds and limestone while upper part contains thin lenses of coal (Dalland et al., 1988).

Age: Probably its age is from Ladinian to Early Norian (Dalland et al., 1988).

Seismic Sequence: Snadd Formation can be correlated with sub-sequence S5, which is part of seismic sequence SS6 and this seismic sequence is sub-category of megasequence MS3 (Fig. 3.6). Sub-parallel reflections with some high amplitude reflections characterize sub-sequence S5 (Glørstad-Clark, 2011).

Stø Formation

This formation consists of mature sandstones which aremedium to well sorted. This formation also contains some units of siltstone and shale (Dalland et al., 1988).

Age: Its time span is from late Pliensbachian to Bajocian (Dalland et al., 1988).

Seismic Sequence: This formation can be correlated with seismic sequence SS7 (Fig. 3.6), which also has other formations in it (Nordmela and Tubåen). Stø formation is considered best reservoir in Hammerfest Basin (Berglund et al., 1986; Dalland et al., 1988; Mørk et al., 1999; Worsley, 2008, all as cited in Glørstad-Clark, 2011).

Hekkingen Formation

Claystones with dark greyish shales with some beddings of siltstones, sandstones, limestones and dolomites are the lithologies which characterize this formation (Dalland et al., 1988).

Age: Its age has been suggested from late Oxfordian/early Kimmeridgian time to Ryazanian time (Dalland et al., 1998).

Seismic Sequence: It is correlated with seismic sequence SS8 of megasequence MS4 (Fig. 3.6). Most of the seismic facies in SS8 are transparent with some stronger amplitude intervals which represent internal flooding surfaces (Glørstad-Clark, 2011).

Kolje Formation

This formation consists of mostly claystone and shales. Small beds of dolomite and limestone are also found in this formation (Dalland et al., 1988).

Age: Its age has been suggested from early Barremian to late Barremian/ early Aptian (Dalland et al., 1988).

Seismic Sequence: Kolje Formation can be correlated with seismic sequence SS10 of mega sequence MS4. This sequence is bounded by high amplitude bounding surfaces. Sub-parallel seismic reflections with little transparency characterize seismic facies of this sequence (Glørstad-Clark, 2011).

Kveite Formation

Claystone of dark grey to greenish color with shales intermixed with dolomites, limestone are lithological units of Kveite Formation (Dalland et al., 1988).

Age: Its time span stretches from late Cenomanian to early Maastrichtian time (Dalland et al., 1988).

Sequence Stratigraphy: Kveite Formation can be correlated with the seismic sequence SS12 of megasequence MS5. Seismic facies can be distinguished by vastly spread sub-parallel reflections with some sub-parallel transparent reflections in between them (Glørstad-Clark, 2011).

3.2.2 Megasequences and Tectonics

In above paragraphs, seismic sequences and megasequences have been mentioned. These megasequences are relating to tectonics and show changes in the southwestern Barents Sea. Details of these megasequences are given below

Megasequence 1: Time span of this megasequence is stretched from Late Devonian to mid-Carboniferous (Clark et al., 2013). This mega sequence represents collapse of Caledonian orogeny, contemporaneously starting of rifting (Gabrielsen et al., 1990; Gudlaugsson et al., 1998).

Megasequence 2: Age of this megasequence ranges from Late Carboniferous to Late Permian. In the southwestern Barents Sea, a change is seen in the thickness of this megasequence (Clark et al, 2011). A major rifting event took place at the lower part of this megasequence. In consequence of which, intra-basinal highs and basins started to develop in fan-shaped array (Gudlaugsson et al., 1998). This fan-shaped array helped restricting environments to deposit evaporites. Rifting of this event took place in inherited Caledonian grain of northeast-southwest direction.

Megasequence 3: The age of this megasequence ranges from Late Permian to Middle Jurassic age. Lower part of this megasequence represent rift phase in the southwestern Barents Sea. Subsequently southwestern Barents Sea started to subside and sag basins are formed in response to rift-relating faulting (Glørstad-Clark, 2011). This megasequence marks changes of depositional environments; from carbonate platforms to clastic sediments (Clark et al., 2013).

Megasequence 4: Middle Jurassic to Early Cretaceous is the time span for this megasequence. Multiple rifting events took place during this time span. Third major rifting event also took place during this time, in result of which Bjørnøya and Tromsø basins were formed (Clark et al., 2013). This rifting event is contemporaneous with rifting in the Northeast Atlantic and Arctic systems (Faleide et al., 1993a).

Megasequence 5: Consists of Late Cretaceous to Eocene age. Final rifting took place in this time and sea floor spreading initiated (Clark et al., 2013). Before breakup of NE Atlantic, rifting regime converted into shear regime due to presence of De Geer Zone (Faleide et al., 1993b; Glørstad-Clark, 2011). Salt adjustments in the centre of Tromsø Basin, in this time, created space for more sediments (Faleide et al., 1993b).

Megasequence 6: The last megasequence has age from Eocene to Recent time. Breakup in Atlantic and Eurasian basins took place at the early age of this megasequence which is contemporaneous with huge magmatic activities in Palaeocene and Eocene transition time (Faleide et al, 1993a, b, 2008).

3.2.3 Interpretation method

Provided seismic surveys were displayed on the base map. Time was spent on seismic lines to familiarize with these seismic lines. Difference between both surveys was observed. Some time was spent to know about Petrel software. Those lines were specially emphasized which are normal to the Ringvassøy-Loppa Fault Complex.

Firstly, key profiles were marked followed by faults interpretation. The northernmost lines were chosen first to interpret. Faults first marked in the northernmost part were searched for in southern part and when it was appropriate, faults were joined.

3.2.4 Fault nomenclature

The main focus is on the Ringvassøy-Loppa Fault Complex which has been divided into four segments (MF1, MF2, MF3 and MF4). But major faults of RLFC have segments in it, so S1,S2 and S3 donates segment number one, two and three respectively. For the Bjørnøyrenna Fault Complex, BFC1, BFC2 and BFC3 are used to mark major faults in this complex. Jason Fault has been denoted by 'J'.

While for smaller faults, lower case letter have been used. Smaller fault in any structural element has been denoted with the lower Initial letter of structural element. Moreover a digit is added to that letter to describe the number of the fault. For example, r3 fault is formed by combining r which is initial letter of RLFC and digit describes the number. In this way r3 is the third smaller fault of RLFC.

Nomenclature of all faults in the study areas has been shown in Table. 3.3. In fault maps, the same nomenclature has been adopted.

Table 3.3: Nomenclature chart for faults with their respective abbreviations. These abbreviations are used in key profiles and fault maps.

Faults association	Abbreviation used
Fauts in Loppa High	L1, L2, L3…
Faults in Polhem Subplatform	p1, p2, p3…
Major faults of Bjørnøyrenna Fault Complex	BFC1, BFC2 and BFC3
Minor faults of Bjørnøyrenna Fault Complex	bf1, bf2….
Faults in Bjørnøya Basin	b1, b2, b3…..
Faults in Veslemøy High	v1, v2..
Major faults of Ringvassøy Loppa Fault Complex	MF1, MF2, MF3 and MF4
Minor faults in RLFC	r1, r2, r3…..
Minor faults in Tromsø Basin	t1, t2, t3…..
Minor faults in Hammerfest Basin	h1, h2, h3……
Major faults of Asterias Fault Complex	AFC
Minor faults of AFC	a1, a2, a3 …..
Jason Fault Complex	J
Sement 1, 2, 3 (With MF1,MF2, MF3, Mf4)	S1, S2, S3

3.3 Interpretation of key profiles

Nine seismic lines were chosen as key profiles. These key profiles cover all structural elements of study area (Fig. 3.7). Six out of nine key profiles provide information about the Ringvassøy-Loppa Fault Complex which is our key fault complex; two east-west oriented key profiles cover northernmost part of the study area and provide information about the Bjørnøyrenna Fault Complex; and one key profile has N-S orientation and covers the boundary between the Loppa High and the Hammerfest Basin. Six profiles which cover RLFC have been chosen through consideration that every two key profiles cover a distinct region (Fig. 3.7). The northernmost two lines of these six cover Loppa High, Polhem Subplatform and Tromsø Basin. The central two profiles give coverage of Loppa High in the east and Tromsø Basin in the west. The southernmost two profiles cover Hammerfest Basin in the east and Tromsø Basin in the west.

Some area of the Tromsø Basin is affected by salt intrusion especially western part of the study area. Interpretation of such area was quite impossible. Survey 1 did not provide quality data to look at deeper parts of the basins. That is why NBR lines were given preference. But the selected NBR lines had only NE-SW orientation. Unfortunately Bjørnøyrenna Fault Complex has same orientation as that of NBR lines. Interpreting this fault complex through NBR was not appropriate. That is why only survey 1 had been used to map the southernmost part of the Bjørnøyrenna Fault Complex. In other words, only two lines were there to look for this fault complex.

The area between Loppa High and Tromsø Basin was hard to interpret. Still two NBR lines have been selected on this region because these NBR lines are better ones in this region.

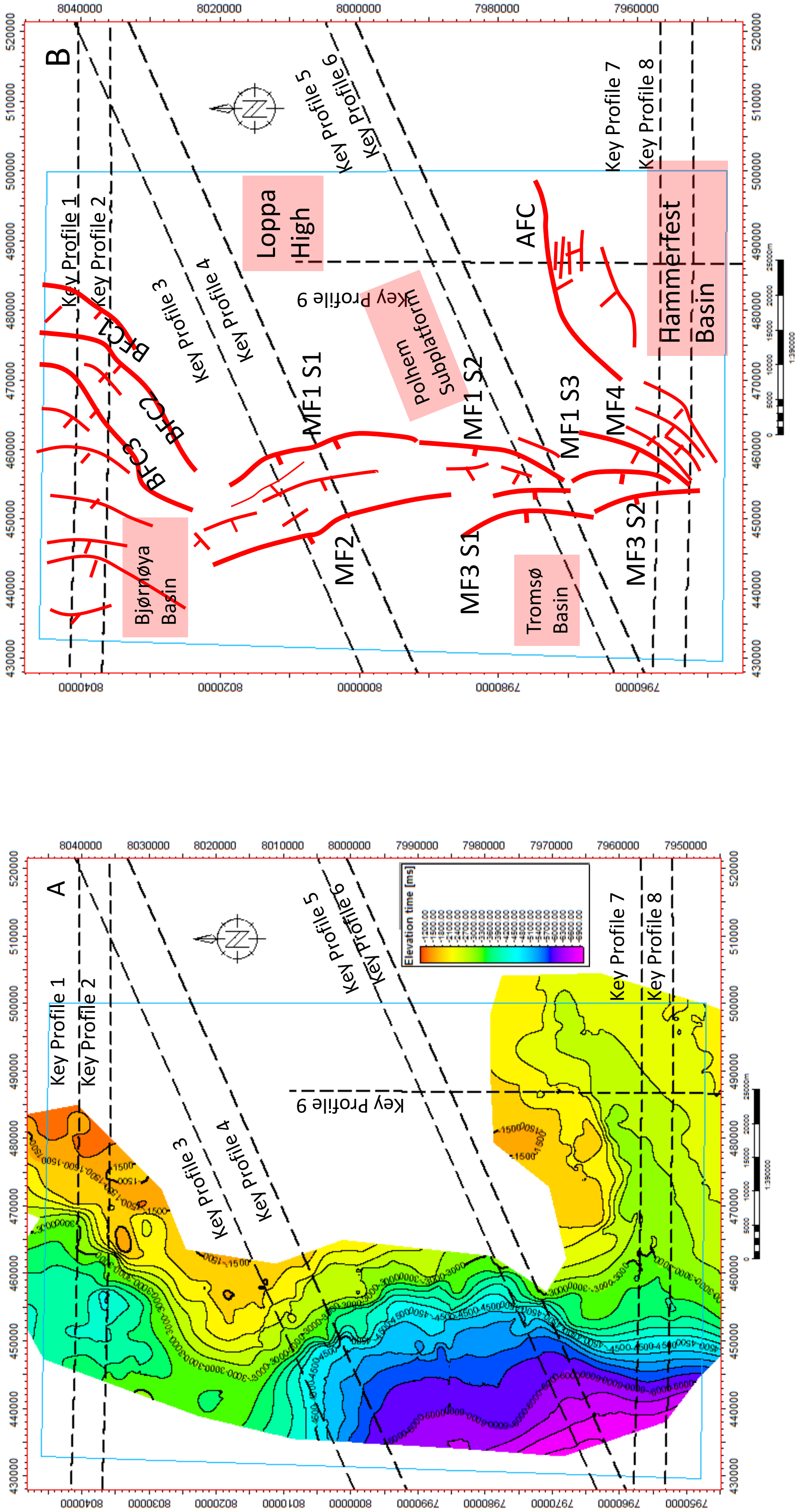


Figure 3.7: (A) Time structure map of Intra Jurassic (B) Fault map at Intra Jurassic level.

3.3.1 Key Profile # 1

This is an E-W orientedseismic line situated in the northernmost part of the study area. The line covers western Loppa High in the east; Polhem Subplatform, Bjørnøyrenna Fault Complex and Bjørnøya Basin in the middle; and some part of Veslemøy High in the westernmost part as shown in Fig. 3.8. The position of this line is shown in Fig. 3.2.

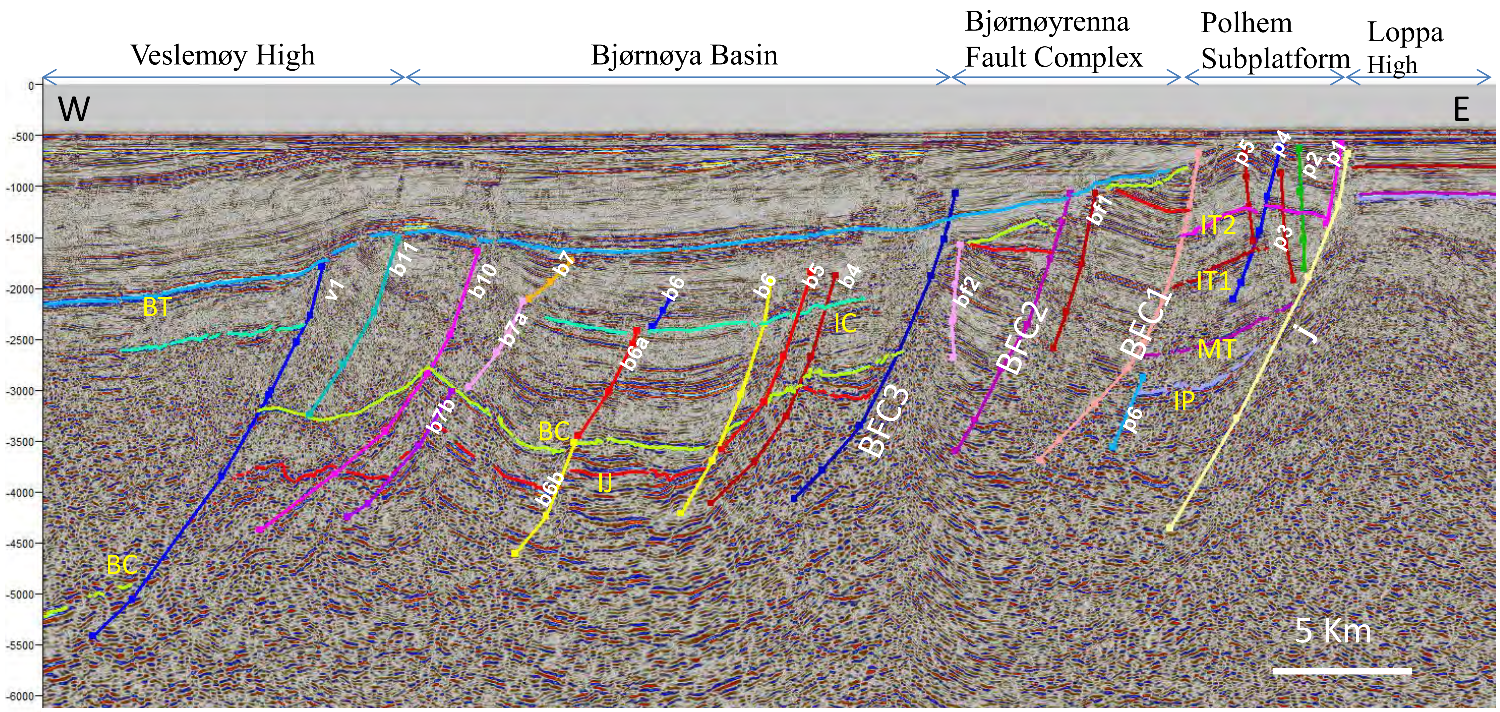


Figure 3.8: Key profile 1 with interpreted horizons and faults. Reflector abbreviations are given in Table , while nomenclature for faults in given in Table 3.3. Position of this line is shown in Fig. 3.2.

The oldest horizon interpreted on this line is Intra Permian (IP) which is interpretable only in the Loppa High and Polhem Subplatform area. On the Loppa High this reflector is relatively horizontal but then it has moved a great distance along the Jason Fault, which shows great displacement along this fault. It also shows normal drag along the Jason Fault. It becomes hard to interpret in the west of BFC1 (Bjørnøyrenna major fault).This reflector shows 1.5 ms offset across the Jason Fault.

The Intra Triassic reflector (Top Kobbe Formation) is the second oldest horizon interpretable in this line. Just like the Intra Permian reflector, this horizon is interpretable in the western Loppa High and PSP. The thickness between the Intra Triassic and IP increases in the PSP as compared to Loppa High which shows this fault remained active between Permian-Triassic time. This horizon is also hard to interpret in the west of BFC1.

In Table 3.2, IT1 and IT2 are two reflectors who have not been correlated with any formation top but these horizons have fairly uniform thickness in the Polhem Subplatform. These horizons correlate with sub-sequence S4 of Glørstad-Clark (2011) and are having age Ladinian and Early Carnian respectively (Fig. 3.6). Between Middle Jurassic and IT1, thickness increases. This increase in thickness may be attributed to wedges. These wedges indicate that eastern Loppa High was probably higher in Early Carnian time and erosion took place which provided sediments for sediments.

These reflectors help to see the magnitude of movement along the faults. These reflectors are making a dome-like shape in the west of Jason Fault Complex which may be due to inversion or may be it is rollover anticline. Bjørkesett (2009) suggested formation of dome-like structure due to inversion.

An Intra Jurassic reflector is interpreted in the rotated fault blocks. These reflectors are dipping generally in the eastern direction. This reflector is only interpreted in Bjørnøya Basin and is missing in Veslemøy High, PSP and Loppa High.

The Base Cretaceous reflector is missing on the Loppa High and Polhem Subplatform. This reflector makes an angle with the underlying reflectors of Intra Jurassic and Late Triassic in such a way that it makes a thin wedge. This wedge is thicker towards faults and thins away from the faults. These syn-rift deposits have got lot of attention in oil industry.

The Intra Cretaceous reflector is missing from the top of Bjørnøyrenna rotated fault blocks. It is traceable in the west of Bjørnøyrenna Fault Complex. It is relatively horizontal but started to rise towards the Veslemøy High and then starts dipping westwards.

The uppermost mapped reflector is Base Tertiary; which is missing from Loppa High and PSP and makes a saddle in the middle of the Bjørnøya Basin. In the western part it is dipping down towards west.

Bjørnøyrenna Fault Complex was defined by Gabrielsen et al. (1990) for having large throws along normal faults. This fault complex shows signs of activation from Intra Jurassic to Base Cretaceous time due to wedges along the faults. But activation also took place in Tertiary time. Signs of inversion have been reported by Gabrielsen et al. (1990) along this fault complex.

3.3.2 Key profile # 2

This line is located south of Key Profile 1 and covers the same geological elements (Fig. 3.2). The interpreted seismic line is shown in Fig. 3.9.

This profile probably represents southernmost extent of the Bjørnøyrenna Fault Complex where Intra Jurassic and Base Cretaceous make normal drags with BFM2, BFM3. Moreover, thickness between Base Cretaceous and Intra Jurassic is increased towards faults of Bjørnøyrenna Fault Complex which shows active periods of rifting. The faulting remained active until Tertiary time as these faults intersect Base Tertiary reflector at certain places. Sign of reactivation can be seen by looking at the horizons of Intra Jurassic and Base Cretaceous as these reflectors have been affected by compression. Gabrielsen et al. (1997) reported inversion of Bjørnøyrenna Fault Complex in Late? Cretaceous and Tertiary times.

Key profile 2 also contains numerous faults which are listric normal faults and show considerable movement along these fault planes. In Polhem Subplatform, most of the faults remain above the Intra Permian reflector. The fault which is cutting through the Intra Permian did not affect horizons above. This different level of faulting indicates presence of any detachment zone. BFC3 and BFC1 seem to cut all horizons until they reach basement.

A considerable thickness variation can be seen between Intra Triassic and IT1 across Jason Fault Complex which is manifestation that this fault remained active in Ladinian time. Bjørkesett (2009) indicated the presence of Triassic wedges for the thickness of this deposit.

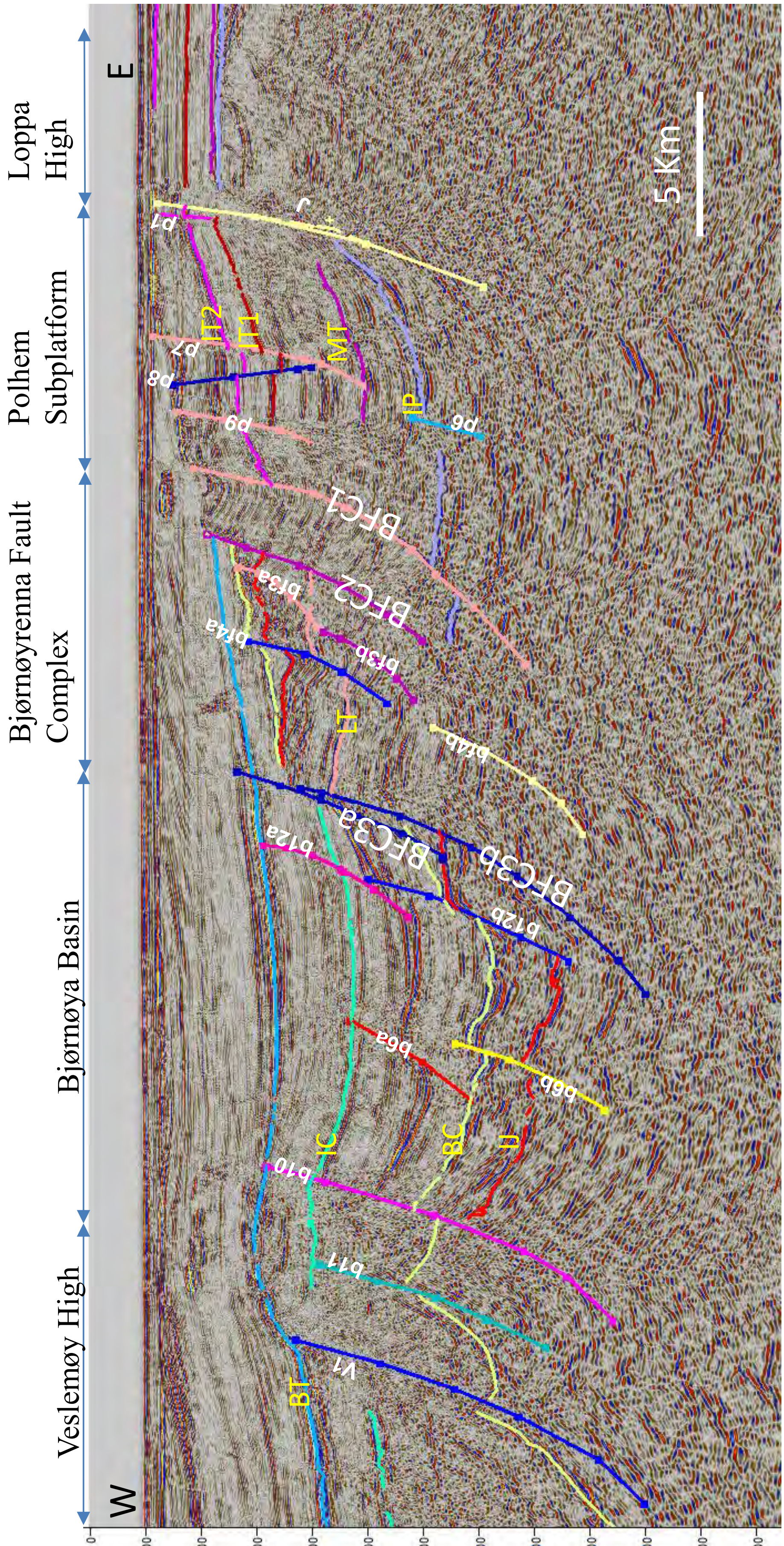


Figure 3.9: Key Profile 2 wi thinterpretation.

3.3.3 Key Profile # 3

This NE-SW oriented seismic line passes through Loppa High, Polhem Subplatform, and Ringvassøy-Loppa Fault Complex and finally enters into the Tromsø Basin (Fig. 3.10). This line is perpendicular to RLFC and provides good resolution of reflectors in deeper part.

In the easternmost part, Selis Ridge is separated from the Polhem Subplatform by the Jason Fault Complex. This ridge is considered as one of the most prominent structural highs of Late Palaeozoic time (Glørstad-Clark, 2011). This complex contains fault which is fairly steep and ends in basement rocks. West of the Jason Fault Complex, Triassic rocks in Polhem Subplatform maintain fairly uniform thickness except between Intra Triassic and MT where thickness increases due to presence of wedges (Bjørkesett, 2009). These Triassic sequences are cut by numerous synthetic faults. Some of them are quite steep and some of them have antithetic sense. All these faults do not show any activation as no growth faults are seen in these. This indicates that faulting developed after all Triassic sequences were deposited. Moreover, faults above than Intra Permian are not affected by faulting below than Intra Permian. This difference of faulting indicates presence of a detachment in Intra Permian reflections.

No well is available to tie with reflectors of the Polhem Subplatform. Interpretation here has been carried out with the help of Bjørkesett (2009).

In the western part, east of RLFC, it becomes hard to interpret the Early Triassic reflector. Intra Permian reflector also seems to disappear after r16 (segment of Ringvassøy-Loppa Fault Complex). In the east of MF1a, BC and Intra Jurassic can be interpreted but these reflectors attain great depth in the middle of the Tromsø Basin but this depth is not as greater as expected. In this locality Tromsø Basin is probably not very deep. Number of faults can be seen in Ringvassøy-Loppa Fault Complex. MF1a is eastern limit of RLFC and MF2C is western limit after which Tromsø Basin begins.

Another feature is the vertical segmentation of Ringvassøy-Loppa Fault Complex. This segmentation indicates presence of detachments which did not all continuation of faults in normal way.

The deepest reflector marked in the Tromsø Basin, on this line, is Base Cretaceous. It is hard to find out Intra Jurassic reflector due to poor data quality. On this key profile, Base Cretaceous has not attained greater depth in Tromsø Basin as it attains in its southern part.

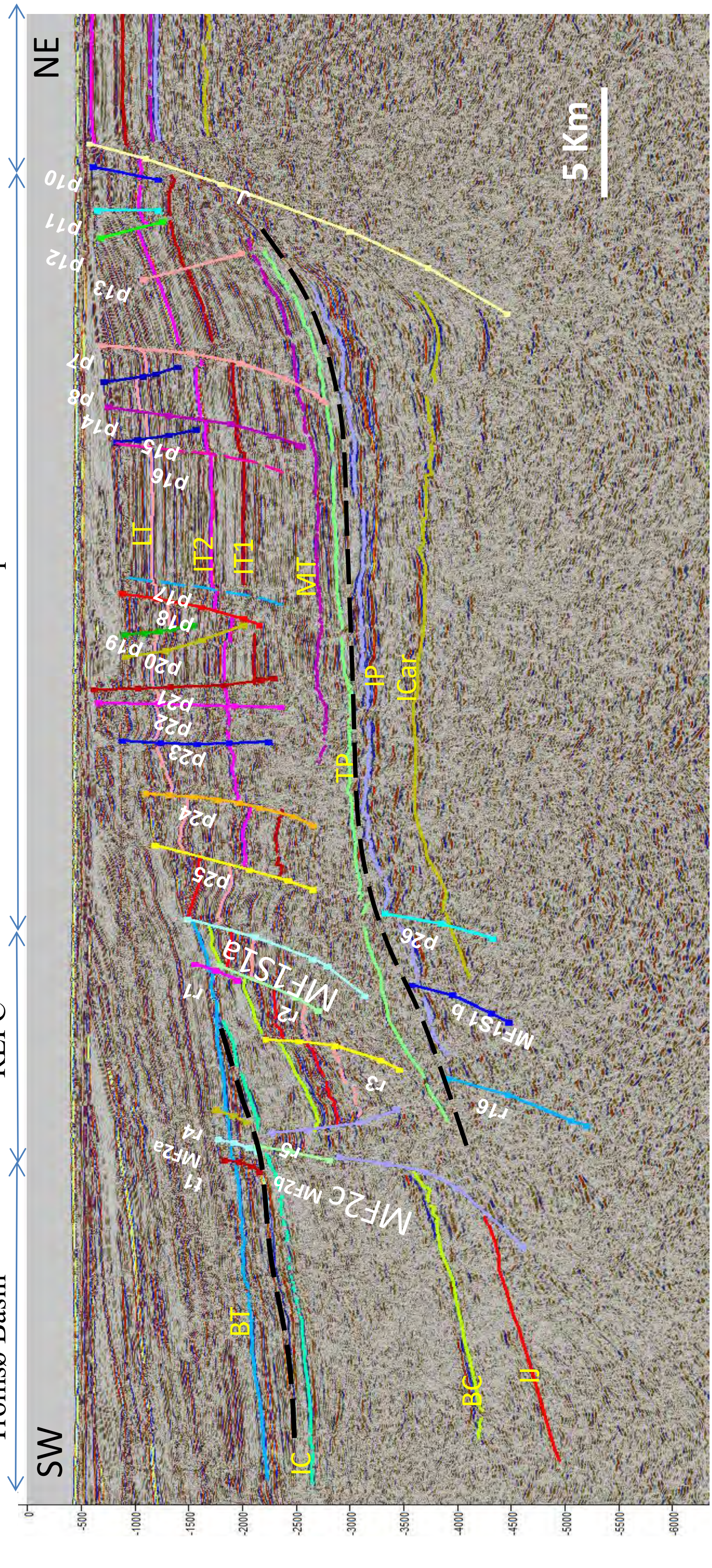


Figure 3.10: Key profile number 3 with interpreted faults and horizons. Black dashed lines are indicating possible detachments.

3.3.4 Key profile # 4

Just like key profile 3, this line has NE-SW orientation and covers four geological elements of study area as shown in Fig. 3.11. This line provides better coverage of Tromsø Basin as compared to previous key profile.

In the west, Jason Fault Complex separates basement rocks of Selis Ridge from the sedimentary rocks of PSP. In the west of Jason Fault Complex, Permian rocks have faults which are not related with the faulting of Triassic rocks. It seems like there is a detachment zone near the Kobbe Formation reflector. Position of possible detachments has been shown in (Fig. 3.11) with black dashed lines.

In Polhem Subplatform, numerous faults can be seen which are mostly listric normal faults. Not a considerable displacement is seen in these faults and growth faulting is missing. These faults are steeper at the top and started to curve westward in the lower part. Probably these faults eliminate near Intra Permian reflections and joins proposed detachment zone.

In the west of Polhem Subplatform, number of faults can be seen in Ringvassøy-Loppa Fault Complex at different levels. This faulting seems to have affected all horizons but these faults are not connected together. These faults are rather connected in a stacking pattern. Deepest reflector affected by RLFC is Intra Permian. At the upper level, some faults can be seen but no defined horizon is there but these faults may have assisted faulting in upper levels. Maximum displacement is seen in rocks which have been affected by Intra Jurassic to Early Cretaceous rifting. Rotation is seen in fault blocks in RLFC. But this rotation is not uniform and uni-directional. One fault block has moved in clock wise direction but other block has rotated slightly in opposite direction.

Rotation of horizons can be seen in the rotated fault blocks. Intra Jurassic reflector is showing different dipping reflector among the faults. First it is dipping in the NE direction and then it dips towards basin side in SW direction.

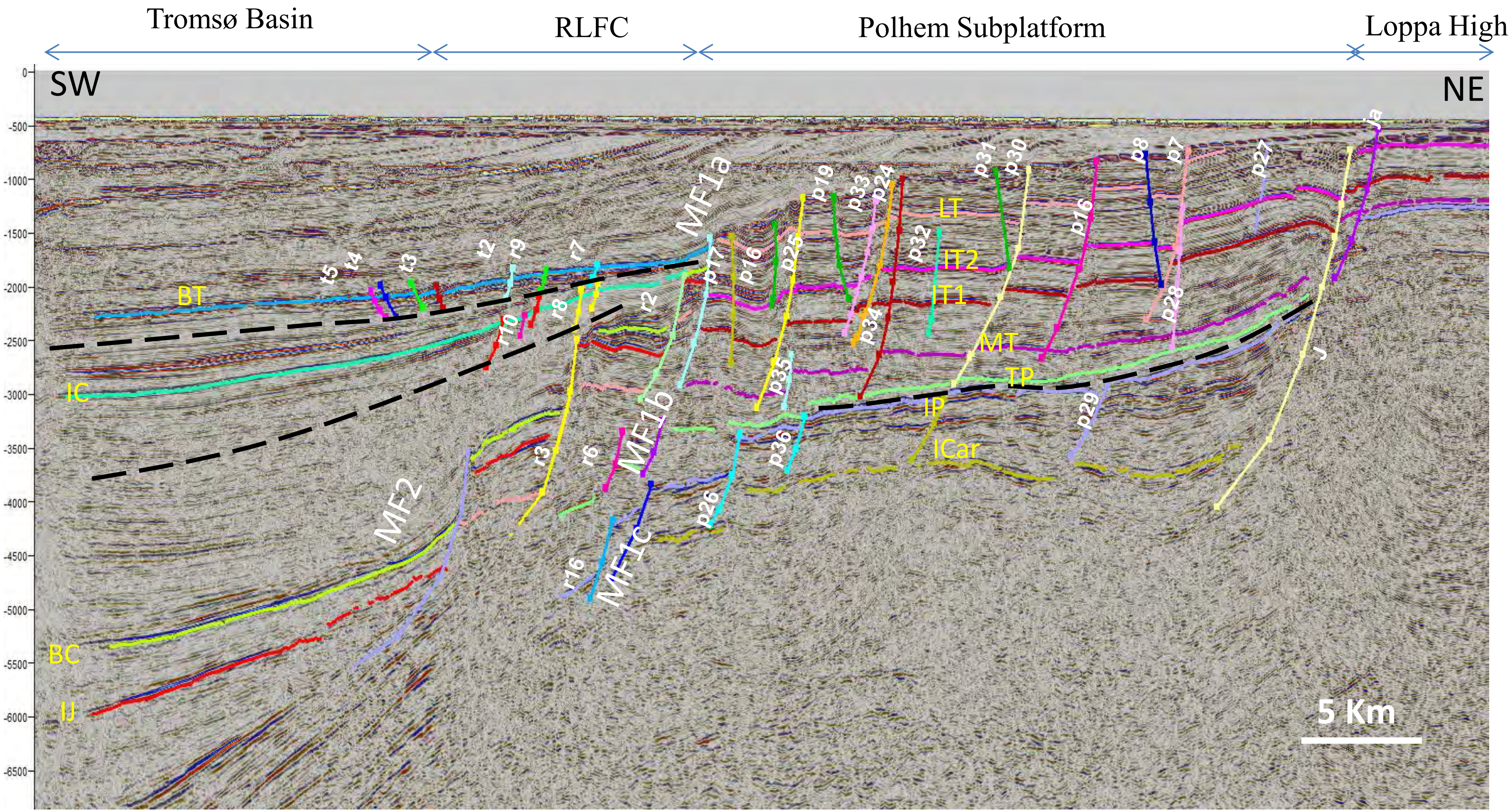


Figure 3.11: Key profile number 4 with interpretation. Black dashed lines are indicating possible positions of detachments.

The western most section of line shows Tromsø Basin where Intra Jurassic and Base Cretaceous reflectors attain greater depth. Intra Permian reflectors have not been marked in Tromsø Basin.

3.3.5 Key Profile # 5

The position of this line can be seen in Fig. 3.2. NE-SW directed seismic line covers Loppa High in the east and Tromsø Basin in the west as shown in Fig. 3.12. In between these two completely different geological elements, Ringvassøy-Loppa Fault Complex is present. The behavior of this fault complex is quite different from lines situated in North which attaches Polhem Subplatform with the Tromsø Basin. Throw of the faults in RLFC is greater in this part as compared to previous key profiles.

Unlike previous lines, RLFC does not show presence of stacking pattern. Rather faults in different horizons are quite free from the effects of lowers faulting. This may be happened due to considerable thickness of cretaceous deposits which absorb the effects of lower level faulting.

Not too many faults are present in south western Loppa High which is NE part of this seismic line. But wedge can be seen between Top Permian and Intra Permian reflector which is manifestation that this fault remained active from Intra Permian to Middle Triassic times. Top Permian reflections are missing from the top of Selis Ridge and Early Triassic is draping over the erosional crest of Carboniferous.

From Middle Triassic to Early Triassic, thickness between rocks is quite uniform and not too much fault activity is seen in Loppa High area. In the west of RLFC scenario changes and thick deposits of cretaceous and Tertiary follow. Reflectors of Intra Jurassic to Base Cretaceous rotate but dip of reflectors vary considerable as these dip in the NE direction in one rotated fault block and SW dip in other rotated blocks. Intra Jurassic reflector shows normal drag along r3 fault.

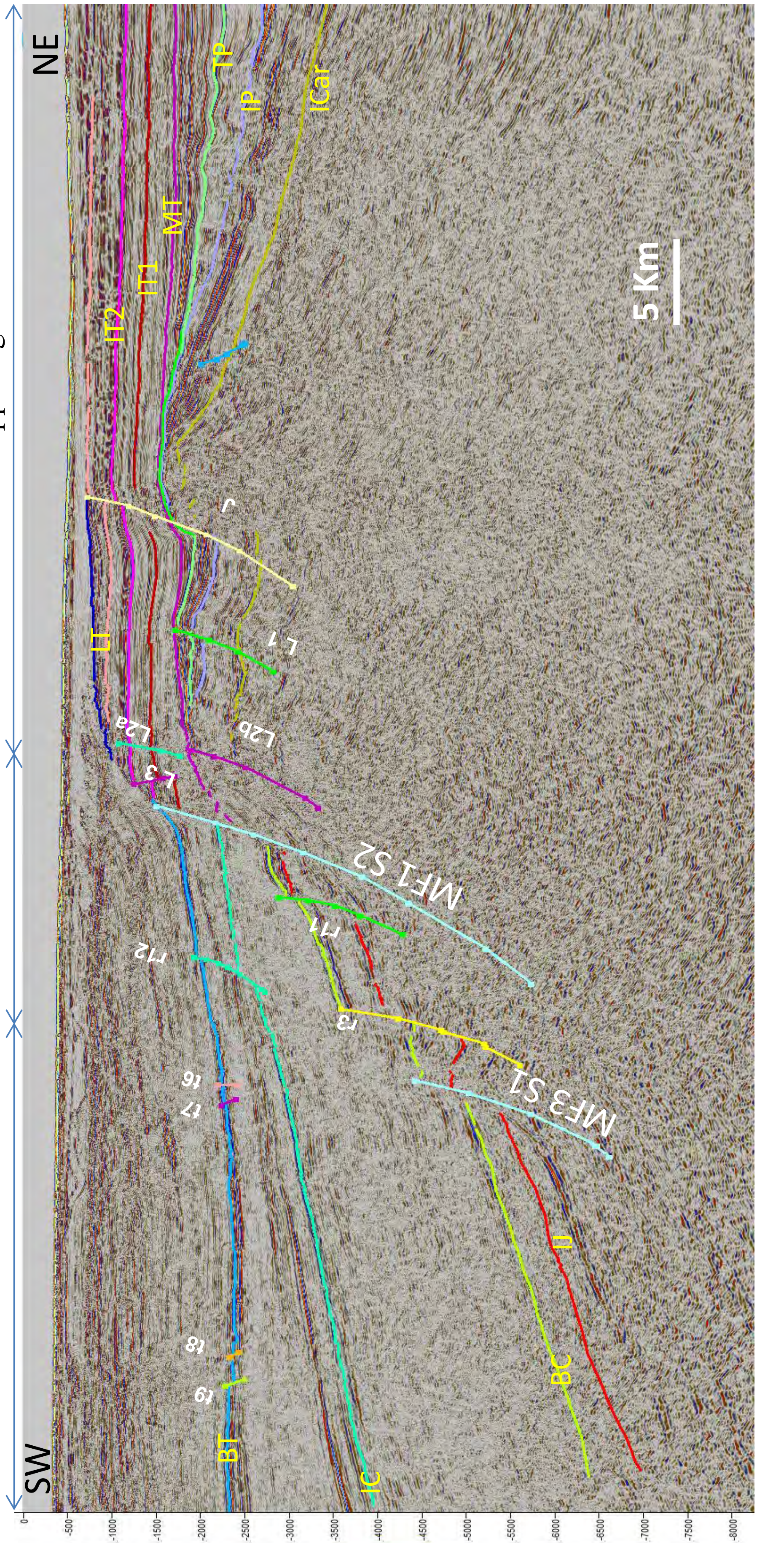


Figure 3.12: Key profile number 5 with interpretation.

3.3.6 Key profile # 6

This is NE-SW directed seismic line and situated in the south of key profile number five and provides coverage of same geological elements. Position of line has been shown in Fig. 3.2 and interpretation of line has been shown in Fig. 3.13.

In the NE part of the line, Selis Ridge is separated by Jason Fault Complex. Along the Jason Fault, a small wedge is formed where well has been drilled and only Top Permian was found. It gives impression that Billefjorden rocks are overlain by no older than Top Permian rocks. Thickness between Intra Carboniferous and Top Permian increases towards Jason Fault Complex which shows fault was active between these times. Southwestern part of Loppa High, which is NE part of this line, does not show great amount of fault activity. But Gipsdalen Group (Intra Permian to Intra Carboniferous) dips towards east which is overlain by Top Permian reflector. Top Permian reflector is missing from the top of Selis Ridge which shows that this ridge gained elevation at this time and Top Permian eroded from this ridge. Top Permian is overlain by pretty horizontal reflectors of Triassic rocks which indicate that in Triassic tilting of Loppa High stopped and Triassic rocks started to deposit and more over Selis Ridge also submerged many times in this time.

Loppa high in the west of Jason Fault Complex is not easy to interpret. Especially reflectors below than Middle Triassic are really hard to interpret. That is why these reflectors have not been interpreted.

MF1 and MF3b represent eastern and western limits of RLFC respectively. Three rotated faulted blocks are identified. Rotation has taken place in eastern most part of RLFC but other two blocks have shown rotation in reverse direction.

Intra Jurassic and Base Cretaceous are deposited deep in the basin. They are greatly displaced along the RLFC. Wedges are formed between Base Cretaceous and Intra Jurassic. Along MF1, Intra Jurassic and Base Cretaceous show signs of minor inversion. Their dip in these reflectors varies as well.

Unlike previous line, where no fault activity affected younger horizons, this line indicates minor effects at younger level. Both Intra Cretaceous and Base Tertiary have been affected along fault MF3a.

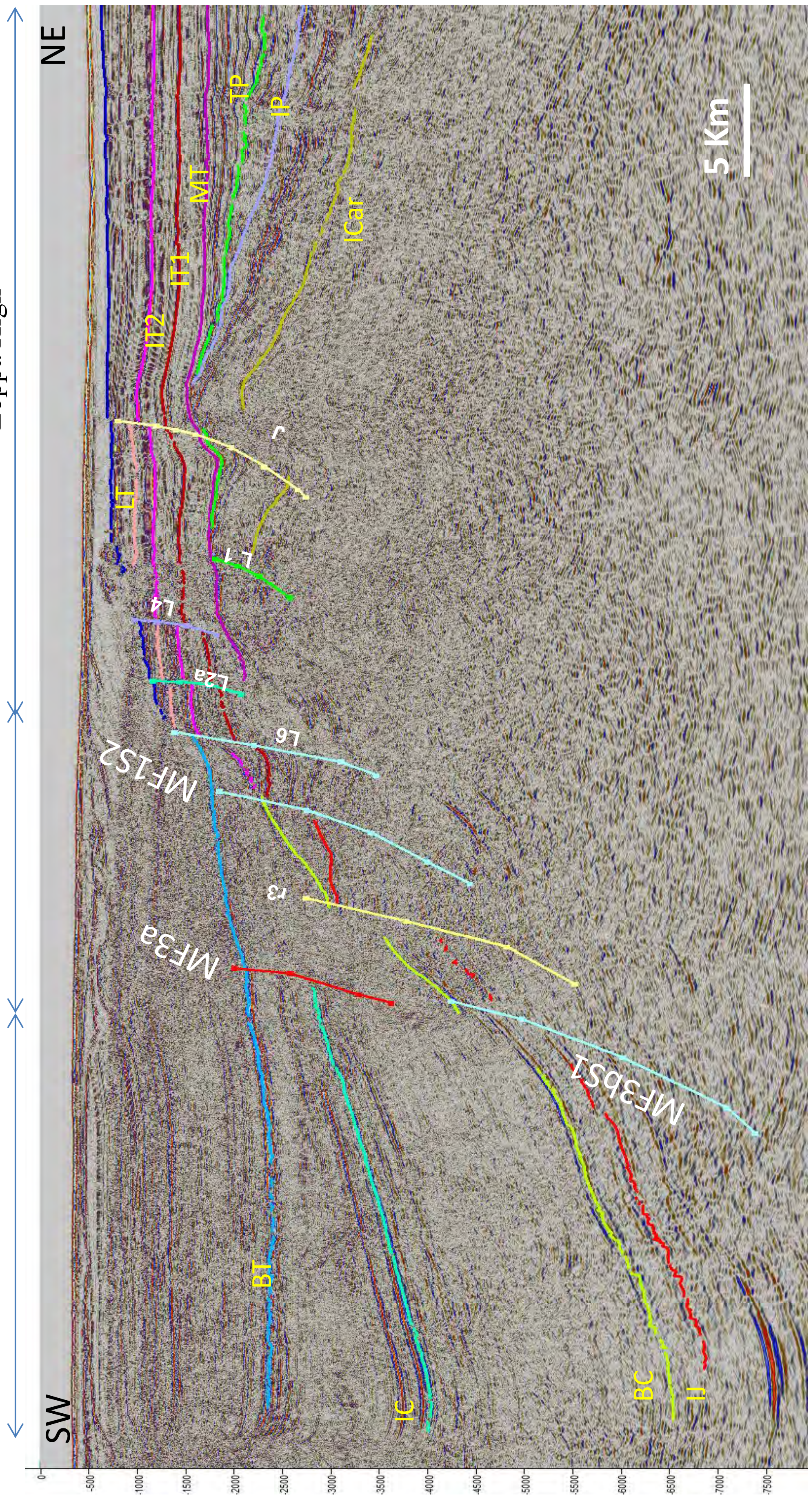


Figure 3.13: Key profile 6 with interpretation.

3.3.7 Key Profile # 7

East west directed seismic line is situated in north of Hammerfest Basin and covers Hammerfest Basin in east and Tromsø Basin in the west. Position of this line is shown in Fig. 3.2 and interpretation is shown in Fig. 3.14.

Though the resolution of this line is not quite good but it is amongst the best to present that part of RLFC which exists between Hammerfest Basin and Tromsø Basin. It can be seen in the (Fig. 3.14) that area in the west of RLFC has very poor resolution. Base Cretaceous and Intra Jurassic reflectors have been marked on the base of crossing from other seismic lines.

In eastern part of line (Hammerfest Basin), Intra Permian and Top Permian make wedges with each other. This shows fault activity which is probably associated with Late Paleozoic rifting event. But they are dipping in the westward direction where they are terminated against a concave fault h1. This fault cuts all interpreted horizons but shows very minute displacement along this fault. Middle Triassic, Top Permian and Intra Permian reflectors are not possible to interpret in the west of this fault. Younger horizons in the basin (Intra Cretaceous and Base Tertiary) are fairly horizontal. Thickness between Intra Cretaceous and Base Cretaceous also increases towards fault h1. But thickness between Base Tertiary and Intra Cretaceous is thinning towards the same direction. This is probably due to erosion of this zone in Intra Cretaceous time.

Three major faults (MF4, MF1, MF3b) are seen in RLFC which are cutting Intra Jurassic and Cretaceous rocks and terminate somewhere in places where resolution is that lousy that mapping is not possible.

Throw of the faults in the RLFC is not massive. But rotation of fault blocks has taken place and Intra Jurassic and Base Cretaceous make wedges along these fault complexes. Thickness between IJ and BC increases towards faults. Late Triassic horizon lies parallel to the IJ reflector.

Faulting in Jurassic to Cretaceous level probably created weak zones in the above rocks. Along these weak zones, faulting took place which affected Intra Cretaceous and Base Tertiary rocks. Many faults in upper level make stacking pattern with lower rocks. Some other faults (r13, t10) also cut Intra Cretaceous and Base Tertiary reflectors but they are isolated from major faults of RLFC. t11 fault only cuts Intra Cretaceous Fault.

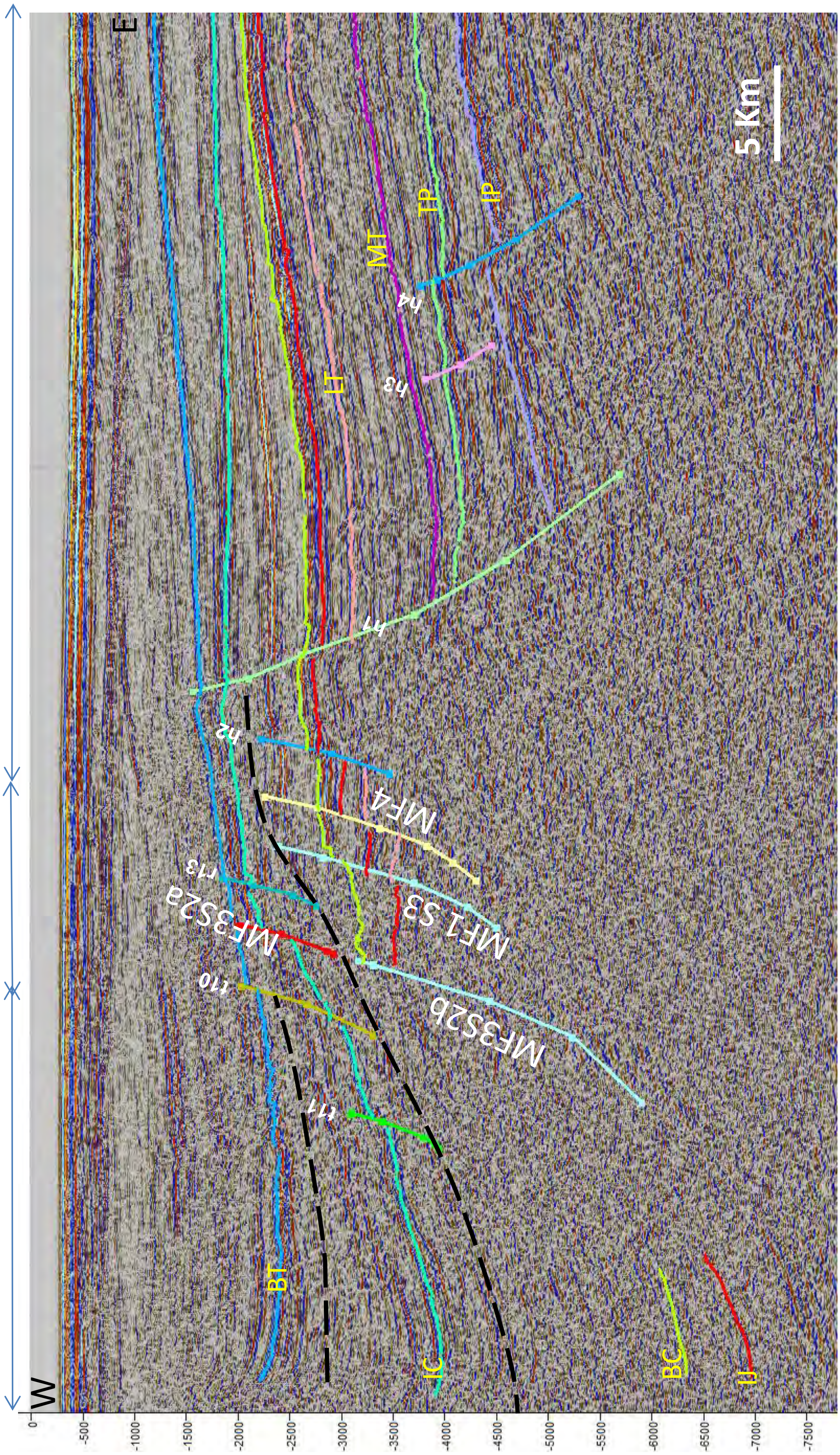


Figure 3.14: Interpretation of key profile number 7.

3.3.8 Key Profile # 8

This line is situated at the southernmost part of the study area as shown in Fig. 3.2. This is EW directed seismic line and nicely perpendicular to RLFC but quality of this line is not very good. Only some part of RLFC is mapped on this line. This line is shown in Fig. 3.15.

Oldest horizons (IP, TP, and MT) in Hammerfest Basin are dipping towards west and terminate against fault h1. Intra Permian and Top Permian reflectors show fault activity and wedges are formed. As mentioned earlier that these wedges can be result of Late Paleozoic rifting. Younger than these horizons, are cut only by two smaller faults in Hammerfest Basin. Intra Cretaceous is almost horizontal and Base Tertiary is dipping in the westward direction. In such way, thickness between Base Tertiary and Intra Cretaceous decreases in the western part of Hammerfest Basin and then it starts to increase rapidly along RLFC and becomes massive in Tromsø Basin. Base Cretaceous and Intra Jurassic reflector are not mapped in Tromsø Basin because this line only gives coverage to 6 sec t.w.t.t. And these reflectors lie probably deeper than coverage.

Ringvassøy-Loppa Fault Complex consists of two faults which cut rocks from Late Triassic to Base Cretaceous. Rotation of Intra Jurassic reflector takes place between these fault blocks. Thickness between Intra Jurassic to Base Cretaceous gradually increases between fault blocks towards faults. Faults at lower level did not continue in the upper level but probably faults at lower level created weak zones through which younger faults were developed. Stacking faulting can be seen here. Few faults are present is the Base Tertiary level which did not develop in lower horizons.

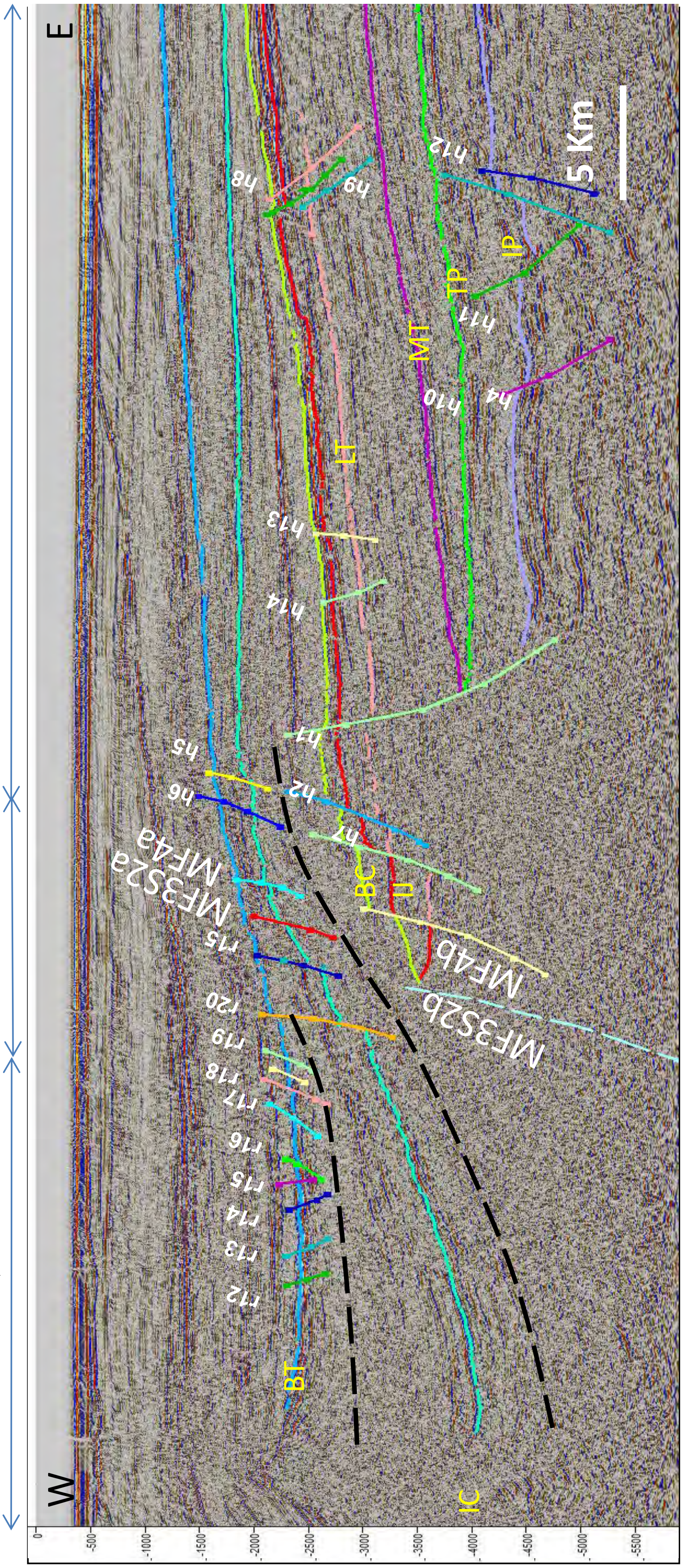


Figure 3.15: Key Profile 8 with interpretation.

3.3.9 Key Profile # 9

North south directed seismic line is the final key profile for this study. Position of this line is shown in (Fig. 3.2). It covers part of southwestern Loppa High in Northern part and northern Hammerfest Basin in southern part as shown in Fig. 3.16. Loppa High and Hammerfest Basins are differentiated from each other through Asterias Fault Complex. Numerous reverse faults are associated with this fault complex, which cut through Base Cretaceous and Intra Jurassic reflectors.

Great amount of displacement is seen between older reflectors (IP, MT). They are displaced along the Asterias Fault Complex. Younger reflectors are terminating against this fault. Signs of inversion can be seen in younger reflectors towards Asterias Fault Complex.

Falk Formation of Carboniferous has been marked on this key profile. This horizon terminates against Asterias Fault Complex which is indication that Asterias Fault Complex existed at least in the Late Carboniferous time.

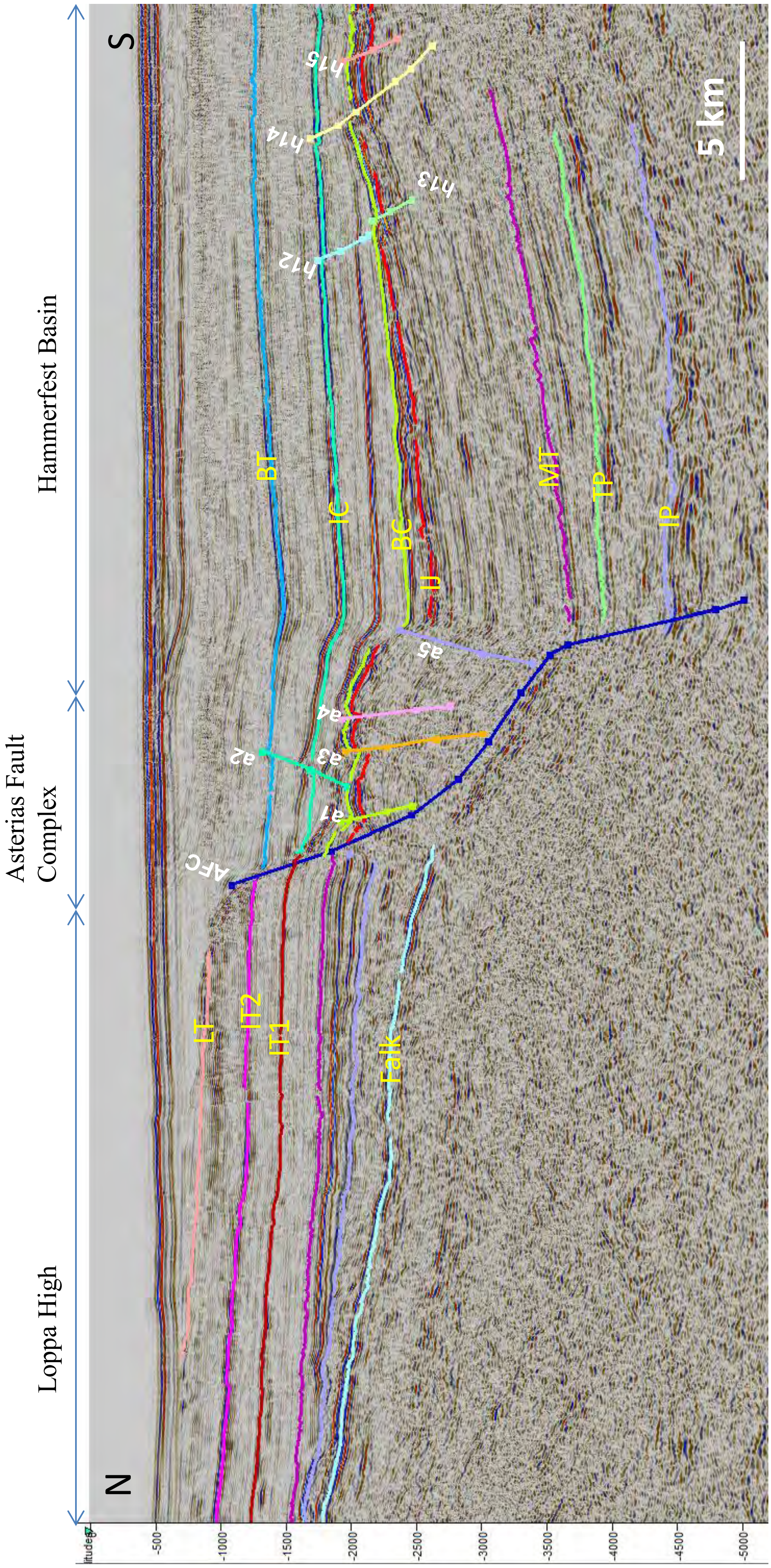


Figure 3.16: Interpretation of key profile 9.

3.4 Time Structure maps and Fault maps

This section will put light on the overall interpretation of all seismic lines of the study area. Not only that, time-structure maps and fault maps put some light on the overall pattern of the area. Time-structure maps depict activation of a fault at different geological time. Time-thickness maps elaborate erosional and depositional history of an area.

Time-structure maps and fault maps will be shown in older towards younger horizons. These maps have been put together in order to give better idea on the role of major faults in deepening of the horizons. Scale and ratio of both of these maps have been kept the same in order to get better observation.

3.4.1 Intra Permian

The time-structure map of Intra Permian indicates presence of interpretation only in eastern part of map because it has been marked only in Loppa High, Polhem Subplatform and Hammerfest Basin. This reflector becomes really shallower above the Selis Ridge. The Selis Ridge is NNE to SSW oriented which is probably under the red color of this map. West of the Selis Ridge, this reflector becomes abruptly deeper across the Jason Fault Complex. Position of the Jason Fault Complex can be seen in Fig. 15B. The time-structure map also indicates deepening of the Intra Permian on the eastern side. This is because the Selis Ridge was uplifted in the past and this reflector shows dipping towards east because this reflector got tilted by the uplift.

The time-structure map (Fig. 3.17A) indicates that the Intra Permian becomes deep in Hammerfest Basin. This deepening was facilitated by the Asterias Fault Complex which is shown in the corresponding fault map (Fig. 3.17B). This map also explains that the Jason Fault Complex and the Asterias Fault Complex were active in Permian time. Though the Ringvassøy-Loppa Fault Complex was active in Permian time but still its activation is

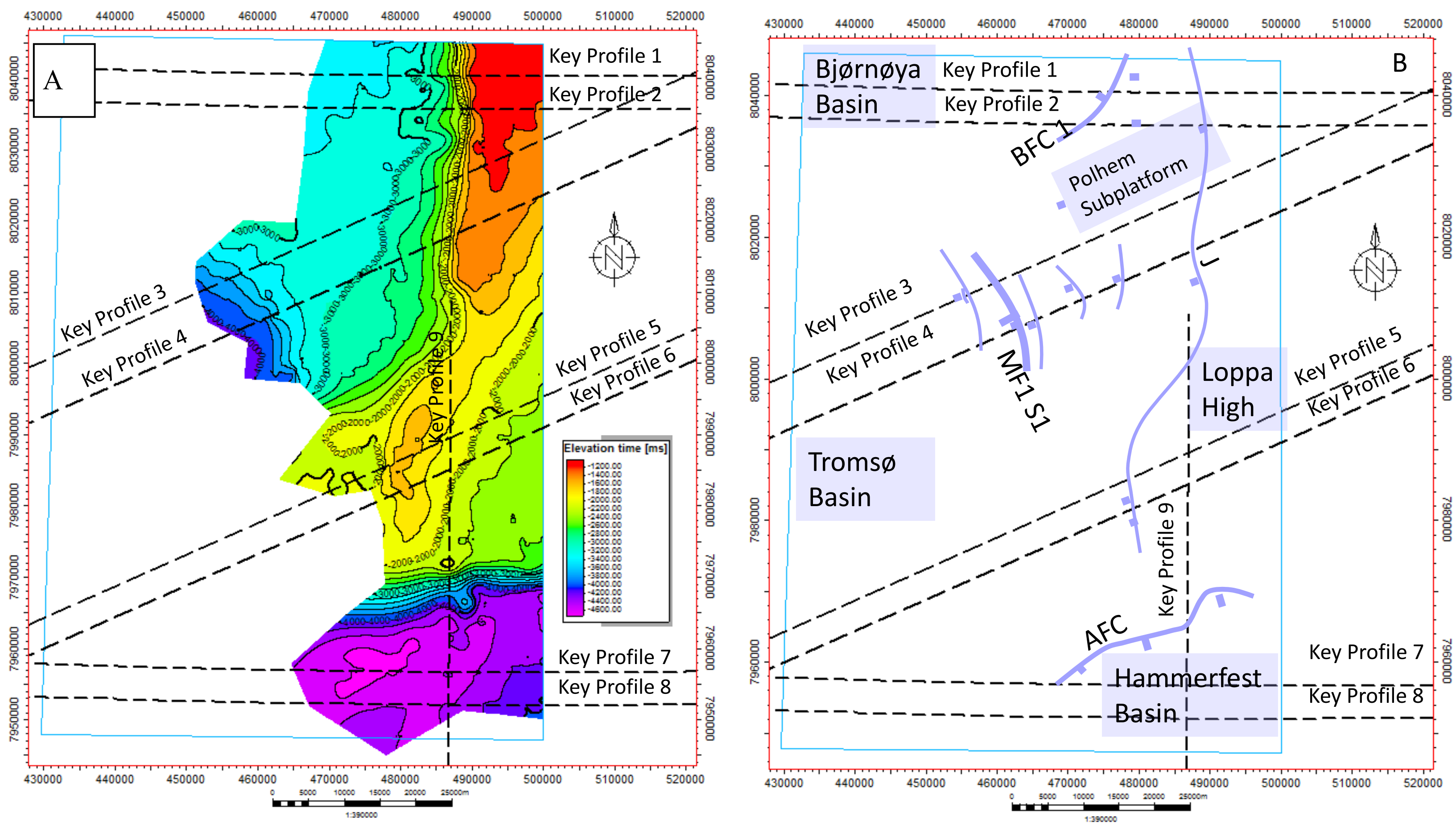


Figure 3.17: (A) Time structure map of Intra Permian age. Intra Permian reflections were mapped only in Loppa High and Hammerfest Basin. (B) Structure map at Intra Permian level. It shows two major fault; Jason fault which has been mentioned with letter J, Asterias Fault Complex which is mentioned by AFC.

observed only on Key Profile 3 and 4. In the northern part of the study area, the southernmost limit of the Bjørnøyrenna Fault Complex is also seen which was active in this time.

In this study, the Intra Permian reflection has not been mapped under Tromsø and Bjørnøya Basin. That is why the time-structure map remains only in eastern side of study area beneath Loppa High, Hammerfest Basin and Polhem Subplatform.

3.4.2 Middle Triassic

The time-structure map of Middle Triassic (Fig. 3.18A) is quite similar that of Intra Permian. The Middle Triassic is not mapped in the Tromsø Basin and Bjørnøya Basin. The map indicates a depression from central part to the north indicating the location of the Polhem Subplatform (Fig. 3.18A). The corresponding fault map (Fig. 3.18B) indicates that major faults of the area (Jason Fault Complex, Bjørnøyrenna Fault Complex, Ringvassøy-Loppa Fault Complex and Asterias Fault Complex) had already developed in Triassic time. The Selis Ridge is having trend of NNE-SSW direction.

In the fault map at Middle Triassic level, three major faults can be seen (Fig. 3.18B). The Jason Fault Complex separates the Loppa High from the Polhem Subplatform. Another fault is the Asterias Fault Complex which is the boundary between the Loppa High and the Hammerfest Basin. MF1 is the major fault; it is part of Ringvassøy-Loppa Fault complex. Comparison of both these maps indicate that Middle Triassic in not mapped across MF1.Color bar in the time-structure map indicates depth variation at different levels, varying from 1000 ms to 3000 ms in twt.

Numerous smaller faults are also seen in the Middle Triassic fault map. These faults are absent in the Intra Permian fault map.

In Triassic time, wedges have formed on Polhem Subplatform area (Glørstad-Clark, 2011). Time-structure map of Triassic probably mimics the setting of the area when this deposition was taking place. Selis Ridge somehow raised high and let the sediments prograde from eastern side to westward direction on Polhem Subplatform.

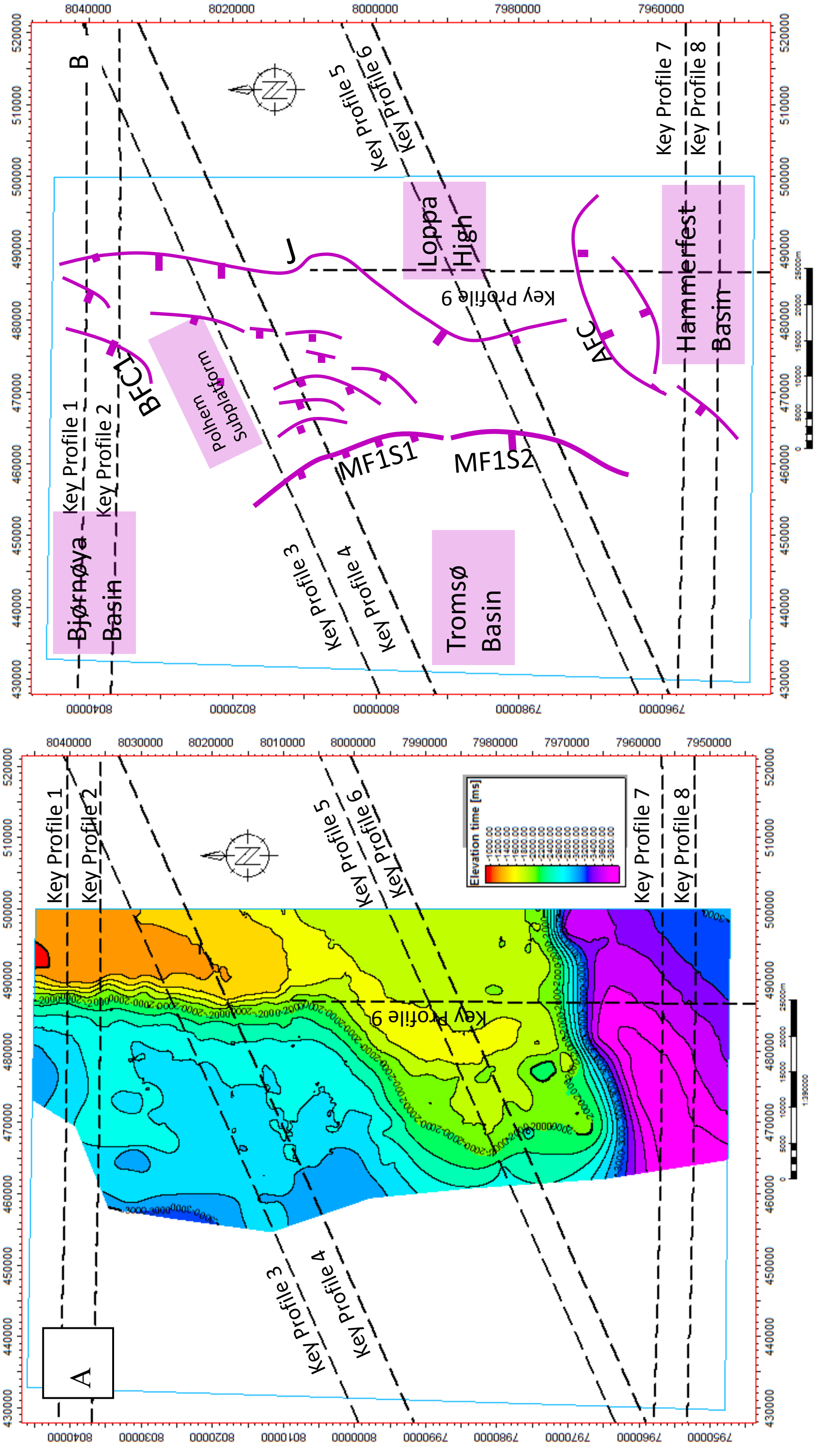


Figure 3.18: (A) Time structure map of Middle Triassic age. (B) Time structure map at the Intra Triassic level.

In Key Profile 3 and 4 (Fig. 3.10 & 3.11) thicknesses difference can be seen in MT and IT1 horizons across Jason Fault Complex/Selis Ridge. This thickness increase may be indication of prograded wedges mentioned by Glørstad-Clark (2011).

3.4.3 Intra Jurassic (Stø Formation)

Depth variation is striking feature in this time-structure map (Fig. 3.7). The depth range is from 1200ms to 7200ms in twt. Time structure map also indicates maximum depth in southwestern part where a complete basin is formed which is Tromsø Basin.

Combining time structure map and fault map will indicate that Intra Jurassic is shallowest, in the east of RLFC, and attain maximum depth across the faults.

A small saddle can also be seen in the northeastern region where another depression is formed, though this depression is not at deep as that of Tromsø Basin. This depression indicates southeastern part of Bjørnøyrenna Basin. This basin formed due to activity along the Bjørnøyrenna Fault Complex. This fault complex has been shown in fault map (Fig. 3.6B).

Another eye catching thing is the amount of faulting present in the fault map. Base Cretaceous and Intra Jurassic contain maximum number of faulting. This faulting is pronounced between MF1, MF2, MF3 and MF4. Numerous smaller faults, which are synthetic faults, are also present in these major faults. Synthetic faults are also seen in southwestern part along the Bjørnøyrenna Fault Complex.

Antithetic faults are observed mostly along Asterias Fault Complex. Cross sectional view indicates these faults are mostly reverse faults.

3.4.4 Base Cretaceous

Huge depth variations can be observed in the Base Cretaceous time-structure map (Fig. 3.19A). Northeastern part is devoid of Base Cretaceous as it is missing from Loppa High and Polhem Subplatform. In the Hammerfest and Bjørnøya basins, depth is increased. Looking at the fault map (Fig. 3.19B) one can see deepening of Hammerfest Basin and Bjørnøya Basin across Asterias Fault Complex, Ringvassøy-Loppa Fault Complex and Bjørnøyrenna Fault Complex. In the Bjørnøyrenna Fault Complex, faults are synthetic but in Asterias Fault Complex faults are antithetic.

Maximum depth is seen in southwestern corner of the study area. This deepening is the result of major subsidence along the Ringvassøy Loppa Fault Complex. MF1, MF2, MF3 and MF4 are parts of the Ringvassøy-Loppa Fault Complex. RLFC consists of number of synthetic faults which may have facilitated large amount of displacement.

The Base Cretaceous fault map (Fig. 3.19B) also depicts the fact that it is quite similar to the fault map of Intra Jurassic level (Fig. 3.7). Reason is that rifting continues from late Middle Jurassic to earliest Cretaceous time.

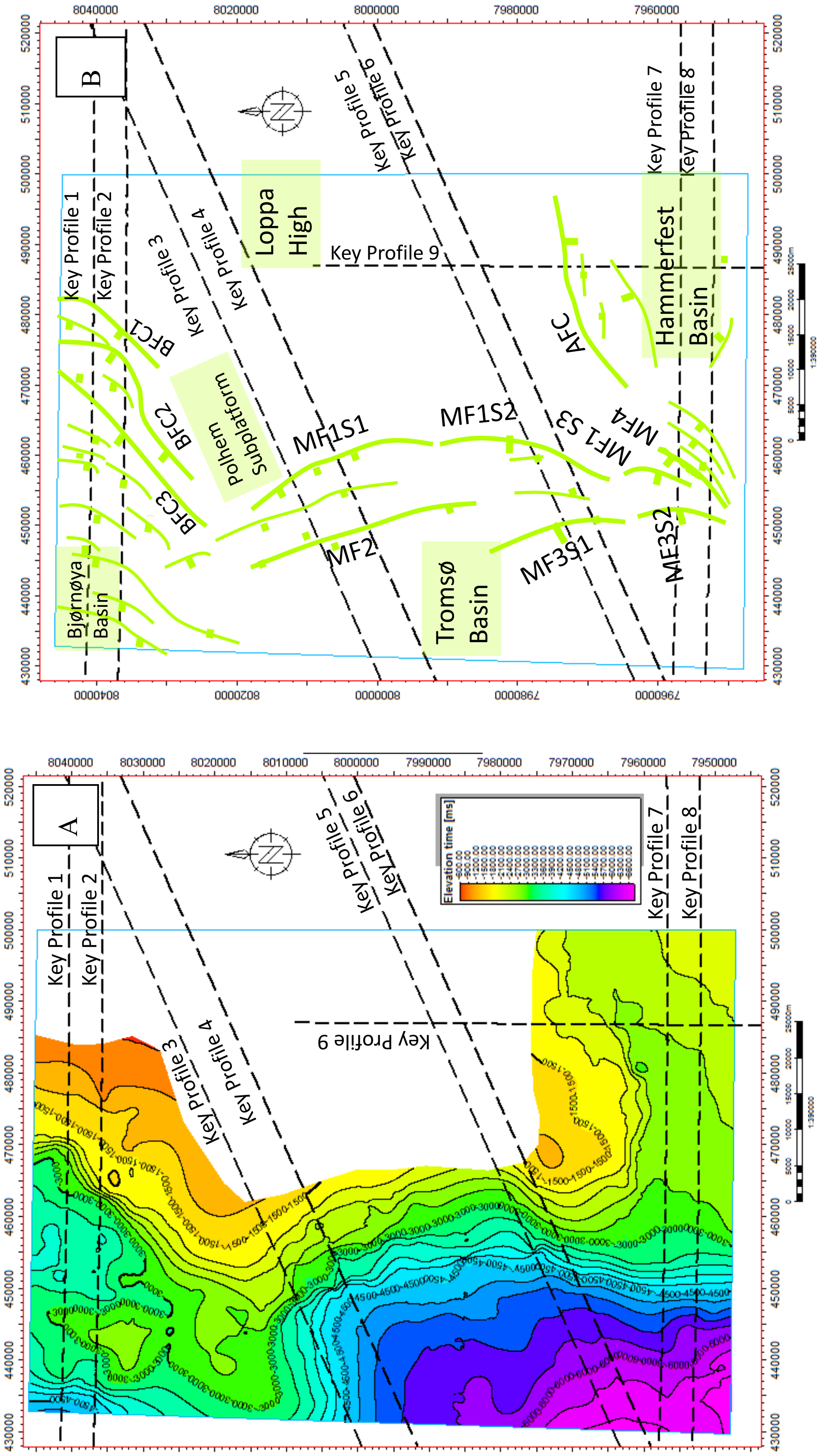


Figure 3. 19(A) Time structure map of Base Cretaceous (B) Fault map at the same level.

3.4.5 Intra Cretaceous

The Intra Cretaceous horizon covers most of the study area, but this is missing on the Loppa High and Polhem Subplatform. Greatest depth is attained in the southwestern corner of the study area as shown in Fig. 3.20A. It is shallower in the Hammerfest Basin and on the saddle situated between the Tromsø and Bjørnøya basins. Gradual deepening takes place from central and southeastern part to southwestern part. This deepening has taken place due to rapid subsidence in the Tromsø and Bjørnøya basins at that time.

Many faults are observable in fault map (Fig. 3.20B) but number of faults is less than Intra Jurassic and Cretaceous. MF1, MF3a, AFC and BFC3 have affected this horizon but effect of faulting is lesser than Base Cretaceous (Fig. 3.19B).

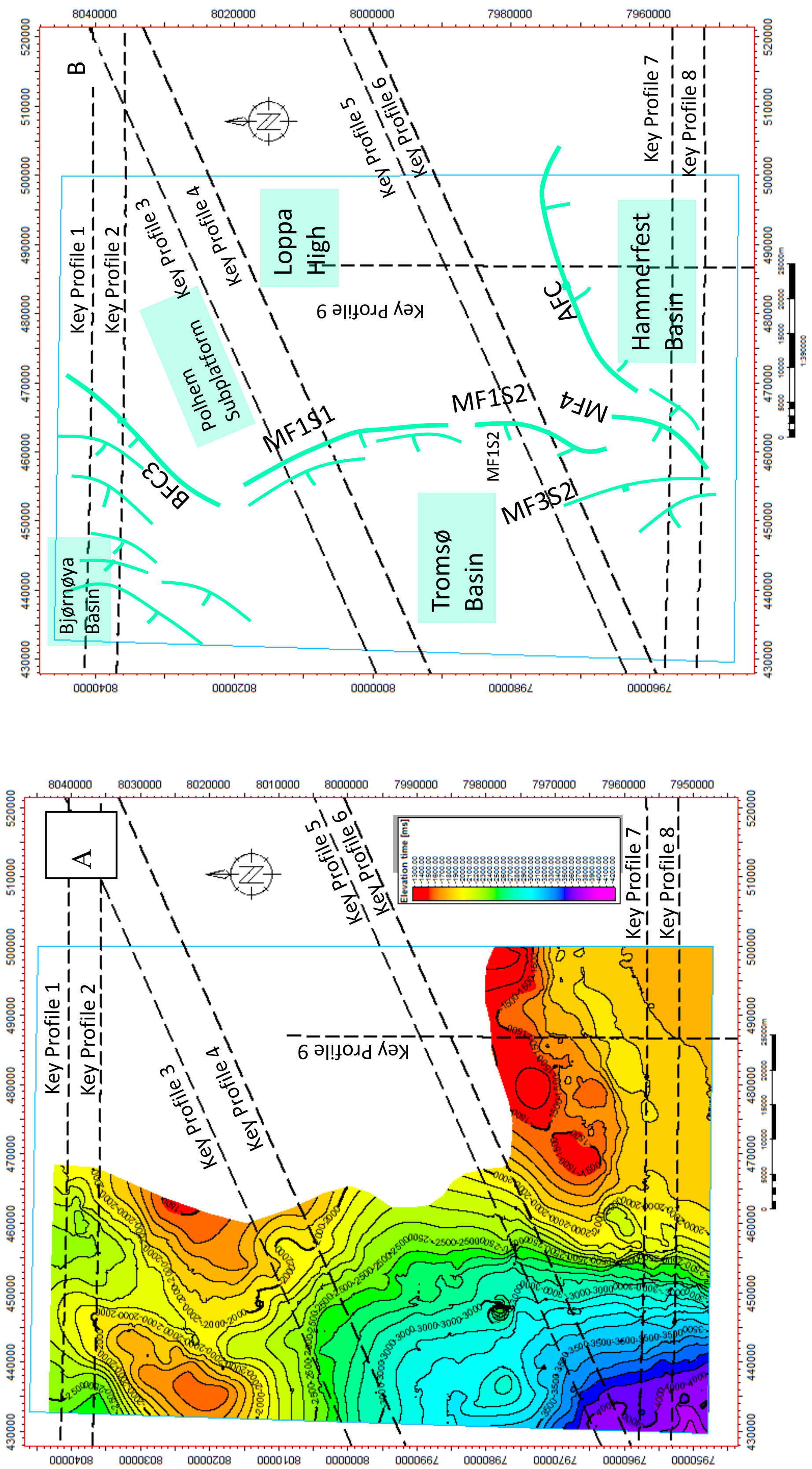


Figure 3.20 : (A) Time structure map at Kolje level (B) Fault map at the same level.

3.4.6 Base Tertiary

The Base Tertiary time-structure map (Fig. 3.21A) shows the same trend of depth as the other time-structure maps indicate. Maximum depth is observed in western and southwestern part (Fig. 3.21B). Maximum depth is seen at 2500 ms twt which is somewhere in the Tromsø Basin. Minimum depth is seen in southeastern part and northwestern part which are the Hammerfest Basin and Bjørnøya Basin respectively. In the Tromsø Basin, the depth trend is gradual and not very abrupt which indicates that not too much movement has taken place along fault complexes.

Looking at the corresponding fault map (Fig. 3.21B), will also indicate lesser effect of major faults. Not too many faults are cutting this reflector. Though last rifting event took place in Tertiary but not all faults reactivated in this time.

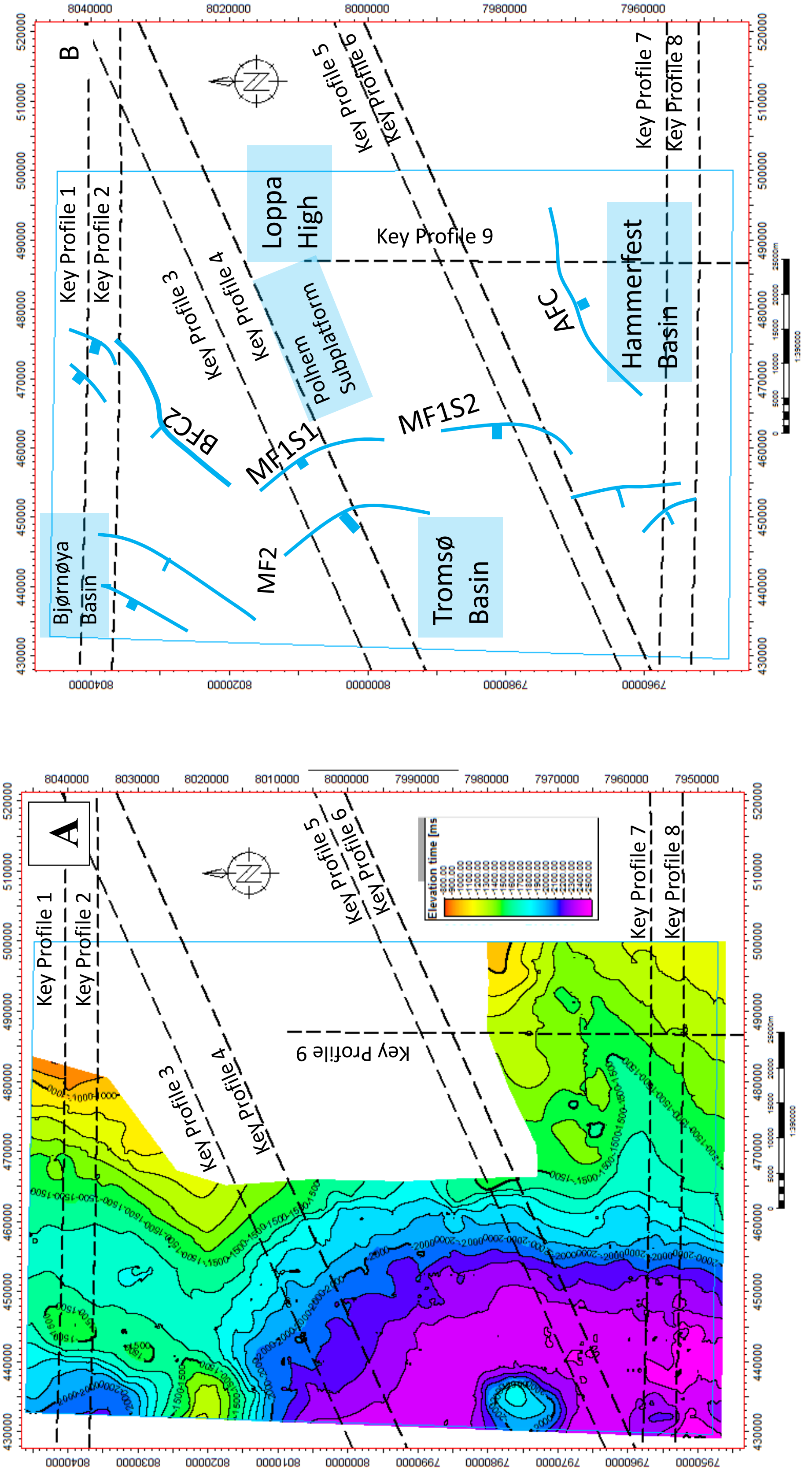


Figure 3.21: (A) Time structure map of Base Tertiary (B) Fault map at Base Tertiary level.

3.5 Time-Thickness maps

The time-thickness maps have been created between most of the horizons in order to get idea of depositional trends between different regimes. It also helps to figure out areas of no deposition in certain time periods in order to determine erosional history. The time-thickness maps are discussed in older-to-newer order. In this way history of the study area can be deduced as well.

3.5.1 Intra Permian - Intra Triassic

A striking feature of this time-thickness map is N-S trending red zone which is no deposition or erosional signature (Fig. 3.22). This region is situated right above the Selis Ridge where uplift took place between Intra Permian and Intra Triassic time. Due to this Intra Permian and top Permian were eroded from the crest of the ridge. This ridge also acted as a barrier for sediment which was coming from east to west (Glørstad-Clark et al., 2010).

Right across the ridge, sedimentation gradually increases on both sides. Probably maximum thickness observed between these horizons is in the Hammerfest Basin.

In Triassic time, fans and wedges have been formed on Polhem Subplatform (Glørstad-Clark, 2011). Time-thickness map (Fig. 3.22) probably duplicates setting of this time. Selis Ridge with no thickness (red color in Fig. 3.22) most probably acted as a barrier and made transportation in fan shaped way from the east to the westward direction.

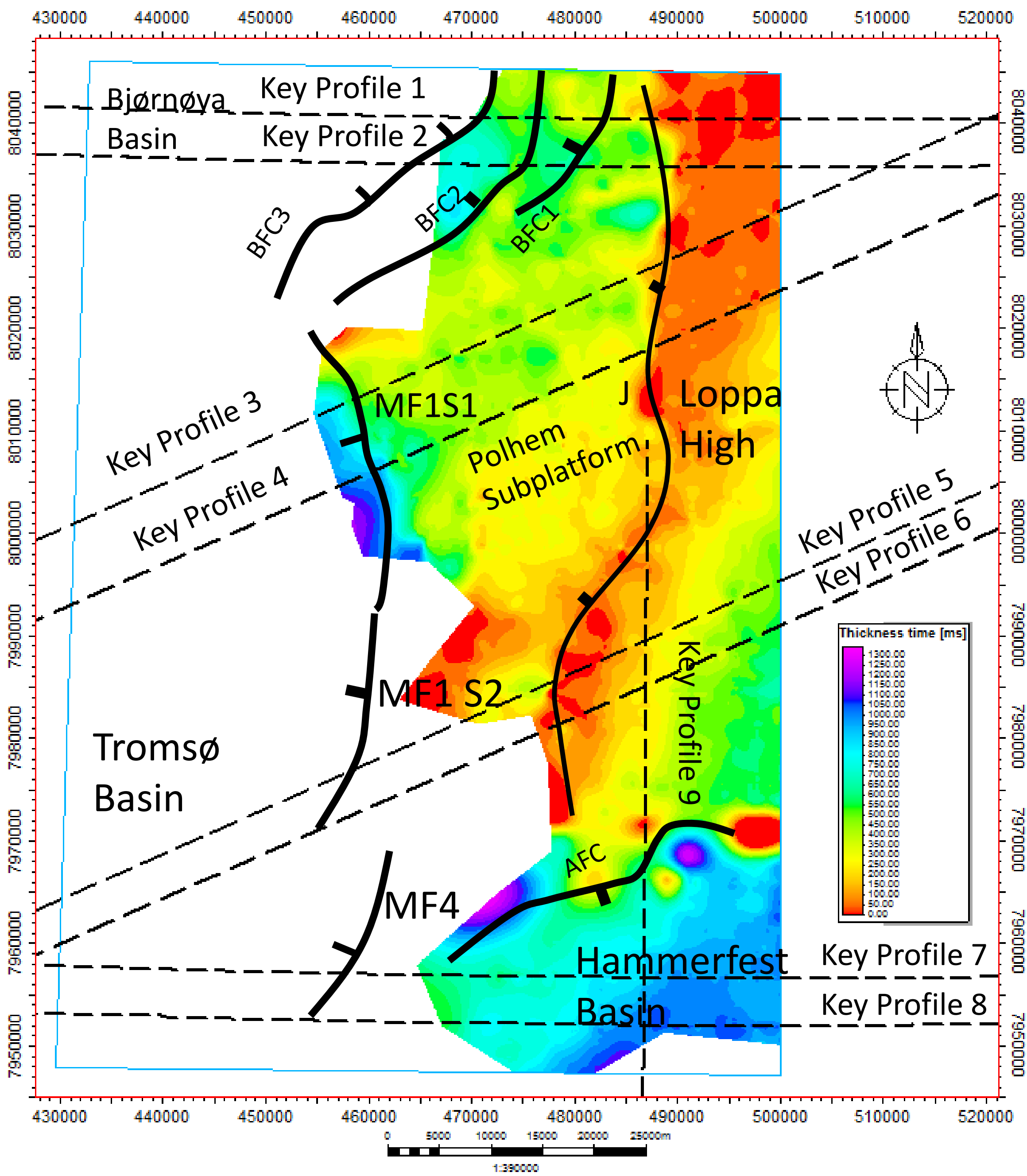


Figure 3.22: Time thickness map between Intra Permian and Middle Triassic.

3.5.2 Intra Triassic - Intra Jurassic

Jurassic rocks are missing from the Loppa High and Polhem Subplatform. On the other hand, Triassic rocks have not been interpreted in Tromsø Basin. That is why thickness between these two horizons may be possible at certain places (Fig. 3.23).

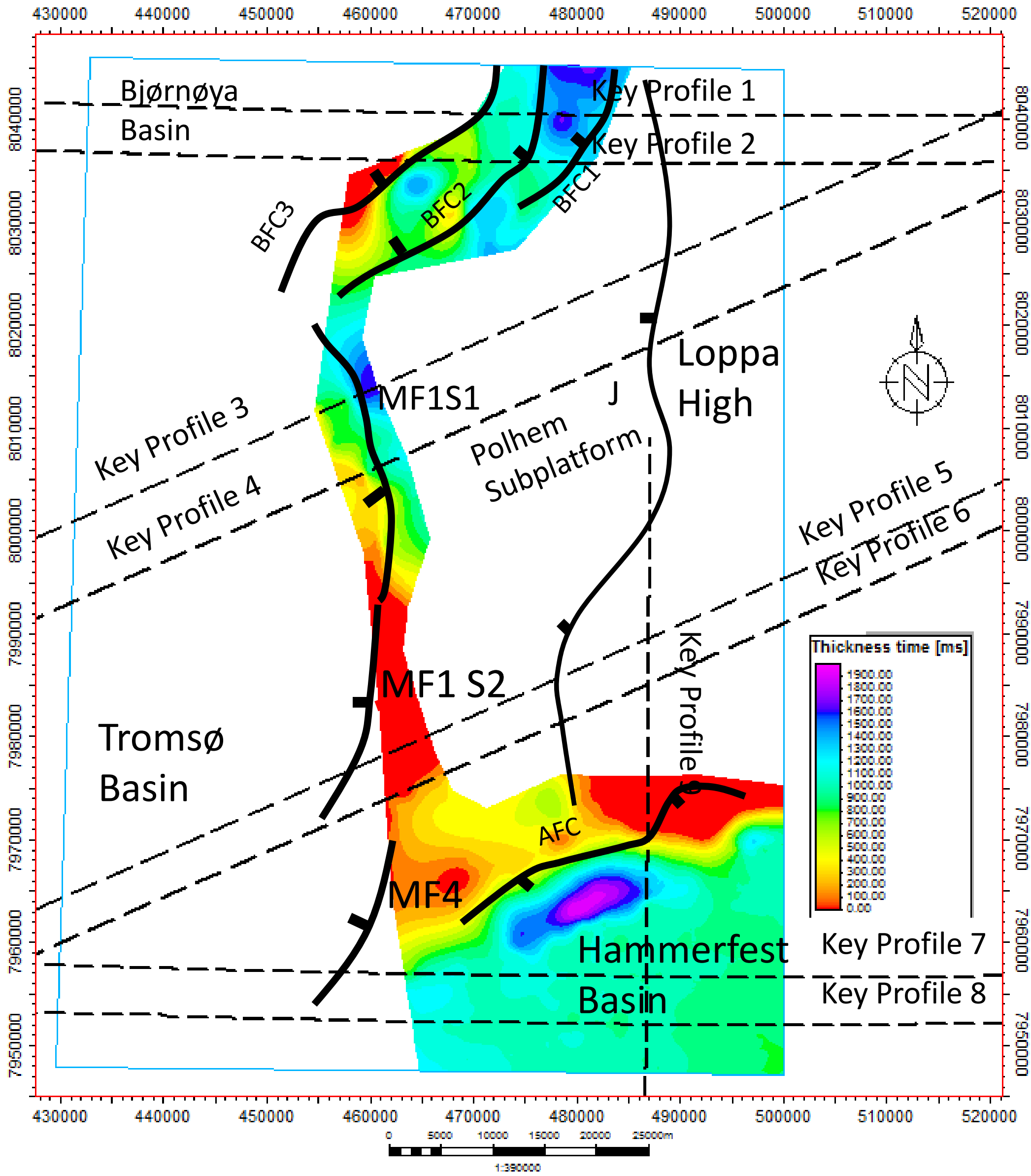


Figure 3.23: Time thickness map between Intra Triassic and Intra Jurassic.

Hammerfest Basin in the only place where both reflections are present and a time-thickness map between them is possible to construct.

3.5.3 Intra Jurassic -Base Cretaceous

Cross sectional view of key profiles suggest that Base Cretaceous and Intra Jurassic horizons make syn-rift wedges with each other. Only place where they are uniformly present without fault activity is in the Tromsø Basin. Otherwise these are cut by lot of faults which is manifestation that fault activity was really strong in between Intra Jurassic and Base Cretaceous time. Syn-rift wedges gain thickness next to faults as shown in Fig. 3.24.

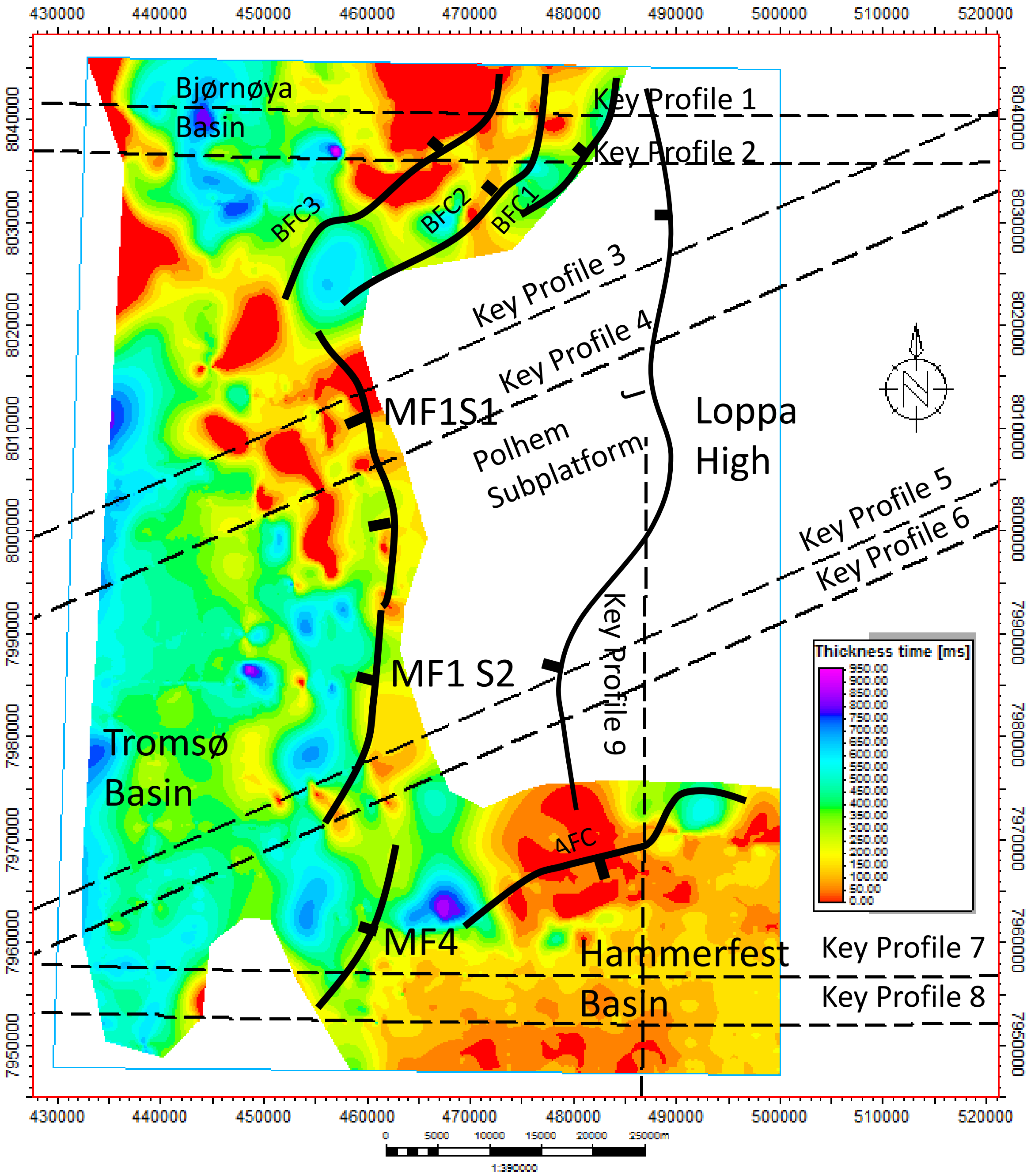


Figure 3.24: Time thickness map between Intra Jurassic and Base Cretaceous. Colour chart is showing variation of thickness in different parts of the area.

N-S trending deposition indicates that deposition between these two reflectors took place in between rotated fault blocks of Ringvassøy Loppa Fault Complex.

3.5.4 Base Cretaceous -Intra Cretaceous

Massive deposition took place in the Tromsø Basin during this time interval. Except for the Loppa High and its flanks. Loppa High remained an Island in Cretaceous time (Faleide, 1993a) and no sedimentation took place on Loppa High in this period. Thickness will not be possible between Base Cretaceous and Intra Cretaceous horizon. This is why; time-thickness map does not show any thickness in Loppa High region (Fig. 3.25).

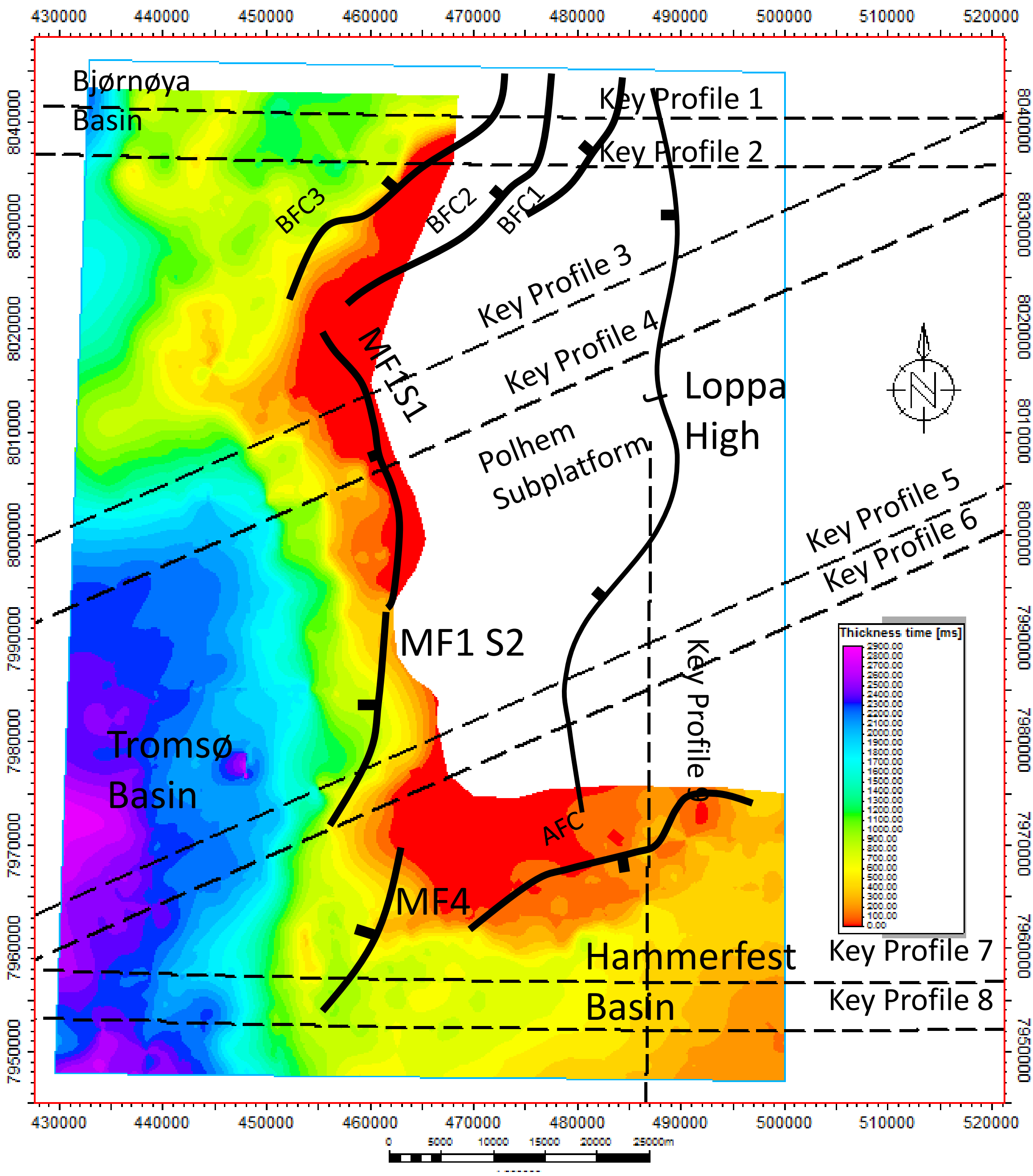


Figure 3.25: Time thickness map between Base Cretaceous and Intra Cretaceous. Color chart indicates thickness variation in different parts of the map. Blue rectangular box is the study area.

Abrupt thickness increase can be seen across the Ringvassøy-Loppa Fault Complex. It shows that faults created enormous space for sedimentation and there was lot of accommodation space available in this regime.

3.5.5 Intra Cretaceous -Base Tertiary

In Cretaceous time, Loppa High remained an island and erosion took place. That is why thickness-map shows no thickness on the Loppa High (Fig. 3.26). Sediments kept on depositing on Tromsø Basin in Early to Late Cretaceous time.

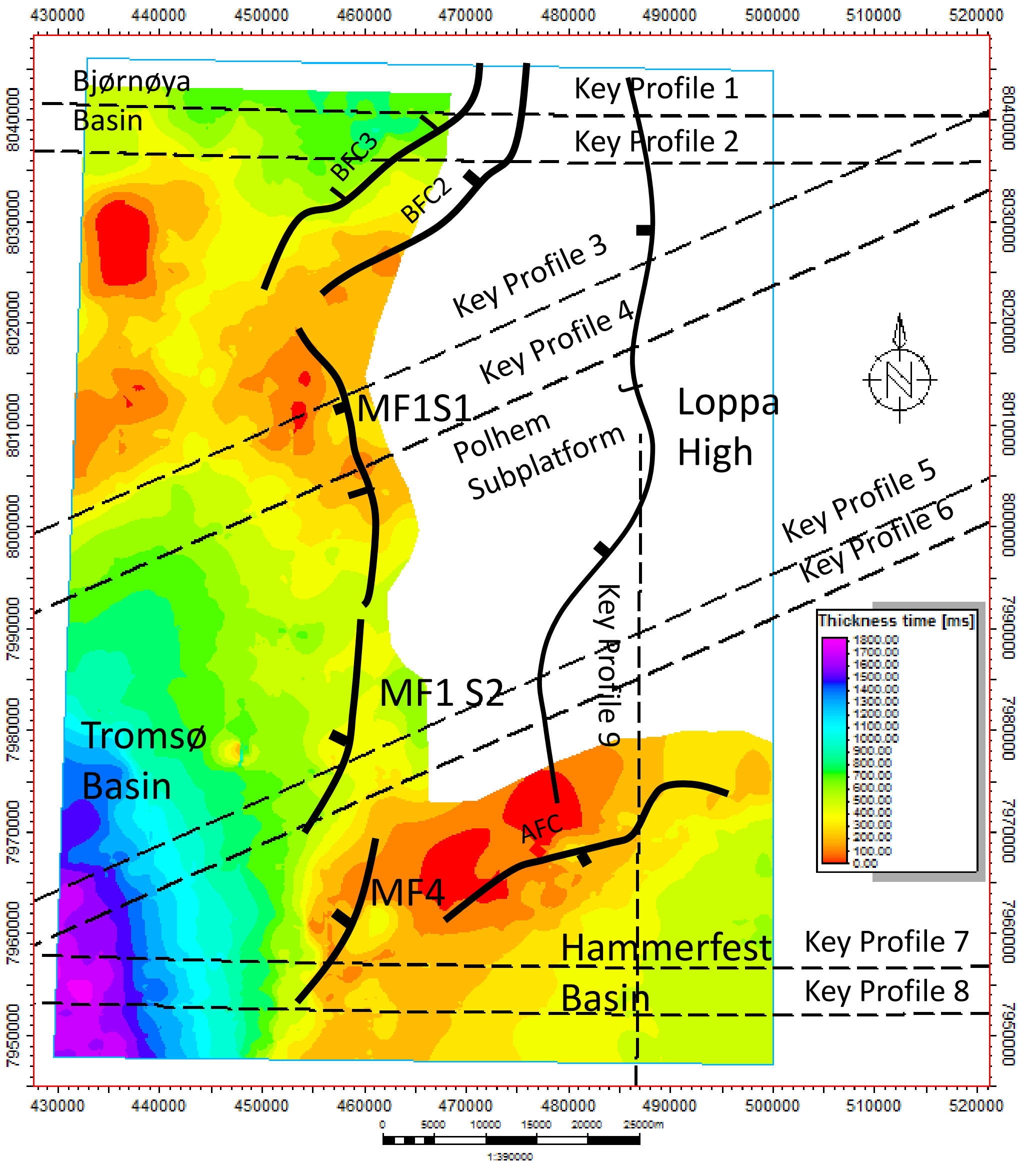


Figure 3.26: Time thickness map between Intra Cretaceous and Base Tertiary. Color chart indicates thickness variation and helps to see places with maximum and minimum thickness in the area.

Massive deposition took place in the Tromsø Basin which was probably still subsiding and there was space created for sediments.

4. Basin Modelling

The aim of basin modelling is to model the thermal history of sediments and maturation of hydrocarbon source rocks. Basin modelling is based on the assumption that the formation of sedimentary basins result from lithosphere extension. Far-field extensional forces trigger local thinning of the crust and mantle lithosphere resulting in surface subsidence. Once extension has ceased, the thinned lithosphere cools down hence providing additional subsidence (McKenzie, 1978; Jarvis and McKenzie, 1980). Basin modelling tools (such as Tecmod2D) help to estimate crust and mantle thinning factors. Assuming thermal properties for sedimentary, crustal and mantle rocks, the thermal history of sediments can then be modelled.

Two basin modelling approaches are generally used; backstripping and time-forward modelling. In backstripping, sedimentary layers are removed and decompacted one by one. At each step, horizons are restored to palaeo-water depths. Tectonic subsidence is computed by removing the isostatic subsidence (due to sediment load) from the total subsidence. It is assumed that tectonic subsidence results from lithospheric stretching/thinning and the stretching factor is determined by trial-and-error to reproduce this subsidence. Time-forward modelling is based on a different approach. Assuming initial arbitrary values for crust and mantle stretching factors, a synthetic stratigraphy is modelled and then compared to the observed one. The misfit is reduced by adjusting palaeo-water depths and β factors through an inversion scheme and iteratively forward modelling (Rüpke *et* al., 2008). Tecmod2D is based on this approach.

Here we use the Tecmod2D basin modelling software, based on a time-forward modelling approach, to model the thermal history of sediments and maturation of source rocks along a seismic profile crossing the Tromsø Basin.

Key profile 5 has been chosen for modelling because it crosses the well 7120/2-1. This transect has a NE-SW direction and crosses the Loppa High, the Selis Ridge, the Ringvassøy-Loppa Fault Complex and the Tromsø Basin (Fig. 3.7). Model inputs

4.1 Stratigraphy input

Three additional horizons have been mapped along the selected profile in order to have better control on basin modelling. Late Carboniferous, Top Triassic and Top Oligocene horizons have been included in the stratigraphic input. Input stratigraphy with respective ages is shown in Table. 4.1.

Table 4.1: Stratigraphic horizons with their respective ages. This information has been used in input file to display stratigraphic horizons in Tecmod.

Geological age	Age for modelling(in million years)
Recent	0
Top Oligocene	23
Base Tertiary	70
Intra Cretaceous	125
Base Cretaceous	145
Intra Jurassic	165
Top Triassic	199
Late Triassic	203
Middle Triassic	237
Top Permian	251
Intra Permian	294
Late Carboniferous	306
Intra Carboniferous	318

Horizons are shown in (Fig. 4.1).

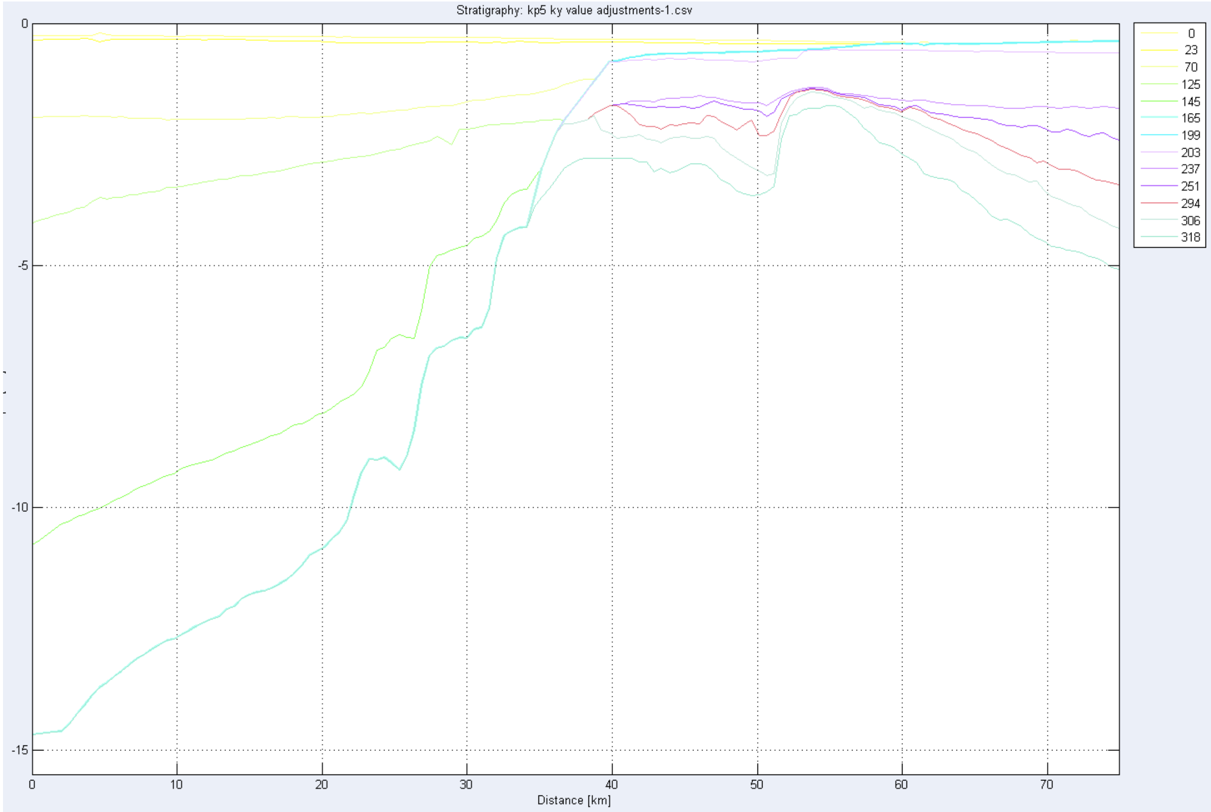


Figure 4.1: Stratigraphic horizons are correctly displayed in Tecmod which do not cross cut each other.

4.1.1 Rifting events

Three major rifting events are assumed in the study area. Timing of these events is described in (Table 4.2).

Table 4.2: Input of rifting events with respective ages.

Rifting events	Rifting interval
First	318-306
Second	294-251
Third	165-145

4.1.2 Lithologies for stratigraphic intervals

Lithologies of stratigraphic intervals are explained in chapter 3. Lithologies have been taken from Clark et al. (2013) and have been given in the (Table 4.3).

Table 4.3: General lithologies of formations which are used in modelling.

Formation/Group	**Modelled lithology**
Sea Bed	50ss, 50sh
Torsk Formation	10ss, 90sh
Kveite Formation	Shale
Kolje Formation	Shale
Hekkingen Formation	Shale (kerogen type 1)
Stø Formation	Sandstone
Fruholmen Formation	Sandstone
Snadd Formation	Sandstone
Kobbe Formation	60ss,40sh
Ørret Formation	Limestone
Ørn Formation	Limestone
Falk Formation	Limestone
Billefjorden Group	Basement

4.1.3 Erosion

The Barents Sea has experienced erosion episodes several times in the past. The Loppa High was an island in Cretaceous time and experienced 1000-1500m erosion (Berglund et al., 1986). The Tromsø Basin has also gone through erosional phases and sediments up to 1000 meters were removed (Riis & Fjeldskaar, 1992). Tecmod deals with erosion in discrete events. In a transect, place and time is mentioned for erosional places and sediments are eroded from that place. But a separate file for erosional rate is also put into Tecmod. For this study, erosion rate has been kept 10mm for recent sediments. But erosion of 1000 meters produced errors in stratigraphic match and mismatch got high. About 500 meters erosion produces match which is <5%.

4.1.4 Inversion parameter

Other parameters have been adjusted in the Inversion Control Panel of Tecmod. A summary of these parameters is given in (Table 4.4).

Table 4.4: General parameters used in basin modelling.

Parameter	Value
$\mathbf{B_{up}}$	0.3
$\mathbf{\Delta_{up}}$	1
$\mathbf{B_{coeff}}$	2
$\mathbf{\Delta_{coeff}}$	2
$\mathbf{W_{up}}$	0.11
$\mathbf{W_{rift}}$	100
$\mathbf{W_{rift\ loop}}$	1
$\boldsymbol{\beta_{rift\ loop}}$	2
Differential thinning	No
Max. Iterations	25
Max. Error (m)	50

4.2 General assumptions

For simplicity reasons, assumptions are made in our model. Chemical compaction, diagenetic changes and even low-grade metamorphism have not been considered to act on deeply buried sedimentary rocks.

Flexural properties and necking depth has been adjusted by considering previously modelled basins (Fjeldskaar et al., 2004; Rüpke et al., 2008, 2010; Theissen & Rüpke, 2010). Elastic thickness T_E has been set to 5 km and necking depth has been given value of 15 km.

Geometry of crust and mantle lithosphere following the collapse of the Caledonides may be complex and thicknesses may vary along the profile. However, this can be hardly constrained. So, for simplicity reasons we assume a constant initial thickness of 35 km for the crust and 120 km for the lithosphere.

Salt in deformation of our beds has been ignored completely. Volcanic activity has also not been considered in modelling. Recent phases of ice loading and subsequent uplift and erosion has also been ignored.

4.3 Results

4.3.1 Stratigraphic match

The final modelled stratigraphy reproduces the observed one with a residual error less than 5 % as shown in Fig.4.2. However, mismatch areas appear (see lower panel of Fig. 4.2). Maximum misfit is found in the top right and top left corners of the profile (Fig. 4.2). This misfit results from erosion which Tecmod did not incorporate in a suitable way. Though erosion is far greater than input given to Tecmod. Greater erosional input resulted in greater mismatch. That is why only 400 meter erosion has been kept which still resulted in mismatched area. Modelled stratigraphy also varies from that of input stratigraphy in areas near faults along our profile (Fig. 4.2A). Overall, residual error is under 5 % (Fig. 4.2B).

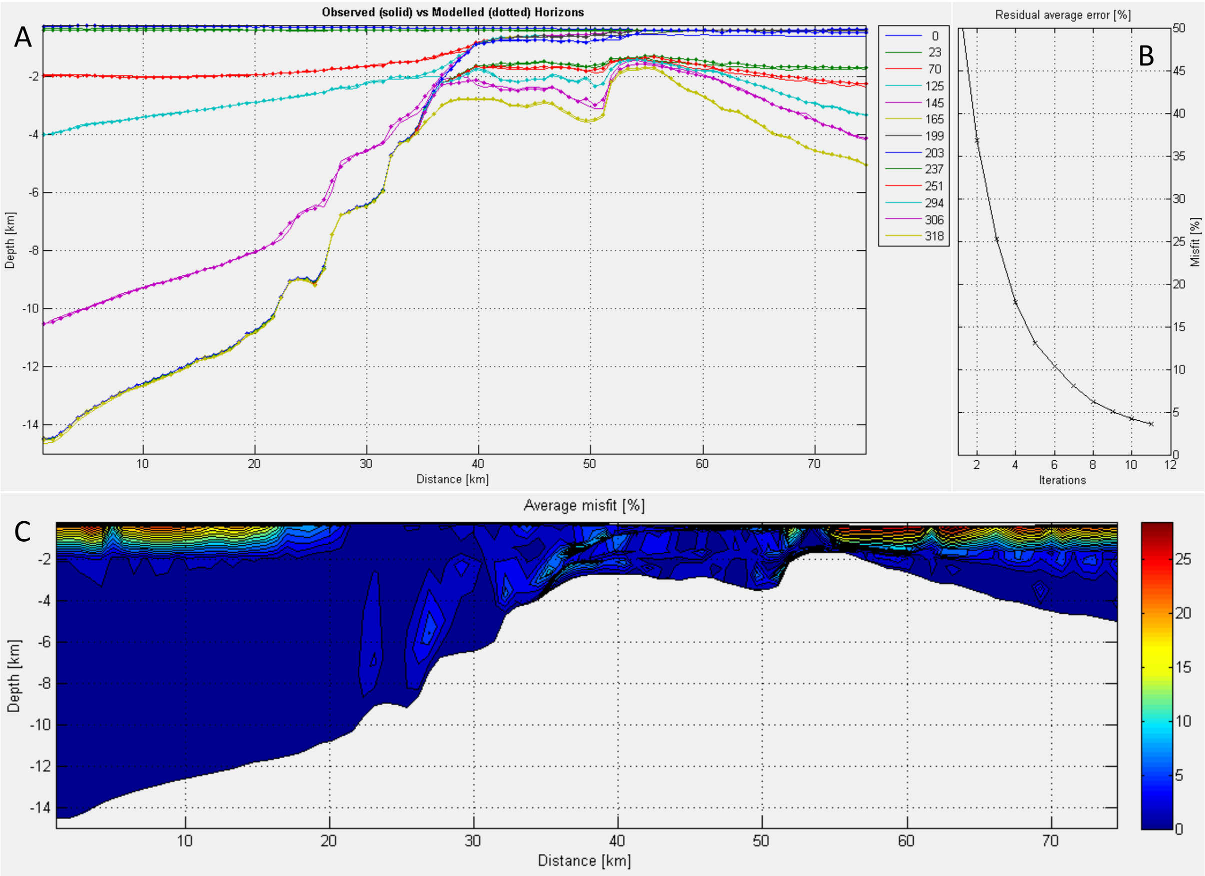


Figure 4.2: The Tecmod-modelled stratigraphy. A) Upper graph is showing modelled horizons (dotted lines) against input (solid lines). Differences are minute except near faults. B) Right hand graph shows average residual error between modelled and observed stratigraphy. C) Lower panel shows misfits along the profile. Maximum misfits are located in the upper right and left hand corners of the profile.

4.3.2 Paleowater depth comparison

Our, modelled palaeo-water depths are far deeper than “observed” depths. Observed palaeo-water depths are taken from (Clark et al., 2013) on the Loppa High (Fig. 4.3).

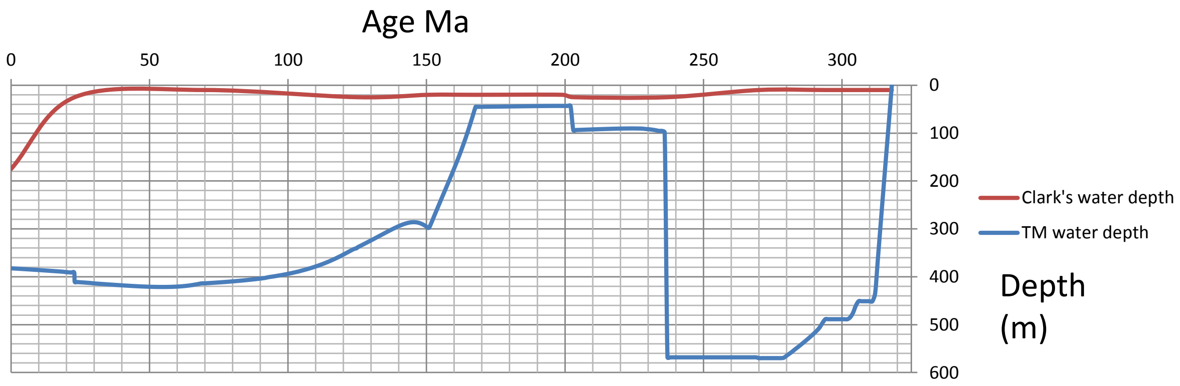


Figure 4.3: Modelled (blue) and observed (red) palaeo water depths on the Loppa High.

4.3.3 Cumulative stretching factor

As explained earlier, we assume three rifting events which affected our study area in the past. These rifting events do have their own independent stretching factors. Computed cumulative stretching factor in the Tromsø Basin is about 2.2. The maximum stretching factor is observed in third rift phase at the center of the Tromsø Basin (Fig. 4.4). This rifting has caused deepening of Tromsø Basin. Second rifting event did not show too much stretching. The reason is that, with our present data, deeper reflectors have not been marked in the Tromsø Basin. Addition of deeper reflectors may have brought different results. From 40 km to 74,5 km, area has not affected too much. This is the area which consists of Loppa High and Loppa High does not seem to have affected by too much rifting except at 50 km area where the Selis Ridge and Jason Fault Complex exist.

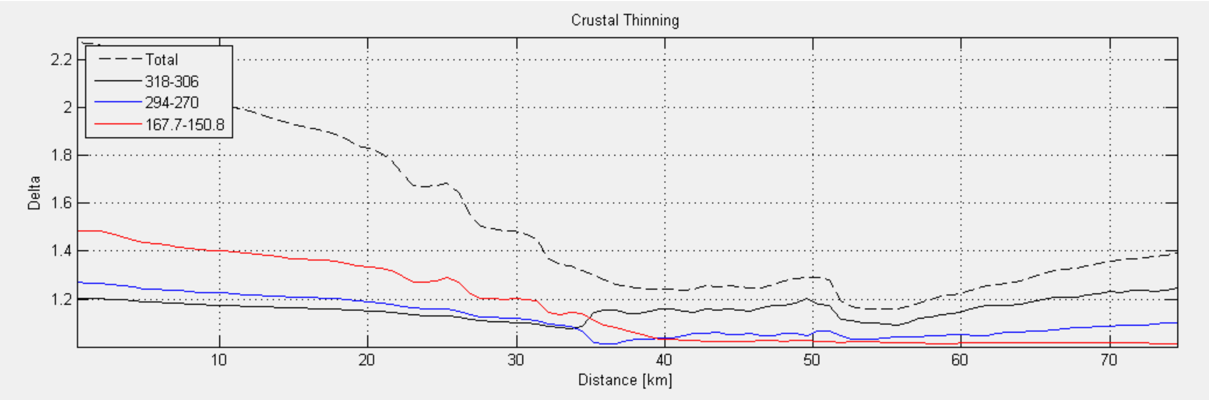


Figure 4.4: Stretching factors calculated by Tecmod. Stretching factors for both rifting events are shown separately. Cumulative stretching factor is also shown.

4.3.4 Temperature match

Well 7120/2-1 is used to check the temperature difference between well data and Tecmod-generated temperature. This well is located on the eastern side of the Selis Ridge as shown in (Fig. 4.5A). Well temperature is obtained from NPD and is plotted against Tecmod data. The spot of bottom-hole temperature (97 ºC) lies very close to vertical graph of Tecmod as shown in (Fig. 4.5B). Temperature matching indicates robustness of predictive power of our model.

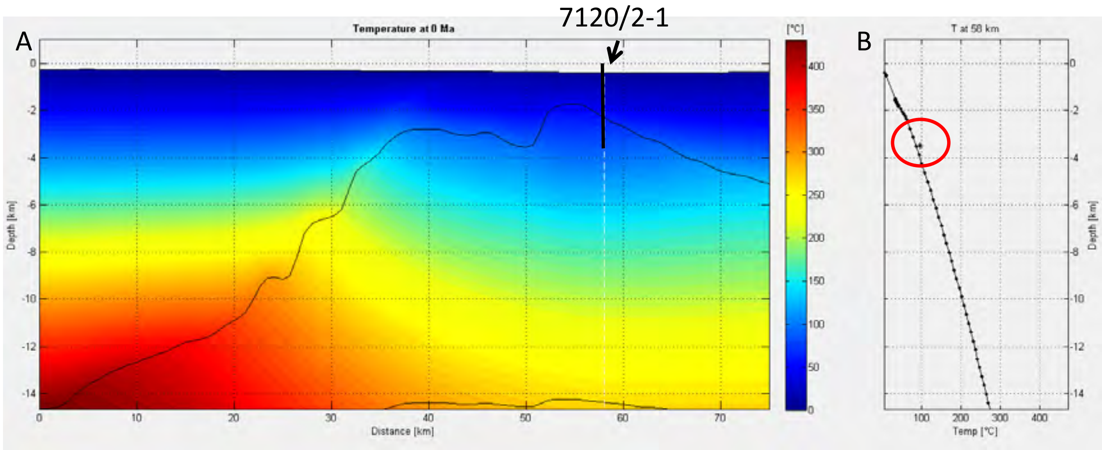


Figure 4.5: Modelled present-day thermal structure. A) Left hand panel is showing position of well with black line. B) Right hand panel is showing Tecmod-generated temperature increase with depth. Plotted well data has been marked in red circle.

4.3.5 Vitrinite reflectance

Vitrinite reflectance (VR) is a good indicator of thermal maturity of source rocks. The reflectance of the vitrinite maceral vary with temperature. ; VR of source rocks, increases with depth due to higher temperature (Fig. 4.6). Tecmod calculates vitrinite reflectance (VR) and these values are compared to well data (7120/2-1). Calculated VR is slightly lower than well data (Fig. 4.6). Well values are higher because Loppa High rocks were buried beneath Jurassic rocks which were later eroded when the high was uplifted. This overburden of rocks caused higher palaeo-temperature; hence these rocks have gained more maturation.

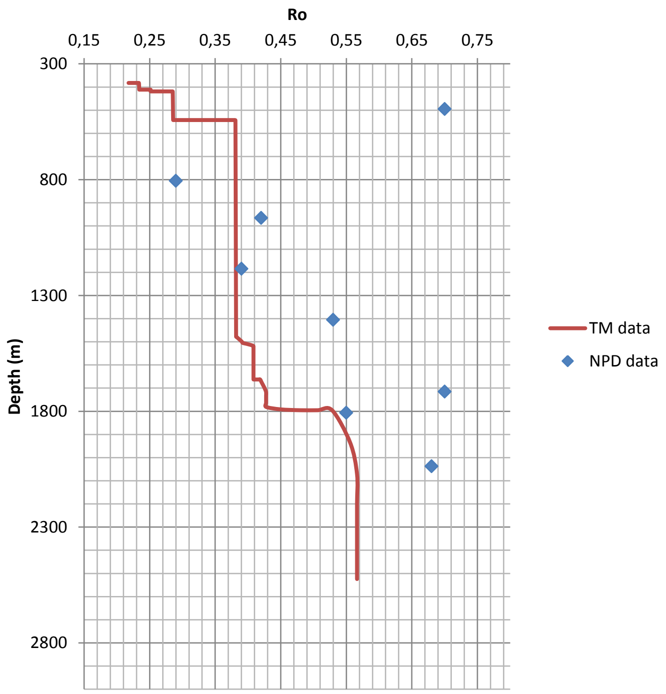


Figure 4.6: Tecmod-calculated vitrinite reflectance and actual vitrinite reflectance found in well 7120/2-1.

4.4 Basin Modelling Conclusions

Main points of basin modelling conclusions are mentioned as follows:

4.4.1 Robustness of our model

- Generate stratigraphy similar to input stratigraphy (less than 5 % misfit).
- Incorporates temperature nicely.
- Can predict locations for potential oil reserves. Gotha discover by Lundin in 2013 in the southwestern Loppa High endorses the predictive power of our model as our model

also predicts oil window in the vicinity of this discovery. Approximate position of this discovery has been marked in (Fig. 4.7)

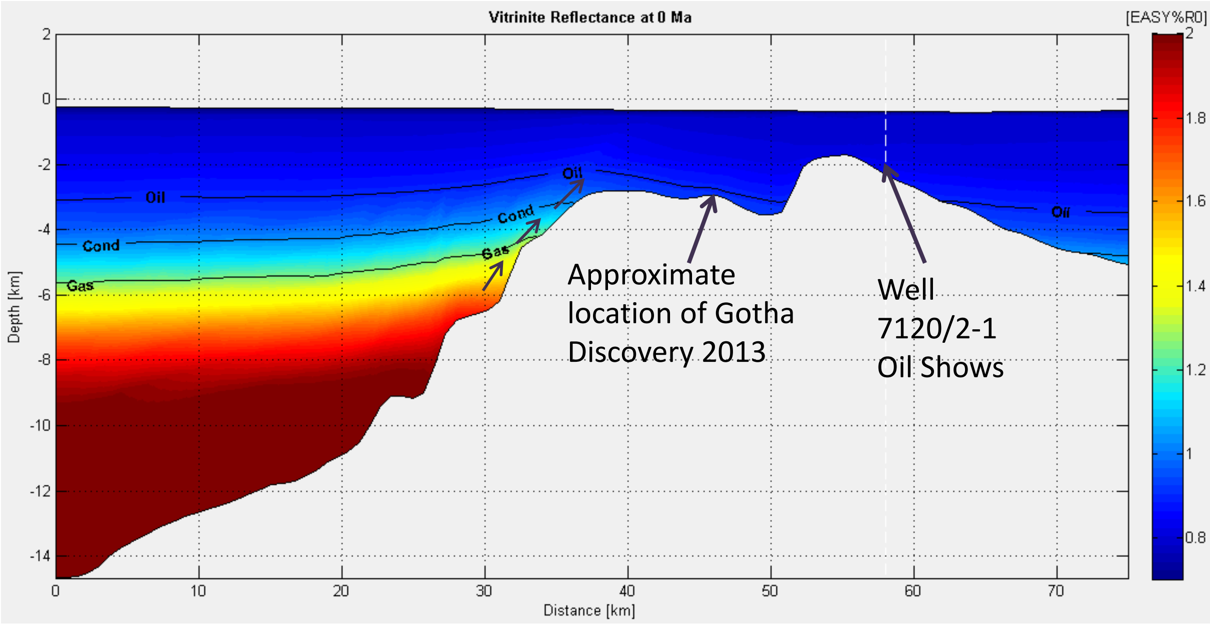


Figure 4.7: Thermal maturity of source rock at present time.

4.4.2 Discrepancies

- Shows less maturity of source rocks in Loppa High. This discrepancy can be dealt by using software which incorporates erosion in better way. Because present data allows erosion of only 400 meters.
- Does not fit "observed" palaeo-water depths.
-

4.4.3 Limitations

- Just one well is available to match the modeled results.
- Interpretation of every reflector in deeper horizons can bring better results.

5. Discussion

In this chapter, detailed analysis of the northern part of Ringvassøy-Loppa Fault Complex is carried out. Previous chapters dealt with general observation and methodology. Here, an attempt has been made to deduce results from observations in the light of structural geology.

Topics which are intended to be discussed in this chapter are as follows:

- Fault Classification of Ringvassøy-Loppa Fault Complex
- Detachments
- Approximate dip of the fault segments
- Displacement along fault segments
- Timing of faulting (RLFC)
- Evolution of the area

5.1 Classification of Ringvassøy-Loppa Fault Complex

Ringvassøy-Loppa Fault Complex can be classified by variety of ways. Here classification is based on

- Fault Class (Gabrielsen's classification)
- Classification based on transfer zones

5.1.1 Fault Class (Gabrielsen's Classification)

This classification was proposed by Gabrielsen (1984) for the southwestern Barents Sea which is based upon the faults' involvement with basement rocks, their extent and reactivation histories. According to this scheme, faults can be divided into three classes depending upon factors mentioned in (Table. 5.1).

On the basis of criteria given in this scheme, we can suggest Class 1 type for Ringvassøy-Loppa Fault Complex. These faults are basement linked as shown in and have been activated several times in their age. Their regional tectonic significance cannot be ignored as these faults caused development of Tromsø Basin.

Table 5.1: Classes of different faults proposed by Gabrielsen (1984) for the southwestern Barents Sea.

Class 1	Basement involved	Regional significance	Reactivated	Separate areas of different tectonic outlines
Class 2	Basement involved	Semi-Regional	Reactivated/ not reactivated	Separate areas of different tectonic outlines
Class 3	Basement detached	Local significance	Not reactivated	Does not separate areas of different tectonic outlines

5.1.2 Classification based on Faults' Linkage

This classification is based on Morley et al (1990). In this classification, basic geometries of faults are seen first. It is seen either faults are dipping in the same direction or in opposite direction (Fig. 5.1A). In case faults in fault complex are dipping towards each other, these are called conjugate faults. If faults are dipping at the same direction, such faults are called synthetic faults. By looking at fault map of Jurassic age which is shown in (Fig. 3.5), we can see that all segments in Ringvassøy-Loppa Fault are dipping in the western direction. These faults are synthetic and no antithetic fault is seen between these faults. That is why we call these faults as synthetic faults.

Synthetic faults are further subdivided into three different classes. This subdivision is based upon the strike relationship of faults with each other. If faults approach each other and faults tip do not surpass each other, we call these faults, synthetic approaching fault. If fault tips surpass each other, we call such faults as overlapping faults. But if the faults are in almost parallel to each other, we call such faults as collateral as shown in (Fig. 5.1B).

In our case, fault segments are approaching, overlapping and collateral at three distinct places. For instance, segments of Major Fault 1(S1, S2 and S3) and synthetic approaching. Segment 1 and 2 of Major Fault 3 are also synthetic approaching. But Major Fault 1 and segment 1 of Major Fault 2 are overlapping.

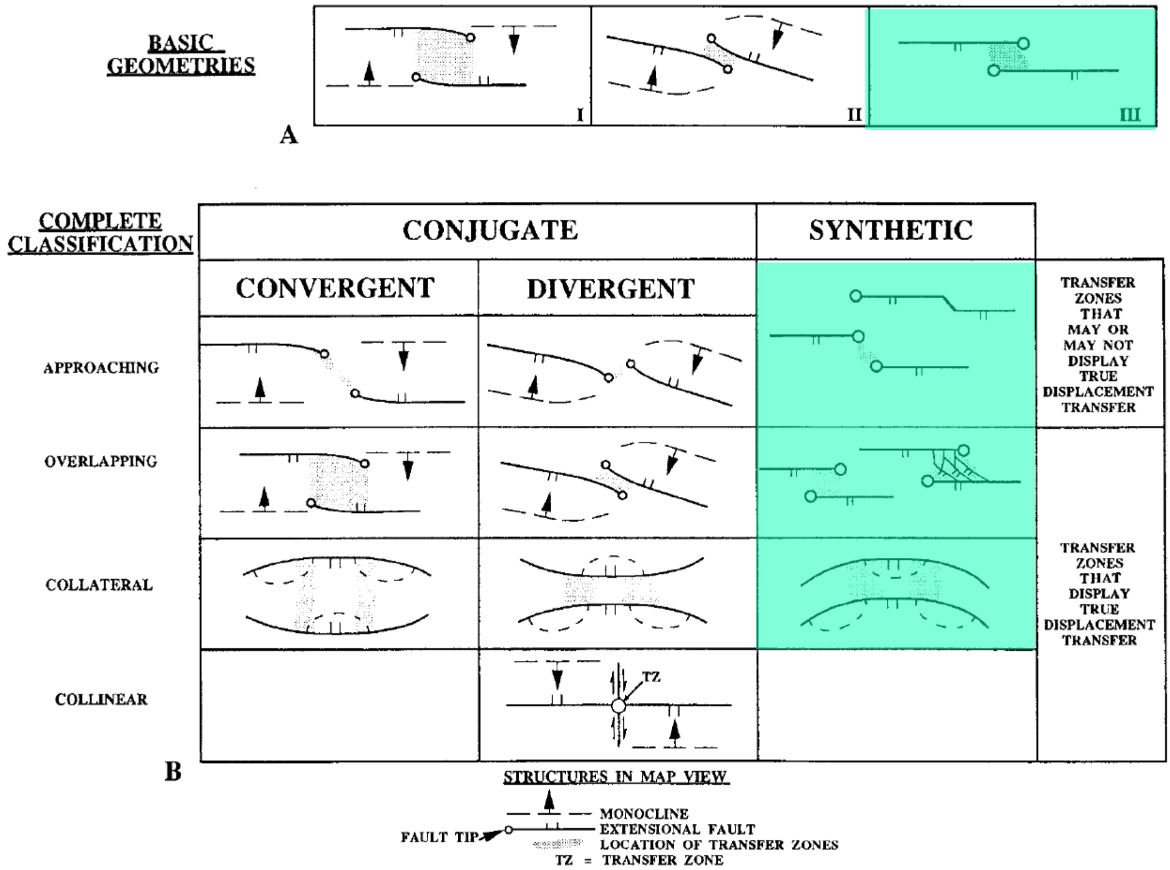


Figure 5.1: (A) Fault division based on basic geometries. In our case all fault segment are dipping, more or less, in same direction. (B) Basis for the classification of faults, on the basis of strike relationship of the faults. Our fault segments are collateral, overlapping and approaching at different places (Modified from Morley, 1990).

By looking at the fault displacement map shown in (Fig. 5.5), it can be seen on a broader way that Major Faults 1, 2, 3 and 4 are collateral (Fig. 5.2), where one fault loses its displacement, parallel fault gains it (Fig. 5.2 B). Lose-and-gain relationship between parallel faults has been shown in (Fig. 5.2).

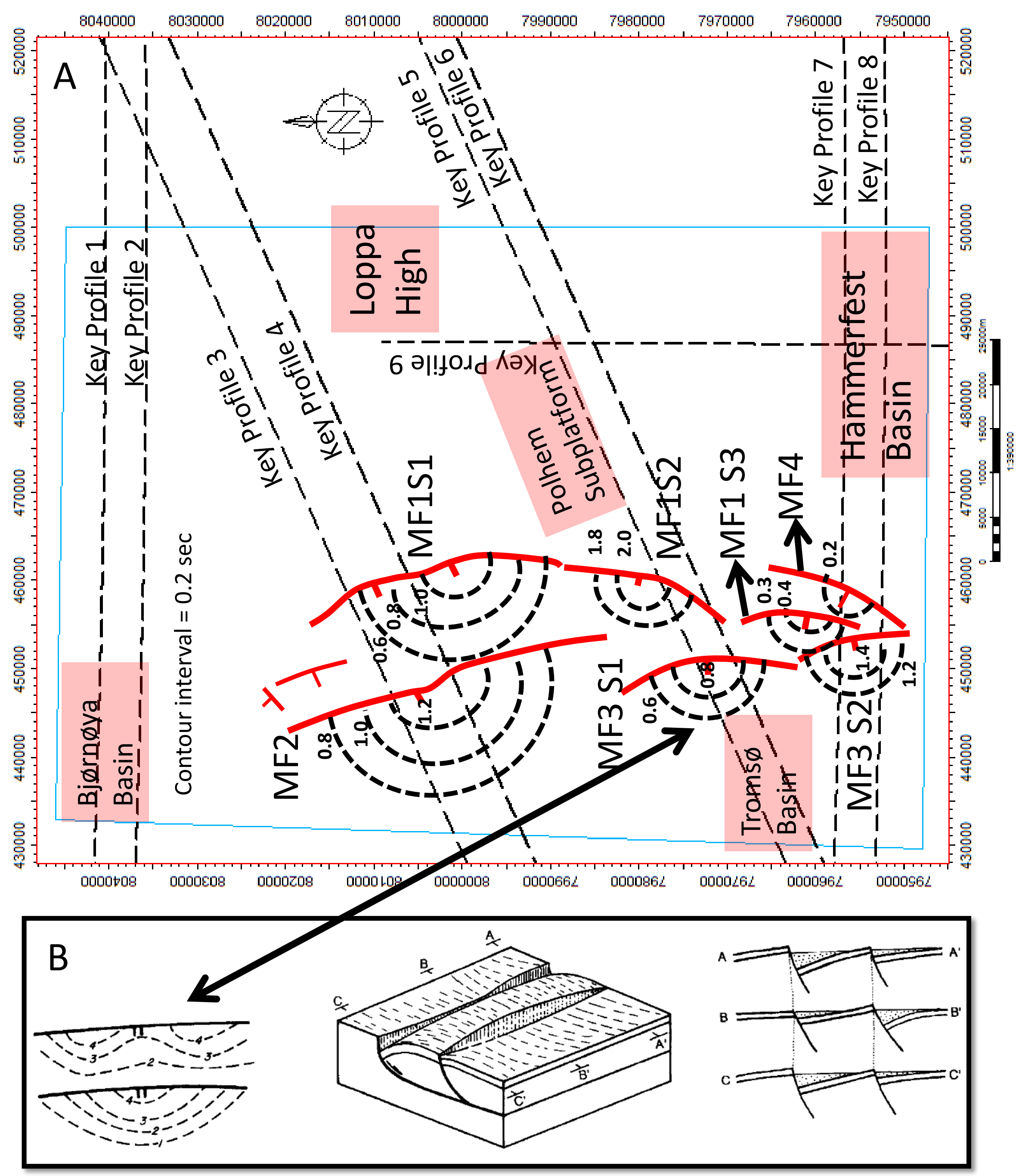


Figure. 5.2. (A). Time-structure map at Intra Jurassic level with displacement contours. (B) Displacement gain-and-lose relationship in synthetic collateral transfer zones (Modified from Morley et al., 1990).

5.2 Detachment zones

A number of authors have carried out studies on the presence of possible detachments in or around study area. First Gabrielsen (1984) proposed three possible detachments in the southwestern Barents Sea. Later more authors (Ahmed, 2012; Braut, 2012; Fitriyanto, 2011; Zalmstra, 2013; Ahmad, 2013) have endorsed the presence of these detachments in different locations of southwestern Barents Sea.

The present study agrees with previous work of above given authors. These detachments have been present between:

- Early Permian and Top Permian
- Base Cretaceous and Intra Cretaceous
- Intra Cretaceous and Base Tertiary

Exact position of these detachments is hard to describe but an attempt has been made to give a best possible position.

5.2.1 Position of First Detachment

The position of this detachment has been marked in key profile 3 and key profile 4 with black dashed lines. Close view of this key profile 4 has been shown in (Fig. 5.3). In cross section view it is quite clear that faults above than Intra Permian have not penetrated deeper than Intra Permian level which is possible detachment. The frequency of faults above of Intra Permian is more than in lower zones. Not only that, amount of displacement on above level faults is different than lower level faults. A Fault map also confirms this detachment zone as number of faults is present at Late Triassic as compared to faults at Intra Permian level. Trend of the faults is also not same (Fig. 5.4).

Heave of the faults have been calculated across this detachment. Faults below this detachment have combined heave of 728 meters. While combined heave of faults situated above this detachment is 1079 meters. It also illustrates that extension on above rocks took place independently, without influence of extension of lower rocks.

Polhem Subplatform

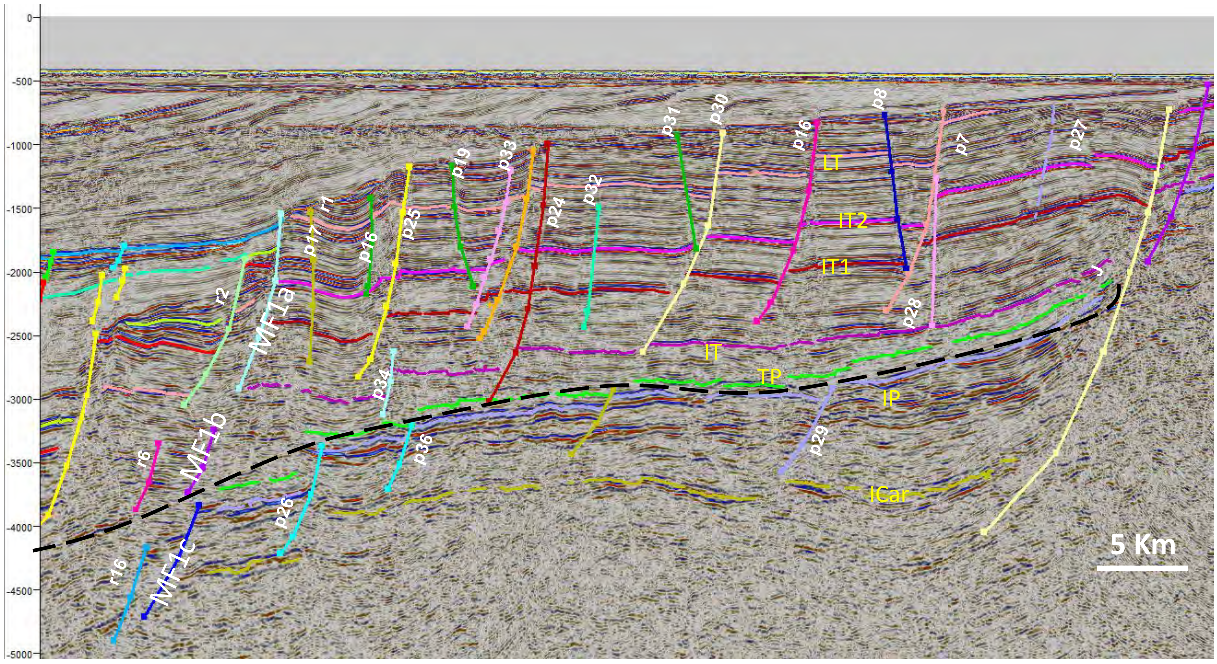


Figure 5.3: Close up view of key profile number 4. Black dashed line is indicating position of possible detachment.

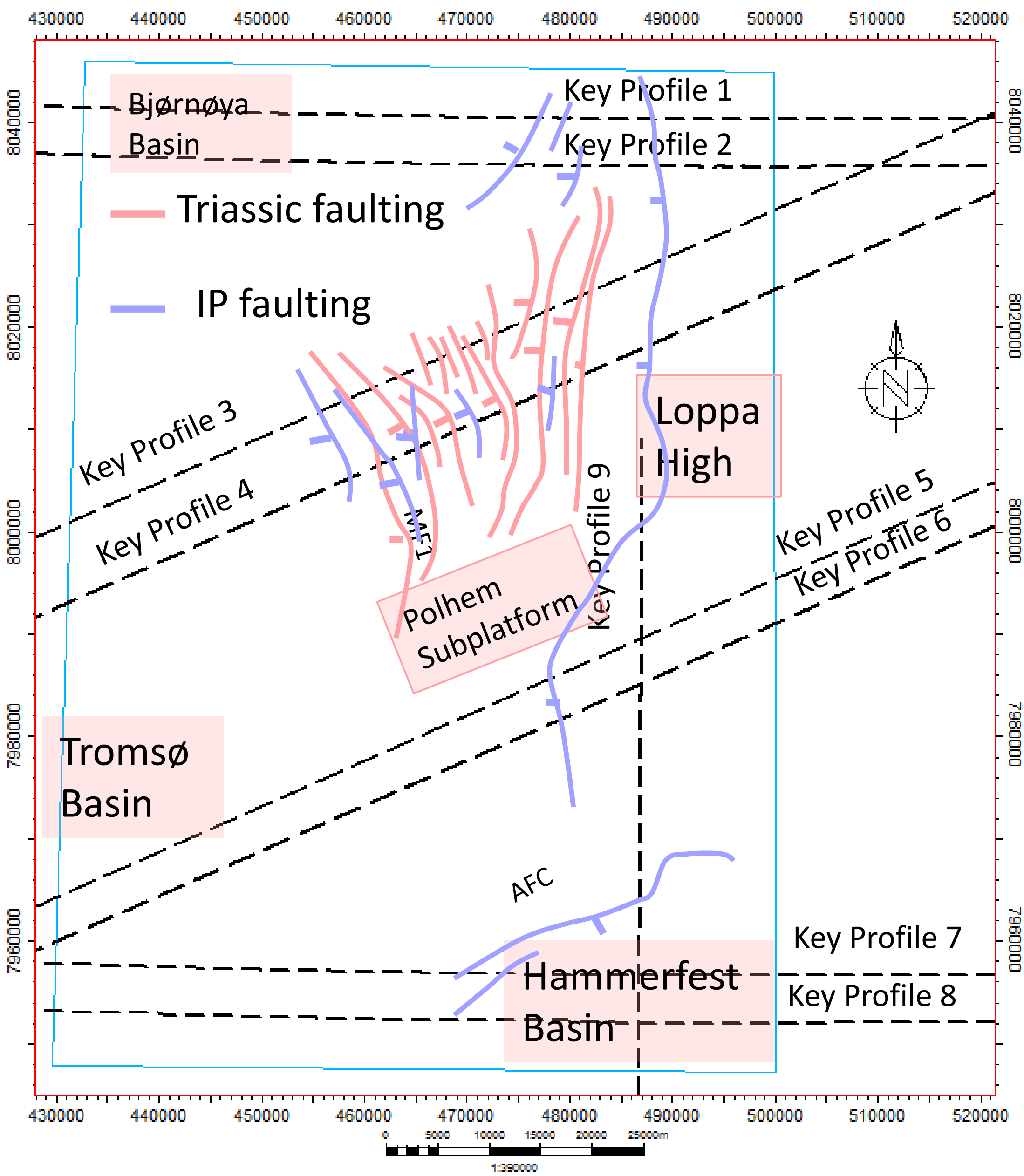


Figure 5.4: Composite fault map of Intra Permian and Intra Triassic levels. Color codes have been shown at the top to indicate level of faulting.

5.2.2 Position of second detachment

Second detachment seems to be lying between Base Cretaceous and Intra Cretaceous. Extensional faulting affects Intra Jurassic and Base Cretaceous but does not disturb or influence faulting of Intra Cretaceous level. Key Profile 4 has been marked with black dashed line to indicate possible position of this detachment.

5.2.3 Position of third detachment

This detachment is also very clear on number of key profiles. This detachment exists between Intra Cretaceous and Tertiary rocks. Key profile numbers 3, 4 and 8 have been marked with black dashed line to explain this detachment zone (Fig. 3.8, 3.9 & 3.13). Numbers of faults are dipping at the same direction but these faults are not affected by lower level faults. In key profile 4, even faulting with opposite direction is also there.

5.3 General geometry of fault plane

In this section, dip of the Ringvassøy-Loppa Fault Complex has been tried to figure out. For this purpose a very simple method has been adopted which is shown in (Fig. 5.5). Dip of the fault can be calculated by drawing a perpendicular on the fault plane in a cross section. In this way, it becomes a right angle triangle. From Petrel, horizontal distance (base) is easily calculated in Km/m. Later perpendicular value is taken in twt which is converted into distance (km/m). By applying trigonometric formula, angle of the dip can be calculated.

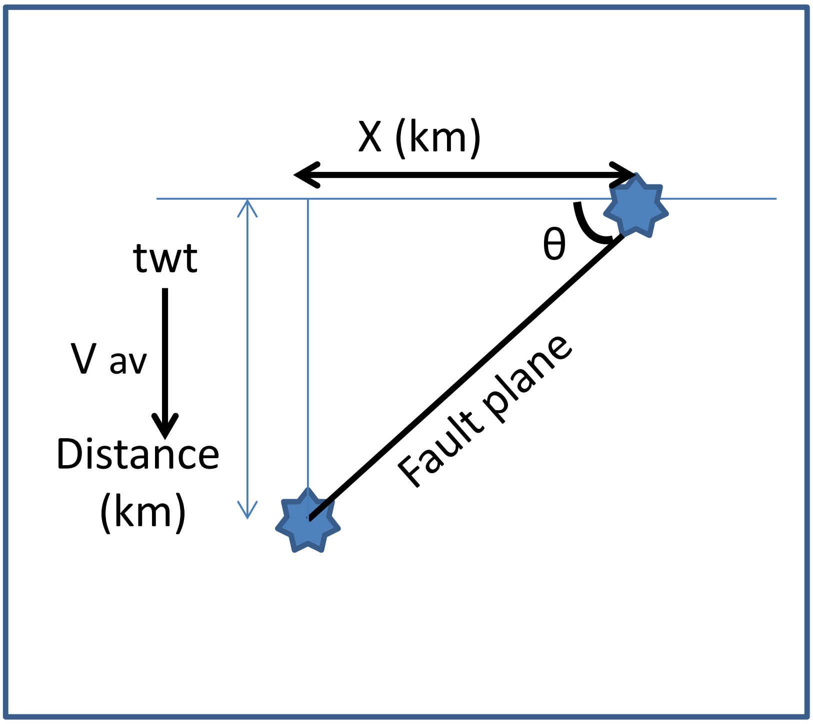


Figure 5.5: Supposed dip of fault has been shown, where X represents heave of the fault. Vav corresponds to average velocity and θ indicates dip angle.

In our case, firstly throw of the faults is measure in twt. Later this twt is divided on 2 to get one way time. This one way time is multiplied by 3.5 Km/s which is average velocity used to get throw is Km. As mentioned earlier, trigonometric formula is applied and dip is calculated. In this way, dip has been measured at regular interval along the strike of the faults. Measured dips have been plotted along the strike of the segments of the faults to put light on their geometry as shown in (Fig. 5.6).

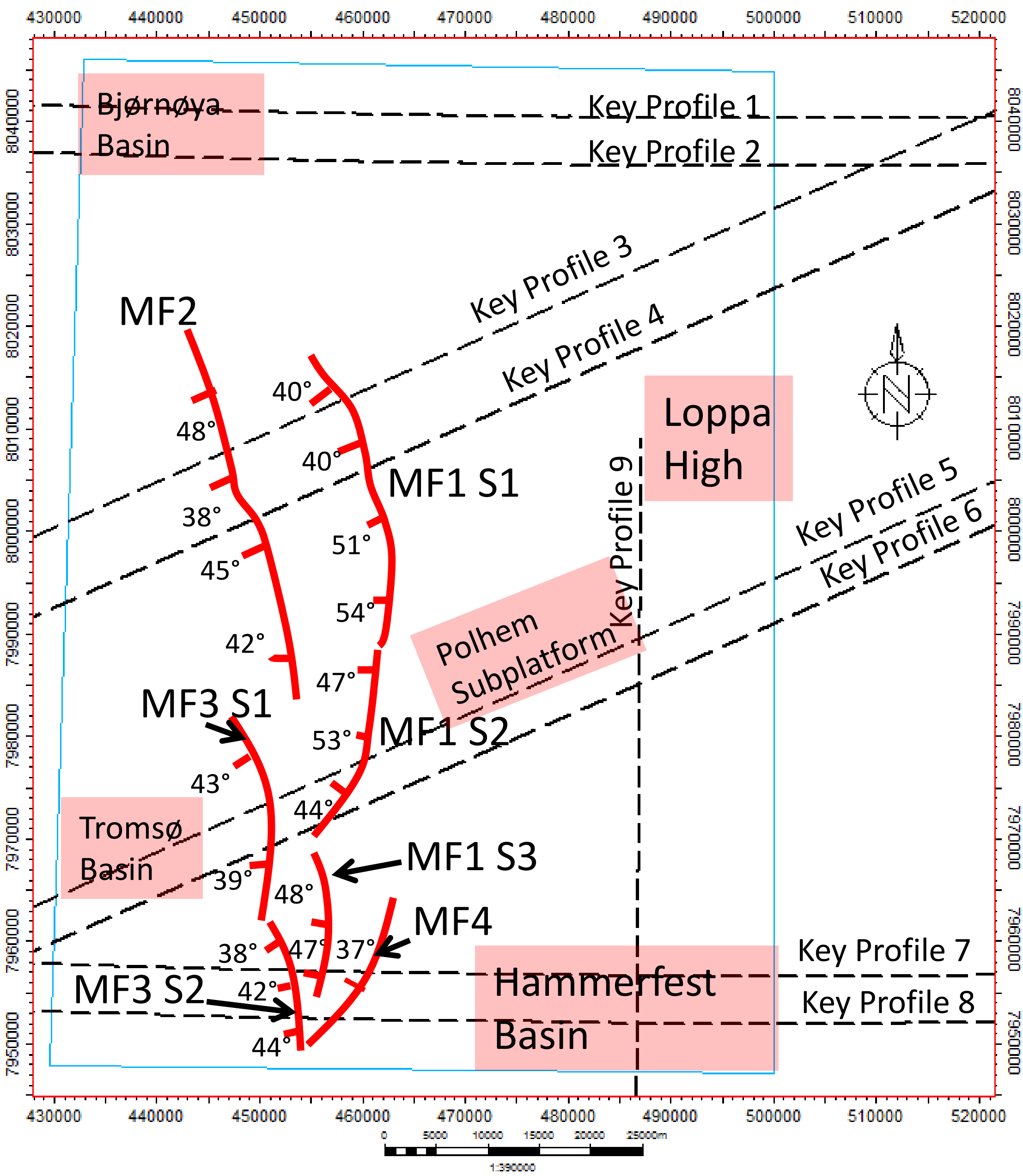


Figure 5.6: Fault segments with their respective dips along the strike of the faults.

This method provides general dip of the faults as velocity used in this method can be different than actual velocity of the layers. Dip calculated by this method for the faults vary between 37º and 54º.

5.4 Fault displacement analysis

In this section, location of fault nucleation has been tried to figure out. To do this, fault displacement along strike of the faults has been determined. Almost all segments of the main fault are analyzed for this purpose. It has been tried to figure out, how these segments started to generate and later joined each other to facilitate considerable displacement.

As mentioned in earlier chapters, the present form of southwestern Barents Sea came through the structural framework of Caledonides (Gudlaugsson et al, 1998). The faulting through Permian rifting beneath Tromsø Basin, is not easy to study because of low resolution of seismic lines beneath Intra Jurassic reflector. It is hard to determine the location where earlier rifting event influenced the later rifting events. That is why faults generated through Intra Jurassic-Early Cretaceous rifting have been studied for fault nucleation purpose.

Major faults in the base map indicate that northern Ringvassøy-Loppa Fault Complex have been exceeding the 20 Km in length. In fact, their length along strike is approaching about 75 km which seems rather too long as normal faults hardly exceed 20 km (Roberts and Jackson, 1991). An attempt has been made to see if the northern Ringvassøy-Loppa Fault Complex has faults segments within it. These segments will help to give some idea about nucleation of faults.

Major faults do have segments (Fig. 5.3), but due to gap between seismic lines, it was not possible to see discontinuities of faults in those gaps. According to present study, MF2 acted as a single fault and it has maximum displacement in the central part of it. MF1 has probably three segments, displacement along strike of these faults also vary considerably. Largest displacement seen is in segment 2 of MF1 where displacement goes up to 2 seconds as shown in (Fig. 5.7).

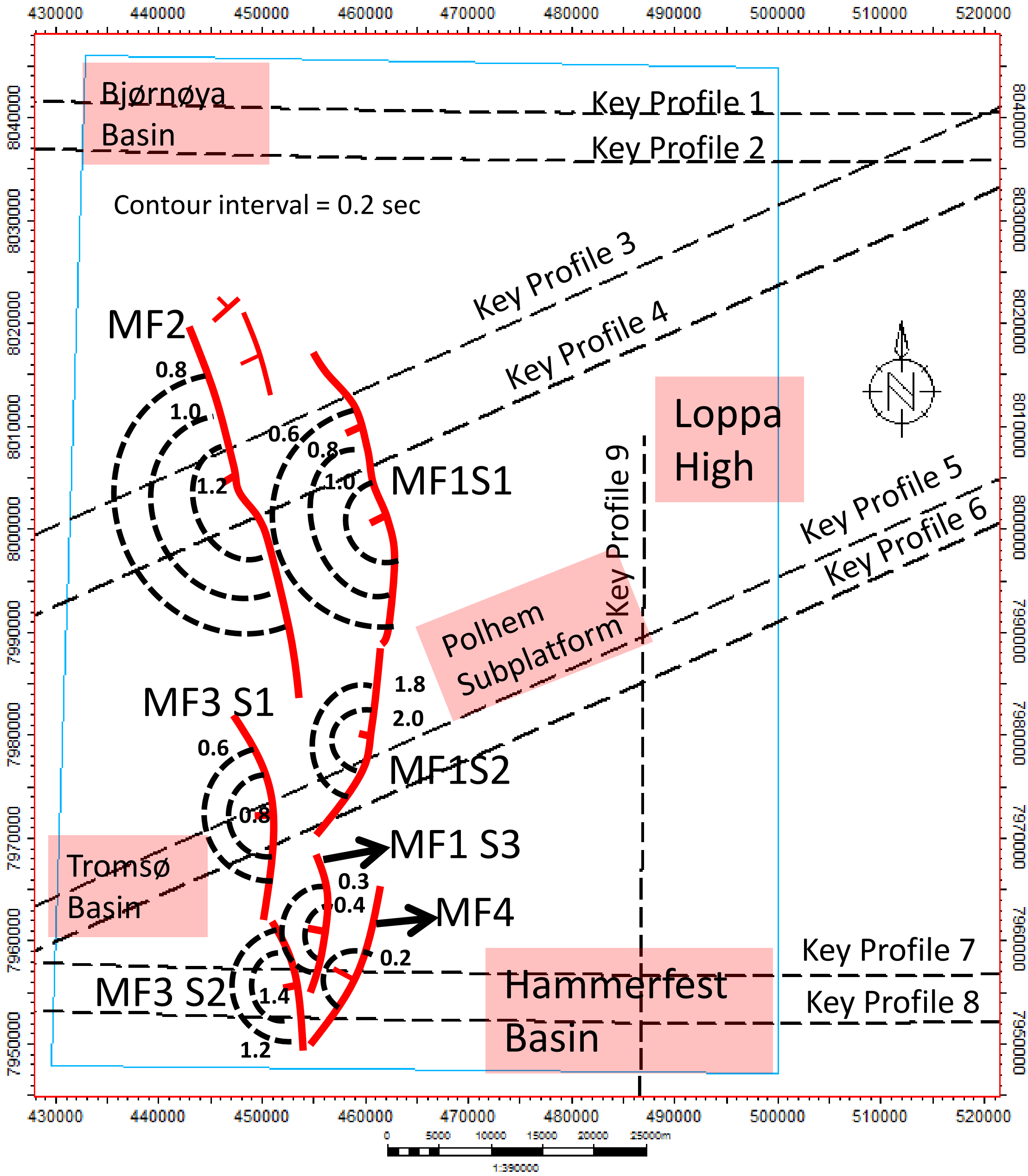


Figure 5.7: Segments of major faults; MF1 S1= Major Fault 1 Segment 1, MF1 S2= Major Fault 1 segment 2, MF1S3 = Major Fault 1 segment 3, MF3S1 = Major Fault 3 segment 1, MF3S2= Major Fault 3 Segment 2. Contours with interval of 0.2 seconds are drawn to indicate displacement of fault along the strike of the faults' segments.

On the basis of displacement data, a hypothesis can be put forward that in the northern RLFC, fault nucleation begins in segment 2 of major fault 1 (MF1 S1 in Fig. 5.7). This segment separates the Loppa High and Tromsø Basin which are two very distinct geological elements. Under the effect of extension, more fault segments started to generate, making more displacement along the first generated segment.

Probably most of the segments in the northern Ringvassøy-Loppa Fault Complex joined each other in a synthetic approaching way.

There is little discrepancy in relationship of displacement and length of strike of the segments. Many authors have given relationship between displacement and length of the strike of the faults (Davison, 1994). According to this relationship, longer is the strike of the fault, long is displacement is going to be expected. But here maximum displacement is seen in segment 2 of Major Fault 1 while longer segments did not show this much displacement. This discrepancy may have arisen due to the fact that longer segments may be having smaller segments which could not be identified in seismic lines. 3D seismic lines can provide better solution to see segmentation in this fault complex.

5.5 Timing of the fault (fault dating)

In this segment, activation periods of Ringvassøy Loppa Fault Complex have been tried to figure out. For that endeavor, the expansion index method, proposed by Thorsen (1963) has been applied. Through this method, a thickness ratio of stratigraphic units across the fault is determined. If expansion index ratio is equal to 1, it means no fault activity took place. In case, value of expansion index ration is greater than 1 then it shows period of fault activity or fault growth.

This technique involves determining the thickness of stratigraphic units in two way travel time, which makes it quite unreliable as velocities increase with the increase of depth. It means, hanging wall, if displaced deeper than footwall, then there are chances that higher velocities will cause it to appear deeper than actual position.

Fault dating has been done on one of the best key profiles as shown in (Fig. 5.8). Ringvassøy Loppa Fault Complex seems to have started from the basement as it is one of the Class 1 type fault (Gabrielsen, 1984). It is really hard to see if this fault remained active before Late Permian because no growth faulting is found at this level along RLFC. Growth faulting can be seen between Intra Permian and Top Permian which is indication of activity of fault between this time period.

Late Triassic rocks visibly are displaced between rotated fault blocks. Syn rift deposits are found between Intra Jurassic and Base Cretaceous which shows that fault remained active during this time. There is huge variation in the thickness of Base Cretaceous and Intra Cretaceous and expansion index is higher than 1. This is manifestation that RLFC remained really active this time period and created enough space for sediments to be deposited in Tromsø Basin.

Younger horizons also got affected by RLFC as MF1a cuts through Intra Cretaceous and Base Tertiary. Time structure maps in chapter 3 also indicate activation of RLFC in younger horizons.

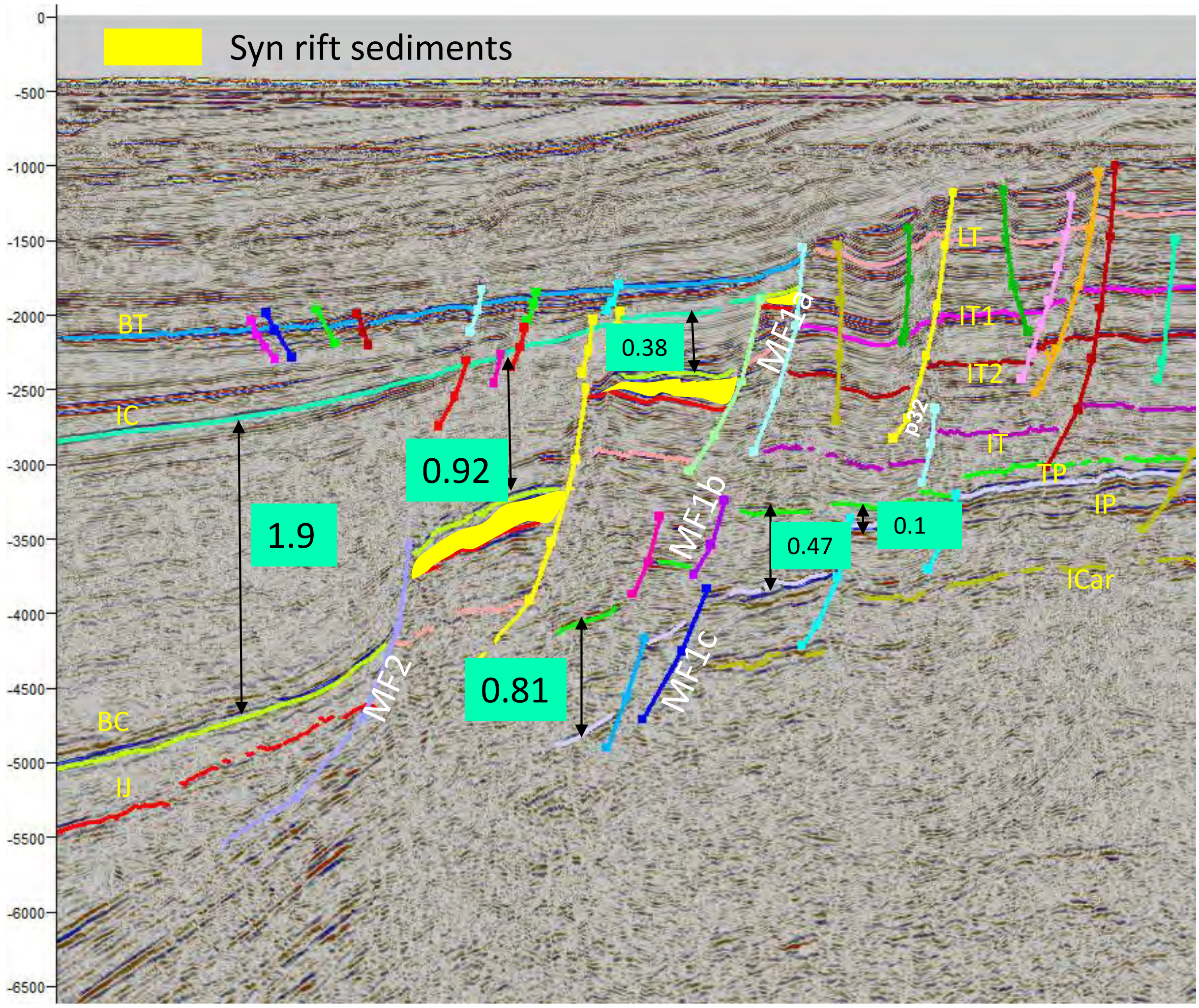


Figure 5.8: Variation of stratigraphic thicknesses across the fault complexes have been shown through errors. Moreover syn rift deposits have been marked in yellow color.

5.6 Sequential evolution of the area

Geological history of the southwestern Barents Sea begins from the Caledonian collapse in result of which, southwestern Barents Sea started to form. But this event is not seen on seismic lines of the study area. Our history begins from Billefjorden Group which has been considered basement rock in Basin Modelling (Fig. 5.9).

Earliest feature recorded on our seismic lines belong to rifting between Billefjorden and Intra Permian units. This event has been recorded on Polhem Subplatform and Loppa High where wedges are seen between these rock units. These wedges can be seen on key profile number 3 and 4. This wedge is formed along the Jason Fault Complex. In this study, we believe that this wedge belongs to first rifting event of Clark et al., (2013) for the southwestern Barents Sea.

Ørn Formation belongs to Early Permian, acts as first detachment of the study area as explained in earlier section. Thick deposition of evoporites has been reported in this time period (Worsley, 2008). This deposition also took place beneath Tromsø Basin and extruded into younger rocks later on. Interpretation of younger than Intra Jurassic rocks has not been carried out. Otherwise evolution of the area must have been different and elaborative.

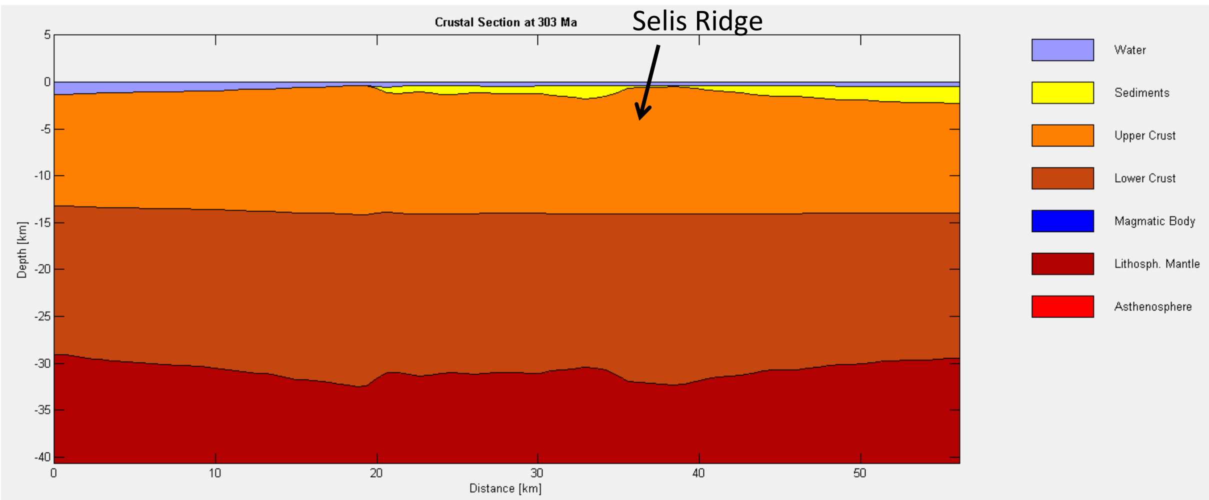


Figure 5.9: Transect indicating situation of key profile number 5 at Late Moscovian time (306 Ma). Position of Selis Ridge has been marked with arrow.

Intra Permian and Top Permian horizons, seems to make growth strata at certain places with each other (Fig. 3.9, 3.13) which is indication of second rifting event in the study area. They make wedge along Jason Fault Complex in (Fig. 3.10) which is indication that some activity took place along Jason Fault Complex between Intra Permian and Top Permian.

Pronounced faulting is seen in Intra Jurassic to Base Cretaceous time which represents third rifting event. Wedges between Intra Jurassic and Cretaceous are observed all around Ringvassøy-Loppa Fault Complex. In Tromsø Basin, deepest horizon marked belongs to Middle Jurassic age. Older horizons were not marked in Tromsø Basin. That is why, Tecmod indicates opening of Tromsø Basin at 164 Ma (Fig. 5.10).

Between Base Cretaceous and Intra Cretaceous time, shales are deposited which act as our second detachment. RLFC remains active in this time period as mentioned earlier.

Last rifting event in the southwestern Barents Sea caused sea floor spreading between Norwegian-Greenland Sea. This rifting caused extension in whole southwestern region which resulted in reactivation of faults formed by previous rifting event. Ringvassøy-Fault Complex reactivated in Tertiary as RLFC, BFC and AFC are reactivated in the Tertiary, probably to extensional forces prevailed at that time.

All events found in our study area have been summarized in (Fig. 5.11).

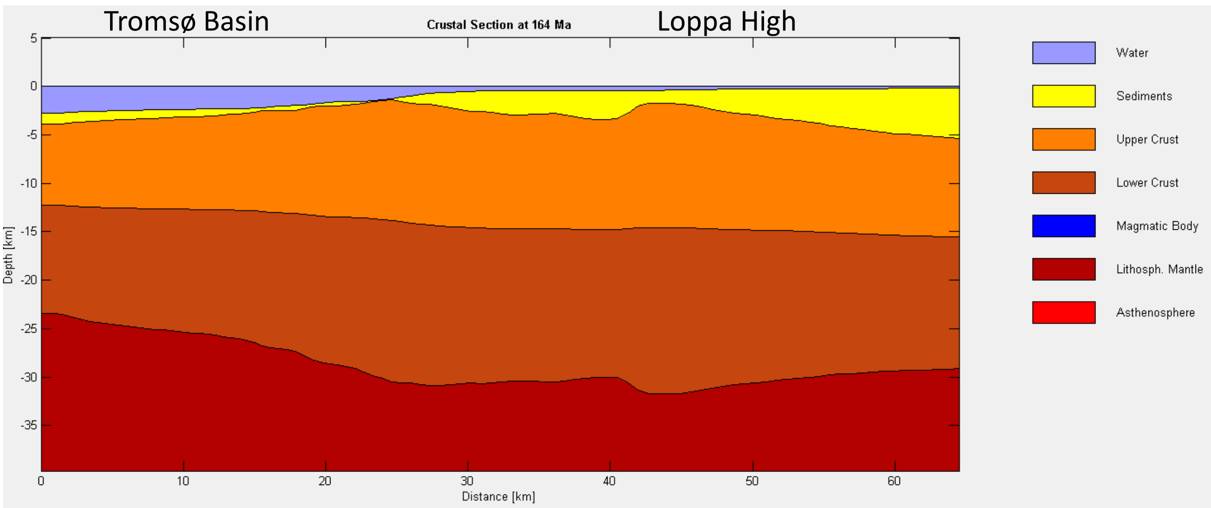
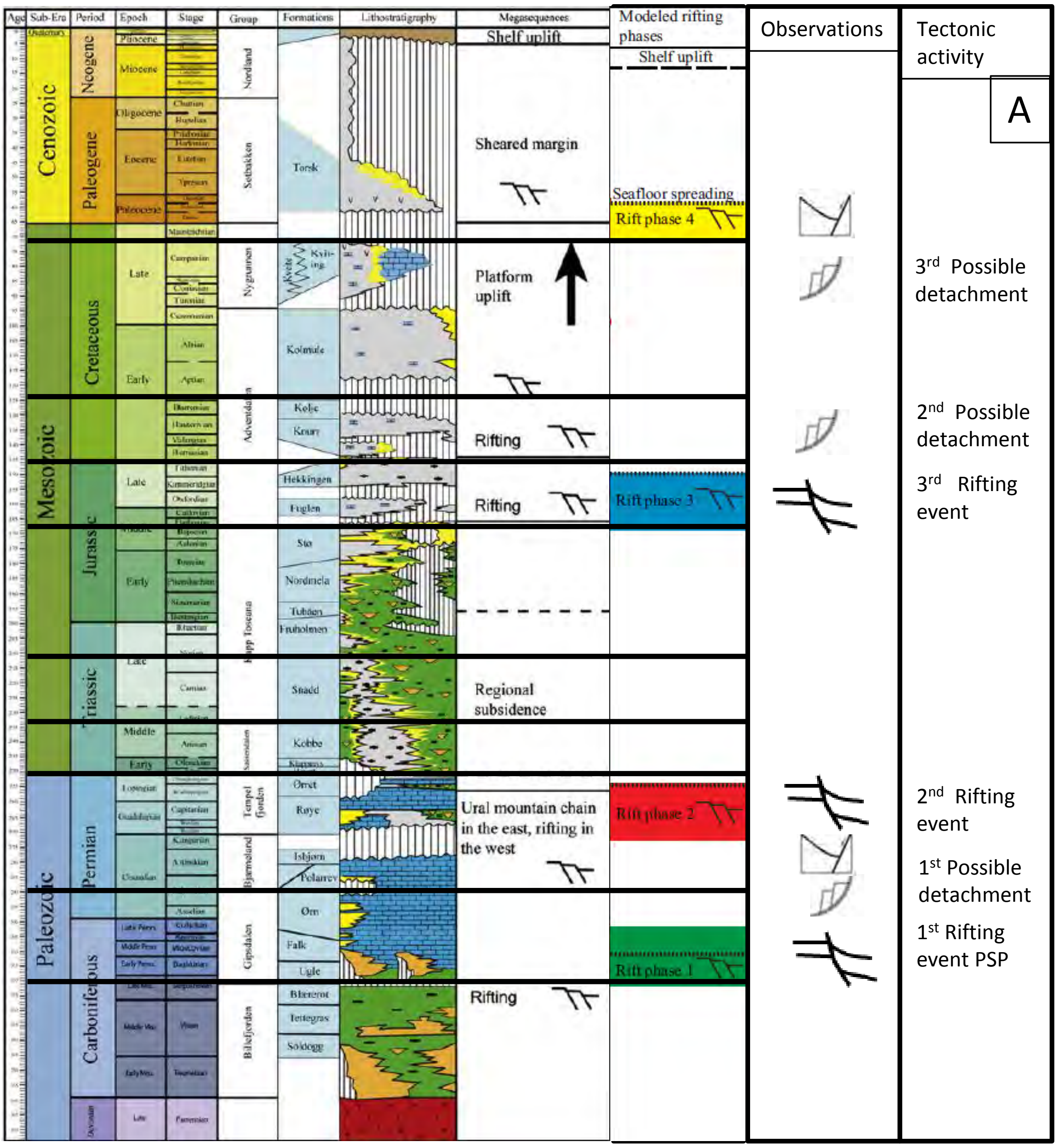


Figure 5.10: Key profile 5 in Tecmod, represents initial stage of third rifting event in the area.



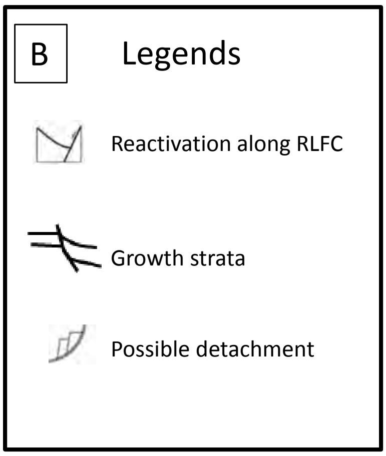


Figure 5.11(A): All tectonic events of the study area have been summarized (Modified after Glørstad-Clark et al., 2011, Clark et al., 2013) (B) Legends for chart A.

6. Conclusions

The main results of this study can be summarized as follows:

- The Ringvassøy-Loppa Fault Complex is a basement-involved fault complex, that's why it belongs to Class 1 type of Gabrielsen (1984) for the southwestern Barents Sea.

- Fault segments in RLFC are synthetic and make approaching, collateral and at some places overlapping behavior with each other.

- Maximum displacement is recorded in the fault segment which exists between the Loppa High and Tromsø Basin. Probably fault nucleated from this place.

- Probably there are three detachments which are approximately located between Intra Permian and Top Permian, Base Cretaceous and Intra Cretaceous, Intra Cretaceous and Base Tertiary.

- Dip of fault segments vary between 37° and 54°.

- The Ringvassøy-Loppa Fault Complex has been found active in Early Permian to Late Permian times. Extensional faulting along this fault complex culminated in Intra Jurassic to Base Cretaceous times. It also got activated in Intra Cretaceous and Early Tertiary times.

- The oldest horizon found displaced along this fault complex is of Top Billefjorden Group of Middle Carboniferous time.

References

AHMAD, T. 2013. Structural Analysis of the SW Troms-Finnmark Fault Complex, SW Barents Sea. 133.

AHMED, W. 2012. Structural Analysis of the Troms-Finnmark Fault Complex, SW Barents Sea. 133.

BARRÈRE, C., EBBING, J. & GERNIGON, L. 2009. Offshore prolongation of Caledonian structures and basement characterisation in the western Barents Sea from geophysical modelling. Tectonophysics, 470, 71-88.

BERGLUND, L.T., AUGUSTSON, J., FARSETH, R., GJELBERG. J. & RAMBERG-MOE, H., 1986, The evolution of the Hammerfest Basin. In: A. M. Spencere (Ed.), Habitat of Hydrocarbons on the Norwegian Continental Shelf, Graham and Trottman, London, p. 319-338.

BRAUT, H. L. 2012. Analogue modeling of detachment zones and structural analysis of the Ringvassøy- Loppa Fault Complex, SW Barents Sea. Master Thesis, University of Oslo.

BREIVIK, A. J., GUDLAUGSSON, S. T. & FALEIDE, J. I. 1995. Ottar Basin, SW Barents Sea: a major Upper Palaeozoic rift basin containing large volumes of deeply buried salt. Basin research, 7, 299-312.

BREIVIK, A. J., MJELDE, R., GROGAN, P., SHIMAMURA, H., MURAI, Y., NISHIMURA, Y. & KUWANO, A. 2002. A possible Caledonide arm through the Barents Sea imaged by OBS data. Tectonophysics, 355, 67-97.

BREKKE, H. & RIIS, F. D. 1987. Tectonics and basin evolution of the Norwegian shelf between 62oN and 72oN. Norsk Geologisk Tidsskrift, 67, 295-321.

CLARK, S. A., GLORSTAD-CLARK, E., FALEIDE, J. I., SCHMID, D., HARTZ, E. H. & FJELDSKAAR, W. 2013. Southwest Barents Sea rift basin evolution: comparing results from backstripping and time-forward modelling. Basin Research.

DALLAND, A., WORSLEY, D. & OFSTAD, K. 1988. A Lithostratigraphic Scheme for the Mesozoic and Cenozoic and Succession Offshore Mid-and Northern Norway, Oljedirektoratet.

DAVISON, I., 1994, Linked fault systems; extensional, strike-slip and contractional. In: Hancok, P.L., (Ed.) Continental Deformation, Pergamon Press, Oxford, . 121-142.

DENGO, C. & RØSSLAND, K. 1992. Extensional tectonic history of the western Barents Sea. Structural and tectonic modelling and its applications to petroleum geology, 91-107.

DORÉ, A. 1991. The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic. Palaeogeography, Palaeoclimatology, Palaeoecology, 87, 441-492.

FALEIDE, J. I., GUDLAUGSSON, S. T. & JACQUART, G. 1984. Evolution of the western Barents Sea. Marine and Petroleum Geology, 1, 123-150.

FALEIDE, J. I., TSIKALAS, F., BREIVIK, A. J., MJELDE, R., RITZMANN, O., ENGEN, O., WILSON, J. & ELDHOLM, O. 2008. Structure and evolution of the continental margin off Norway and the Barents Sea. Episodes, 31, 82.

FALEIDE, J. I., E. VÅGNES, AND S. T. GUDLAUGSSON, 1993a, Late Mesozoic--Cenozoic Evolution of the Southwester Barents Sea. Vol. 4, In: Petroleum geology of Northwest Europe, Proceedings of the 4th Conference, edited by J. R. Parker, 933-950. London: The geological Society of London References 108

FALEIDE, J. I., E. VÅGNES, AND S. T. GUDLAUGSSON, 1993b, Late Mesozoic--Cenozoic Evolution of the South Western Barents Sea in a Regional Rift Shear Tectonic Setting. Marine and Petroleum Geology 10, 186-214.

FALEIDE, J. I., SOLHEIM, A., FIEDLER, A., HJELSTUEN, B. O., ANDERSEN, E. S. & VANNESTE, K. 1996. Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. Global and Planetary Change, 12, 53-74.

FALEIDE, J. I., TSIKALAS, F., BREIVIK, A. J., MJELDE, R., RITZMANN, O., ENGEN, O., WILSON, J. & ELDHOLM, O. 2008. Structure and evolution of the continental margin off Norway and the Barents Sea. Episodes, 31, 82.

FITRIYANTO, A. 2011. Structural Analysis of The Hoop Fault Complex, SW Barents Se. Master Thesis, University of Oslo.

FJELDSKAAR, W., ter VOORDE, M., JOHANSEN, H., CHRISTIANSSON, P., FALEIDE, J.I. & CLOETINGH, S.A.P.L. (2004) Numerical simulation of rifting in the Northern Viking Graben: the mutual effect of modelling parameters. Tectonophysics, 382, 189–212.

GABRIELSEN, R. 1984. Long-lived fault zones and their influence on the tectonic development of the southwestern Barents Sea. Journal of the Geological Society, 141, 651-662.

GABRIELSEN, R. H., FAERSETH, R. B. & JENSEN, L. N. 1990. Structural Elements of the Norwegian Continental Shelf. Pt. 1. The Barents Sea Region, Norwegian Petroleum Directorate.

Gabrielsen, R. H., Faleide, J. I., Pascal.C. & Torsvik,T. H., 2011, Plate tectonics and tectonic inversion in the Barents Sea, Abstract: AAPG 3P Arctic, The Polar Petroleum Potential Conference & Exhbition, 30 August – 2 September, Halifax, Nova Scotia, Canada, Search and Discovery Article # 90130

GABRIELSEN, R., FÆRSETH, R. & TOWNSEND, C. 1989. The inner shelf of North Cape, Norway and its implications for the Barents Shelf-Finmark Caledonide boundary: a comment. Reply. Norsk geologisk tidsskrift, 69, 57-65.

GABRIELSEN, R. H., GRUNNALEITE, I. & RASMUSSEN, E. 1997. Cretaceous and tertiary inversion in the Bjørnøyrenna Fault Complex, south-western Barents Sea. Marine and petroleum geology, 14, 165-178.

GABRIELSEN, R. H., FOERSETH, R., HAMAR, G. & RØNNEVIK, H. 1984. Nomenclature of the main structural features on the Norwegian Continental Shelf north of the 62nd parallel. Petroleum Geology of the North European Margin. Springer.

GLØRSTAD-CLARK, E., BIRKELAND, E., NYSTUEN, J., FALEIDE, J. & MIDTKANDAL, I. 2011. Triassic platform-margin deltas in the western Barents Sea. Marine and Petroleum Geology, 28, 1294-1314.

GLØRSTAD-CLARK, E., FALEIDE, J. I., LUNDSCHIEN, B. A. & NYSTUEN, J. P. 2010. Triassic seismic sequence stratigraphy and paleogeography of the western Barents Sea area. Marine and Petroleum Geology, 27, 1448-1475.

GUDLAUGSSON, S., FALEIDE, J., JOHANSEN, S. & BREIVIK, A. 1998. Late Palaeozoic structural development of the south-western Barents Sea. Marine and Petroleum Geology, 15, 73-102.

JARVIS,G. T., ANDD. P.MCKENZIE, 1980, Sedimentary basin formation with finite extension rates: Earth and Planetary Science Letters, 48, p. 42–52.

JENSEN, L. & SØRENSEN, K. 1992. Tectonic framework and halokinesis of the Nordkapp Basin, Barents Sea. Structural and tectonic modelling and its application to petroleum geology. Norwegian Petroleum Society (NPF) Special Publication, 1, 109-120.

Johansen, S. E., Ostisty, B. K., Birkeland, Ø., Fedorovski, Y. F., Martirosjan, V. N., Christensen, O. B., Cheredeev, S. I., Ignatenko, E. A. & Margulis, L. S. , 1993, Hydrocarbon potential in the Barents Sea region: play distribution and potential. In: T. O. Vorren, E. Bergsager, Ø. A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie, & T. B. Lund, (Eds.), Arctic Geology and Petroleum, Potential Norwegian Petroleum Society Special Publication No. 2, Elsevier, Amsterdam, p. 273-320.

LARSSEN, G., ELVEBAKK, G., HENRIKSEN, L. B., KRISTENSEN, S., NILSSON, I., SAMUELSBERG, T., SVÅNÅ, T., STEMMERIK, L. & WORSLEY, D. 2002. Upper Palaeozoic lithostratigraphy of the Southern Norwegian Barents Sea. Norwegian Petroleum Directorate Bulletin, 9, 76.

LARSSEN, G.B., ELVEBAKK, G., HENRIKSEN, L.B., KRISTENSEN, S.-E., NILSSON, I., SAMUELSBERG, T.J., SVA°NA° , T.A., STEMMERIK, L. & WORSELY, D. 2005 Upper Paleozoic Lithostratigraphy of the southern Norwegian Barents Sea. Norw.Geol. Surv. Bull., 444, 3–45.

LIPPARD, S. & ROBERTS, D. 1987. Fault systems in Caledonian Finnmark and the southern Barents Sea. Norges geologiske undersøkelse Bulletin, 410, 55-64.

MCKENZIE, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.

MORLEY, C., NELSON, R., PATTON, T. & MUNN, S. 1990. Transfer Zones in the East African Rift System and Their Relevance to Hydrocarbon Exploration in Rifts (1). AAPG Bulletin, 74, 1234-1253.

NORWEGIAN PETROLEUM DIRECTORATE, 2012, FactPage, Available at: http://factpages.npd.no/factpages/Default.aspx?culture=en (accessed 10th March, 2014)

NYLAND, B., JENSEN, L., SKAGEN, J., SKARPNES, O. & VORREN, T. 1992. Tertiary uplift and erosion in the Barents Sea: magnitude, timing and consequences. Structural and tectonic modelling and its application to petroleum geology, 153-162.

RIIS, F. & FJELSKAAR, 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: Structural and Tectonic Modelling and Its Application to Petroleum Geology, Vol. 1 (Ed. by R. M. Larsen, H. Brekke, B.T. Larsen & E. Talleraas), pp. 163–185.

RITZMANN, O. & FALEIDE, J. I. 2007. Caledonian basement of the western Barents Sea. Tectonics, 26.

ROBERTS, D. & GEE, D. 1985. An introduction to the structure of the Scandinavian Caledonides. The Caledonide orogen–Scandinavia and related areas, 1, 55-68.

ROBERTS, D. 2003. The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. Tectonophysics, 365, 283-299.

ROBERTS, S. & JACKSON, J. 1991. Active normal faulting in central Greece: an overview. Geological Society, London, Special Publications, 56, 125-142.

ROBERTS, D. & GEE, D. 1985. An introduction to the structure of the Scandinavian Caledonides. The Caledonide orogen–Scandinavia and related areas, 1, 55-68.

ROUFOSSE, M. 1987. The formation and evolution of sedimentary basins in the Western Barents Sea. Petroleum Geology of North West Europe, Graham and Trotman, London, 1149-1161.

RÜPKE, L.H., SCHMALHOLZ, S.M., SCHMID, D.W. & PODIADCHIKOV, Y.Y., 2008 Automated thermotectonostratigraphic basin reconstruction: Viking Graben case study. AAPG Bull., 92, 309–326.

RÜPKE, L.H., SCHMID, D.W., HARTZ, E.H. & MARTINSEN, B. (2010) Basin modelling of a transform margin setting: structural, thermal and hydrocarbon evolution of the Tano Basin, Ghana. Petrol. Geosci., 16, 283–298.

STEEL, R. J. & WORSLEY, D. 1984. Svalbard’s post-Caledonian strata—an atlas of sedimentational patterns and palaeogeographic evolution. Petroleum geology of the North European margin. Springer.

THEISSEN, S. & R€UPKE, L.H. (2010) Feedbacks of sedimentation on crustal heat flow: new insights from the V Circle Divide Ring Basin, Norwegian Sea. Basin Res., 22, 976–990.

WOOD, R.J., EDRICH, S.P. & HUTCHISON, I. (1989) Influence of North Atlantic tectonics on the large-scale uplift of the Stappen High and Loppa High, western Barents Shelf. In: Extensional Tectonics and Stratigraphy of the North Atlantic Margins (Ed. by A.J. Tankard & H.R. Balkwill) AAPG Mem., 46, 559–566.

WORSLEY, D. 2008. The post-Caledonian development of Svalbard and the western Barents Sea. Polar Research, 27, 298-317.

ZALMSTRA, H. 2013. Reactivation in the Ringvassøy-Loppa Fault Complex - the role of detachments. Master Thesis, Univesity of Oslo.

ZIEGLER, P. A. 1988. Evolution of The Arctic-North Atlantic And The Western Tethys--A Visual Presentation Of A Series Of Paleogeographic-Paleotectonic Maps. Mem.-Am. Assoc. Pet. Geol, 43, 164-196.