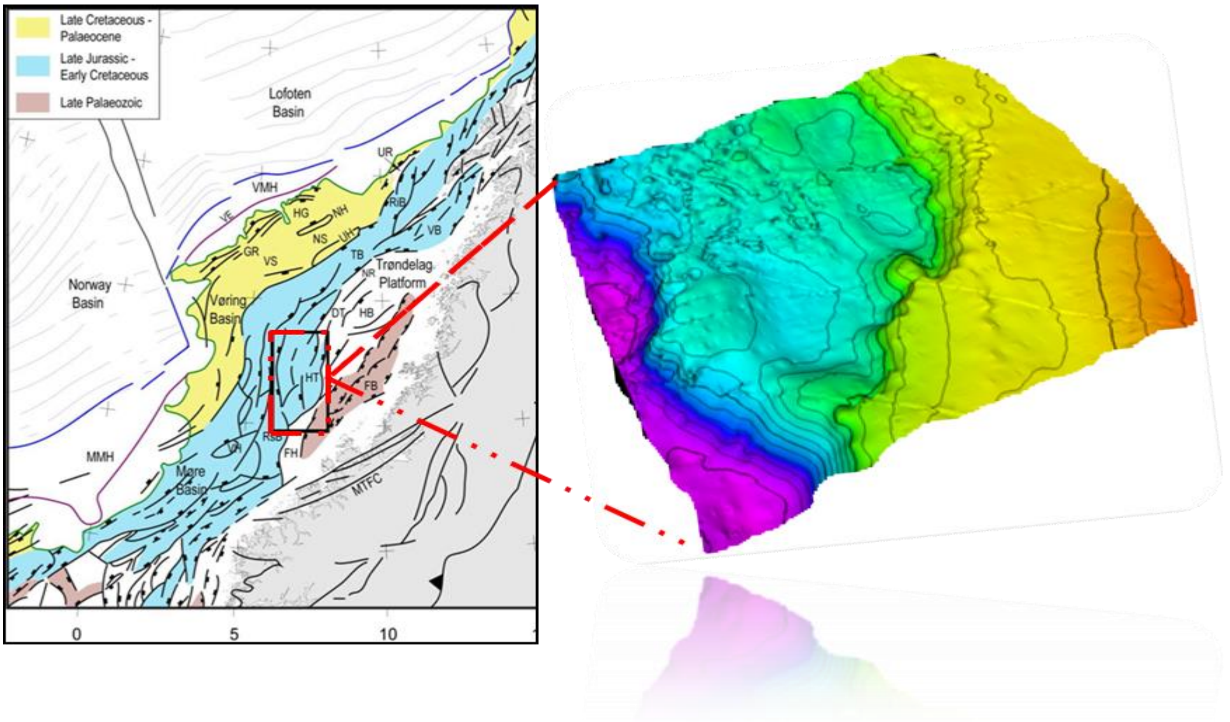
Master Thesis, Department of Geosciences

Structural analysis of fault complexes bounding the Halten Terrace, offshore mid-Norway

Issak Habtemicael



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Master Thesis in Geosciences

Discipline: Petroleum Geology and Geophysic

Department of Geosciences

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Abstract

The mid-Norwegian continental margin that has been tectonically active from Caledonian Orogeny to early Cenozoic time is divided into a number of structural provinces and the main tectonic phases records the transition from rifting to sea-floor spreading between Norway and Greenland in Cenozoic . Seismic and well data as well as literature studies were used in the structural analysis of fault complexes bounding the Halten Terrace, such as the Vingleia, Bremstein and the Klakk fault complexes and the Kya Fault zone.

Four segments of the Vingleia Fault Complex were recognized in detail using the nine key profile lines that crosses the Vingleia Fault Complex and were integrated with time-structure and thickness maps of the key selected stratigraphic levels. Segments I and III are characterised by listric fault geometry where the evaporite unit is the detachment layer, whereas Segments II and IV show a characteristic ramp-flat-ramp fault geometry of deep-rooted fault complexes. A pronounced rollover structure above the flat was distinct observation along segments II and IV and the basement as well as the evaporite unit have strong influence in modifying the shape of the fault complexes. Therefore the Vingleia Fault Complex shows changes in strike and dip direction as well as variation in heave and throw. The northeastern part is characterized by wider heave and larger throw compared to the southern part of the study area.

Two sets of fault generation, where one set faults are populated above, whereas the second set of faults are populated below the evaporite unit and terminate from top and from the base at the evaporite unit particularly in the northern part. This phenomenon indicates that the area was subject to several tectonic events or tectonic of the same event. Faults which terminate on the Triassic evaporite unit from bottom (blind faults) form fault propagation folds, whereas faults (normal faults) displacing the evaporite unit are characterized by basement-involved faults. The evaporite movement and salt related deformation has strongly affected the structural style and fault geometry in the study area where the evaporite unit displays thicker and slightly deformed away from the master fault, whereas thinner and strongly deformed towards the Vingleia Fault Complex.

The three tectonic phases (Late Palaeozoic-Early Mesozoic phase, Late Jurassic-Early Cretaceous phase, and Late Cretaceous-Cenozoic phase) decribe the geological evolution of the study area.

Well penetration confirms the pre- Devonian fractured granitic basement along the Frøya High and this is supported by the strong seismic reflectivity of the basement on the seismic data. Time-thickness of the selected stratigraphic levels indicates the existence of the Vingleia Fault Complex in pre-Triassic events.

Acknowledgment

I would like to express my special thanks to my supervisors Prof. Jan Inge Faleide, Prof. Roy Helge Gabrielsen and Dr. Michel Heeremans for their guidance, encouragements and inputs starting from assigning the master topic through weekly progress meetings and discussions. Particularly Prof. Jan Inge Faleide has been tremendously supportive in shaping the thesis paper.

I particularly want to acknowledge TGS and Fugro for providing the seismic data for this thesis study.

I wish also express my gratitude to Rikke for the discussions and comments we shared.

Last but not least, I would like to thank my wife and my son for their patience in achieving the master’s degree.

Table of contents

1. Introduction

The Norwegian continental margin comprises a NE-SW trending passive margin bounded to the west by a volcanic margin escarpment and to the east by the Norwegian mainland (62-70°N) (Blystad et al., 1995; Lundin and Doré, 1997; Faleide et al., 2008). The mid-Norwegian continental margin is divided into a number of structural provinces (Fig. 1.1), the Trøndelag Platform, the Vøring Basin and the Vøring Marginal High forming the Vøring Margin; and the Møre Basin and the Møre Marginal High forming the Møre Margin. (Blystad et al., 1995; (Grunnaleite and Gabrielsen, 1995); Gabrielsen et al., 1999; Brekke et al., 2001; Osmundsen et al., 2002. The Early Cenozoic continental breakup and subsequent opening of the Norwegian-Greenland Sea formed the preset Norwegian Margin (Faleide et al., 2008). The Rås Basin, Halten Terrace, Froan Basin, Frøya High and the Trøndelag Platform are situated within mid Norwegian continental margin. The Halten Terrace is a highly prospective geological province in the Norwegian Sea. Notable giant fields include Åsgard, Kristin, Victoria, Tyrihans and Heidrun. These accumulations are mainly located in Jurassic tilted fault blocks and in inversion anticlines and stratigraphic traps containing Cretaceous sandstones. Key producing formations include Garn, Ile and Tilje and Spekk and Åre formations are the main source rock in the study area.

Seismic interpretation, well data and literature studies were used to see the structural elements that bound the Halten Terrace, the Vingleia, Bremstein and the Klakk fault complexes and the Kya Fault zone. The Halten Terrace is bounded from the deeper, Rås Basin to the west by Klakk Fault Complex and from the shallower, Trøndelag, Frøya High and the Froan Basin by the Vingleia-Bremstein fault complexes to the east.

The main focus of this thesis is to study the structural style and evolution of the fault complexes bounding the Halten Terrace and areas around it, the Frøya High, Froan Basin and Trøndelag Platform. In particular the Vingelia Fault Complex was studied in detail and compared to the results of previous published studies around and within the study area (Fig. 1.1). Nine key profile lines that cross the Vingleia Fault Complex were used to look in detail the fault geometry and style of deformation on hangingwall and footwall of the Vingleia Fault Complex.

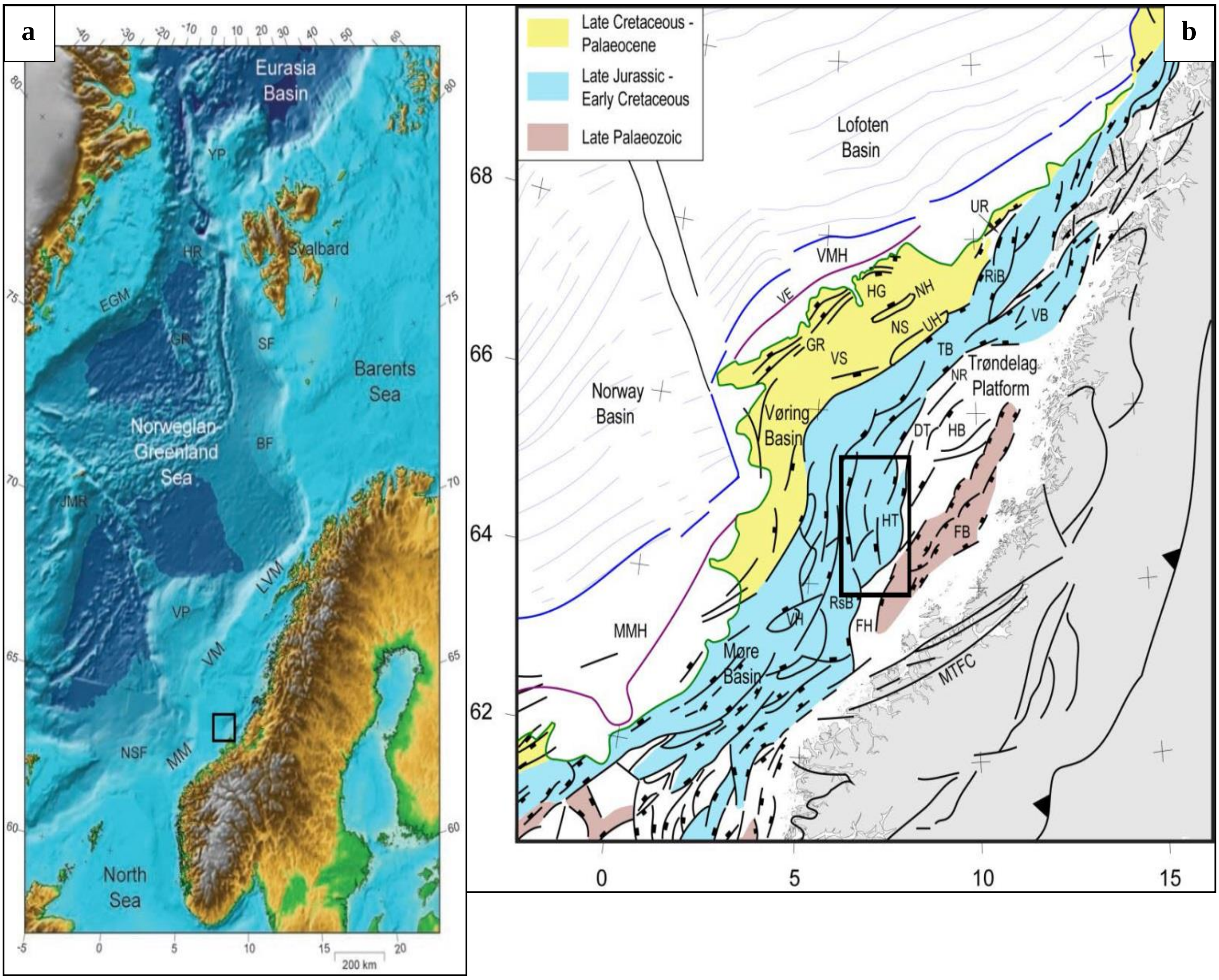


Figure-1.1: (a) Regional setting (bathymetry) of the Norwegian continental margin and location of the study area (Faleide et al., 2008). (b) Main structural elements of the mid-Norwegian Margin and adjacent areas (Faleide et al., 2010). EGM: East Greenland Margin, JMR: Jan Mayen Ridge, LVM: MM: Møre Margin, North VM: Vøring Margin, VP: Vøring Plateau FH: Frøya High, RsB: Rås Basin, HT: Halten Terrace, FB: Froan Basin, DT: Dønna Terrace, MTFC: Møre-Trøndelag Fault Complex.

2. Geological setting of the Mid-Norwegian continental shelf

The Norwegian Sea continental margin is dominated by two major basins (62° N and 69° N), Vøring and Møre basins with a very thick Cretaceous basin fill (Figs 1.1, 2.1 & 2.2). The basins are flanked by the uplifted mainland and the Cretaceous Trøndelag Platform to the east and by the Møre and Vøring Marginal Highs capped by Eocene lavas to the west (Figs. 2.3 & 2.4). The three main margin segments (Møre, Vøring and Lofoten-Vesterålen) are each 400-500 km long and they are separated by the East Jan Mayen Fracture Zone and Bivrost Lineament (Blystad et al., 1995; Brekke, 2000; Faleide et al., 2008). Two structural trends, NE-SW and NW-SE controls the tectonic development and the area has been tectonically active from Caledonian Orogeny to early Cenozoic time with the main tectonic phases in Early to Middle Devonian, Carboniferous, Late Permian to Early Triassic, late Middle-Jurassic to Early Cretaceous and Late Cretaceous to Early Eocene (Bukovics et al., 1984, Blystad et al., 1995; Doré et al., 1997; Brekke, 2000; Skogseid et al., 2000; Marsh et al., 2009; Faleide et al., 2010).

The NE Atlantic rift system developed as a result of a series of rift episodes from the Caledonian Orogeny to early Cenozoic time (Fig 2.7 & Table 2.1). The Caledonian Orogeny was followed by Middle to Late Devonian change in tectonic configuration from compression to extension, where thick intra-continental deposition occurred onshore Norway by collapsing of the mountain chain (Ziegler, 1988; Fossen, 1992**;** Brekke et al., 2001). The platform areas that border the Mesozoic rift systems of the NE Atlantic margin are characterized by a thin Mesozoic succession, underlain by Permian deposits (Doré et al. 1999; Osmundsen et al., 2002).

The Late Jurassic to Cretaceous rifting is described as propagation of the NE-directed rift northeastward through the Rockall Trough and this Intra-continental rifting caused around 50-70 km of crustal extension (Lundin & Doré, 1997; Faleide et al., 2008). Deep seismic data and plate reconstructions (Figs 2.5, & 2.6) illustrate the relative movements between Eurasia and Greenland back to Mid-Jurassic time (Mjelde et al., 2005; Breivik et al., 2011). Late Cretaceous to Early Cenozoic was characterized by global sea level increase that reached its maximum. The area between Norway and Greenland was an epicontinental sea at that time in which crust had been weakened by the multiple post-Caledonian rift events (Skogseid et al., 2000). Early Cenozoic to Eocene marks the final Maastrichtian-Paleocene rift episode, which led to the separation and onset of the seafloor spreading. The lithospheric breakup was accompanied by massive, regional magmatism within the North Atlantic Volcanic province and the voluminous igneous activities across a 300 km wide zone (Skogseid et al., 2000; Faleide et al., 2008).

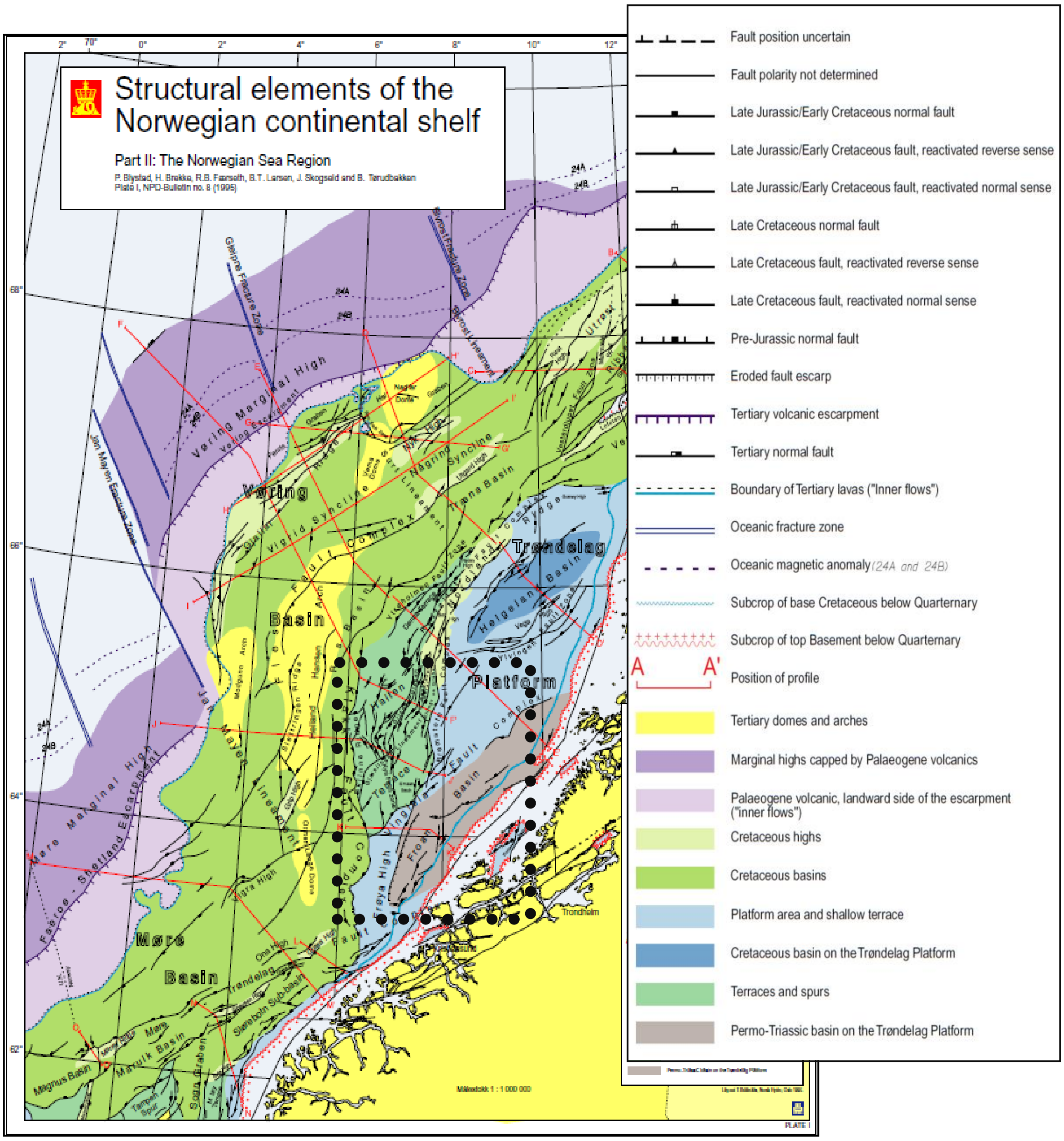


Figure-2.1: Structural elements of the Norwegian continental shelf (Blystad et al., 1995)

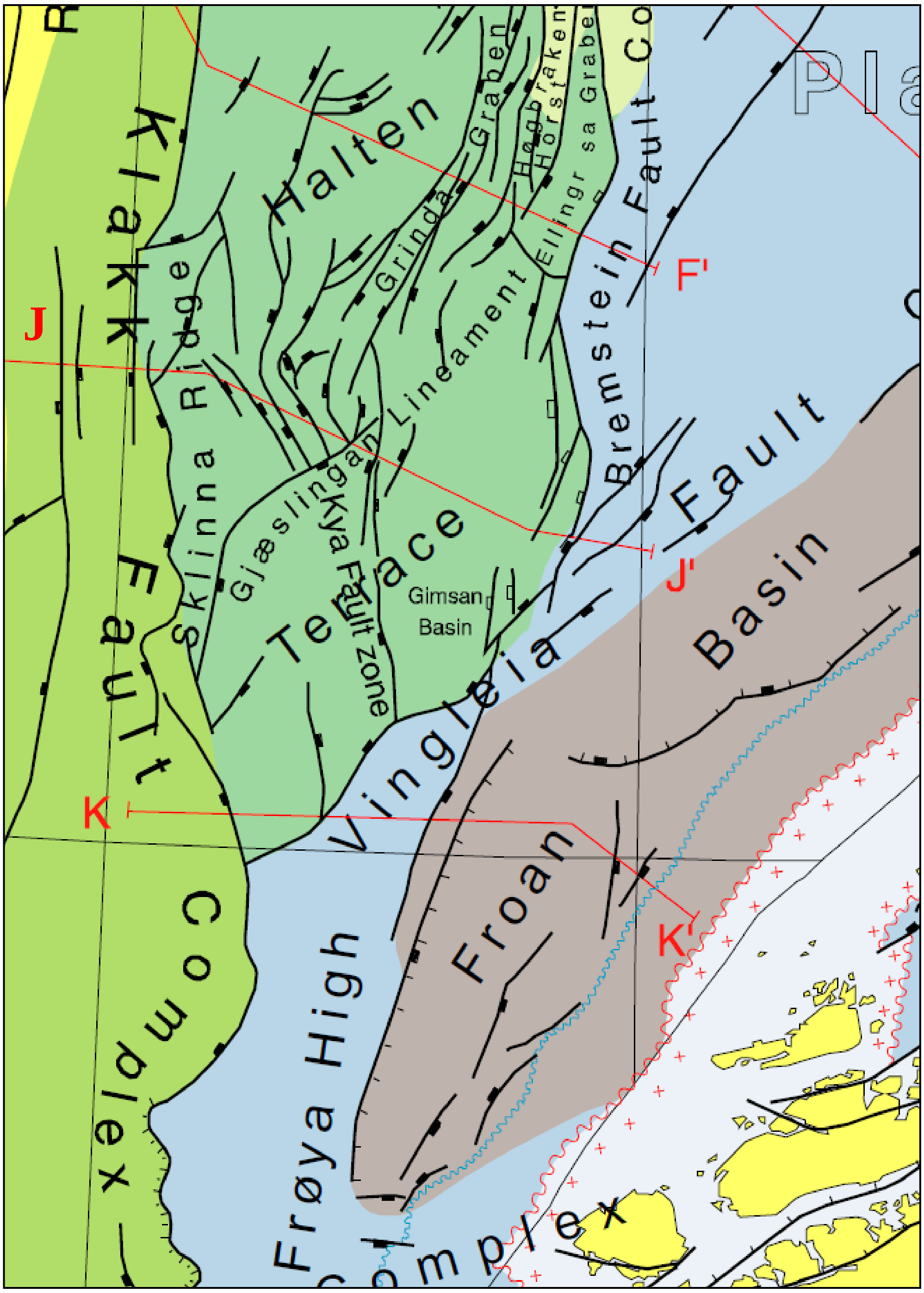


Figure-2.2: Detailed structure of the study area showing the J-J' and K-K' cross-sections (Blystad et al., 1995)

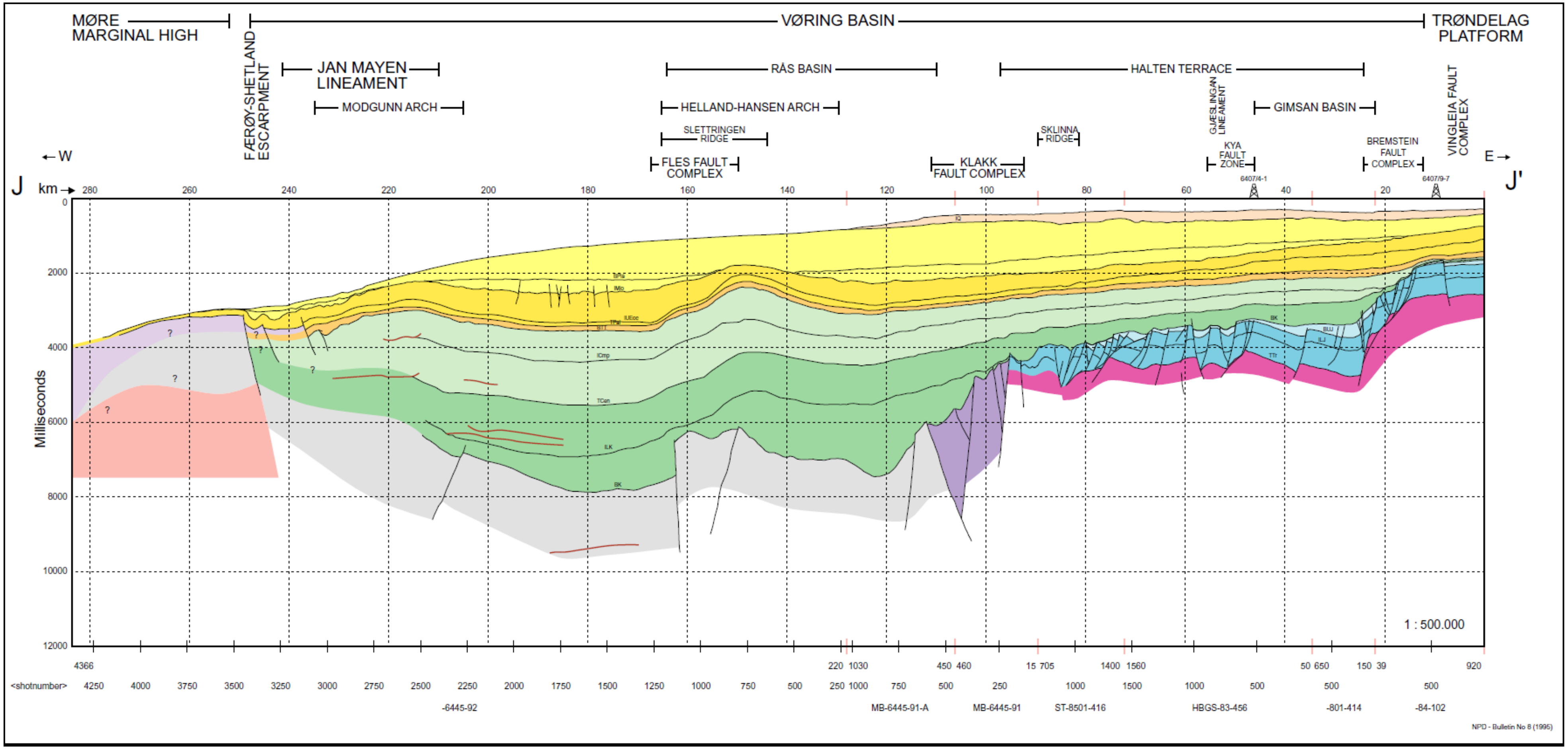


Figure-2.3: Cross-section J-J' along the northern part of the study area (Blystad et al., 1995)

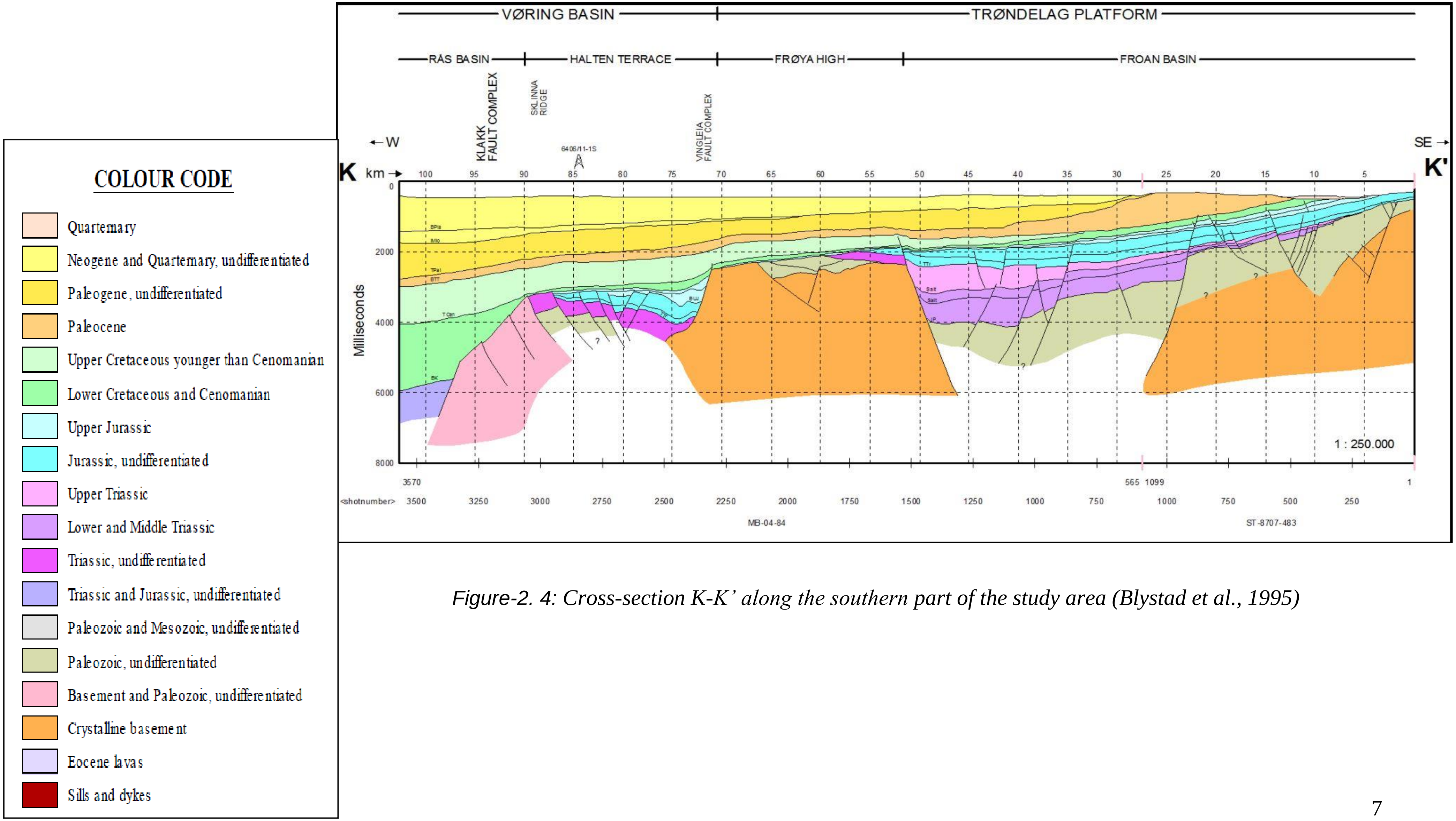


Figure-2. 4: Cross-section K-K' along the southern part of the study area (Blystad et al., 1995)

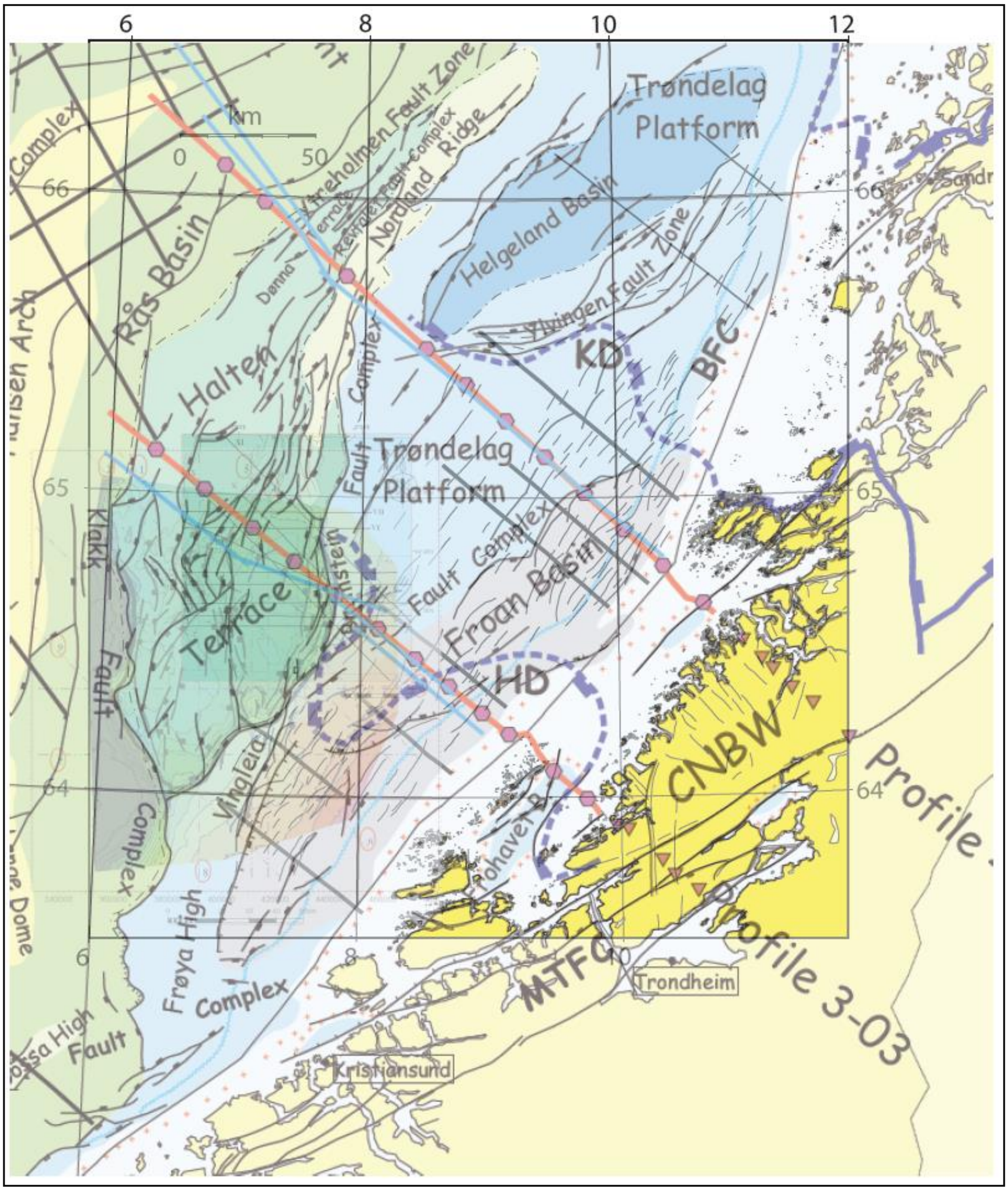


Figure-2.5: Profile 3-03 shot lines shown as bold red lines with purple hexagons marking OBS/OBH receiver positions, and inverted triangles marking land station and the blue lines mark the location of individual MCS lines used for the composite stratigraphic section (Breivik et al., 2011). The structural base map is from Blystad et al. (1995), CNBW: Central Norway Basement Window, HD: Høybakken Detachment, KD: Kollstraumen Detachment, ND: MTFC: Møre-Trøndelag Fault Complex.

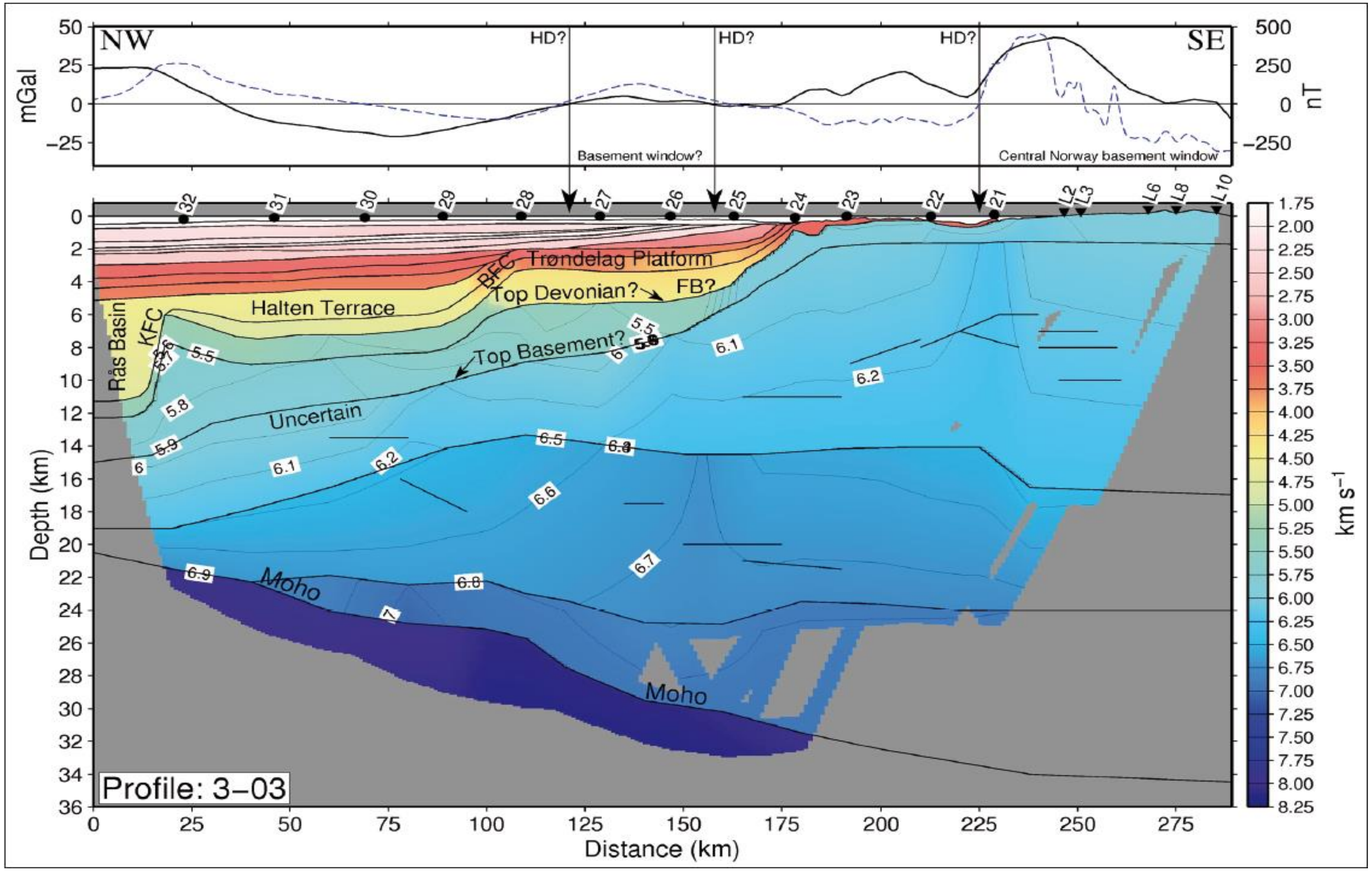


Figure-2.6: *Upper panel: Observed gravity- (heavy line), magnetic anomalies (dashed blue line) along Profile- 3-03. Lower panel: Gridded crustal velocity model of Profile 3-03. Contour interval within the basement is 0.1 km s-1. The intersections of the profile (Fig. 2.6) with the proposed offshore extension of the Høybakken Detachment (HD) (Skilbrei et al. 2002) are indicated. BFC: Bremstein Fault Complex, FB: Froan Basin, KFC: Klakk Fault Complex (*Breivik et al., 2011)

2.1 Pre-breakup tectonic setting of the Mid Norwegian Margin

The tectonic history of the North Atlantic margin can in general be divided into the time intervals summarized in Table 2-1. The present thesis focuses mainly on the second and third tectonic periods.

Table 2-1: Three main tectonic periods in the North Atlantic margin tectonic history

No.	**Tectonic regimes**	**Main tectonic periods**	**Age (Ma)**
1	Compression	Prior to Devonian (Caledonian Orogeny)	> ~400
2	Extension	1)Late Paleozoic-Early Cenozoic 2)Late Jurassic-Cretaceous 3)Late Cretaceous-Early Cenozoic	~370 ~55
3	Break-up	Early Cenozoic (nearly Paleocene-Eocene)	~55

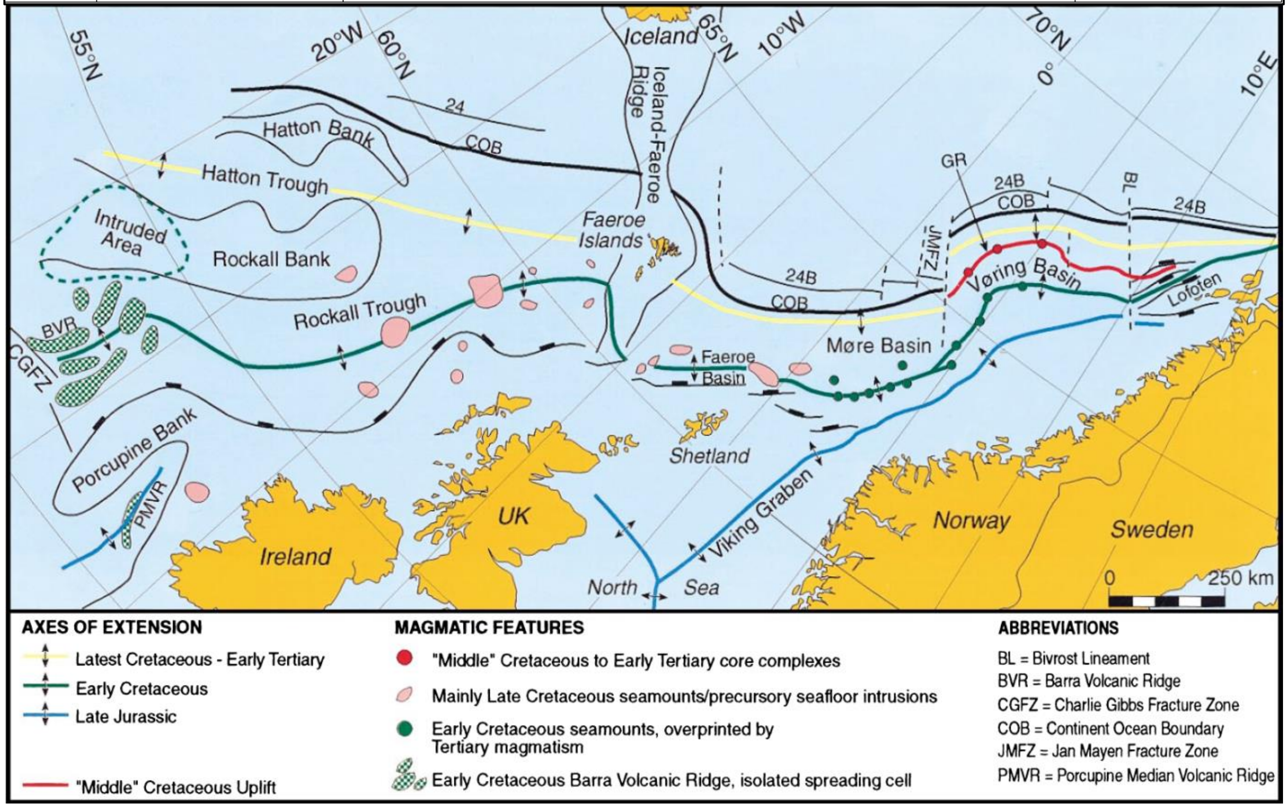


Figure-2.7: Simplified map of the NE Atlantic margin, showing location of rift axis between Jurassic and Early Tertiary and migration of the rift system northwards (Lundin and Dorè, 1997).

A transverse NW-SE structural trend is expressed as major lineaments that probably reflect the old, Precambrian grain of the basement. The collisional stage was succeeded by comprehensive top-to-the WNW to NW extensional deformation, consistent with extensive crustal thinning and development of the Devonian basins along the western coast of Norway (Gabrielsen et al., 1999). In Carboniferous time the extensional tectonics were related to within-plate continental rifting (Doré et al., 1997). The later Triassic basin evolution was characterized by regional subsidence and deposition of large sediment volumes (Gabrielsen et al., 1999; Faleide et al., 2008).

Reactivation of Late Paleozoic to early Mesozoic faults has influenced the development of the Jurassic rift systems on the present day Norwegian margin (Doré et al., 1997; Osmundsen et al., 2002). The Late Jurassic–Early Cretaceous rift episode is the dominant structural margin framework during the pre-opening, which is responsible for the development of major Cretaceous basins such as the Møre and Vøring basins off mid-Norway (Faleide et al., 2008).

2.1.1 Caledonian orogeny and collapse

Four orogenic events within the Caledonian orogen were recognized in Norway: Finnmarkian (Late Cambrian), Trondheim (Early Arenig), Taconian (Mid-Late Ordovician) and Scandian (Mid Silurian-Early Devonian) (Roberts, 2003). The first two events involved accretion between Baltica and adjacent microcontinent and Iapetan arcs. The Mid-Late Ordovician event is the arc accretion event within the Laurentian margin. During Silurian-Devonian times, the Iapetus Ocean underwent closure and the Baltoscandian margin of Baltica was subducted beneath Laurentia. The development of the Caledonian mountain belt was marked by series of eastward allochthons thrust onto Archaean and Proterozoic crystalline rocks of the Fennoscandian Shield (Ziegler, 1988; Fossen, 1992; Gabrielsen et al., 1999; Roberts, 2003).

The extension at the end of the Caledonian orogeny was closely related to post-collisional, lower to Middle Devonian plate divergence (Fossen, 1992, 2000). The Post-collisional extensional deformation can be separated into two closely related modes of deformation. The first is characterized by structures indicating a plain reversal of the nappe translation direction whereas the other involves the development of major oblique extensional shear-zones

(Fossen, 1992, 2000). The collisional stage was succeeded by comprehensive top-to-the WNW to NW extensional deformation, consistent with extensive crustal thinning and development of the Devonian basins along the western coast of Norway (Gabrielsen et al., 1999). This extension is associated with the deposition of thick sedimentary sequences preserved in the Norwegian shelf (Gabrielsen et al., 1999).

2.1.2 Late Devonian- Permian extensional setting

Devonian and Permian times represent the period of active tectonics along the NE Atlantic margin. Permian-early Triassic thinning of a crustal section with variable thickness between 29-24 km, affected the Norwegian shelf (Gabrielsen et al., 1999). The rift system was dominated by N-S to NE-SW-trending normal faults with NW-SE-trending transfer faults and tectonic activity was concentrated on the Trøndelag Platform and Halten Terrace. The rift system was filled mainly with continental clastics (Brekke et al., 2001). Fig. 2.8a shows the paleogeography of Early Carboniferous times plotted on a 300 Ma plate reconstruction (Brekke et al., 2001). The rift system was dominated by N-S to NE-SW-trending normal faults with NW-SE-trending transfer faults and tectonic activity was concentrated on the Trøndelag Platform and Halten Terrace. The rift system was filled mainly with continental clastics (Brekke et al., 2001).

2.1.3 Late Jurassic - Cretaceous extensional setting

Lundin and Doré, (1997) proposed that by Late Jurassic - Early Cretaceous, rifting of the NE Atlantic propagated northeastward through the Rockall Trough, West Shetland/Faeroe Trough, central Møre Basin and eastern Vøring Basin (Fig. 2.8b & c) contemporaneously with rifting in the Labrador Sea. On a regional scale, the Late Jurassic rift system was linked to rifting in Central Europe and seafloor spreading in Tethys and is characterized by N-S trending rifting (Ziegler, 1988; Lundin & Doré, 1997; Gabrielsen et al., 1999).

2.1.4 Late Cretaceous - Early Cenozoic extensional setting

The Late Cretaceous was characterized by global sea level increase and reached its maximum when the area between Norway and Greenland was an epicontinental sea in which crust had been weakened by the multiple post-Caledonian rift events (Gabrielsen et al., 1999). The tectonism was expressed as faulting, accelerated basin subsidence and conjugate uplift, tilting of the bounding platforms areas to the major basins (Fig. 2.8d), as e.g. Møre and Vøring basins. The flanks of the basins were deeply eroded.

The onset of Late Cretaceous tectonic episode and accelerated subsidence of the Vøring and Møre basins coincides with the rapid subsidence of basins along the Barents Sea margin. Skogseid et al. (2000) assumed that this episode lasted for c. 20 m.y. leading to the onset of sea-floor spreading at the Paleocene-Eocene transition. The event was associated with regional uplift of the Norwegian–Greenland rift system possibly due to increased heat flow just prior to break-up (Gabrielsen et al., 1999; Skogseid et al., 2000).

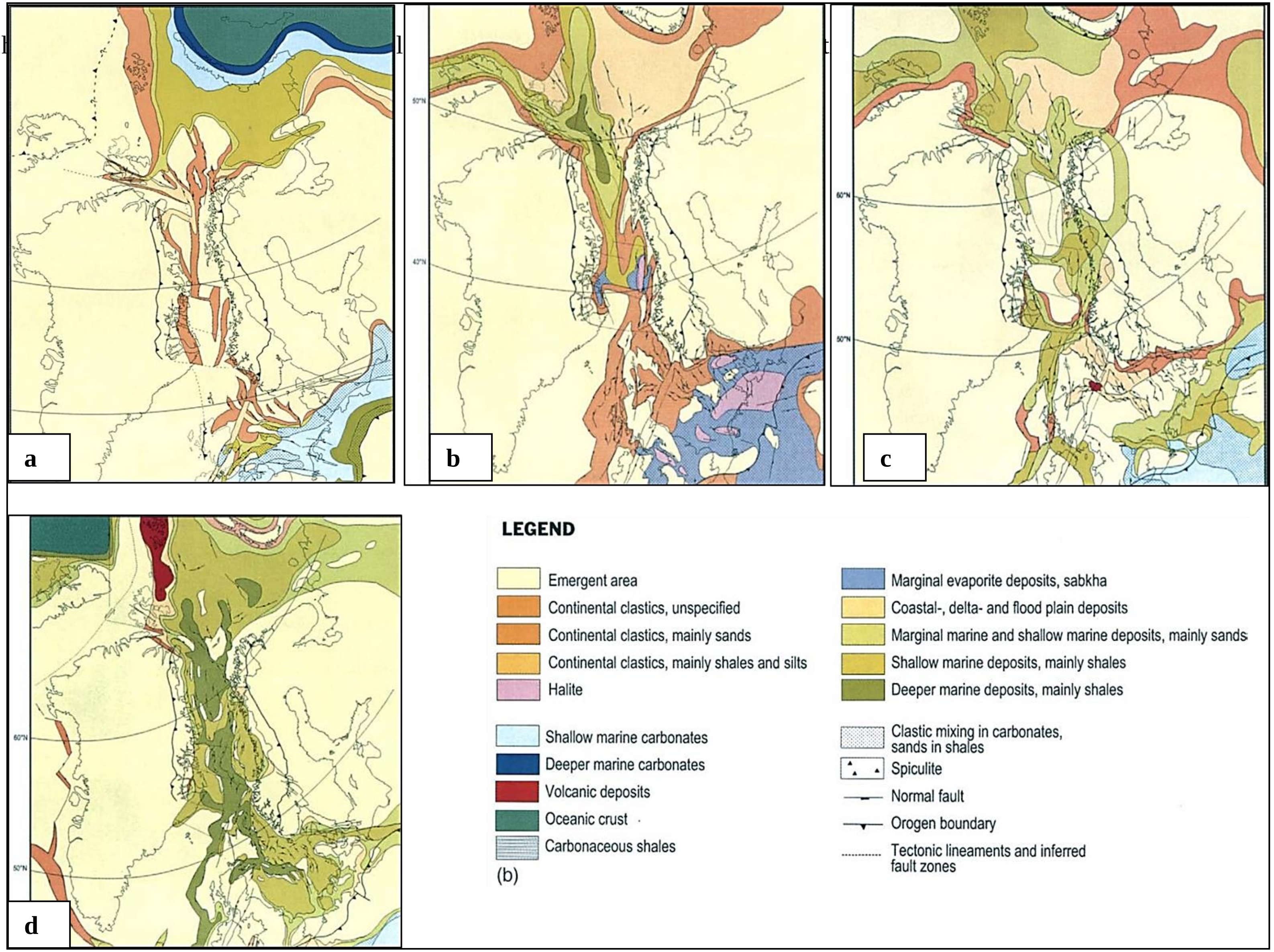


Figure-2.8: From top left to bottom,300 Ma, 150Ma, 150 Ma and 70 Ma, Plate reconstruction plot of Early Carboniferous, Triassic (late Carnian), Jurassic and Early Cretaceous times paleogeography respectively. (a), the rifting system is filled mainly with continental clastics. (b) Continental clastic and marginal evaporate deposit. (c) Marginal to shallow marine deposits mainly sands. (d) Characterized by infill of shallow and deeper marine deposits, mainly shales (Brekke et al., 2001).

2.2 Breakup and post breakup tectonism and magmatism

The final NE Atlantic rift episode that initiated near the Campanian-Maastrichtian boundary, lasted until continental separation near the Paleocene-Eocene transition, and caused around 140 km extension (Fig. 2.7) (Skogseid et al., 2000). The lithospheric breakup was accompanied by massive, regional magmatism within the North Atlantic Volcanic Province and the voluminous igneous activity across 300 km wide zone along the rifted plate boundary has left a distinct imprint on the rifted margin segments in terms of extrusive and intrusive magmatism at various crustal levels (Skogseid et al., 2000; Faleide et al., 2008).

The final Maastrichtian-Paleocene rift episode led to the separation and onset of seafloor spreading in the Paleocene-Eocene transition (Lundin & Doré, 1997; Skogseid et al., 2000) (Fig. 2.9). This event led to the 300 km wide zone with lithospheric thinning and post-break subsidence. The resulting break-up between Eurasia and Greenland was accompanied by extensive volcanism. As Faleide et al. (2008) discussed, the Norwegian Margin formed in response to early Cenozoic continental breakup and subsequent opening of the Norwegian-Greenland Sea. The fault activity continued toward breakup but appears to have been less frequent during the Paleocene.

During plate separation in Early Eocene time, a compressive regime gave rise to local domes with reverse-movement of normal faults (e.g. Helland-Hansen Arch) (Blystad et al., 1995; Brekke, 2000; Lundin & Doré, 2002; Faleide et al. 2010). Uplift occurred in several phases during Cenozoic, and the main component of uplift took place in Late Pliocene and Pleistocene time and was associated with glaciations (Lundin and Doré, 2002). This uplift caused an increase in sediment supply and westward progradation of deltaic systems. During the last 2.6–2.7 Ma, the Naust Formation which comparing a thick succession of low angle sediment wedges and sheet like units were developed by the erosional products from Mid Norway and the inner shelf (Dolland et al., 1988; Rise et. al., 2005).

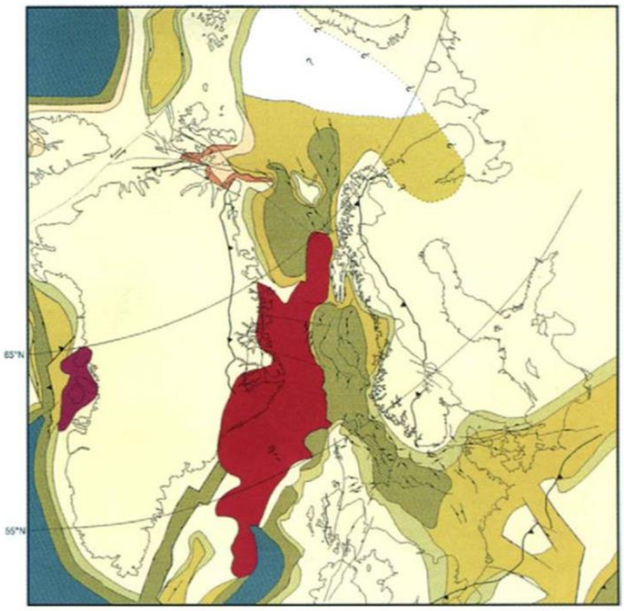


Figure-2.9: The Paleogeography of Early Eocene times plotted on a 53 Ma plate reconstruction. The sedimentary environment of the Tertiary at the Palaeogene transition from rift to drift settings (Brekke et al., 2001).

2.3 Main structural elements in the study area

The main structural elements in the study area are the Vingleia, Bremstein and the Klakk fault complexes which bounds the Halten from the Rås Basin to the west by Klakk Fault Complex and to the east from the Trøndelag, Frøya High and the Froan Basin by the Vingleia Fault Complex.

2.3.1 Halten Terrace

The Halten Terrace forms a rhomboidal structural feature separated from Trøndelag Platform and Frøya High by the Vingleia-Bremstein fault complexes to the east and from the Rås Basin by the Klakk Fault Complex (Figs 2.2, 2.3 & 2.4). It is approximately 80 km wide and 130 km in length and total area of 10400 km² (Blystad et al., 1995; Enhrik & Gabrielsen, 2004; Marsh et al., 2009). The area comprises several sub-basins (Koch and Heum, 1995). The relationship between the pre- Middle Triassic basins in the Trøndelag Platform area and the Jurassic basins on the Halten Terrace involves the successive development of two generations of extensional detachments and their interaction with a deep-seated, antiformal culmination (metamorphic-core-complex) (Osmundsen et al., 2002; Osmundsen & Ebbing, 2008).

According to Bell et al. (2014) the seismic expression of the Sklinna Ridge is similar to that of the Frøya High and is characterized by a west-dipping prominent planar surface at Base Cretaceous Unconformity. This ca. 16 km wide erosion surface truncates eastward tilted Early–Middle Jurassic stratigraphy. The eastern margin of the Sklinna Ridge is onlapped by Early Cretaceous strata, the Lange Formation.

2.3.2 Vingleia–Bremstein fault complexes

The Vingleia and Bremstein fault complexes bound the Halten Terrace at its eastern and southeastern margins (Osmundsen et al., 2002; Ehrlich & Gabrielsen, 2004; Osmundsen & Ebbing, 2008). The Vingleia Fault Complex has a general NE-SW strike (Blystad et al., 1995). It forms the southwestern continuation of the Bremstein Fault Complex and terminates towards the south against the Klakk Fault Complex and the Sklinna Ridge (Ehrlich and Gabrielsen, 2004). The fault complex displays a pronounced bend along its strike, from SW–NE to EW and again into SW–NE around the Njord structure. According to Ehrlich & Gabrielsen, (2004) the southeast segment is characterized by listric fault geometry and the northeastern is characterized by a listric fault with a relatively simple geometry at depth whereas the central segment is characterized by ramp flat ramp fault geometry. The Vingleia Fault Complex that envelopes the Njord Structure is the most striking feature in the structural map, the dip-slip separation at this location from the Frøya High being more than 1000 m (Blystad et al., 1995; Ehrlich & Gabrielsen, 2004).

Activity along the **Kya Fault zone** follows a complex pattern time vise spanning from the mid-Jurassic to the early Cretaceous (Blystad et al., 1995; Koch and Heum, 1995). Kya Fault Zone is an N–S-striking mainly west facing extensional fault zone, which splays off from the master fault in a northerly direction. To the north of the Njord structure, part of the faults change polarity and delineate the Gimsan Basin to the west (Ehrlich & Gabrielsen, 2004). The terrace is characterized by intermediate sedimentary thickness of the Cretaceous deposits in relation to the Rås Basin. Relative sea level rise since the Triassic within the Halten Terrace and Rås Basin clearly may be taken to imply that the sedimentary successions are of marginal marine-to-shallow marine sediments in the Early–Middle Jurassic, and deep water marine sediments in the Late Jurassic, Cretaceous and Cenozoic (Bell et al., 2014).

2.3.3 Trødelag Platform and Froan Basin

The Trøndelag Platform and the Froan Basin are characterized by a Permo-Triassic phase of crustal extension which is generally poorly dated (Blystad et al., 1995; Brekke, 2000; Osmundsen et al., 2002). They are located east of the Halten Terrace separated by the Vingleia- Bremstein fault complexes and are dominated by shallow water Late Jurassic to Early Cretaceous sediment deposition (Blystad et al., 1995; Marsh et al., 2010). The Trøndelag Platform is underlain by an array of deep, pre-Middle Triassic half-graben basins bounded by N-S and NE-SW-trending dip-slip or oblique normal faults and these fault system most likely originated as a result of late/post-Orogenic extension of the Caledonian nappe pile lasting from the Devonian in to the Early Carboniferous (Osmundsen et al., 2002). Subsequent re-activation of this fault pattern controlled Permian to lower Triassic basin deposition (Osmundsen et al., 2002; Osmundsen & Ebbing, 2008).

The Froan Basin comprises a series of half-grabens and becomes progressively shallower towards its southern and eastern margin due to depositional thinning of the succession, combined with later uplift and erosion (Blystad et al., 1995; Brekke, 2000; Osmundsen et al., 2002).

2.3.4 Frøya High

The Frøya High forms the footwall block to the northwest ward-dipping Vingleia Fault Complex, which forms the southeast margin of the Halten Terrace (Blystad et al., 1995). It is separated from Halten Terrace by the Vingleia Fault Complex and from Froan Basin by the fault splay extending southeast of Vingleia Fault Complex (Blystad et al., 1995; Ehrlich & Gabrielsen, 2004). The top of the Frøya High is defined by a flat, very gently westward-dipping surface, which is ca. 5 km wide Blystad et al., 1995; Marsh et al., 2010). Seismic data indicate that Upper Cretaceous strata directly overlie a thin (ca. 10 m) Upper Jurassic interval across this surface and this interval itself unconformably overlies a severely truncated, Middle Jurassic succession and the lack of sediment deposition on the Frøya High between the Lower Jurassic and Lower Cretaceous suggests area may have been subaerial or close to sea level at this time (Bell et al., 2014).

3. Seismic interpretaion and results

This section displays observations and results from seismic and well data using the available seismic interpretation tools in Petrel. Special emphasis was given to the interpretation of the structural style and evolution of the Vingleia Fault Complex. Lithostratigraphic units and faults were interpreted for the entire survey. Reflection seismic data were not depth converted. Therefore cross-sections, time-structure maps and time-thickness maps are presented with vertical axis in two way travel time (TWT). The interpretation workflow followed during the seismic interpretation is summarized below.

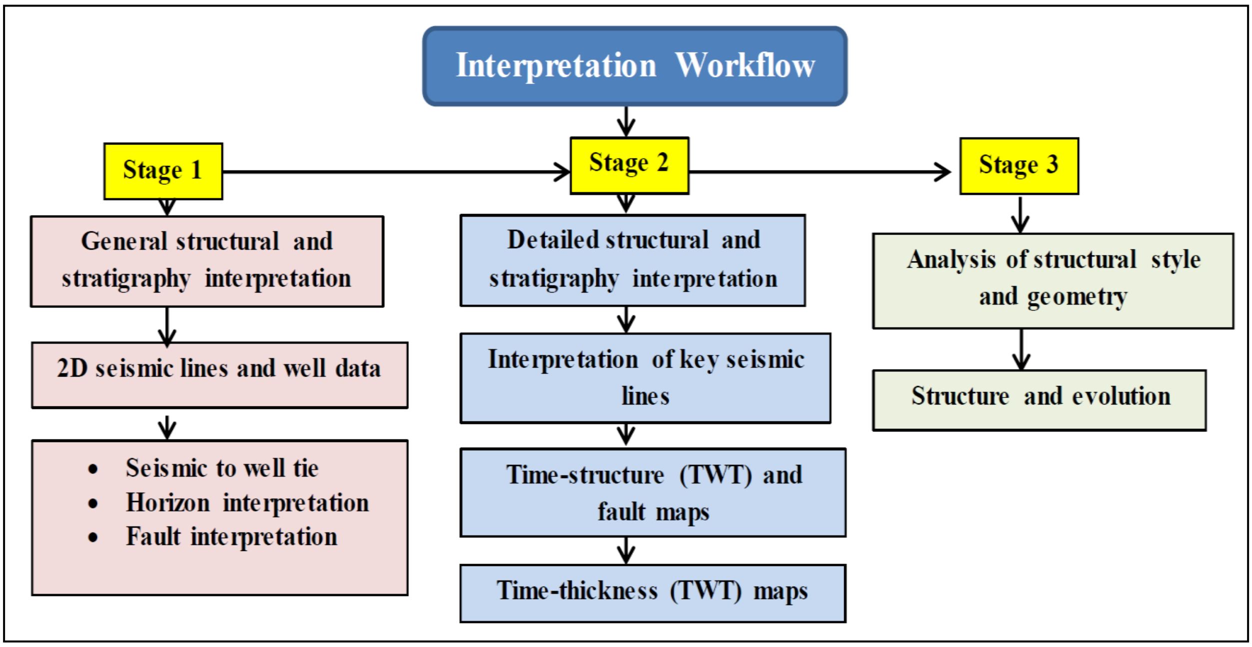


Figure-3.1: Interpretation workflow, where stages 1& 2 are the main focus of this chapter, whereas stage 3 is addressed in the discussion part of chapter 4.

3.1 DATA SET

The study area comprises parts of the Trøndelag Platform, Frøya High, Froan Basin, Halten Terrace and the Rås Basin (Fig. 1.1). 2D seismic reflection data and well data were used in this study. The data covers most of the study area with the main line orientation of NW-SW, W-E and N-S and localised seismic data sets of different strike orientation. The NW-SW and

W-E oriented seismic lines are orthogonal to the strike of the main structure, the Vingleia Fault Complex whereas the W-E seismic lines are parallel to sub- parallel to main structure. Wellbore data from nine wells were used to tie between the seismic data and stratigraphy of the wells. Detailed information of these wells was taken from NPD (Tables 3.1 & 3.2).

3.1.1 Seismic and well data

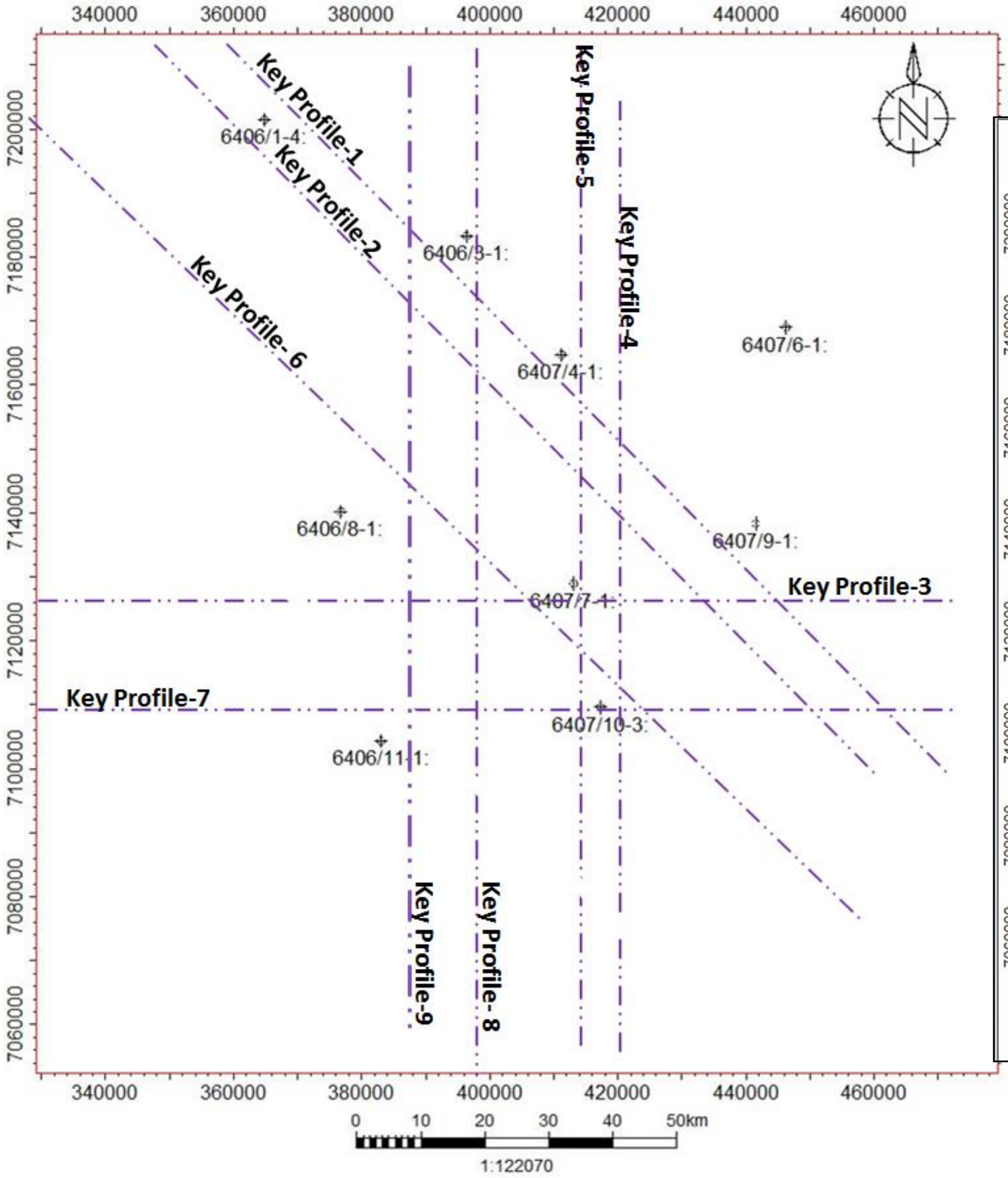
Most of the 2D seismic reflection data used in this thesis comes from a regional high quality, lines having E-W, N-S, and NW-SE orientations. In addition, several semi-regional data sets covering parts, of the study area were available. The selected key seismic profile lines (Fig. 3.2) make good crossings of different segment of the Vingleia Fault Complex. Seismic coverage varies through the study area; northern part of the study area is densely covered whereas in the southern part the seismic data are more spaced. This has difficulty in following the faults, especially around the Njord field area and south of the structure. Seismic resolution varies from poor to good and some of the sedimentary sequences are poorly known due to the seismic resolution.

Wellbore data from nine wells, (6407/10-3, 6407/9-1, 6407/6-1, 6406/ 11-1s, 6407/ 7-1s, 6406/8-1, 6407/ 4-1, 6406/ 3-1, and 6406/1-4) have been integrated with the seismic data to establish tie between the seismic data and stratigraphy of the wells. Detailed information of these wells is taken from NPD (Tables 3.1 & 3.2) and Fig. 3.2, shows the location of the selected wells for seismic to well tie. Scarcity of wells that penetrate levels below the Late Triassic age led to poor identification of the sedimentary sequences at Middle Triassic and deeper levels. However Cretaceous-Jurassic sedimentary rocks are interpreted using the nine key wells.

The nine wells are well distributed in the study area where wells 6407/10-3, 6407/9-1, and 6407/6-1 are roughly located within Frøya High, Froan Basin and Trøndelag Platform respectively. Here the total depth (MD) is not more than 3000 [m RKB]. Wells 6406/ 11-1s, 6407/ 7-1s, and 6406/8-1, which are located southwest in the study within the Halten Terrace, have total depth (MD) of well below 3000 [m RKB]. Wells 6407 / 4-1, 6406 / 3-1 and 6406/1-4 are located on the northwestern part of the Halten Terrace area with total depth (MD) of more than 4500 [m RKB] (Tables 3.1 & 3.2). Dating in well 6407/10-3 situated within the

Froan Basin confirms the oldest penetrated age and formation of pre- Devonian and basement respectively (Table 3.2). Generally Late Triassic is the deepest penetrated age and Åre Formation as well as the Red Beds of the Late Triassic is the oldest formation penetrated within the Halten Terrace. Therefore well 6407/10-3 is the only well from the selected nine wells within the study area that has penetrated pre- Devonian, basement and could give valuable information in making seismic-to-well tie.

There are large uncertainties in the interpreted and stratigraphic geometries, especially around the Njord Structure. The uncertainties were much greater in the deeper stratigraphic level where identification and correlation of seismic horizons were difficult. This could be due to the lack of the well-spaced seismic lines and wells that penetrate levels below the Late Triassic. Therefore seismic interpretation alone is not conclusive.



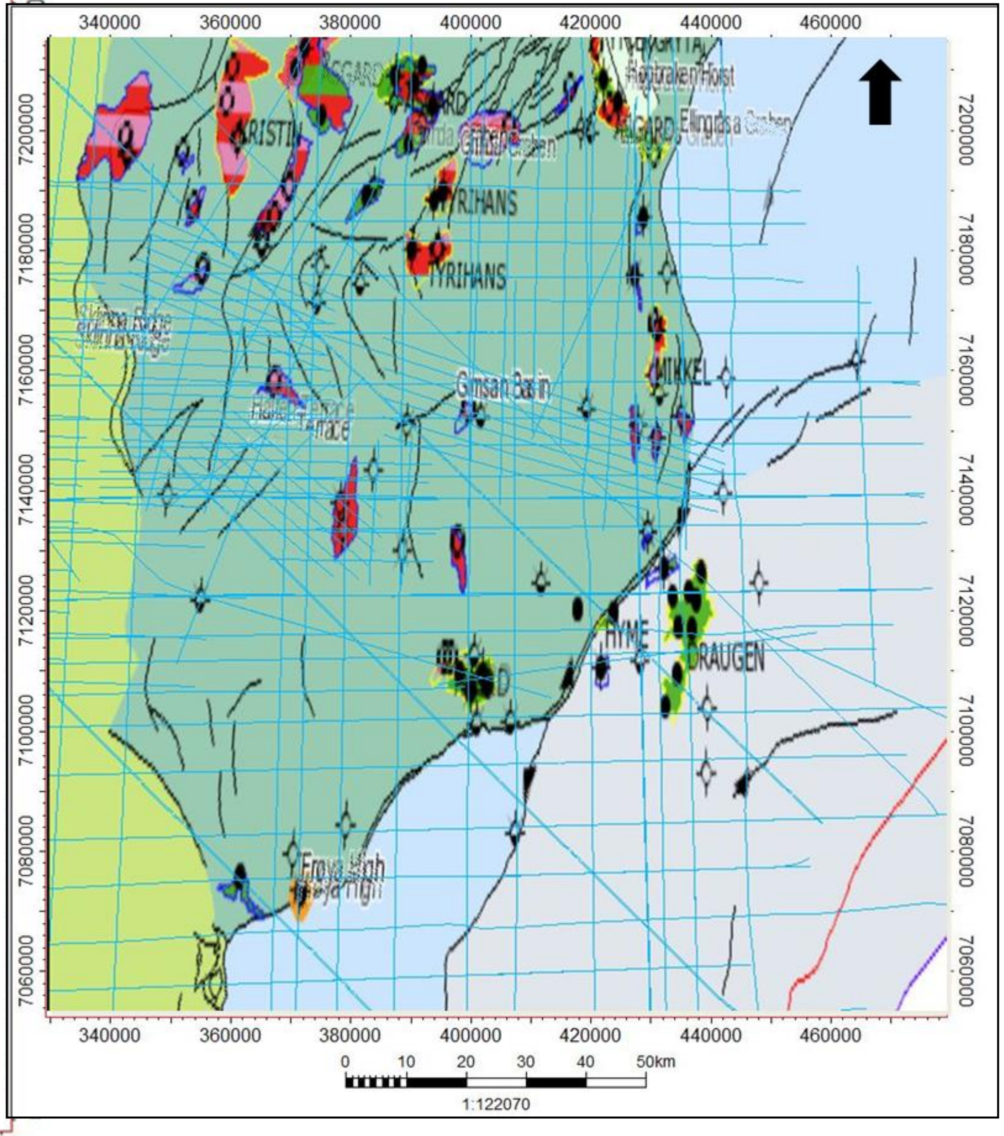


Figure-3.2: Base map of the study area showing orientation of the seismic lines and location of boreholes in the study. The broken lines show the orientation of key profiles and wellbores are indicated by black star (www.npd.no).

Table-3.1: Wellbore data from the Norwegian Petroleum directorate (www.npd.no)

Wellbore name	6407/10-3	6407/9-1	6407/6-1	6406/ 11-1s	6407/ 7-1s	6406/ 8-1	6407/ 4-1	6406/ 3-1	6406/1-4
NS UTM [m]	7109795.67	7138488.30	7169163.29	7104524.70	7129107.11	7140372.60	7164900.01	7183474.26	7201599.89
EW UTM [m]	417314.23	441548.41	446258.70	383011.32	413114.25	376765.25	411212.79	396410.13	364794.60
UTM zone	32	32	32	32	32	32	32	32	32
Drilling operator	Norsk Hydro Produksjon AS	A/S Norske Shell	Den norske stats oljeselskap a.s	Saga Petroleum ASA	Norsk Hydro Produksjon AS	Elf Petroleum Norge AS	Den norske stats oljeselskap a.s	Den norske stats oljeselskap a.s	Eni Norge AS
Completion date	27.06.1992	07.09.1984	26.10.1984	18.02.1991	07.04.1986	11.04.1988	15.11.1985	14.08.1984	26.12.2005
Type	Exploration	Exploration	Exploration	Exploration	Exploration	Exploration	Exploration	Exploration	Exploration
Content	shows	oil	dry	Oil	Oil/Gas	Gas shows	Gas/Condensate	Gas shows	shows
Kelly bushing [m]	23.5	25.0	27.0	26.0	23.0	27.0	22.0	22.0	22.0
Water depth [m]	323.5	248.0	226.0	315.0	328.0	348.0	225.0	256.0	363.0
TD (MD) [m RKB]	2973.0	2500.0	2895.0	4185.0	3950.0	4910.0	4835.0	4902.0	4596.0
Oldest penetrated age	Pre-Devonian	Late Triassic	late Triassic	Late Triassic	Late Triassic	Early Jurassic	Late Triassic	Late Triassic	Middle Triassic
Oldest formation	Basement	Red Beds	Red Beds	Red Beds	Red Beds	Åre FM	Åre FM	Red Beds	Red Beds

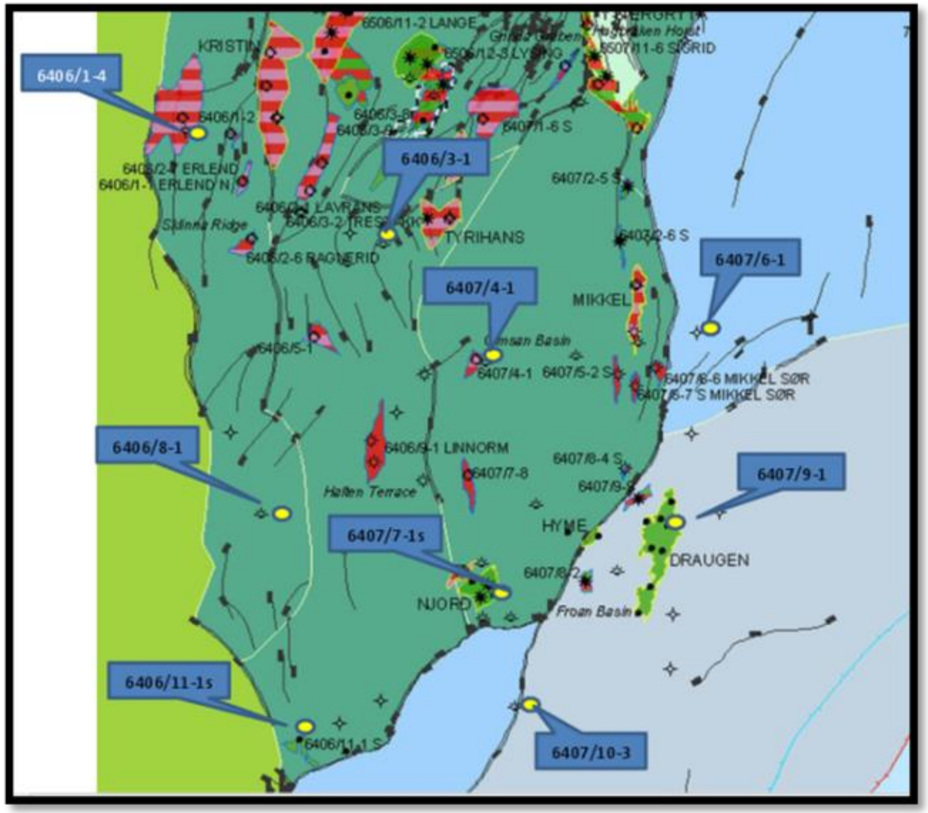
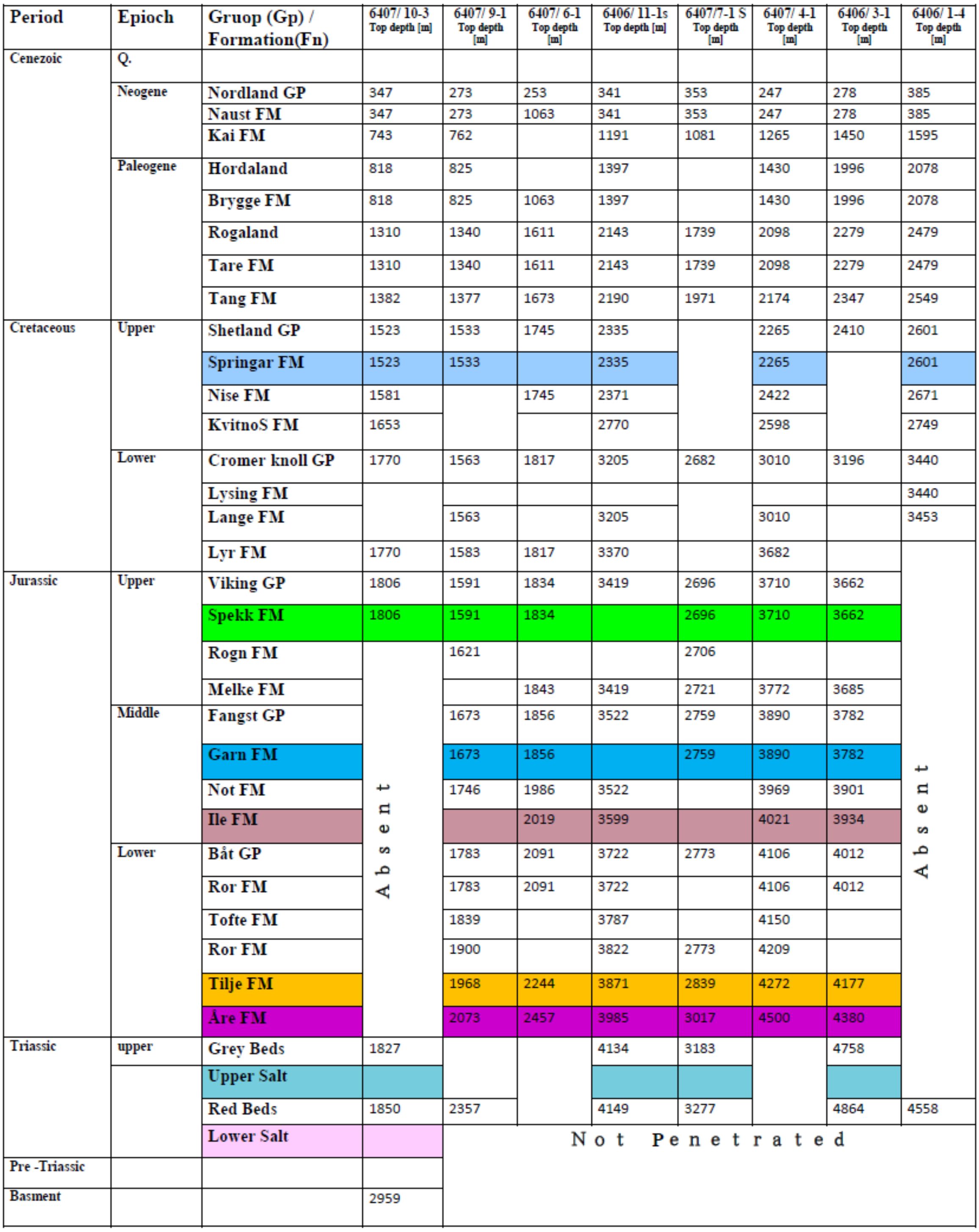


Figure-3.3: location of the selected wells which appears to penetrate the oldest formation (www.npd.no)

Table-3.2: Well Top correlation of the nine selected wells with interpreted formations highlighted and Top depth in (DM)



Period	Epioch	Gruop (Gp) / Formation(Fn)	6407/ 10-3 Top depth [m]	6407/ 9-1 Top depth [m]	6407/ 6-1 Top depth [m]	6406/ 11-1s Top depth [m]	6407/7-1 S Top depth [m]	6407/ 4-1 Top depth [m]	6406/ 3-1 Top depth [m]	6406/ 1-4 Top depth [m]
Cenezoic	Q.									
	Neogene	Nordland GP	347	273	253	341	353	247	278	385
		Naust FM	347	273	1063	341	353	247	278	385
		Kai FM	743	762		1191	1081	1265	1450	1595
	Paleogene	Hordaland	818	825		1397		1430	1996	2078
		Brygge FM	818	825	1063	1397		1430	1996	2078
		Rogaland	1310	1340	1611	2143	1739	2098	2279	2479
		Tare FM	1310	1340	1611	2143	1739	2098	2279	2479
		Tang FM	1382	1377	1673	2190	1971	2174	2347	2549
Cretaceous	Upper	Shetland GP	1523	1533	1745	2335		2265	2410	2601
		Springar FM	1523	1533		2335		2265		2601
		Nise FM	1581		1745	2371		2422		2671
		KvitnoS FM	1653			2770		2598		2749
	Lower	Cromer knoll GP	1770	1563	1817	3205	2682	3010	3196	3440
		Lysing FM								3440
		Lange FM		1563		3205		3010		3453
		Lyr FM	1770	1583	1817	3370		3682		Absent
Jurassic	Upper	Viking GP	1806	1591	1834	3419	2696	3710	3662	
		Spekk FM	1806	1591	1834		2696	3710	3662	
		Rogn FM	Absent	1621			2706			
		Melke FM			1843	3419	2721	3772	3685	
	Middle	Fangst GP		1673	1856	3522	2759	3890	3782	
		Garn FM		1673	1856		2759	3890	3782	
		Not FM		1746	1986	3522		3969	3901	
		Ile FM			2019	3599		4021	3934	
	Lower	Båt GP		1783	2091	3722	2773	4106	4012	
		Ror FM		1783	2091	3722		4106	4012	
		Tofte FM		1839		3787		4150		
		Ror FM		1900		3822	2773	4209		
		Tilje FM		1968	2244	3871	2839	4272	4177	
		Åre FM		2073	2457	3985	3017	4500	4380	
Triassic	upper	Grey Beds	1827			4134	3183		4758	
		Upper Salt								
		Red Beds	1850	2357		4149	3277		4864	4558
		Lower Salt		Not Penetrated						
Pre -Triassic										
Basment			2959							

3.2 Interpretation procedure and strategy

The study was carried out by using the software "Petrel- 2012" by Schlumberger. The task has been done by using mainly 2D seismic data, scientific papers to support seismic ties and the seismic well-tie tool was used for correlating and calibrating interpreted seismic horizons and faults to well data. The main seismic reflections were chosen as shown in Table-3.2, in order to map the geometry and analyses the extensional fault system. Mainly the E-W, N-S and diagonal NW-SE seismic lines were used to interpreted and map out the main reflectors. Most of the selected horizons were interpreted manually because of difference in seismic resolutions for each seismic line. The following steps are applied in interpretation the study area:

- Interpretations of regional 2D seismic lines.
- Map the horizons starting from the key seismic line by connecting the selected key lines and going south toward the Njord oilfield area which is strongly deformed zone.
- To map horizons, specially the Triassic evaporite and see the relationship, distribution and tectonic effect within the Halten Terrace, northern and southern parts.
- Mapping fault geometry, structural analysis, timing and style of faulting of the Vingleia Fault Complex.
- To look for fault segmentation, style of deformation and thickness variations along and across the Vingleia Fault Complex.
- To see salt related structures and geometry of deformation.

3.2.1 Seismic stratigraphy – Lithostratigraphy

The stratigraphic framework of the Halten area was defined by Dalland et al. (1988) and Gradstein et al. (2010). The units from Late Triassic to Early Cretaceous are the main focus in this study (Figs. 3.4 & 3.5). According to Koch and Heum, (1995) the sedimentary sequence of the study area can be grouped into pre-rift, syn-rift and passive-margin sequences. As shown in Figs. 3.4 & 3.5 and Table-3.3, the interpreted seismic stratigraphic levels are grouped in terms of formations age of deposition and tectonic events. Units below Top Tilje Formation stratigraphic level are grouped as pre-rift sequence, between Top Garn to Top Spekk (Base Cretaceous Unconformity) formations as syn-rift and above Top Springer Formation as passive-margin sequence.

The stratigraphy of the study in Triassic is characterized by non-marine and evaporites overlain by thick fluvio-deltatic and an open marine Jurassic sequence (Båt, Fangst and Viking Groups) (Dalland et al., 1988; Koch and Heum, 1995; Richardson et al., 2005 and Bell et al., 2014). The Base Cretaceous Unconformity (Top Spekk Formation) seismic reflection separates the Jurassic from Cretaceous sediments and the deep marine, composed of claystones and sand sediments of the Cromer Knoll and Shetland groups overlies this regional stratigraphic marker (Dalland et al., 1988,). The Rogaland, Hordland and Nordland groups the Cenozoic period consist mainly claystones overlies the Cretaceous sediment sequences (Dalland et al., 1988; Bell et al., 2014). The selected and interpreted lithostratigraphic characteristics are going to be discussed below and examples from the five selected wells, well 6407/10-3, well 6406/11-l S, 6407/4-1, well 6406/8-1, and well 6407/6-1 along the selected seismic cross section are shown below (Figs. 3.6, 3.7, 3.8, 3.9 & 3.10).

Well 6407/10-3 is located in the Frøya High and with a TD of 2973 m (Table 3.2 & Fig. 3.6), terminating in the basement. It was the only of the nine wells which penetrated the basement and seismic and well data confirms that the Frøya High is an uplifted area showing the basement at shallower depth. The Upper Jurassic Viking Group was encountered at 1806 m (1800 ms in TWT) and consists of claystone characteristic of the Spekk Formation. From 1850 m to 2155 m undifferentiated Late to Middle Triassic Red Beds are present and continued to 2958.5 m (2500 ms in TWT), were the bore passed into fractured granitic basement (npd) and shows strong seismic reflection in seismic data with irregular structure locally along the entire Frøya high.

Well 6406/11-l S , drilled within the hangingwall anticline structure bounded by two major faults near the southern end of the Halten Terrace and drilled to TD at 4185 m (3500ms in TWT), terminating in the Late Triassic Red Beds (Fig. 3.7). Stratigraphically the Ile Formation is penetrated at 3599 m, Tlje and Åre formations at 3871 and 3985 m in TD respectively. In the seismic profile Ile to Åre formations are represented between 3200-3500 ms in (TWT).

Well **6407/4-1** , drilled in the Gimsan Basin on the Halten Terrace and with a TD of, 4500 m (3750 ms in TWT) (Fig. 3.8), terminating in the Late Triassic of the Åre Formation. The well is located on a structural high immediate to the listric fault on the hangingwall where sedimentary packages are thick and seismic reflections on the seismic profile observed to show divergent seismic reflection pattern away from the fault. Wedge shaped, Syn-rift sediment deposition is observed between Base Cretaceous and Top Tilje seismic reflections whereas below Tilje Formation a uniform thickness between selected seismic horizons are observed which characterize as pre-rift sedimentary deposition.

Well 6406/8-1 is located on the southwestern corner of the Halten Terrace (Fig. 3.9) and was drilled to a TD at 4914 m (4000 ms in TWT), terminating in the Early Jurassic Åre Formation. The seismic profile that crosses well 6406/8-1 shows similar structure as seismic profile that crosses well 6407/4-1 (Fig. 3.8) but in this section (Fig. 3.9) the whole lithostratigraphy is tilted toward the east and terminated at the Base Cretaceous unconformity seismic horizon. The seismic reflection of the early and middle Jurassic observed to show toplap truncation to the Base Cretaceous unconformity seismic horizon.

Well 6407/6-1 was drilled on the Trøndelag Platform, terminating in the Late Triassic of the Red beds of a TD at 3985 m and displayed in (Fig. 3.10) as W-E seismic section. The well data (Table 3.2), and the seismic stratigraphy (Fig. 3.10) of the area shows the Cromer knoll Group of the post-rift sedimentary sequence, the Viking Group of the syn-rift sedimentary sequence and the Fangst, and Båt Group of the pre rift sedimentary sequence to the Triassic evaporites of the bottom sedimentary sequence of the study area. The well is situated on the footwall part of the Bremstein -Vingleia Fault Complex relatively undeformed represented as parallel to sub-parrallel seismic reflectors.

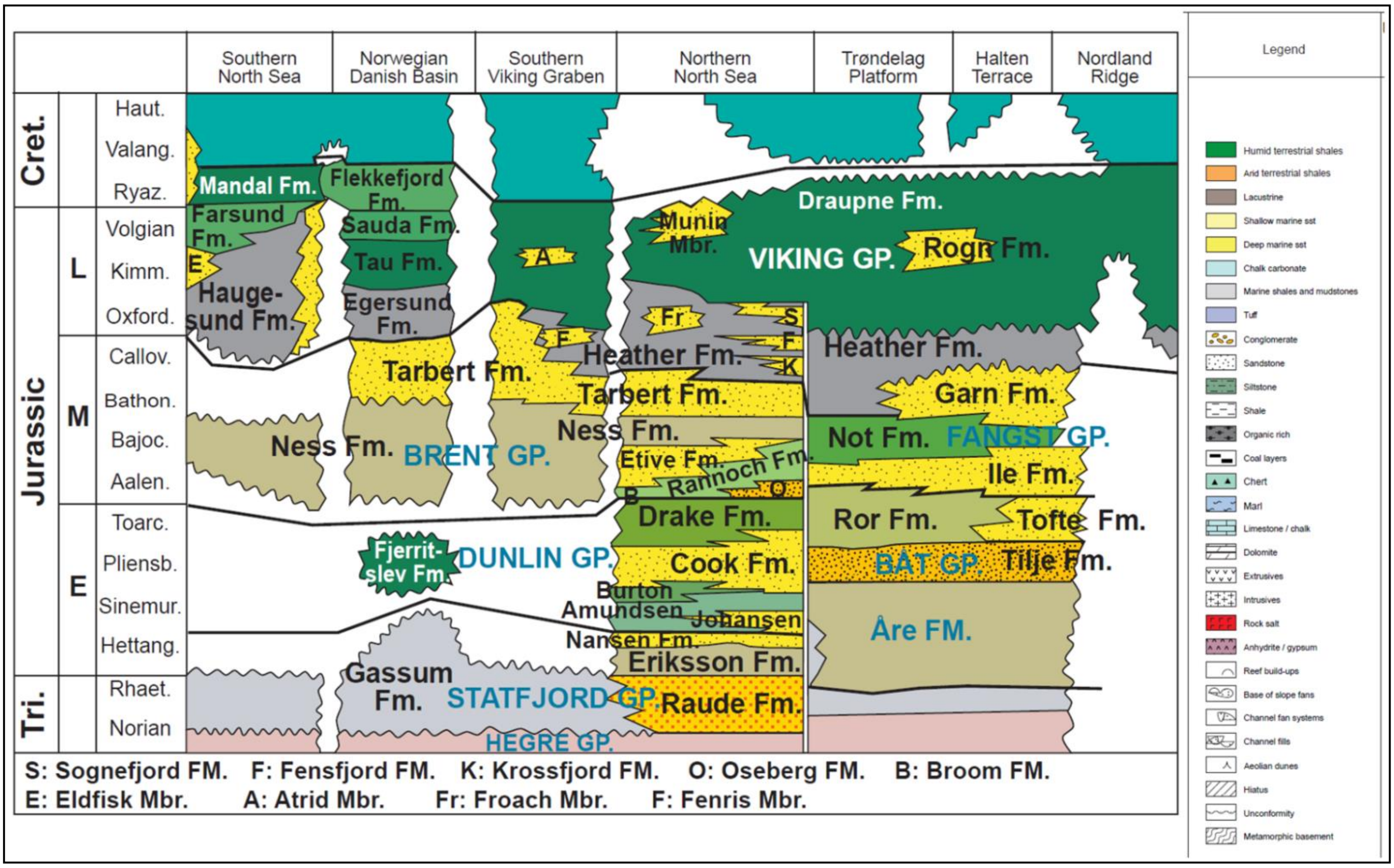


Figure-3. 4: Regional lithostratigraphy offshore Norway (Gradstein et al., 2010)

Table-3. 3: Color code of the interpreted key seismic horizons of the study area

Reflector age (Ma)	**Formation**	**Color code**	**Tectonics**
Base Tertiary (65)	**Top Springar**	🟦	**Post -rift**
Base Cretaceous (140)	**Top Spekk**	🟩	**Syn-rift**
Upper Jurassic (165)	**Top Garn**	🟦	**Pre-rift**
Middle Jurassic (175)	**Top Ile**	🟨	
Lower Jurassic (190)	**Top Tilje**	🟧	
Lower Jurassic (201)	**Top Åre**	🟪	
Upper Triassic (220)	**Top Triassic Salt_A**	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	**Top Triassic Salt_B**	🟥	
	Base Triassic Salt_B	🟪	
Basement			

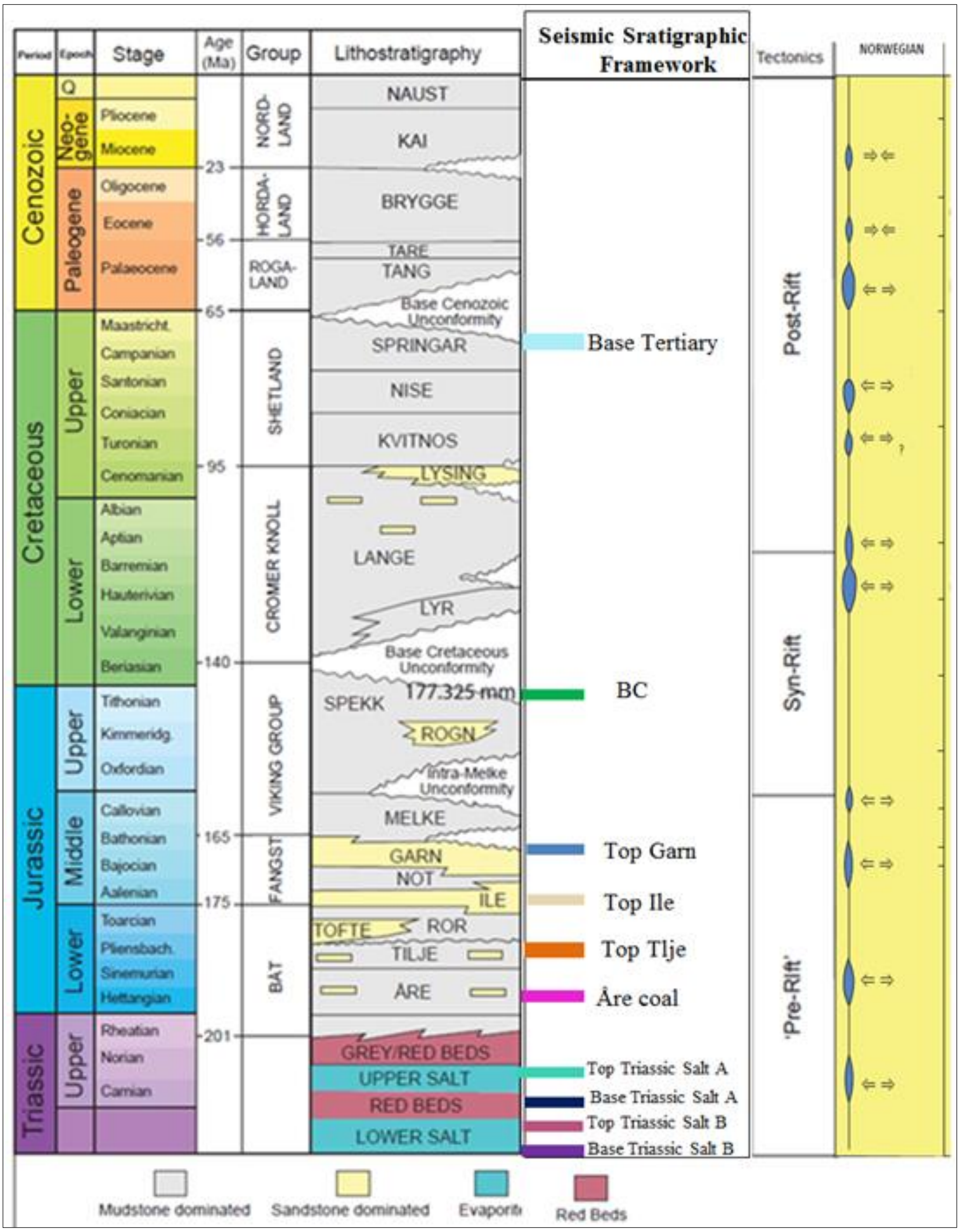
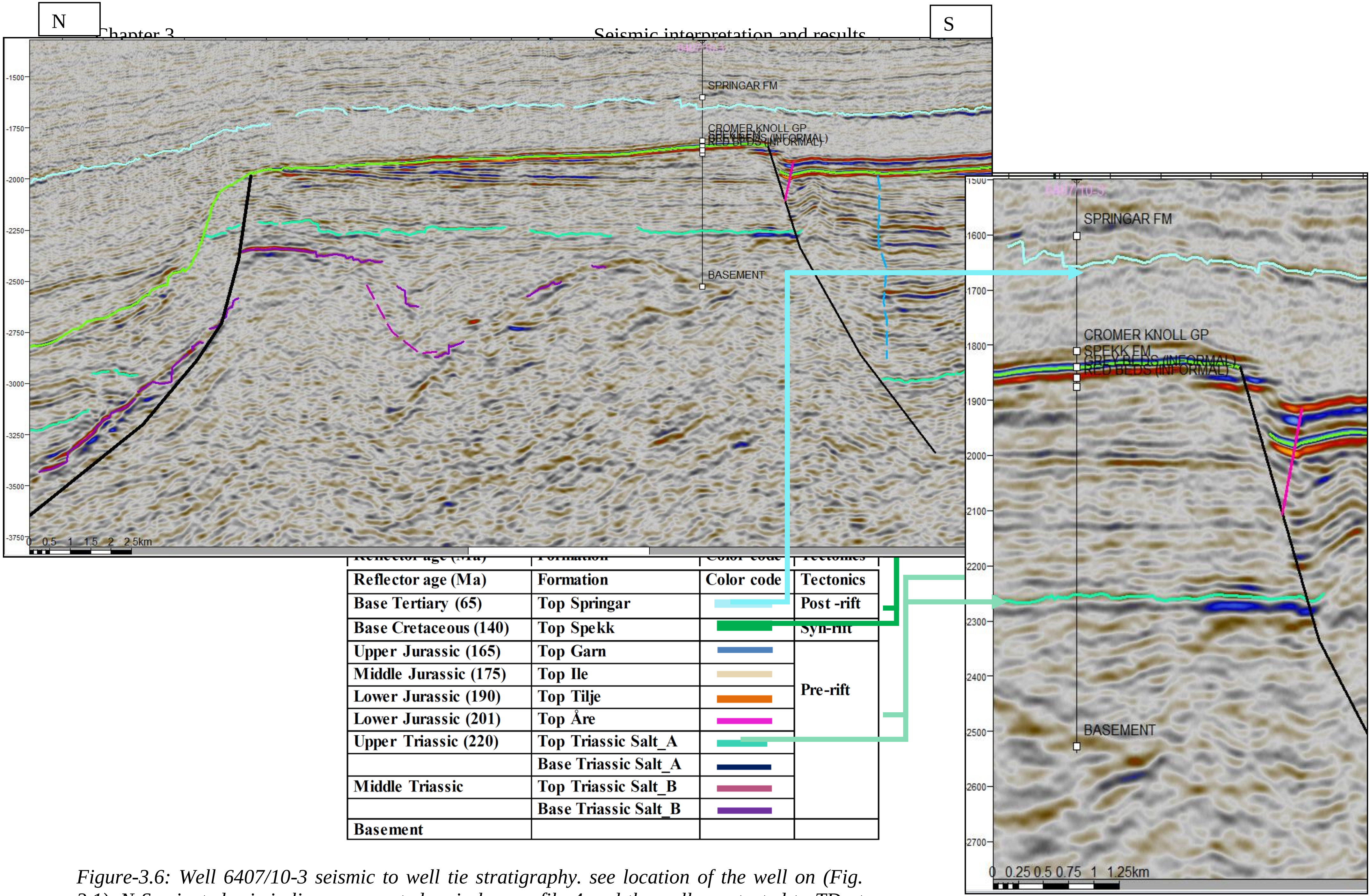
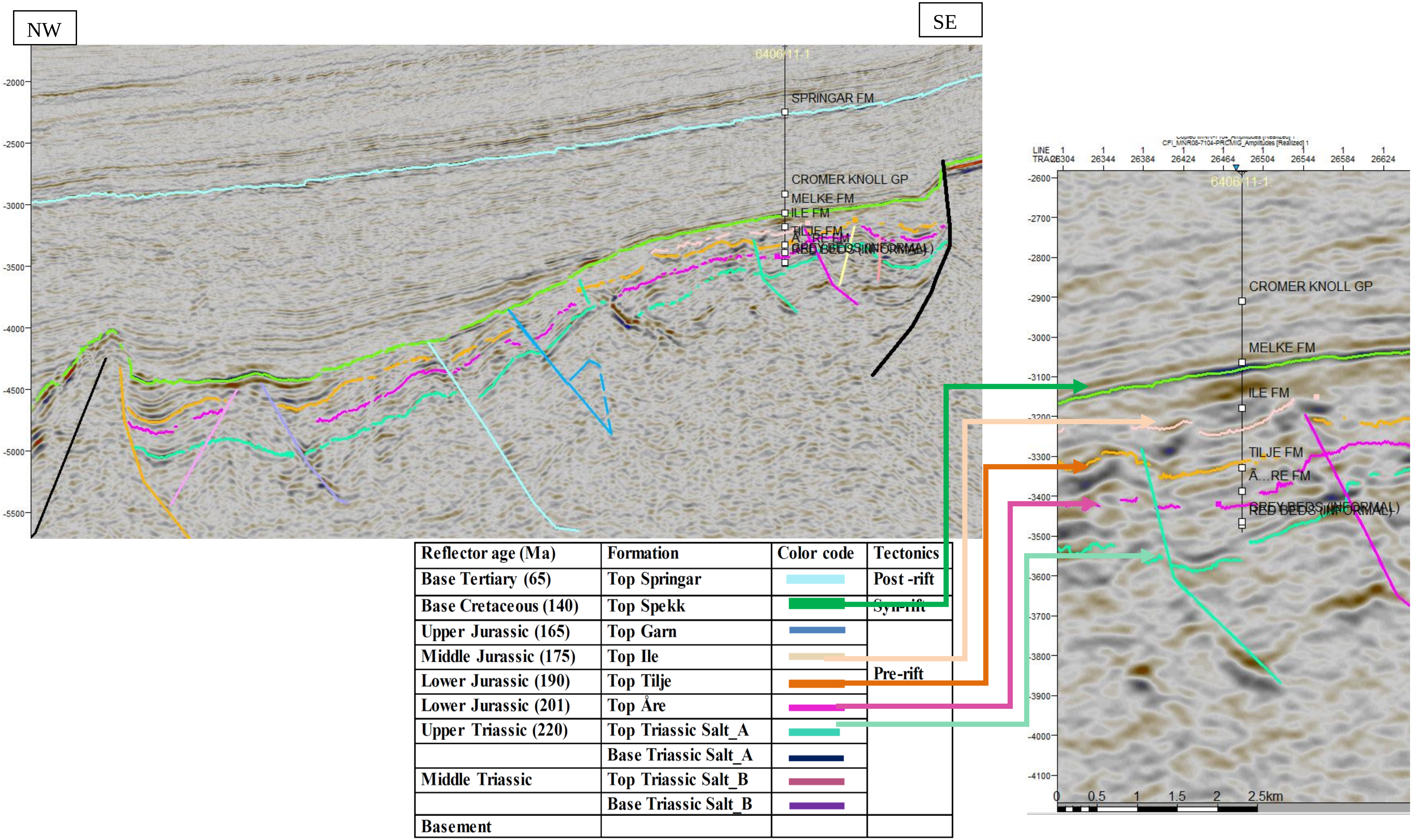


Figure-3.5: *Lithostratigraphy of the study area After Dalland et al., 1988; Bell et al., 2014*)



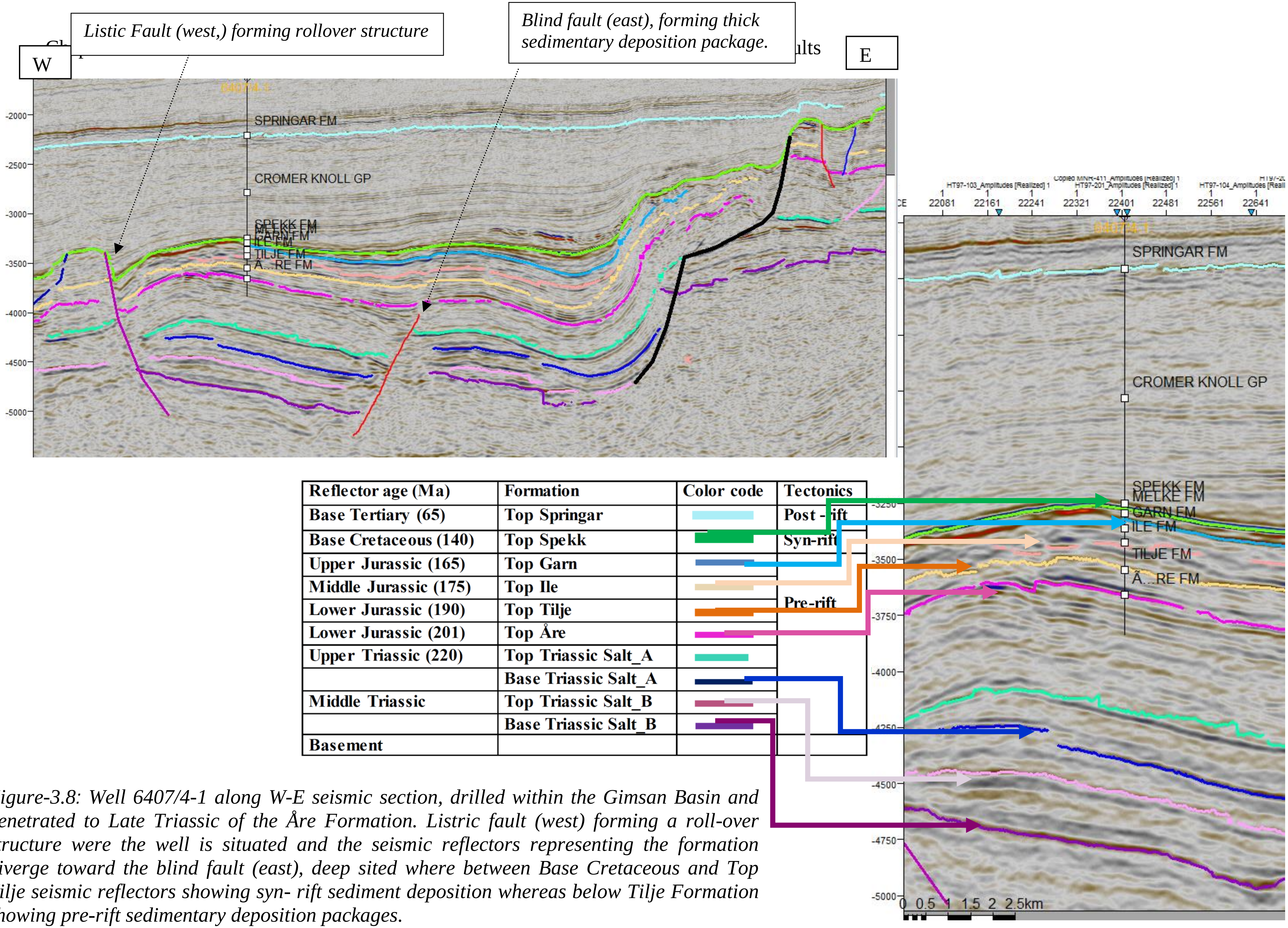
Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.6: Well 6407/10-3 seismic to well tie stratigraphy. see location of the well on (Fig. 3.1). N-S oriented seimic line represented as in key profile-4 and the well penetrated to TD at 2973 m, Basement.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	▬	Post -rift
Base Cretaceous (140)	Top Spekk	▬	Syn-rift
Upper Jurassic (165)	Top Garn	▬	Pre-rift
Middle Jurassic (175)	Top Ile	▬	
Lower Jurassic (190)	Top Tilje	▬	
Lower Jurassic (201)	Top Åre	▬	
Upper Triassic (220)	Top Triassic Salt_A	▬	
	Base Triassic Salt_A	▬	
Middle Triassic	Top Triassic Salt_B	▬	
	Base Triassic Salt_B	▬	
Basement			

Figure-3.7: Well 6406/11-1 s located on the southern end of the Halten Terrace, along the key profile-9 (NW-SE orientation) and drilled to TD of 4185 m (3500 ms in TWT) in the Late Triassic Red Beds. The well is drilled within the hangingwall anticline structure bounded by two major faults.

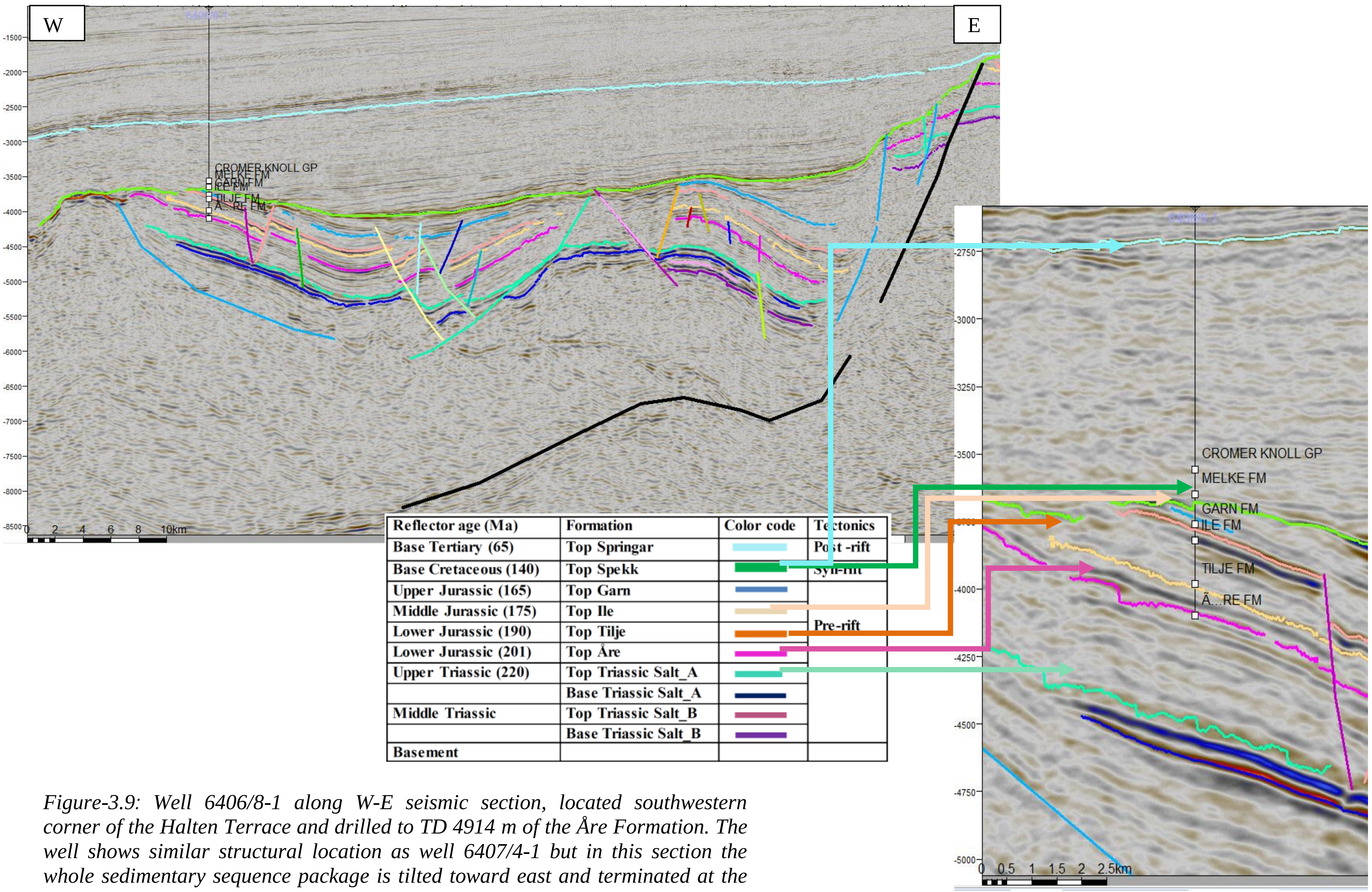


Listic Fault (west,) forming rollover structure

Blind fault (east), forming thick sedimentary deposition package.

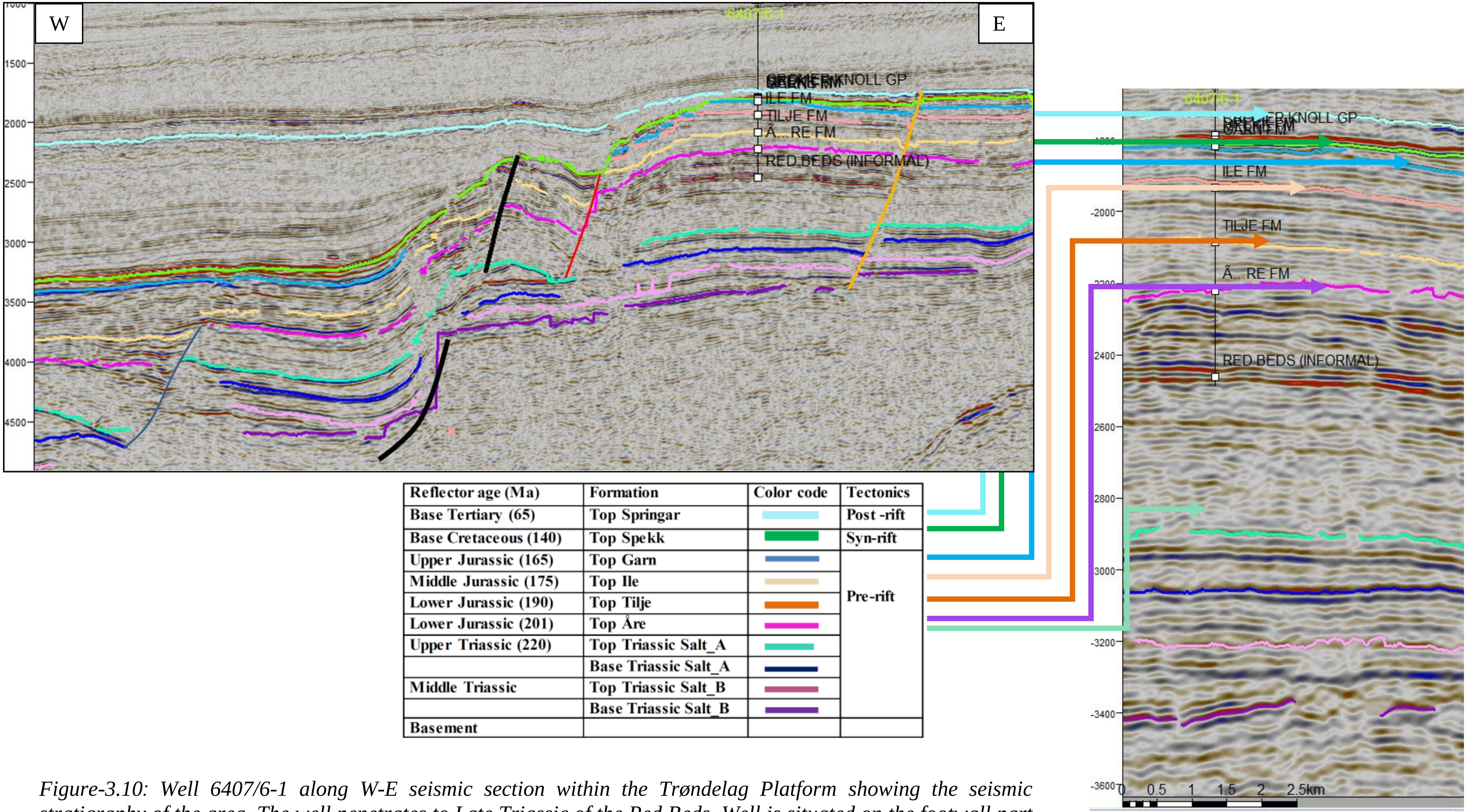
Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post - ift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	Pre-rift
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.8: Well 6407/4-1 along W-E seismic section, drilled within the Gimsan Basin and penetrated to Late Triassic of the Åre Formation. Listic fault (west) forming a roll-over structure were the well is situated and the seismic reflectors representing the formation diverge toward the blind fault (east), deep sited where between Base Cretaceous and Top Tilje seismic reflectors showing syn- rift sediment deposition whereas below Tilje Formation showing pre-rift sedimentary deposition packages.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	Pre-rift
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.9: Well 6406/8-1 along W-E seismic section, located southwestern corner of the Halten Terrace and drilled to TD 4914 m of the Åre Formation. The well shows similar structural location as well 6407/4-1 but in this section the whole sedimentary sequence package is tilted toward east and terminated at the Base Cretaceous unconformity seismic reflector.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	▬	Post -rift
Base Cretaceous (140)	Top Spekk	▬	Syn-rift
Upper Jurassic (165)	Top Garn	▬	Pre-rift
Middle Jurassic (175)	Top Ile	▬	
Lower Jurassic (190)	Top Tilje	▬	
Lower Jurassic (201)	Top Åre	▬	
Upper Triassic (220)	Top Triassic Salt_A	▬	
	Base Triassic Salt_A	▬	
Middle Triassic	Top Triassic Salt_B	▬	
	Base Triassic Salt_B	▬	
Basement			

Figure-3.10: Well 6407/6-1 along W-E seismic section within the Trøndelag Platform showing the seismic stratigraphy of the area. The well penetrates to Late Triassic of the Red Beds. Well is situated on the footwall part of the Bremstein-Vingleia fault complexes. Sedimentary packages are relatively uniformed represented in the seismic section as parallel to sub-parallel seismic reflectors.

3.2.2 Seismic interpretation

The selected seismic reflections, Triassic evaporites (top and bottom Triassic evaporite-A, top and bottom Triassic evaporite-B), Top Åre, Top Tilje, Top Ile, Top Garn formations, Base Cretaceous Unconformity (Top Spekk Formation) and Base Cenozoic (Top Springar Formation) (Figs, 3.6, 3.7, 3.8, 3.9 & 3.10) were mapped within the study area and seismic well-tie was implemented for lithostratigraphic correlation and quality check.

Since the northern part of the study area is densely covered by the seismic survey, interpretation started there, with reference to key profiles 1 and 2 oriented NW-SE, and the interpretation continued systematical to southern part of the study area by avoiding the Njord deformation zone at the initial stage of the interpretation. Also literature papers (Ehrenberg et al., 1992, Færseth and Lien, 2002, Ehrlich and Gabrielsen, 2004, Osmundsen and Ebbing, 2008, Bell et al., 2014) were used to tie seismic lines in the seismic interpretation prior to the in placement of the selected key nine wellbores.

Triassic evaporites: Generally in this thesis the Triassic evaporite represents, the top and bottom Triassic evaporite-A, as well as the top and bottom Triassic evaporite-B sequences. Major emphasis was given to the Top Triassic evaporite-A level (Figs. 3.6, 3.7, 3.8, 3.9 & 3.10), characterized by strong seismic reflectivity. The evaporite units show variation in thickness within the study area. Particularly, the northern part of the Halten Terrace is characterized by a thick Triassic evaporite sequence and different types of structures whereas the southern part, especially around the Njord structure has only thin layer of evaporites was interpreted. Therefore seismic to well-tie correlation of this evaporite unit was difficult in the area. Unfortunately, the selected nine wells did not confirm the presence of the evaporite units.

Top Åre and Top Tilje formations: The horizons are grouped as pre-rift sedimentary sequence of the early to middle Jurassic (Fig. 3.6, 3.7, 3.8, 3.9 & 3.10). The Top Åre Formation is characterized by strong seismic reflectivity and is the source rock for gas and gas-condensate in the study area (Koch and Heum, 1995) whereas Top Tilje Formation shows no strong seismic reflection as the Top Åre Formation do and the unit is characterized by mudstone dominated sedimentary sequence (Koch and Heum, 1995).

Top Garn and Top Ile: The horizons are grouped as pre-rift to syn-rift sedimentary sequence transition and are of Middle Jurassic in age. Lithostratigraphically the formations are characterized as reservoir unit that pinching out locally in the Froan Basin and in the Halten Terrace (Koch and Heum, 1995, Blystad et al., 1995). The units are highly affected by the tectonic events within the Halten Terrace (wells 6406/11-1s, Fig. 3.7 and 6407/4-1, Fig. 3.8) whereas in Froan Base the units show parallel to sub-parallel seismic reflection which indicates that the units are tectonically unaffected (wells 6407/10-3, Fig. 3.6 and 6407/9-1).

Base Cretaceous Unconformity (BCU) (Top Spekk Formation): A major erosional surface, formed at the base of the Cretaceous succession, picked as Top Spekk Formation using the seismic well-tie (Figs. 3.6, 3.7, 3.8, 3.9 & 3.10). The Base Cretaceous Unconformity, which is associated with the Jurassic–Cretaceous rifting, defines strong reflection and a mapable horizon at the transition from syn-rift to post-rift sequences. It is well known as a reference marker for both seismic and well-log interpretations and covers most of the basin and the Late Jurassic Spekk Formation is the major source rock in the study area (Koch and Heum, 1995). The diagram below (Fig. 3.11) is used to show how the Base Cretaceous Unconformity erosion and fault initiated. First erosion took place and then the small fault on the footwall initiated. The area circled (Fig.3.10&3.11) show the possible area of erosion and later fault activation.

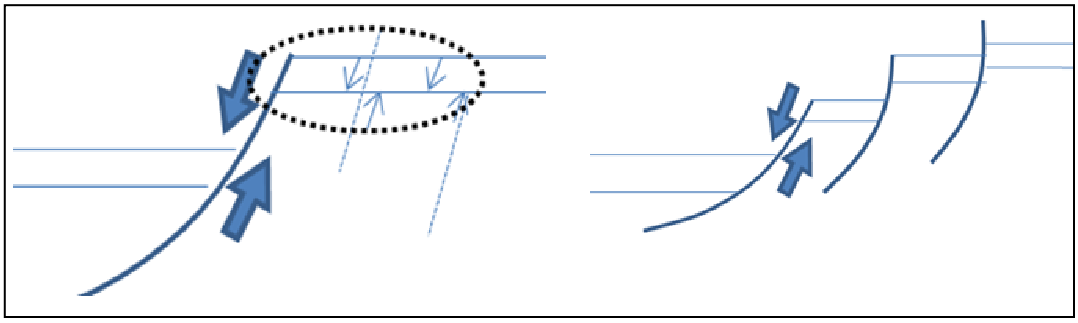


Figure-3.11: Diagram illustration of the Base Cretaceous Unconformity erosional surface and fault initiation.

Formation which is located within the post-rift successions above the Base Cretaceous Unconformity is characterized by west-dipping seismic reflection and shows generally a sub-parallel seismic reflection. Towards the Trøndelag Platform and the Froan Basin areas the horizon shows onlap seismic reflection (Figs. 3.6, 3.7, 3.8, 3.9 & 3.10), whereas on the northwest and southwest part of the study area Rås Basin and Halten Terrace, it show sub-parallel seismic reflection.

3.2.3 Fault interpretation

Fault interpretation was accomplished by using the fault interpretation tool in Petrel 2012. Interpretation was done manually first on paper and then by the help of Petrel, by selecting each seismic line with orientation W-E and N-S and, the NW-SE seismic lines were used to tie and follow the fault extends throughout the study area. The nine key profile lines (Fig. 3.14) orthogonal, at strike and at dip to Vingleia Fault Complex show the regional fault geometry and style of deformation around the fault complex and the whole study area. Due to the seismic data are widely spaced difficulty was experienced following and mapping the fault linkage geometry, especially for the small faults in the southern part of the study area. To calibrate fault and horizon interpretation time-structure maps for key stratigraphic levels were constructed.

Time-structure and fault maps of the key stratigraphic levels were used to observe the structural style and deformation of the Vingleia Fault Complex. The Vingleia fault Complex delineates the Halten Terrace in the northeast from Trøndelag Platform, east from Froan Basin and southeast from Frøya High (Figs. 3.13 & 3.14). Across the study area, the Vingleia Fault Complex shows different types of fault geometry

Faults (Figs. 3.8, 3.10 & 3.12) which were nucleated at the basement level and can be followed as a structural feature, active emerging faults (Withjack & Callaway, 2000; Marsh et al., 2010) with characteristic wedge-shaped syn-rift sedimentation in the hangingwall and blind fault that were active beneath the evaporite layer leading to the development of fault propagation folds within the salt layer were observed on some of the seismic profiles, (example Fig. 3.8 & 3.10) seismic profile W-E oriented at orthogonal to the strike of the Vingleia Fault Complex and (Figs 3.12A & B) shows the illustration of these faults.

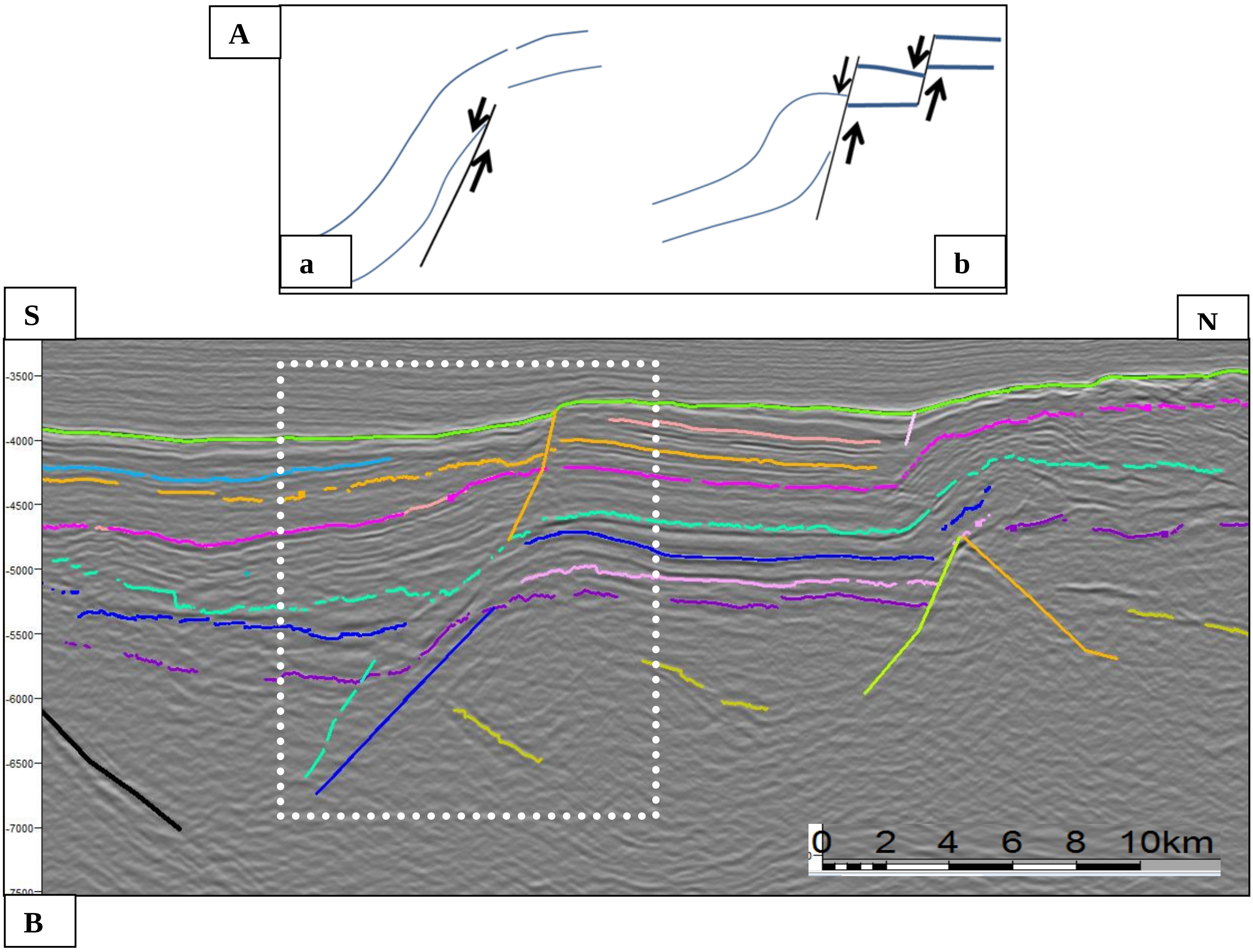
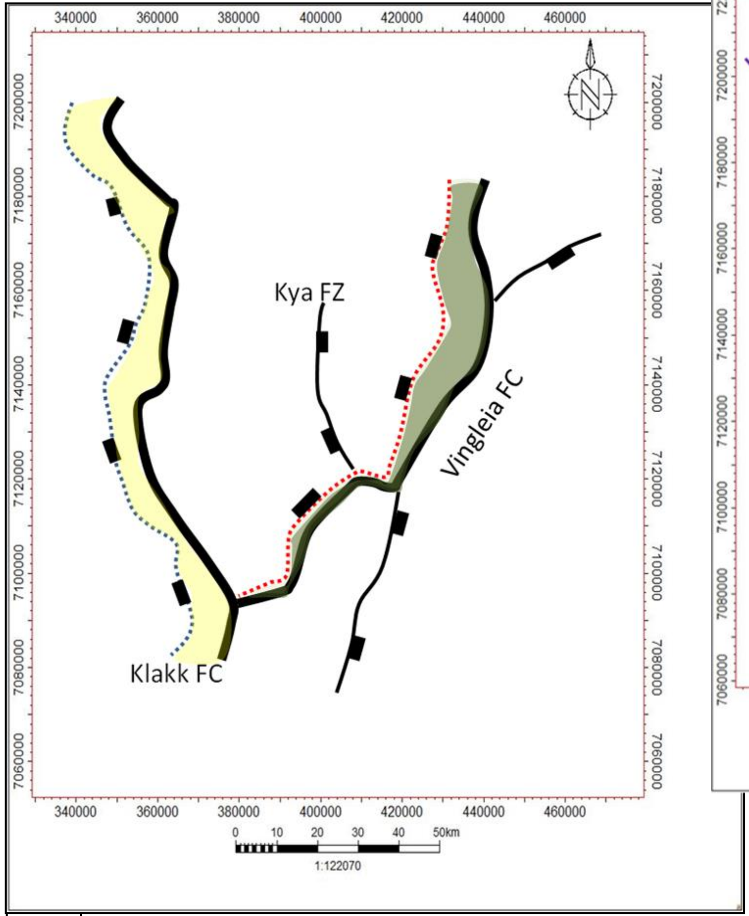


Figure-3.12: (A) Illustration of faults geometry where a, Blind fault dies out in the salt layer and cause folding of the upper sedimentary strata. b, Normal fault nucleate at the base and passes through the salt layer to the surface.(B)key profile-8 oriented N-S the blind normal fault nucleated from basement dies at the evaporite unit and fault propagation fold is created as the result of the fault movement.

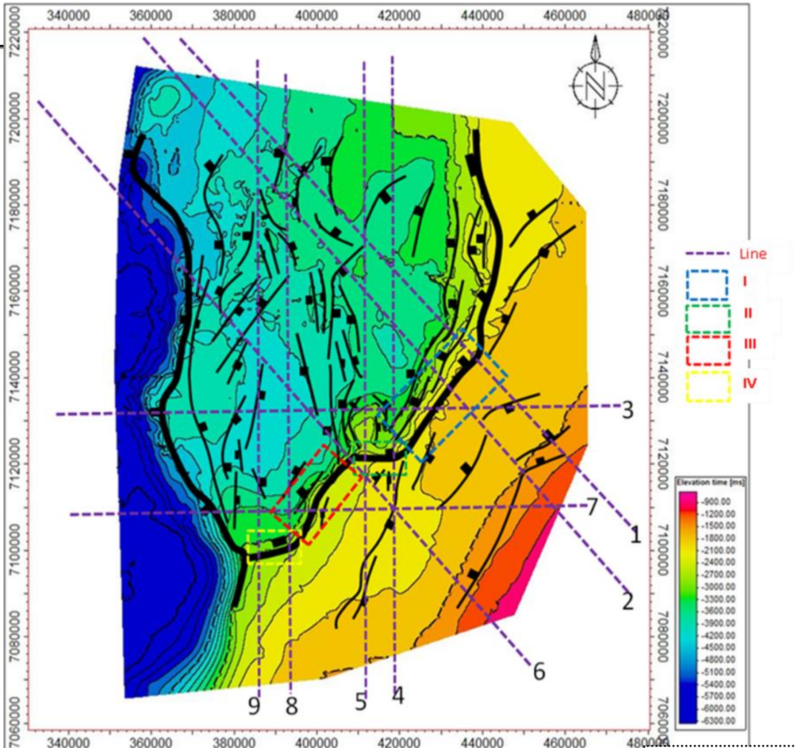
Fault polygons (Footwall cutoff)

Footwall cutoff technique (Fig. 3.13c) was applied to construct the fault polygons on the Base Cretaceous Unconformity (Top Spekk Formation) stratigraphic level. The width of the fault polygons were drawn accordingly to each fault displacement/ heave **(**Fig. 3.13c**)** by connecting footwall and hangingwall cutoff points where the master fault intersects the marker seismic surface, Base Cretaceous Unconformity. Therefore the technique was applied to the main fault complexes in the study area, the Klakk and Vingleia fault complexes. The Klakk Fault Complex, generally west-dipping shows a wider heave zone and larger fault throw than does the Vingleia Fault Complex (Fig. 3.13a) The Vingleia Fault Complex show variation in heave and throw. Northeastern part of the study area along the Vingleia-Bremstein fault complexes intersection, the heave is wider and decreases southwest ward around the Njord structure.

The Kya Fault Zone (Figs. 3.13a & b) separating the Halten Terrace from the Gimsan Basin show smaller heave and throw compared to Klakk Fault Complex and Vingleia Fault Complex. It is splay fault which terminated at the Vingleia Fault Complex and form a half Graben as seen on the seismic section.



a



b

c

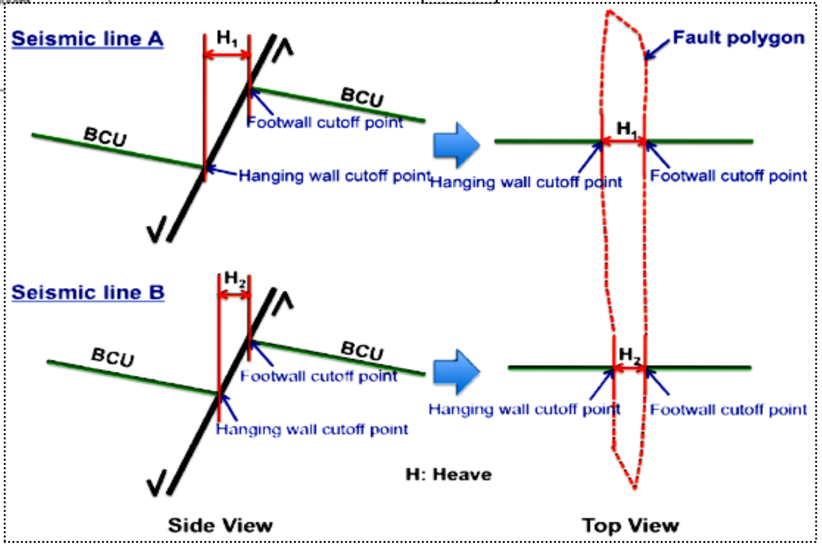


Figure-3.13: Fault polygon construction on the Base Cretaceous (Top Spekk Formation). (a), Fault polygon with colored area showing the cutoff (heave), yellow colored Klakk Fault Complex and gray colored area the Vingleia Fault Complex and the black mark show dip direction of the major faults bounding the Halten Terrace. (b), shows the Base Cretaceous structural time map with fault polygon on the top and the nine key profiles. (c), Illustrates the technique used to construct the fault cutoff on the Base Cretaceous (Top Spekk Formation).

3.3 Vingleia Fault Complex segmentation

Vingleia Fault Complex segmentation and the relationship between the fault geometry and the deformation of the hangingwall are the main objectives of this section. Four major fault segments of the Vingleia Fault Complex were identified (Fig. 3.14) based on dip, strike, fault geometry and deformation style variation along the strike of the Vingleia Fault Complex and the result are presented below.

Segment-I, strikes NE-SW and is located in northeastern part of the study area, at the Bremstein-Vingleia fault complexes intersection. Key profiles 1, 2, and 3 (Figs. 3.16, 3.17 & 3.18) represent the segment where key profiles 1 and 2 are at angle to the strike of the fault segment whereas key profile 3 is perpendicular to the strike of the segment. These three profiles were used to observe the dip and strike variation along the fault segment.

Segment-II, strikes W-E and is located around the Njord structure. It is represented by key profiles 4, 5 and 6 where key profiles 4 and 5 are perpendicular to the strike of the segment. Key profile 4 (Fig. 3.20) strikes N-S and displays the steeper dip of master fault. Key profile 5 (strikes N-S) and 6 (strikes NW-SE) generally show steeper upper ramp and a splay fault toward the footwall within the southern part of the profile is observed to detach along the master fault at around 4000 ms TWT.

Segment-III, strikes NE-SW and is located southeast of the Njord oilfield. Key profiles 6 and 7 are perpendicular and at angle to the strike of the segment respectively. Key profile- 7 strikes W-E to the segment and marks change of the master fault geometry from ramp-flat-ramp along segment two to listric fault geometry.

Segment-IV, strikes W-E and is located where Vingleia Fault Complex terminate south-wards against the Klakk Fault Complex. Key profiles 8 and 9 strikes perpendicular and at angle to the strike of the segment and generally displays a ramp-flat-ramp fault geometry. The fault plane surface can be traced to ca. 8 s TWT.

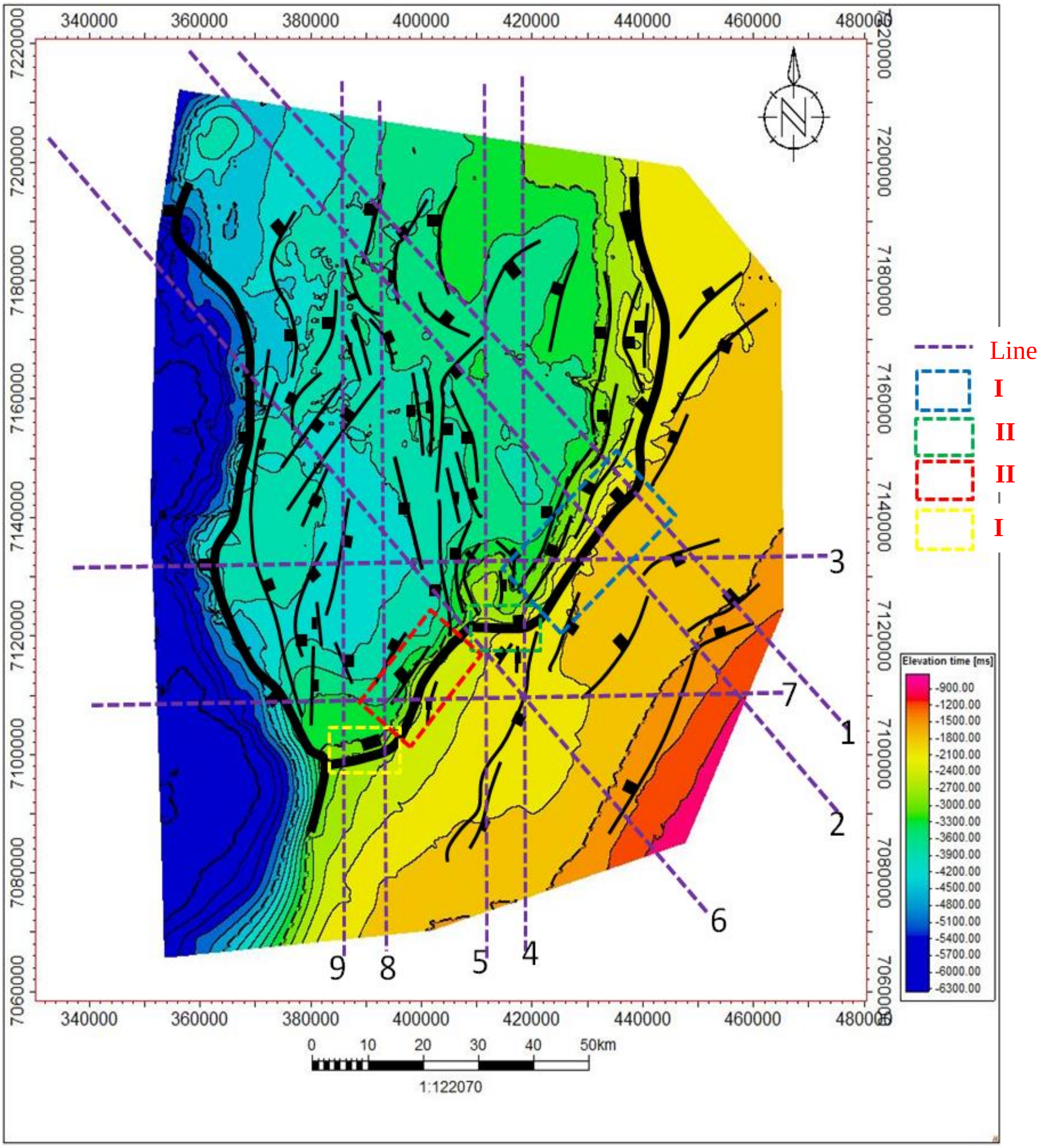


Figure-3.14: Location of the nine selected key profile (pinkish dots) numbered from 1to 9 used to discuss the fault segmentation along the Vingleia Fault Complex and the regional fault geometry and structural style of the Halten Terrace and areas bounding it. Time structural map of the Base Cretaceous is used as location and fault geometry outline of the study area and the legend descries the seismic lines and segmentation.

3.3.1 Segment-I:

Segment-I, located in the northeastern part of the study area shows a NE-SW strike orientation. Key profiles 1 and 2 oriented NW-SE strikes at angle to the segment and the first profile shows a ramp-flat-ramp fault geometry with steeper upper and lower ramp and wider flat where the Triassic evaporite unit is a detachment layer whereas key profile-2 shows listric fault geometry. Key profile-3 oriented W-E strikes orthogonally to the Vingleia Fault Complex, which is located around the Njord field area displays the ramp-flat-ramp geometry nature of the segment. The segment was characterized by wider fault zone on the northeast part (Fig. 3.13), whereas narrower on the southwest on the time structural and fault map of the Base Cretaceous Unconformity (Top Spekk Formation) stratigraphic level.

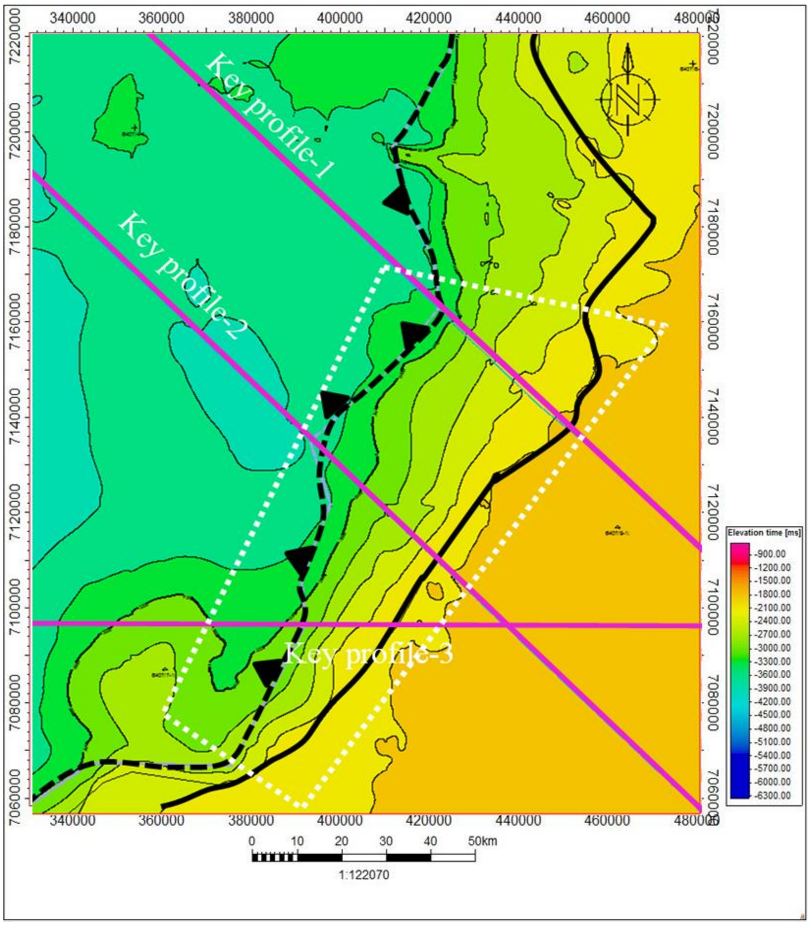


Figure-3.15: Location of segment-I on top of the Base Cretaceous time map and fault cutoff with throw direction dipping northwest is showing in black color. Thickness variation along the fault segment is observed. Wider fault zone (heave) in the northern part whereas smaller in the southern part of the segment. The heave variation could indication fault propagation from northeast to southwest.

Key profile-1

The NW-SE oriented profile, strikes orthogonally to the strike of the Vingleia Fault Complex as shown in (Figs. 3.15 & 3.16). The profile displays ramp-flat-ramp geometry of the fault segment with steeper upper and lower ramp and wider flat, defined as Triassic evaporites, a detachment layer where the layer decouples the upper strata from the basement and this is characterized as soft link (Withjack et al., 1989; Richard et al., 2005). Faults sets on the hangingwall and footwall of the Vingleia Fault Complex show different dip direction to the master fault where faults dipping opposite to the Vingleia Fault Complex are antithetic faults whereas these dipping in the same dip direction are synthetic faults. Some of the synthetic and antithetic faults in the hangingwall and footwall terminate on the evaporites layer. Faults b, e and f (Fig. 3.16) on the hanging wall and fault sets immediate on top of flat terminate from top at the evaporite layer whereas faults a and c nucleated at the basement terminated at the evaporite layer. Fault-1 on the footwall of the Vingleia Fault Complex at ca. 4.5 s TWT observed to displace a unit that shows a strong amplitude seismic reflection much below the interpreted Base Triassic evaporite stratigraphic level (Fig. 3.16).

Between bottom Triassic evaporite to Top Åre Formation stratigraphic levels seismic reflection show a sub-parallel, gently dipping toward the Vingleia Fault Complex and show less deformation on the hangingwall (Fig. 3.16). The thickness of these units are constant on the depocenter immediate to the master fault, whereas from Top Åre Formation to Base Cretaceous Unconformity stratigraphic levels the seismic reflection displays wedge-shaped sedimentary packages, thickening toward the Vingleia Fault Complex.

The Base Cretaceous Unconformity stratigraphic level shows a discontinuous seismic reflectivity on the footwall side whereas on the hangingwall the seismic reflectivity of this horizon is strong. The seismic reflection of this stratigraphic level above the Vingleia Fault Complex is folded. This could either be related to a blind fault growing up section, extensional forced fold geometry (Withjack et al., 1989) or evaporite movement. The Base Cenozoic seismic reflection (blue color coded) onlaps to the Base Cretaceous Unconformity at the top of the Vingleia Fault Complex and the sedimentary packages between the two stratigraphic levels show thicker sediments towards the Rås Basin and the Halten Terrace whereas onlap truncation toward the Base Cretaceous Unconformity on hangingwall of the fault complex.

Key profile-2:

This NW-SE oriented profile runs orthogonal to the strike of the Vingleia Fault Complex and displays the Rås Basin on the west, the Halten Terrace and, Gimsan Basin at the center and the Froan Basin in the east. Generally the Vingleia Fault Complex shows listric fault geometry with steeper dip angle. The seismic reflectivity of the fault plain at depth is highly attenuated and the fault is observed to detach on evaporite layer (Fig. 3.17).

Faults a, b & c (Fig. 3.17) close to the Vingleia Fault Complex on the hangingwall are dipping toward the basin. These faults terminate at the bottom on the Vingleia Fault Complex and are synthetic to the master fault. The seismic reflectivity within these faults is highly attenuated and was difficult to interpret. Faults e & d with opposite dip direction displaces the evaporite layer and the seismic reflectivity of the top tips of these faults terminates on the evaporite layer whereas seismic reflectivity of the bottom tips of faults i & g terminate on the evaporite layer. Deep seated faults f and h with opposite dip direction is observed to displace sediments belonging to the deeper below the Base Triassic evaporite and to the top these faults terminates at the evaporite unit. Therefore two sets of fault generation on the hangingwall of the Vingleia Fault Complex were observed. Faults sets above the evaporite unit and below terminated on the evaporite unit.

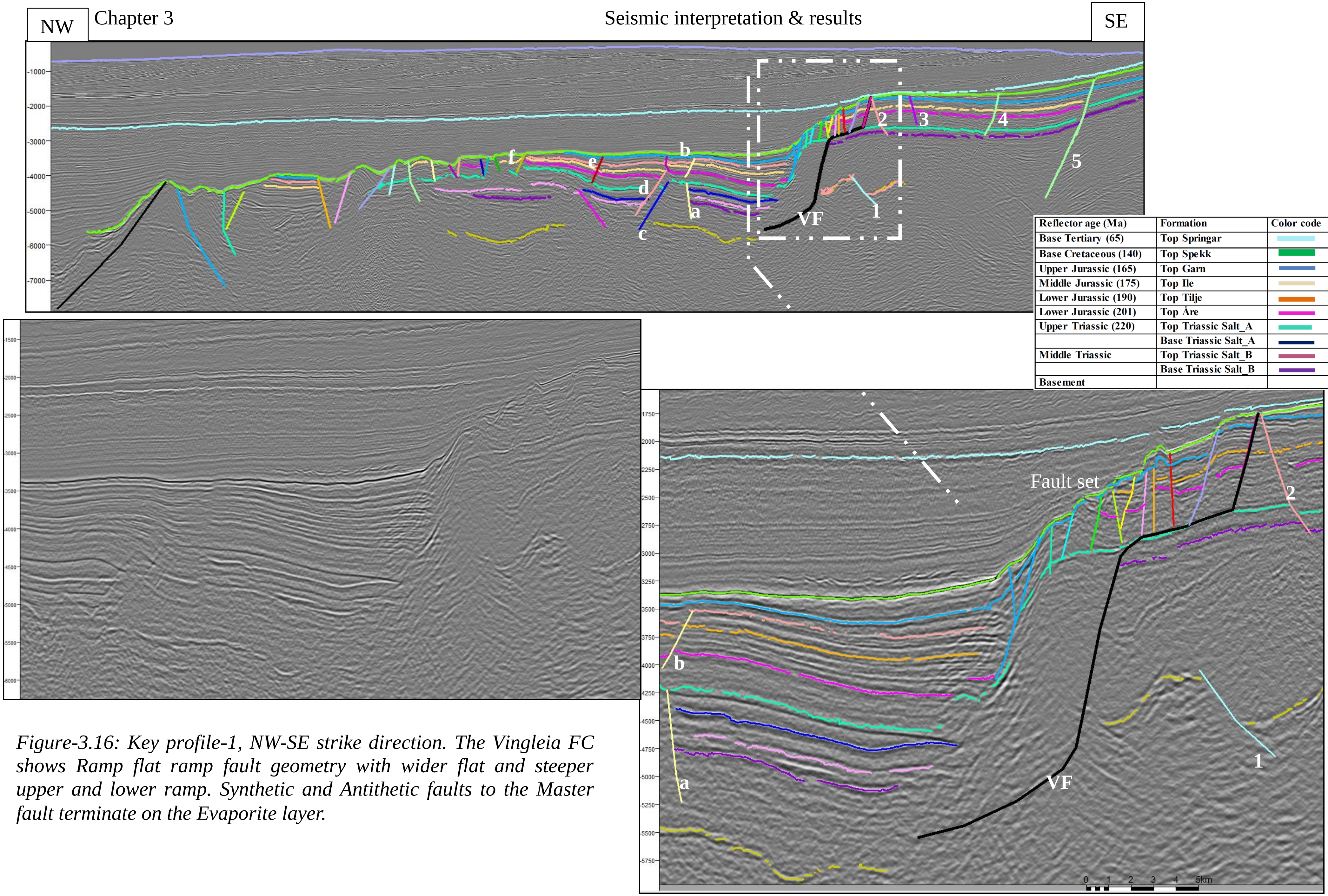
Faults 2 & 3 on the footwall of the Vingleia Fault Complex below the Froan Basin dips towards the basin whereas fault-1 dips opposite to these faults. Fault-3 is characterized by strong seismic reflection that can be traced up to 6 s TWT below Froan Basin and thick sediment infill on the hangingwall of the fault is observed whereas faults 1 & 2 are shallower faults that terminate on the Triassic stratigraphic level.

On the hangingwall between Triassic evaporite to Top Garn Formation stratigraphic levels, seismic reflection show a sub-parallel, gently tilting sediment infill toward the Vingleia Fault Complex. Away from the Vingleia Fault Complex basin-ward, the Linnorm area (Fig. 3.17) sediments of the above units are folded and truncated by the major fault-g, SE-dipping. Between Top Garn Formation and Base Cretaceous stratigraphic levels the seismic reflection show relatively sub-parallel, wedgeshaped sediment filling and terminate onlap to the Top Garn Formation on the NW side and the Vingleia Fault Complex on the SE side.

Key profile-3:

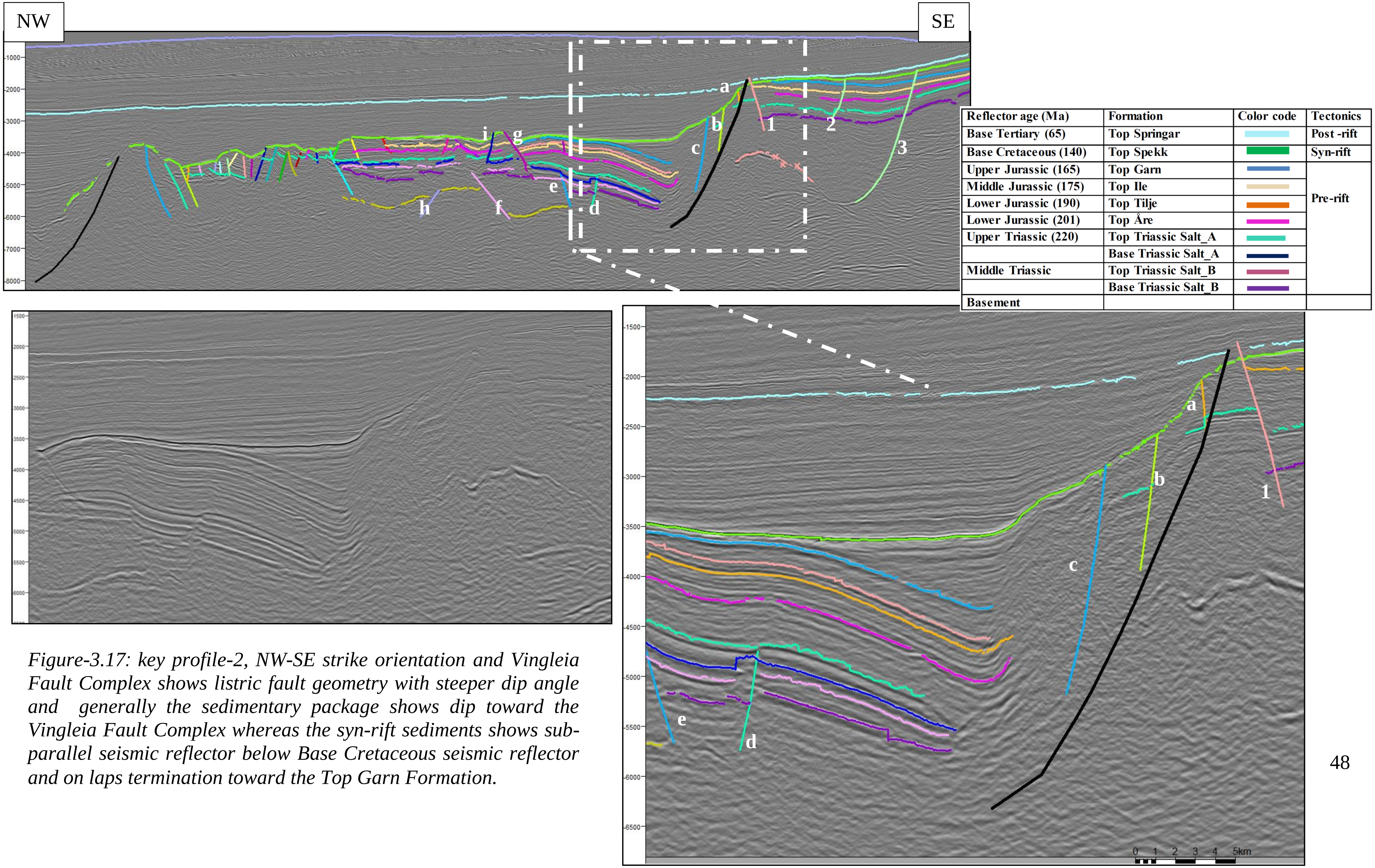
This W-E orientated profile (Fig. 3.18) runs at angle to the strike of the Vingleia Fault Complex and show a ramp-flat-ramp fault geometry with wider flat and steeper upper and lower ramp. The hanging wall is strongly deformed, showing rotated rollover fold structure of large amplitude. The fault plane reflection can be traced to ca. 9 s TWT under the Halten Terrace. At 4.5 s TWT (Fig. 3.18) within the Halten Terrace a culmination of large amplitude with more than 10 km flat is observed in this profile, possibly representing the basement.

Fault sets, antithetic and synthetic to the Vingleia Fault Complex, around the rollover fold on the hangingwall show variable dip. Majority of these faults terminate on the Base Cretaceous stratigraphic level. Faults a & b dipping basin-ward are synthetic to the Vingleia Fault Complex. Fault-a, detaches at bottom to the Vingleia Fault Complex whereas fault-b detaches at the evaporite layer. Faults e & d dipping opposite to each other show collapsed sedimentary strata. Faults, f to k east-dipping are located within Sklinna Ridge and to the bottom these faults terminates on the evaporite layer. Sediments within the rollover structure (Fig. 3.18) are strongly deformed, tilted and rotated. The Triassic evaporite layer is hard to distinguish from the rest of the sediment strata on the rollover structure. Only the Top Triassic stratigraphic level is interpreted within the structure



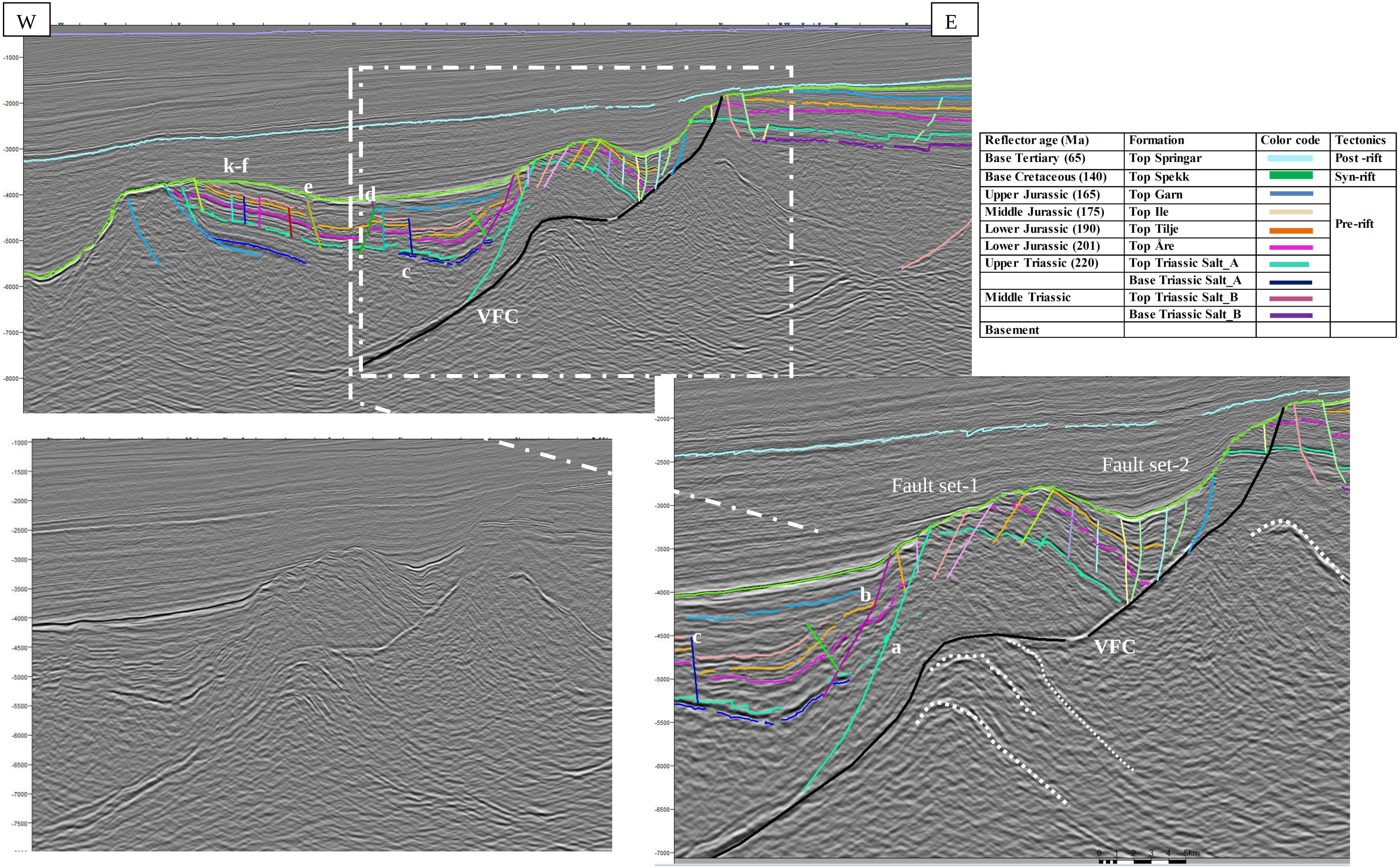
Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	▬	Post -rift
Base Cretaceous (140)	Top Spekk	▬	Syn-rift
Upper Jurassic (165)	Top Garn	▬	Pre-rift
Middle Jurassic (175)	Top Ile	▬	
Lower Jurassic (190)	Top Tilje	▬	
Lower Jurassic (201)	Top Åre	▬	
Upper Triassic (220)	Top Triassic Salt_A	▬	
	Base Triassic Salt_A	▬	
Middle Triassic	Top Triassic Salt_B	▬	
	Base Triassic Salt_B	▬	
Basement			

Figure-3.16: Key profile-1, NW-SE strike direction. The Vingleia FC shows Ramp flat ramp fault geometry with wider flat and steeper upper and lower ramp. Synthetic and Antithetic faults to the Master fault terminate on the Evaporite layer.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟦	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.17: key profile-2, NW-SE strike orientation and Vingleia Fault Complex shows listric fault geometry with steeper dip angle and generally the sedimentary package shows dip toward the Vingleia Fault Complex whereas the syn-rift sediments shows sub-parallel seismic reflector below Base Cretaceous seismic reflector and on laps termination toward the Top Garn Formation.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.18: Key profile-3, W-E orientated profile where the Vingleia Fault Complex shows ramp-flat-ramp fault geometry with wider flat and steeper upper and lower ramp. The hanging wall is strongly deformed, rotated roll-over fold structure. The reflector can be traced to 9 s TWT under the Halten Terrace. Antithetic and synthetic faults shows dip variation. At 4 s TWT with in the Halten Terrace shows culmination (white colored) of large amplitude with larger than 10 km cross section aerial coverage

3.3.2 Segment-II

Segment-II is located on the central part of the study area around the Njord Oilfield area (Figs. 3.19 & 3.20). The segment shows W-E strike orientation, ramp-flat-ramp fault geometry with wider flat and steeper upper and lower ramp. It links segment-I (northeast) and segment-III (southwest) through direct mutual linkage of the tip lines of the master fault as proposed by Ehrlich & Gabrielsen (2004). Key profiles 4 and 5 oriented N-S and 6 oriented NW-SE, is used to observe the dip and strike variation of the segment as well as style of deformation along the fault segment. The three key profiles show strong deformation on the hangingwall where a large amplitude rollover structure is observed on the hangingwall of the Vingleia Fault Complex. The segment shows steeper dip compared to segment one and the fault plane reflection along the three key profiles can be traced to 9 s TWT under the Halten Terrace.

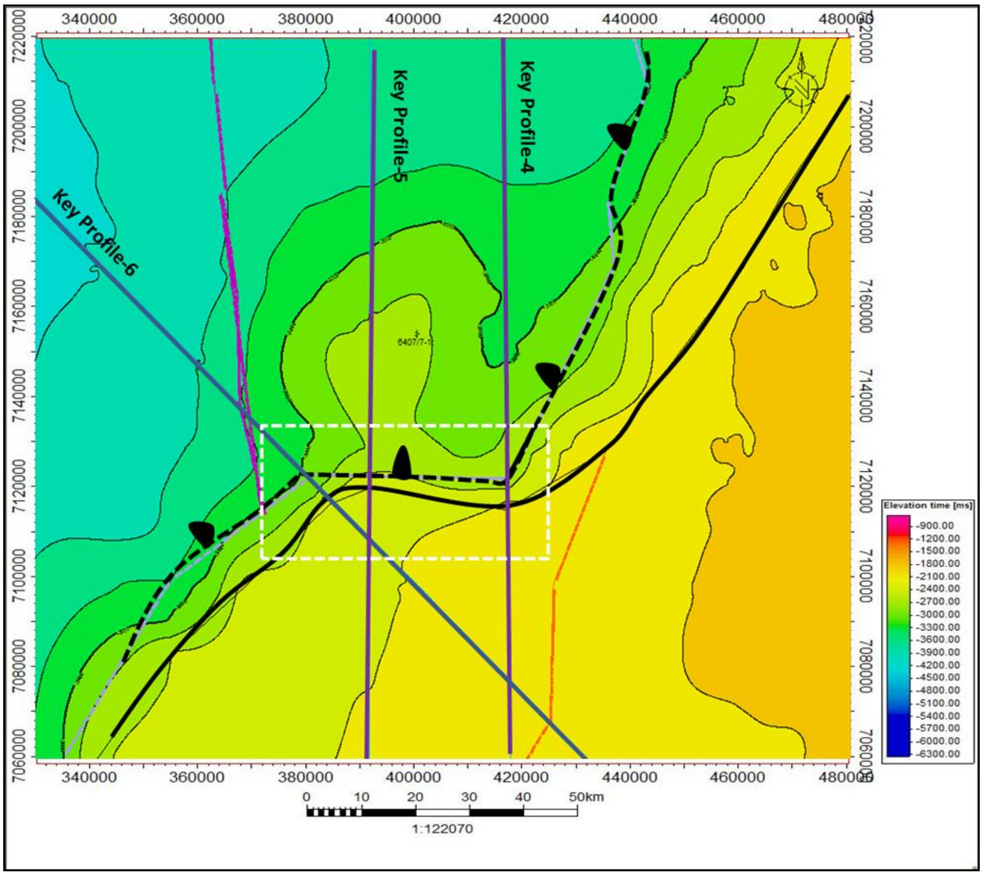


Figure-3.19: Location of segment-II and fault cutoff above the Base Cretaceous time map. The two pinkish colored lines are key profile-4 and 5 which are orthogonal to the Vingleia Fault Complex and key profile-6 at the junction of segments II and III. The circular contours around immediate hangingwall of the fault segment two indicate folded structure above the Base Cretaceous time-structure map (Njord structure).

Key profile-4:

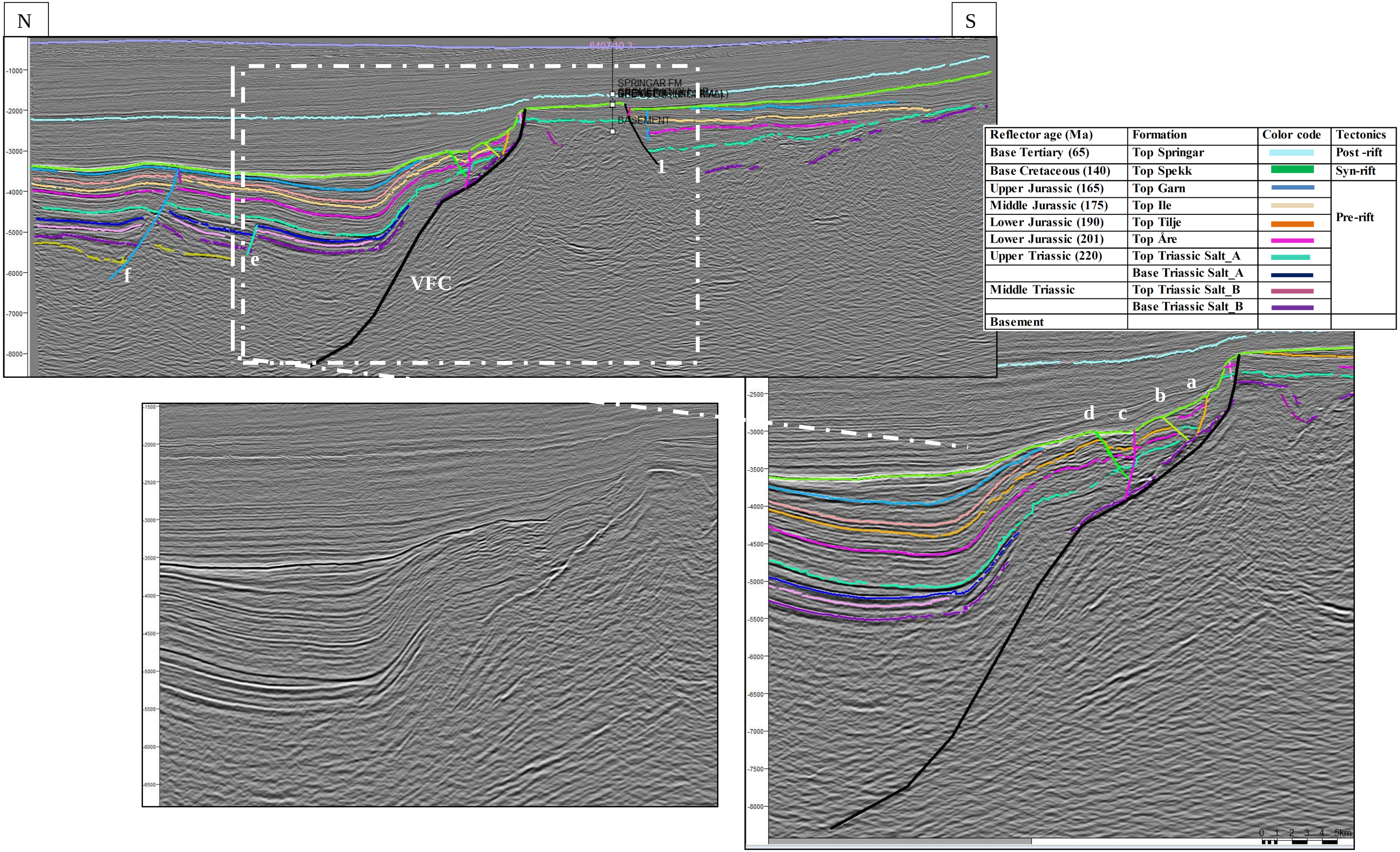
This N-S oriented seismic line is orthogonal to the strike of the Vingleia Fault Complex (Fig. 3.20). The profile displays the ramp-flat-ramp fault geometry of the Vingleia Fault Complex, showing steeper upper and lower ramp where faults a, b, c & d on the hangingwall terminated on the Vingleia Fault Complex. Faults a & c dipping toward the basin, synthetic to the master fault whereas faults b & d dipping to the opposite direction, antithetic to the master fault. Fault-f dipping north is located northeast part of the study area and observed to displace the Triassic and Jurassic units, where thickening in sediment infill is observed toward the fault on the hangingwall and can be characterized as hard linked fault geometry. The small fault-e dipping north observed to terminate on the evaporite unit from bottom.

Based on the data from well 6407/10-3, the basement is intersected at ca. 2.5 s TWT on the footwall below the Frøya High and is shows strong and irregular seismic reflectivity. Fault-1 dipping south, located at Frøya High-Froan Basin boundary is a major fault separating the Froan Basin from Frøya High and the seismic reflection of this fault plane can be traced to deeper level below the Triassic stratigraphic level.

Key profile-5:

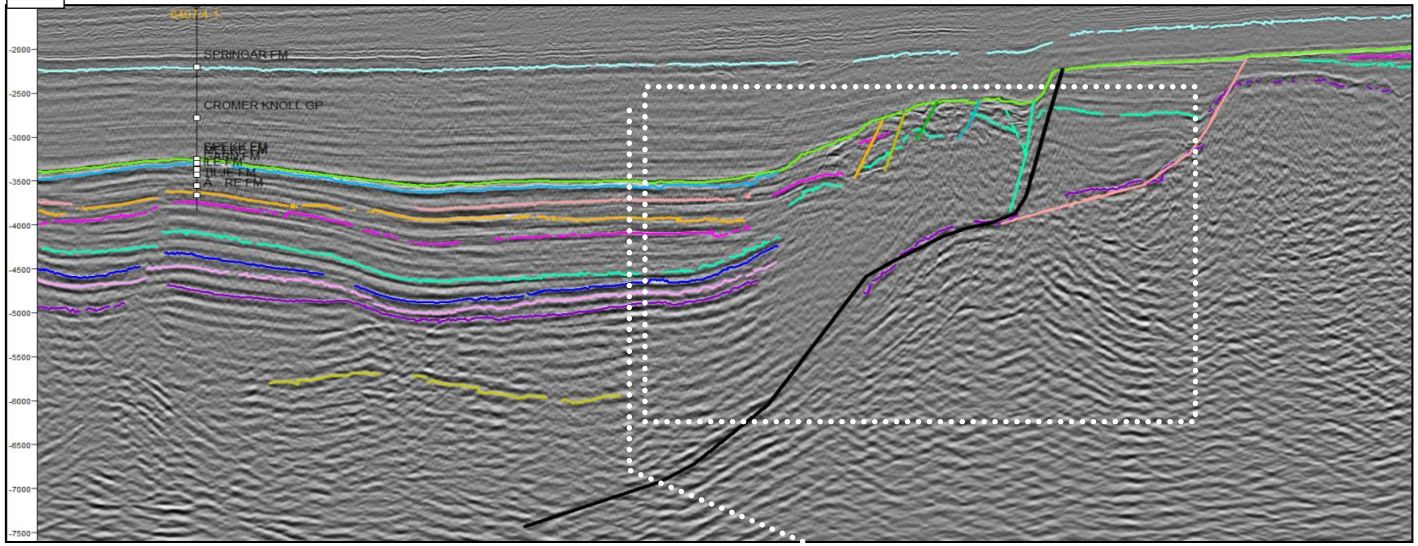
This profile is oriented N-S orthogonal to the strike of the Vingleia Fault Complex (Fig. 3.21) and is located near to key profiles 4 and 6. This profile differs from key profile-4 that this profile displays wider flat of the ramp-flat-ramp fault geometry of the Vingleia Fault Complex. Faults a, b, c, d & e are basin-ward dipping, synthetic to the master fault observed to loose seismic reflectivity down below ca. 3.5 s TWT and are probably terminated on the strongly deformed evaporite layer. The rollover anticline structure is characterized by large amplitude and strongly faulted where seismic resolution is very poor around the fold area and observation in the deeper was difficult.

Fault-1 basin ward dipping synthetics to the Vingleia Fault Complex observed to detach along the Vingleia Fault Complex at ca. 4 s in TWT where the anticlinal culmination is located. Sediment infill between these two faults shows onlap truncation where the sediment strata are characterized by parallel to sub-parallel seismic reflectivity.

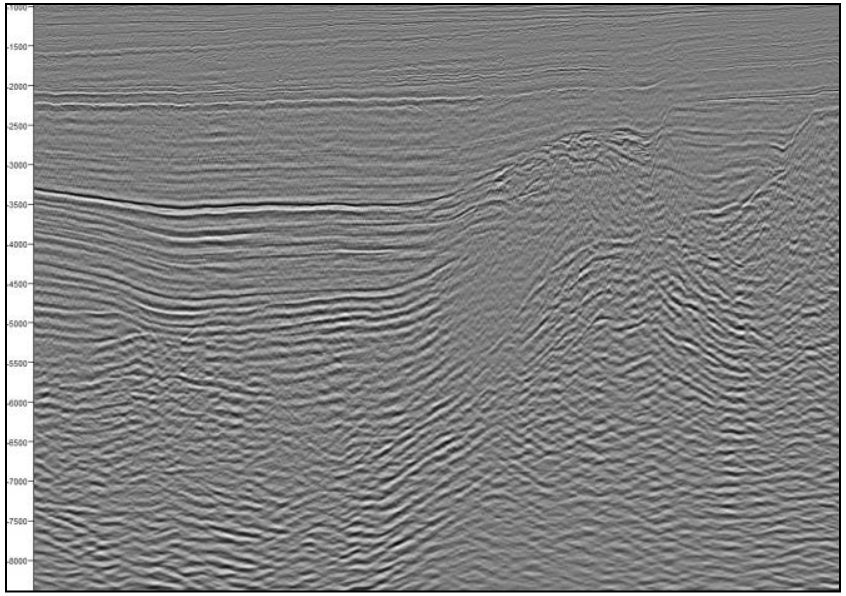


Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.20: Key profile-4, N-S orientation and the Vingleia Fault Complex shows ramp-flat-ramp fault geometry with wider flat and steeper upper and lower ramp. The hanging wall is strongly deformed where the whole strata are rotated forming roll-over anticline fold structure. The reflector can be traced to 9 s TWT under the Halten Terrace.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			



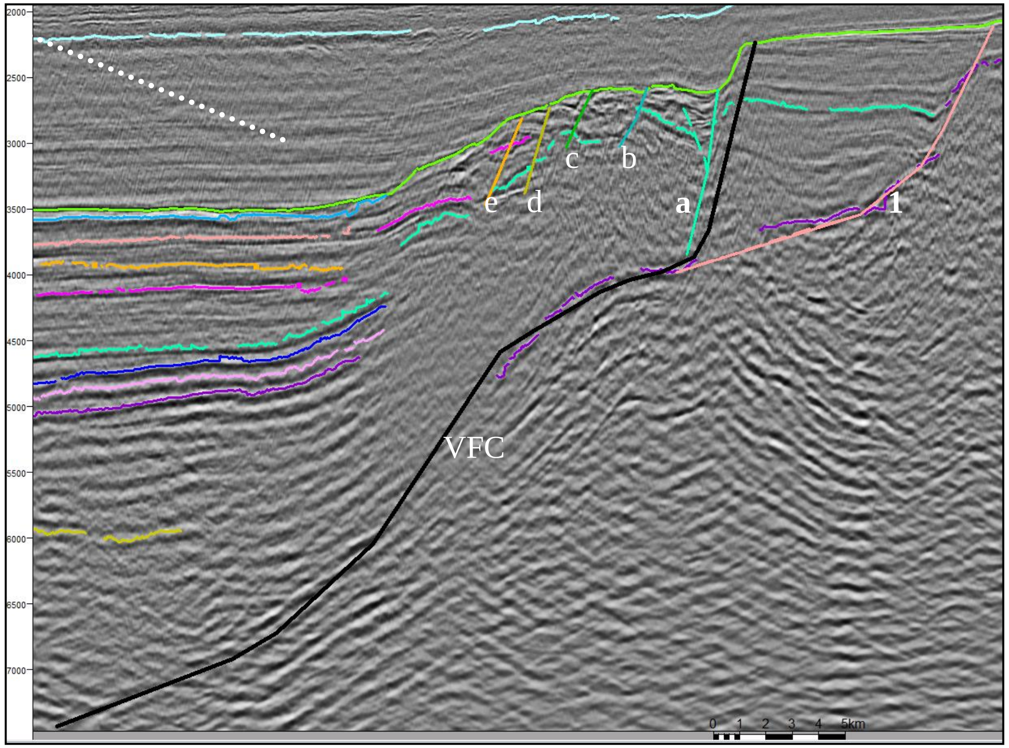


Figure-3.21: key Profile-5, N-S orientation, ramp-flat- ramp fault geometry of the Vingleia Fault Complex with steeper upper and lower ramp and narrower flat area.

3.3.3 Segment-III

Segment-III has a NE-SW strike orientation, located south of the Njord field (Fig. 3.22). Key profiles 6 and 7 oriented NW-SE and W-E respectively to the strike of the Vingleia Fault Complex display the strike and dip of the structure (Fig. 3.23 & 3.24). The two profiles demonstrate the change in fault geometry of the Vingleia Fault Complex from ramp-flat-ramp, key profile-6 to listric, key profile-7. Along the two profiles the segment is characterized by less pronounced hangingwall rotation than in the central part. But the Triassic layer in profile-6 shows variable sediment thickness and deformation in the hangingwall.

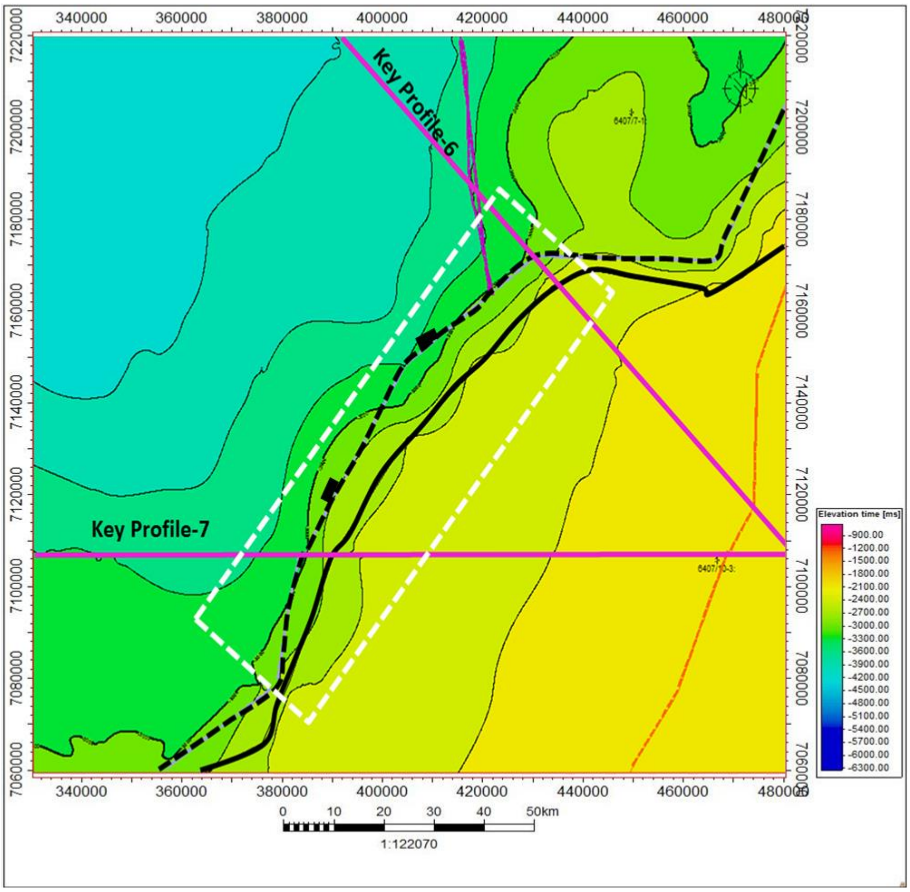


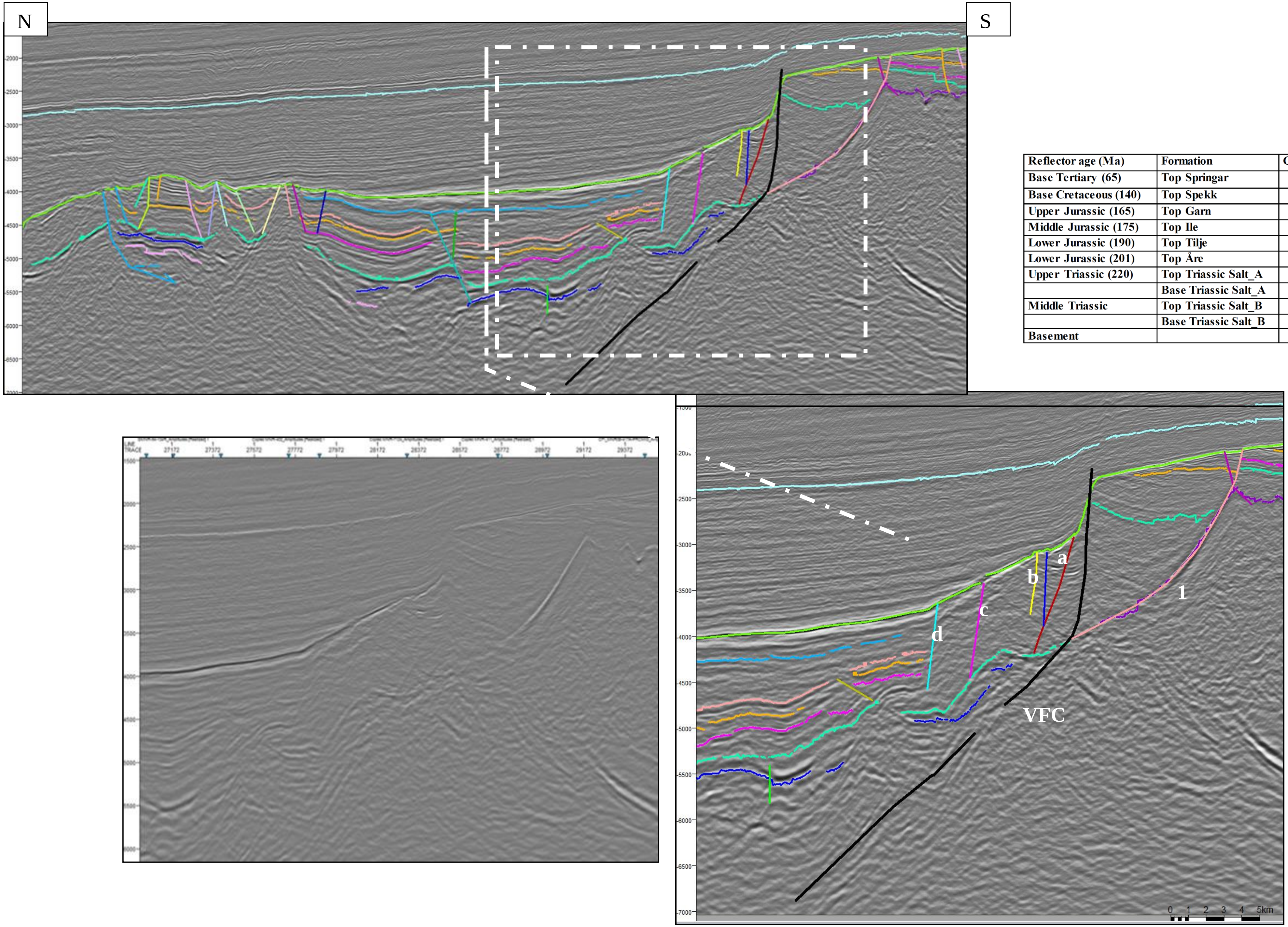
Figure-3.22: Location of segment-III (white rectangle) and fault cutoff above the Base Cretaceous time map, key profiles 6 & 7 orientation. The fault segment is observed to change in heave where the central part show wider fault zone (heave) whereas the two end points decrease in wide of the fault cutoff.

Key profile-6:

This NW-SE profile (Fig. 3.23) is oriented orthogonal to the master fault. The profile is located at the junction between segments II and III . The general setting displayed in this profile is similar to key profile-5, but in this profile the master fault displays narrow flat and much steeper ramp. Faults a, b, c & d basin-ward dipping and synthetic to the master fault, terminates on the evaporite layer and interpretation on this faulted area was difficult. The evaporite layer thins towards the master fault and thicker as well as deformed away from the master fault. This observation could lead to the evaporite movement and salt related deformation.

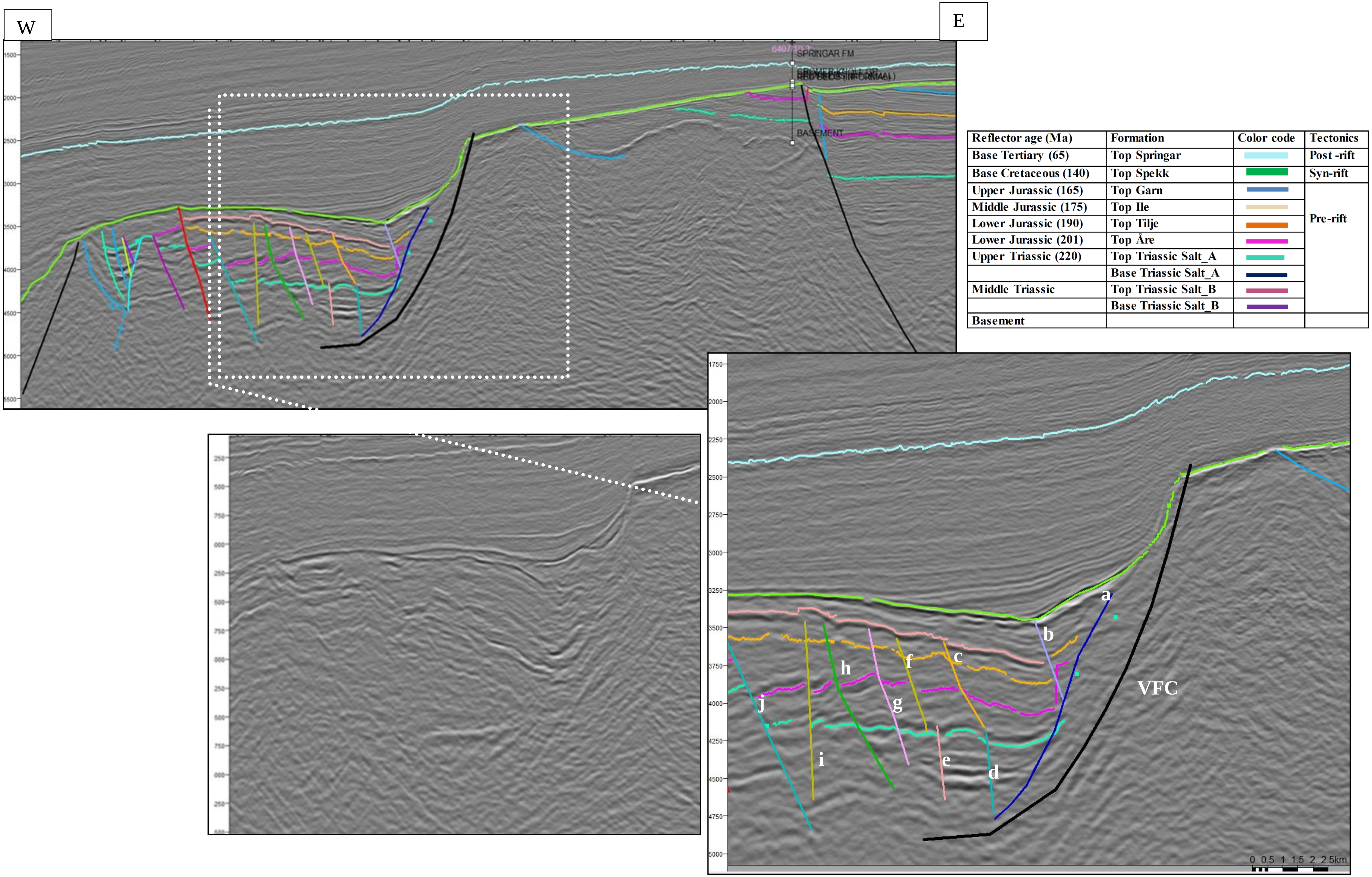
Key profile-7:

This W-E oriented profile (Fig. 3.24) orthogonal to the strike of the Vingleia fault Complex, displays Rås Basin to the west and Halten terrace centrally and the Frøya High and Froan Basin in the east. The master fault is characterized by listric fault geometry detached at the Triassic evaporite unit. Fault-a dipping basin-ward is synthetic to the master fault, whereas faults b, c, d, e, f, g, h, i and j are dipping opposite to the master fault. Faults c and f terminates on the Triassic evaporite layer whereas faults g, h, i and j displaces the evaporite unit. Fault-1 east-dipping and interpreted in key profile-4 as fault bounding Froan Basin and Frøya High, is displayed in this section as a normal fault with strong seismic reflectivity to below ca. 6 s TWT below the Base Triassic stratigraphic level.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.23: key profile-6, NW-SE strike orientation Steep dipping ramp-flat-ramp geometry, steeper upper ramp and narrow flat area.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.24: Key profile-7, W-E strike orientation and the master fault is characterized by listric fault geometry detached at the evaporite layer.

3.3.4 Segment-IV

Segment-IV shows WSW-ENE strike and is located where the Vingleia Fault Complex terminates south-wards against the Klakk Fault Complex (Figs. 3.25). Key profile 8 & 9 with N-S orientation are orthogonal to the strike of the master fault and displays geometry (Figs. 3.26 & 3.27). The two profiles show the strongly deformed sedimentary strata in the hangingwall and the master fault shows smaller throw compared to profiles 6 & 7. The fault plain in profiles 8 & 9 show strong reflectivity and can be traced down to ca. 8 s TWT. The evaporite unit within the two profiles shows thickness variation in the hangingwall and thickening away from the Vingleia Fault Complex.

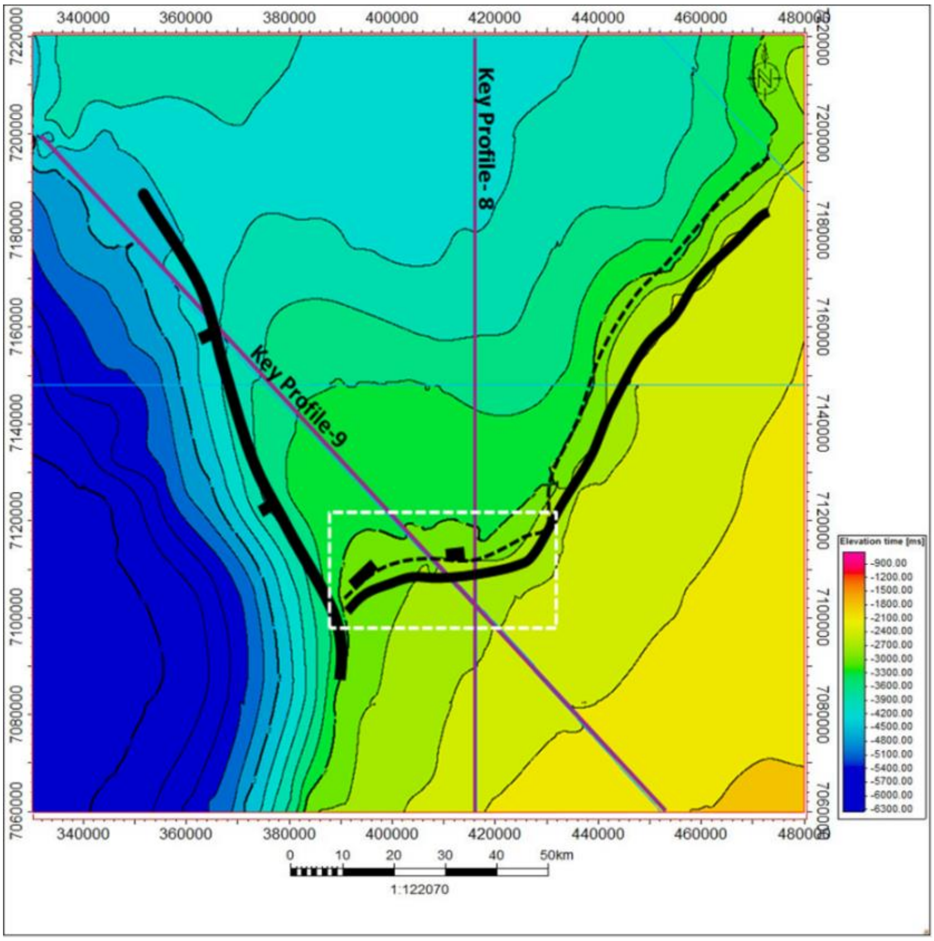


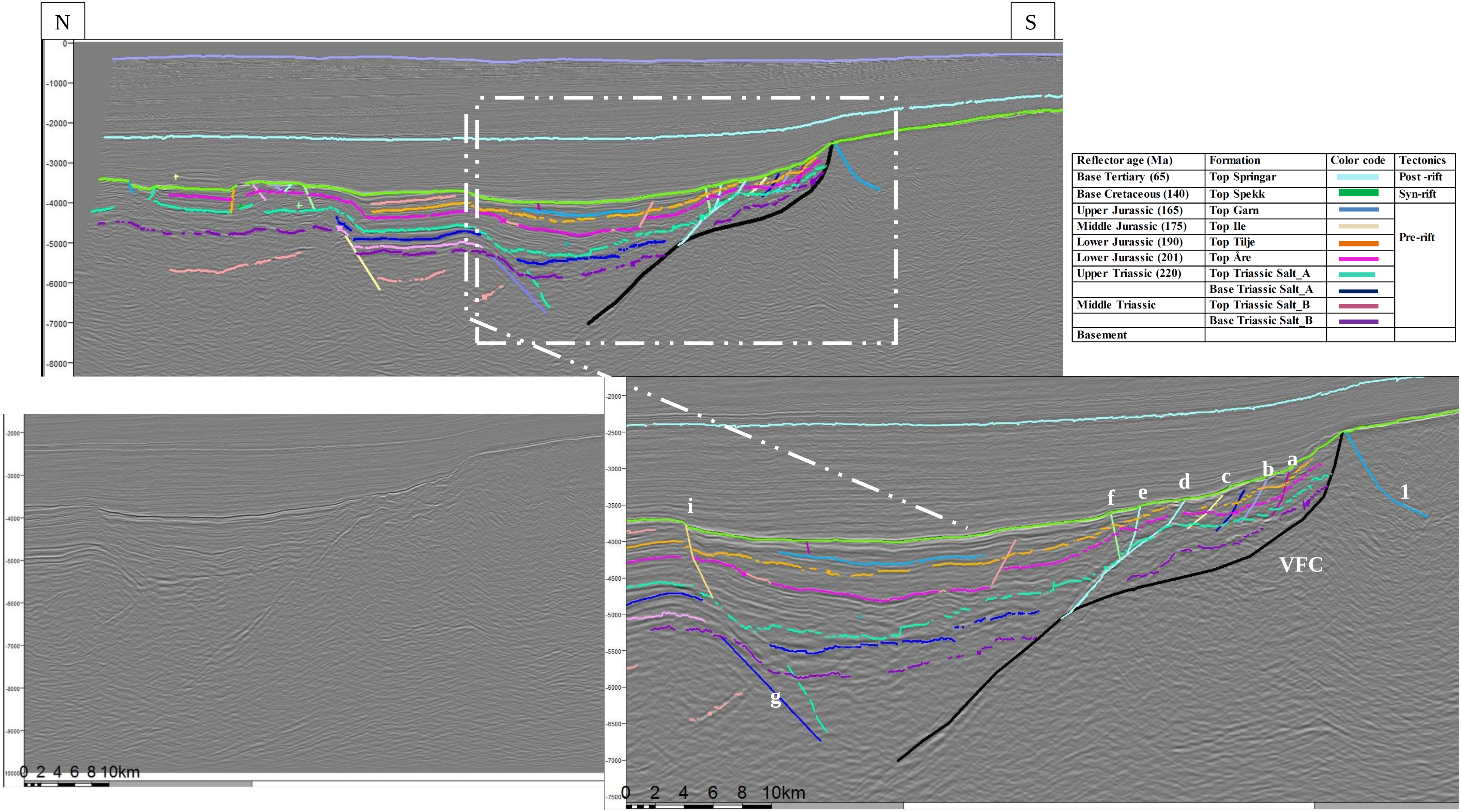
Figure-3.25: Segment-IV showing the location and fault cutoff above the Base Cretaceous time-structure map. See the contour variation forming anticlinal and syncline structure on the two seismic profiles. The segment shows wider fault zone in the middle part of the fault segment and decreasing in heave, fault cutoff at the two edges.

Key profile-8:

This N-S oriented profile (Fig. 3.26) is orthogonal to the strike of master fault. The master fault shows gentler dip angle to ca. 4.5 s TWT and is flattened at the evaporite unit. Therefore the evaporite unit acts as a detachment layer where the fault plain seismic reflectivity is attenuated. The strong seismic reflectivity of the fault plain was observed to continue below the evaporite unite to a ca. 8 s TWT. Therefore the master fault in this profile can be characterized as ramp-flat-ramp fault geometry. On the hangingwall sedimentary units are strongly deformed by the faults which are synthetic and antithetic to the master fault. Faults a, b, c, d and e terminates within the evaporite unit whereas fault-f basin-ward dipping displaces the evaporite unit and was observed to detach on the master fault at ca. 5.5 TWT. Fault-g dipping opposite to the master fault observed to terminate on the evaporite unit from the base and the evaporite unit above this fault shows anticline structure, a characteristic extensional forced fold. The evaporite unit on this extensional forced fold geometry varies in thickness.

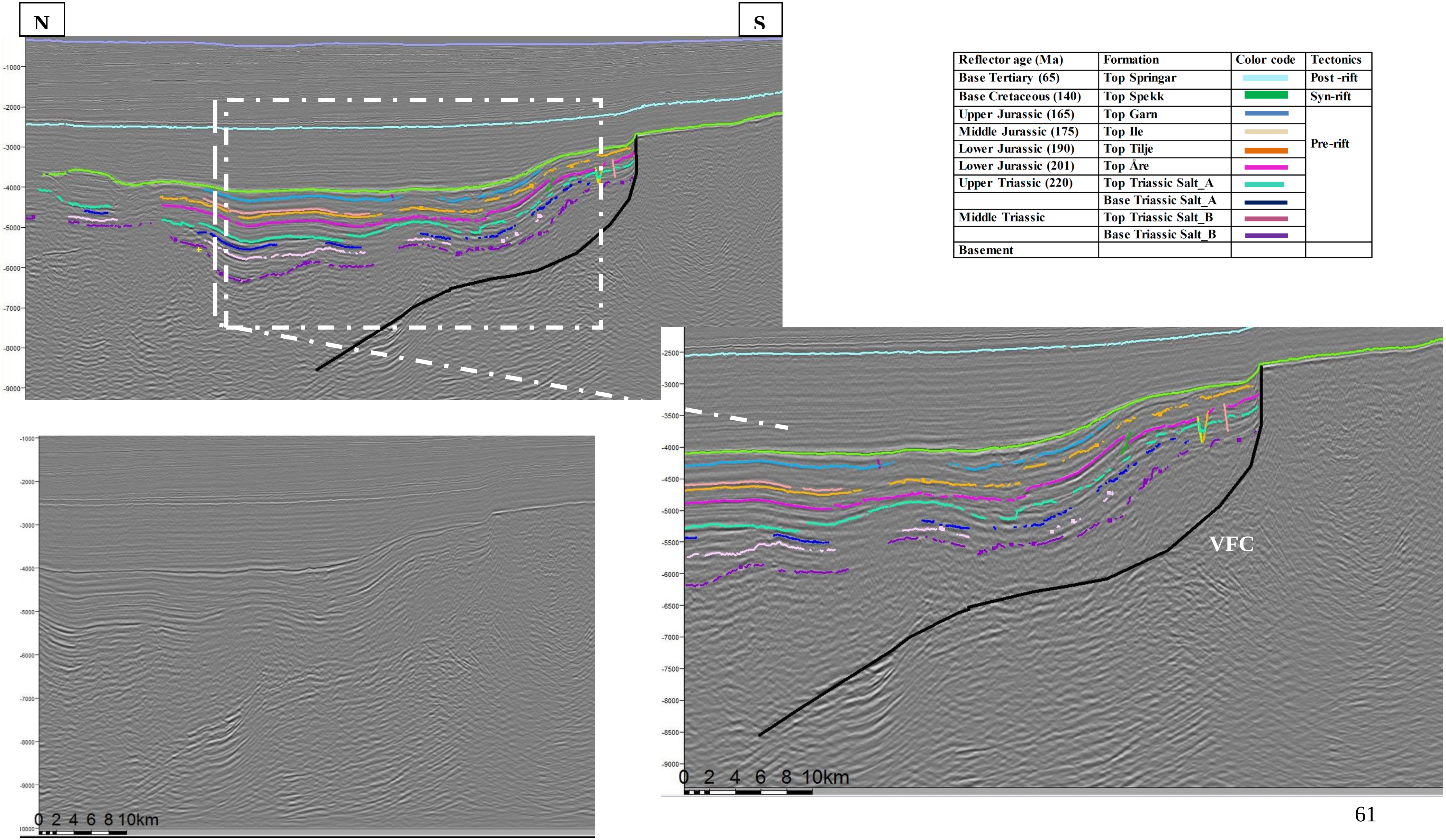
Key profile-9:

This N-S orientated profile (Fig. 3.27) has the same orientation as profile-8 and is orthogonal to the master fault. In this profile the fault geometry appears to show steeper dip angle and relatively small thrown compared to the profiles 6 & 7 (Figs. 3.23 & 3.24). Below the interpreted evaporite unit ca. 4.5 to 5.5 s TWT the master fault seismic reflectivity is unclear and was difficult to decide where the fault continues but the strong seismic reflectivity below ca. 6 TWT which shows gentler dip angle could lead that the master fault is deep routed fault and the strong seismic reflectivity of the fault plain can be traced to below ca. 8 s TWT. Therefore the master fault in this profile can be characterized ramp-flat-ramp with wider flat and gentler lower ramp. The footwall, within the Frøya High is characterized by thin sediment packages, an elevated area where the pre-Cretaceous stratigraphic level is eroded. Well 6407/10-3 located within the Frøya High, confirms the penetration of the basement at TD of 2973 m. Well 6406/11-1 s located within the Halten Terrace penetrated to Late Triassic of the Red Beds, at TD of 4185 m in the hangingwall confirms that the basement in this area is at greater depth much below 5 s TWT.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.26: key profile-8, N-S strike orientation and the Vingleia Fault Complex (Black colored) shows ramp-flat-ramp fault geometry and the Vingleia Fault Complex is detached at the Triassic evaporite layer and show continuous fault plane reflection to below 7 s TWT. The hanging wall show strong deformation. A culmination occurs in hanging-wall at 4.5 s TWT.



Reflector age (Ma)	Formation	Color code	Tectonics
Base Tertiary (65)	Top Springar	🟦	Post -rift
Base Cretaceous (140)	Top Spekk	🟩	Syn-rift
Upper Jurassic (165)	Top Garn	🟦	Pre-rift
Middle Jurassic (175)	Top Ile	🟨	
Lower Jurassic (190)	Top Tilje	🟧	
Lower Jurassic (201)	Top Åre	🟪	
Upper Triassic (220)	Top Triassic Salt_A	🟩	
	Base Triassic Salt_A	🟦	
Middle Triassic	Top Triassic Salt_B	🟥	
	Base Triassic Salt_B	🟪	
Basement			

Figure-3.27: Key profile-9: N-S profile orientation and the Vingleia Fault Complex shows a ramp-flat-ramp fault geometry, where the fault plane seismic reflection continues below 8.5 s TWT. An anticline structure above the flat is observed and the throw is much smaller than sections 3, 4, 5 and 6.

3.4 Structural maps

Time-structure and fault maps generated on Base Triassic evaporite-B, Top evaporite-A, Top Åre and Top Tilje formations, Base Cretaceous Unconformity and Base Cenozoic have been used to observe the fault geometry and style of deformation of the study area. Particular emphasis was given to the Base Cretaceous Unconformity time-structure and fault maps which provide good observation of the faults bounding the Halten Terrace.

3.4.1 Top Triassic evaporite-A

The Top Triassic evaporite-A time-structure map (Fig. 3.28) reflects the strong seismic reflection picked as representative to the Middle–Late Triassic evaporite. The structural elements of Late Triassic in the study area mainly consist of a set of NE-SW trending normal faults separating the Halten Terace from Trøndelag Platform, Frøya High and the Froan Basin.

The depocenters, adjacent to the Vingleia Fault Complex shows higher values of >4 s TWT (Fig. 3.28). The central part 3-3.5 s TWT shallower where the majority of the faults located is the Kya Fault Zone, dipping to the west near to the anticlinal structure around the Njord area and change polarity, dipping toward east farther north delineating the Halten Terrace from the Gimsan Basin. Key profiles 2 & 6 in (Figs. 3.17 & 3.23) also confirms the above observation.

3.4.2 Top Åre Formation

Top Åre Formation time-structure and fault maps define the Late Triassic to Early Jurassic structural elements (Fig. 3.29 & 3.30) in the study area which is characterised by normal faults and major period of fault reactivation. The western part of the Halten Terrace is characterised by small complex fault blocks forming smaller sized graben whereas the eastern part of the Halten Terrace is characterised by large fault blocks, Vingleia Fault Complex.

The time-structure map (Fig. 3.30) shows the deeper basins, Rås Basin and the Halten Terrace separated by Vingleia Fault Complex from the Trøndelag Platform and the Frøya High. Areas with greater than 3400 ms TWT represent the Rås Basin and the Halten Terrace areas whereas and areas with less than 2400 ms in TWT represent the Trøndelag and the Frøya High as well as the Froan Basin. The majority of the faults terminate at the Base Cretaceous seismic reflection.

Segment-I, located in the northeast part is characterised by faults of NE-SW orientation and at the junction with the Bremstein Fault Complex, the fault complex shows NNE-SSW strike orientation (Fig. 3.30). Segment-II, located in the central part is characterised by W-E oriented fault. The area between segments I and II shows ca. 5000 ms TWT indicates a depocenter of thick sediment strata and syncline structure immediate to the Vingleia Fault Complex along profile-3 (Fig. 3.18). Segment-III, south of Njord field shows NE-SW strike orientation and is bounded to the east by the Frøya High forms a depocenter adjacent to the master fault. Key profiles 6 and 7 (Figs. 3.23 & 3.24) shows the depocenter represented here with > 4000 ms TWT. Segment-IV, shows W-E strike and the hangingwall is strongly faulted and majority of faults on the hangingwall are oriented synthetic to the master fault.

3.4.3 Top Tilje Formation

The Top Tilje Formation time structure and fault maps (Figs. 3.31 & 3.32) define the Early to Middle Jurassic structural elements in the study area and show similar structural element as the Top Åre Formation time structure and fault maps. The majority of the faults terminate at the Base Cretaceous unconformity seismic reflection.

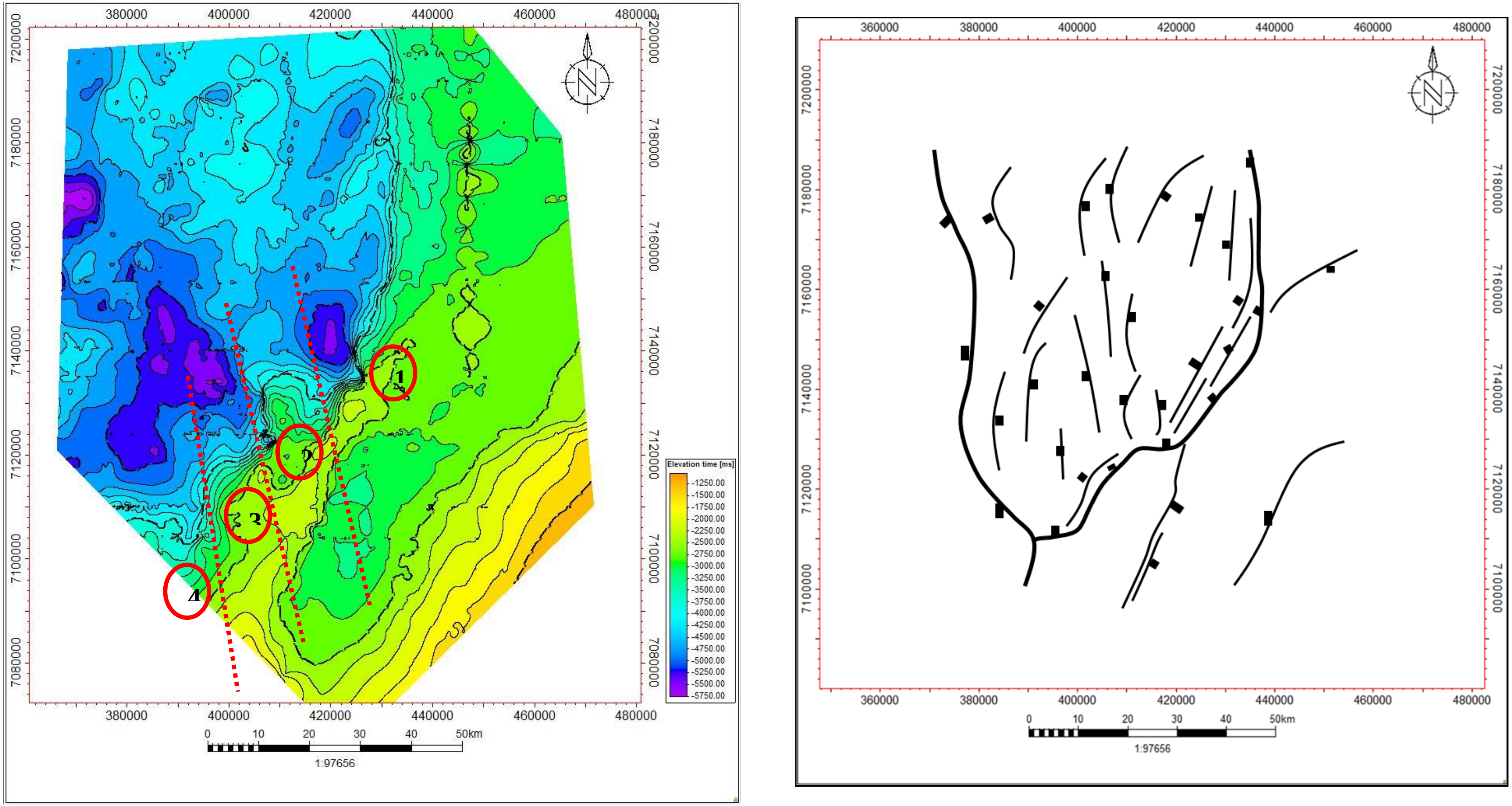


Figure-3.28: Top Triassic evaporite-A time-structure and fault maps. The dark blue areas are observed to be the depocenter immediate to the Vingleia Fault Complex showing higher values of TWT, >4000 ms. The central part with relatively shallow, light blue area is observed to be the Kya Fault Zone, dipping to the west immediate to the anticlinal structure around the Njord area and change polarity, dipping toward east farther north delineating the Halten Terrace from the Gimsan Basin.

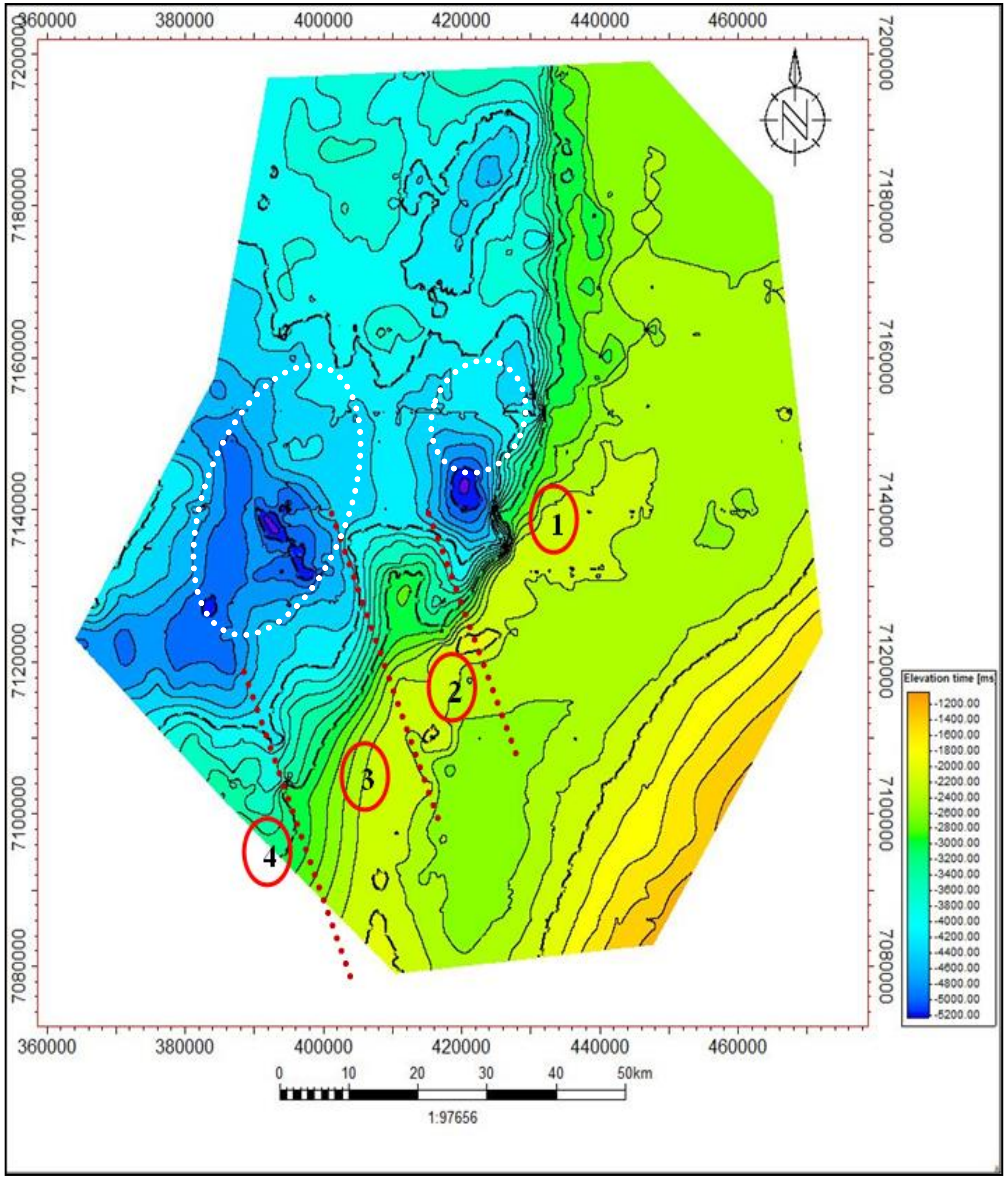


Figure-3.29: Top Åre Formation time-structure map, numbers 1-4 and the dotted red lines show the fault segment.

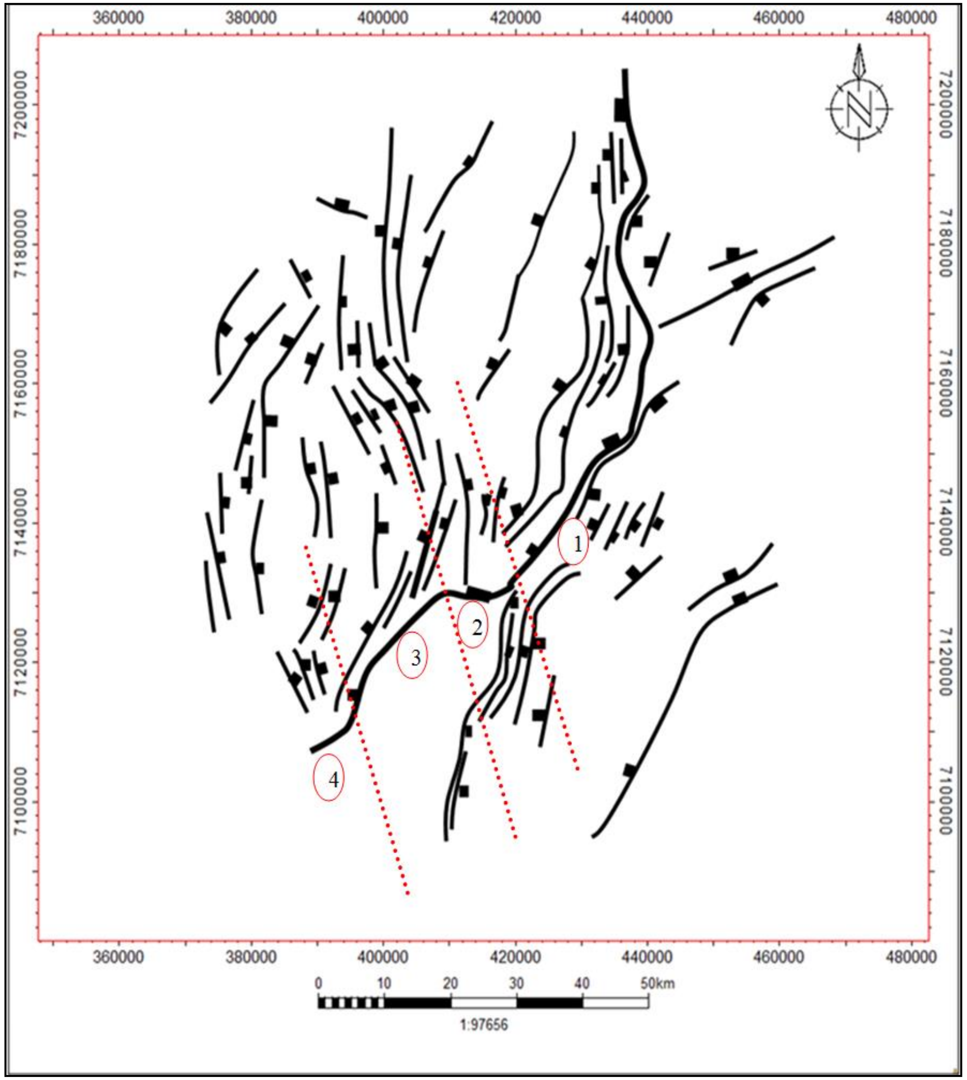


Figure-3.30: Top Åre fault map, numbers from 1-4 and the dotted red lines show the Vingleia fault segment.

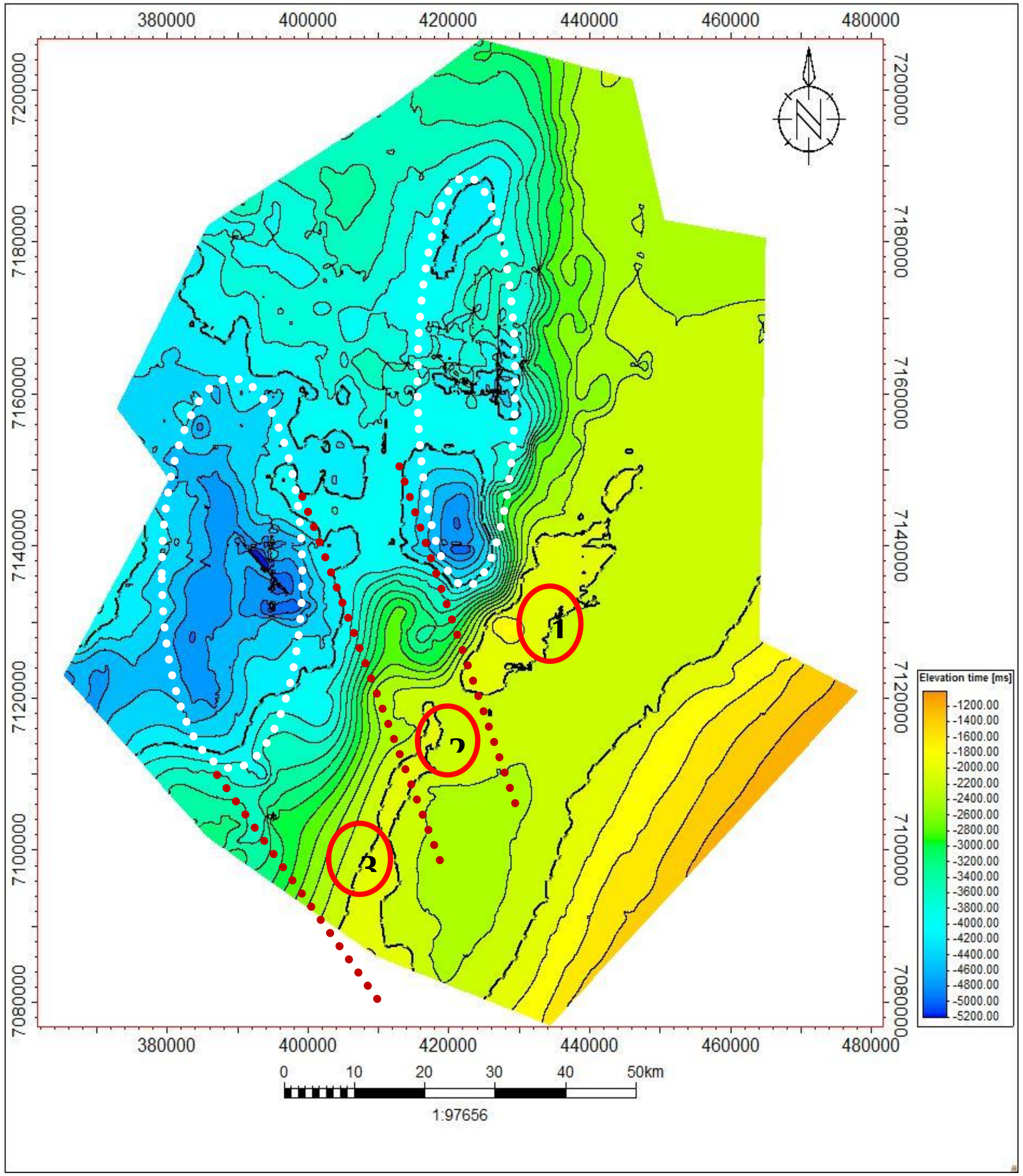


Figure-3.32: Top Tilje Formation time-structure map, red circles indicates the fault segments and the white circle represent the two major depocenters within the Halten Terrace.

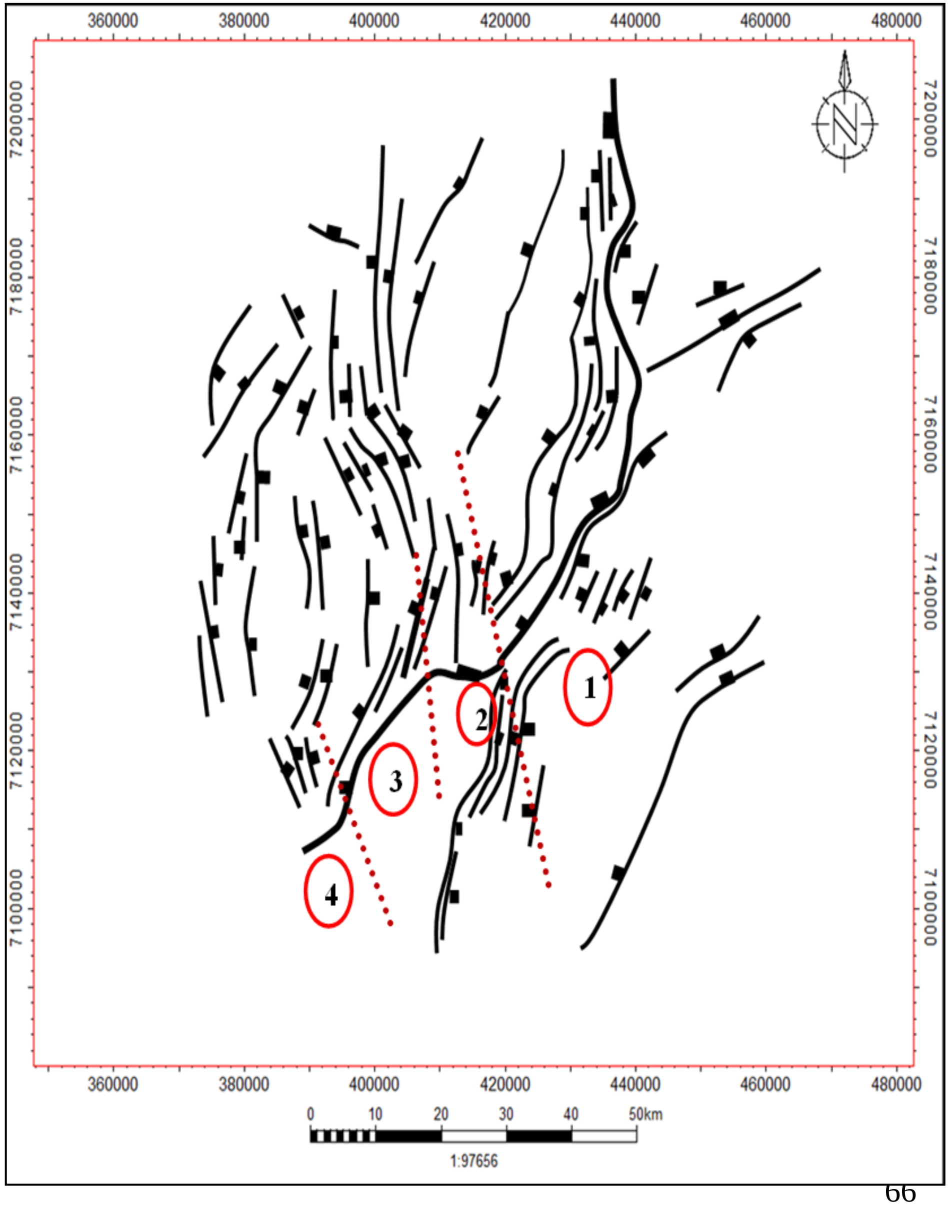


Figure-3.31: Top Tilje Formation fault map red circles represent the fault segments and the doted red lines show the rough boundary between segments

3.4.4 Base Createaceous Unconformity (Top Spekk Formation)

The Base Cretaceous Unconformity time-structure and fault maps (Figs. 3.33 & 3.34) show most of the structural elements that bound the Halten Terrace. The Halten Terrace with the present shape at the Base Cretaceous, formed in the Late Middle Jurassic-Early Cretaceous rift phase is well displayed.

The time-structure map (Fig. 3.33) shows the deeper basins with > 5400 ms TWT, the Rås Basin separated by the Klakk Fault Complex from the Halten Terrace and the Trøndelag Platform and the Frøya High are shallower with >2400 ms TWT are separated from the Halten Terrace by the Vingleia Fault Complex. The fault geometries and fault segmentation along the Vingleia Fault Complex and the Klakk Fault Complex as well as the Kya Fault Zone is well displayed and as on (Fig. 3.13) shown the throw and heave variation within the Vingleia Fault Complex is showed in (Fig. 3.33) where the counters shows the variation in elevation in TWT.

3.4.5 Base Cenozoic (Top Springar Formtion)

The Base Cenozoic time-structure map (Fig. 3.35), shows a generally west dipping structural elements. In this time-structure map the fault segmentation of the Vingleia Fault Complex and the anticline of the Njord structure were not observed. These two structures were presented at Base Cretaceous and below succession. Therefore The Base Cenozoic time-structure map could point out that at this stratigraphic level the tectonic activity was quite stable. The Trøndelag Platform, Frøya High and the Froan Basin are characterized by shallower sediment strata with <1600 ms TWT whereas the Rås Basin and Halten Terrace shows deeper sediment strata >2400 ms TWT.

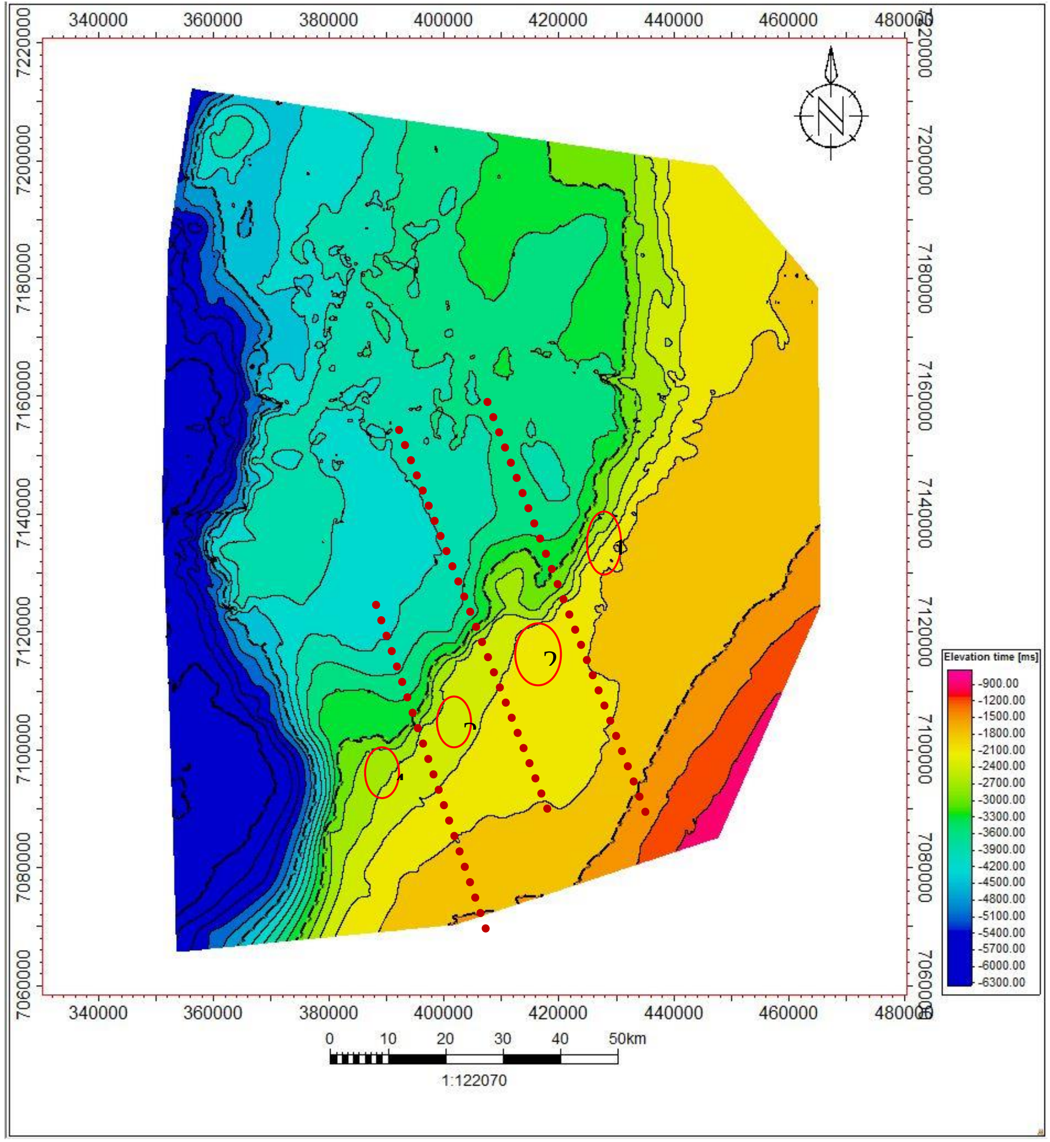


Figure-3.34: Base Cretaceous time-structure map. Color code shows change in elevation in (ms). Pink colored coded Rås Basin, light blue to light green, Halten Terrace, yellow colored Frøya High, light yellow to reddish colored Froan Basin and light green to light yellowish colored Trøndelag Platform.

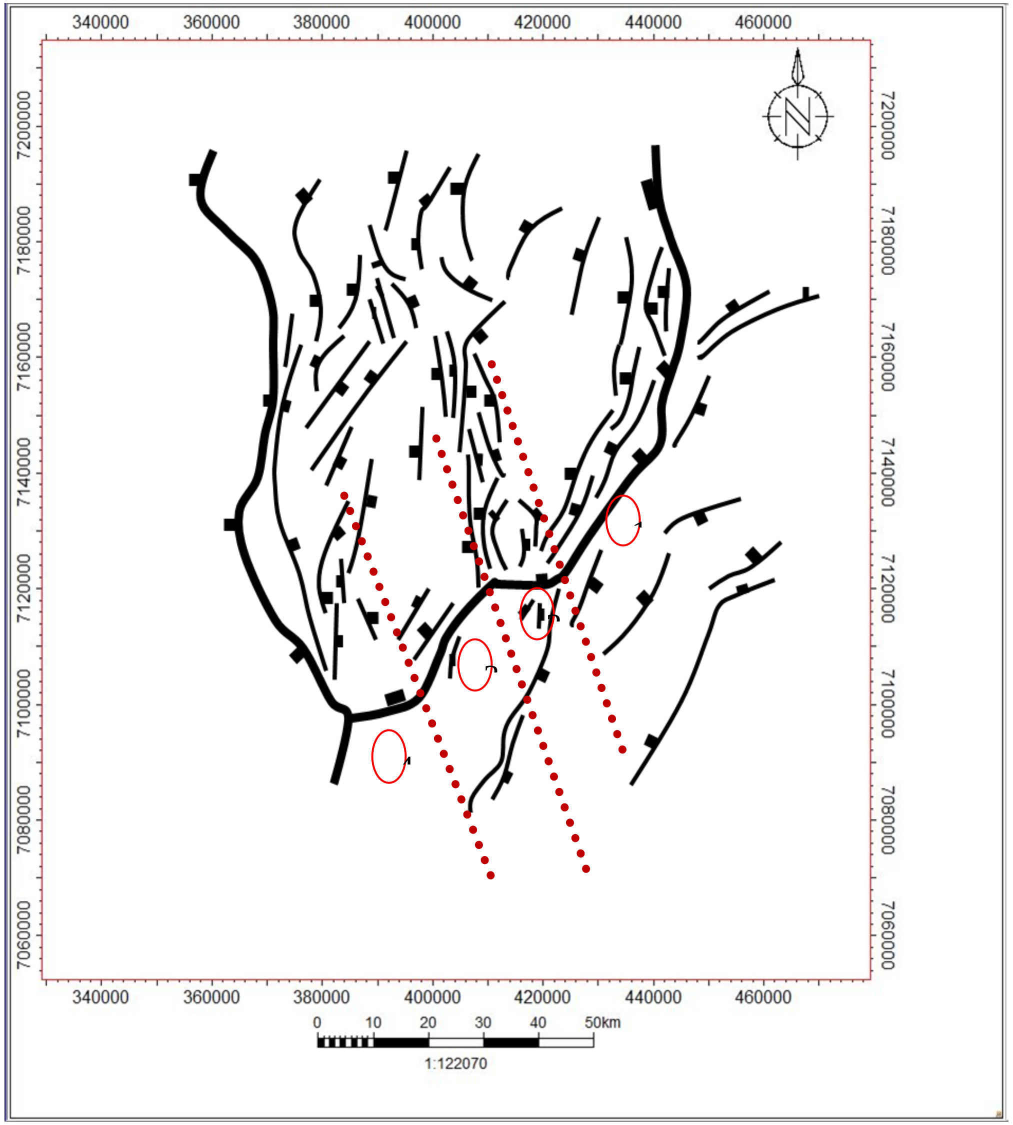


Figure-3.33: Base Cretaceous fault map. Most of the faults terminate along this unconformity and the number of fault observed to decrease in diversity.

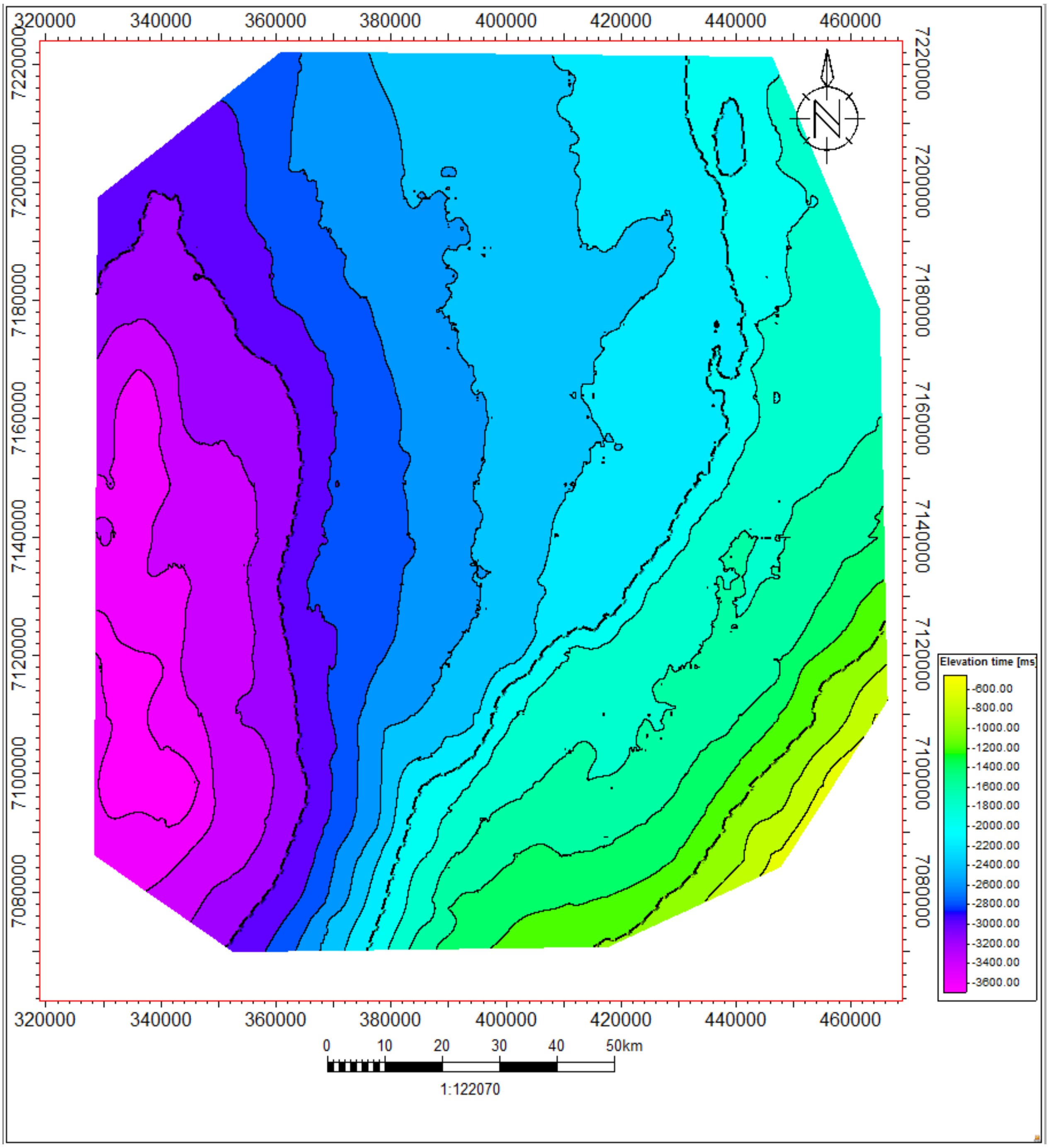


Figure-3.35: Base Tertiary structural map. Pinkish color coded (> 3200 ms) is the Rås Basin and the Halten Terrace (Deep Basin), Dark Blue to light blue color coded, Gimsan Basin and light–light green color coded (< 1900 ms) Trøndelag Platform, Frøya High and the Froan Basin.

The time-thickness map (isochore map) displays lines of equal thickness in a layer where the thicknesses are measured vertically in two way travel time (TWT). To see the lateral thickness variation of sediments which is related to the faulting activity and depositional patterns within certain time interval is constructed on the Top Åre Formation -Top Triassic evaporite-A unit, Top Tilje-Top Åre formations, Base Cretaceous-Top Tilje Formation, Base Cenozoic (Top Springar Formation) to Base Cretaceous Unconformity (Top Spekk Formation).

3.5.1 Top Åre Formation -Top Triassic evaporite-A unit

The lateral time-thickness variations between Top Åre Formation and Top Triassic evaporite-A unit (Late Triassic to Early Jurassic) are shown in (Fig. 3.36). The thinner sediment strata ca. < 100 ms TWT represent the footwalls of the Vingleia Fault Complex and the Kaya Fault zone. The Halten Terrace and Froan Basin shows thicker sedimentary strata with thickness ca. > 500 ms TWT. The area with very thinner in TWT represents the Frøya High where sediments, Late Triassic to Early Jurassic were reported on well data; well 6497/10-3 as missing.

3.5.2 Top Tilje -Top Åre formations

The lateral time-thickness variations between Top Tilje and Top Åre formations (Early to Middle Jurassic) are shown in (Fig. 3.37) and the area with circular couture shows very thin sediment strata, below 100 ms TWT is the Frøya High where sediments of the Early to Middle Jurassic were reported on the well data to be missing . Within the Halten Terrace and the Froan Basin the thickness of the sediment strata shows no big variation except in some small areas close to the fault.

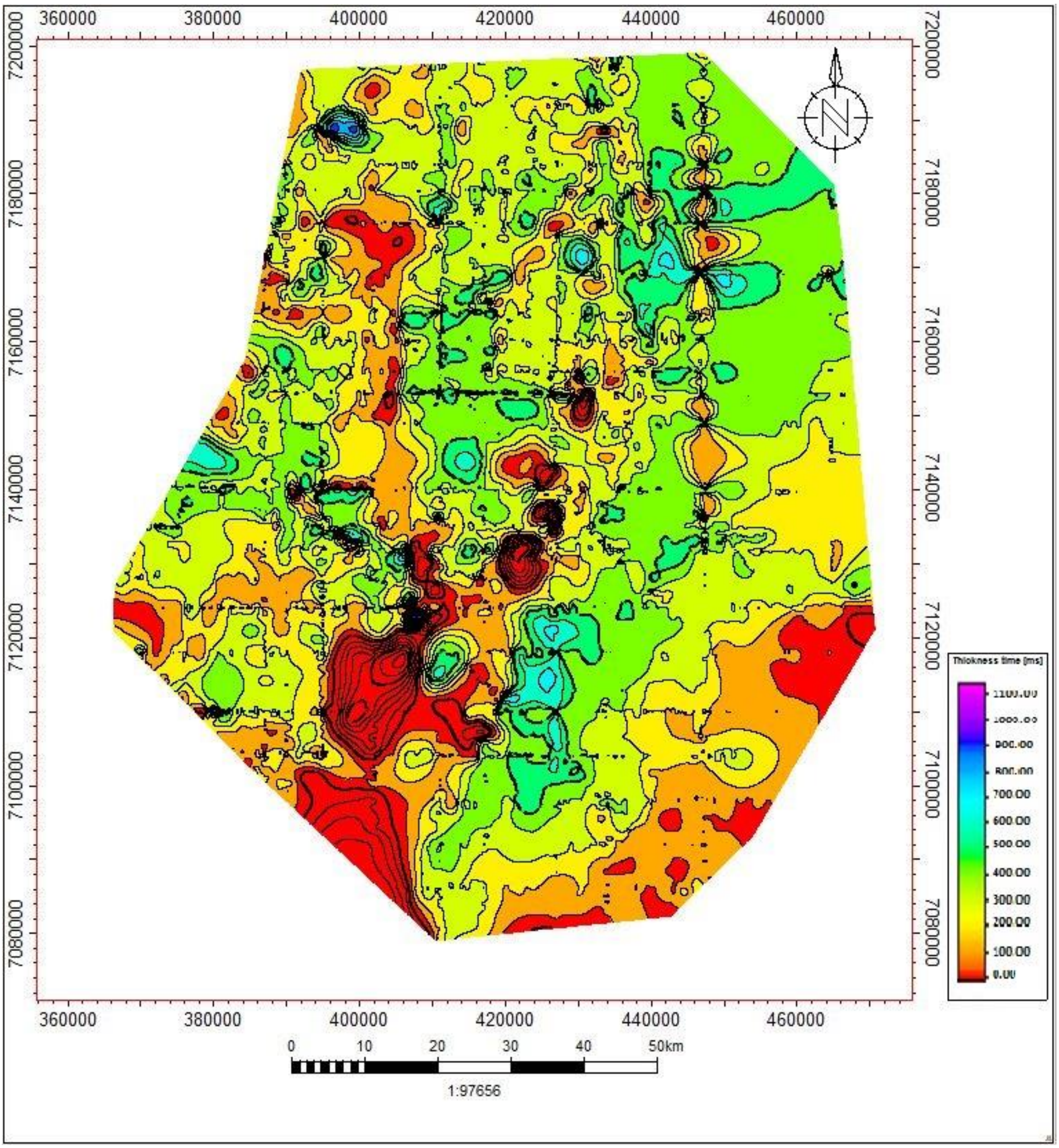


Figure-3.36: Top Åre Formation-Top Triassic evaporite-A time-thickness map showing local deep depocenters along the major fault zones. The reddish colored Frøya high indicated as thinn area.

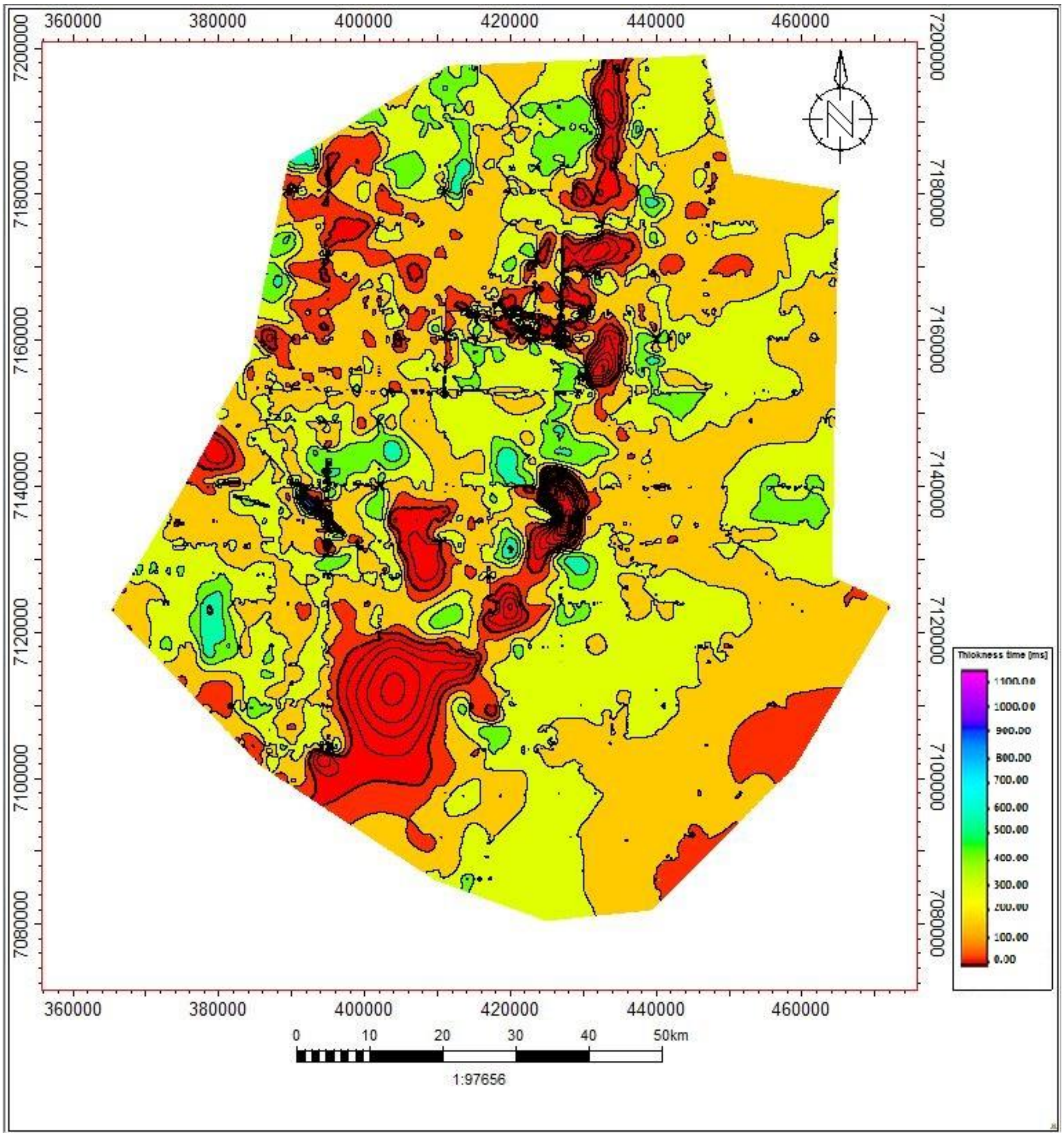


Figure-3.37: Top Tilje–Top Åre Formation represents the uniform thickness of the sedimentary package along the Halten Terrace and the Froan Basin and the Trøndelag Platform. The Vingleia Fault Complex is outlined as linear feature, yellowish colored, less-thicker in TWT.

3.5.3 Base Createaceous Unconformity –Top Tilje Formation

The lateral time-thickness variations between the Base Cretaceous Unconformity (Top Spekk Formation) and Top Tilje Formation (Middle Jurassic to Early Cretaceous) are shown in (Fig. 3.38). In this map, thick sediment strata between the Njord structure and the Vingleia Fault Complex is showing >1200 ms TWT. The footwall of the Vingleia Fault Complex is outlined with thinness < 100 ms TWT across the study area. Thickness variation of sediment may indicate faulting activity during this time interval.

3.5.4 Base Cenozoic–Base Createaceous Unconformity

The lateral time-thickness variations between Base Cenozoic (Top Springar Formation) and Base Cretaceous unconformity (Top Spekk Formation), (Early Cretaceous to Early Palaeocene) are shown in (Fig. 3.39). This map displays the structural features bounding the Halten Terrace. The Rås Basin show thicker sediment strata (>2600 ms TWT), separated from the Halten Terrace with intermediate thickness (800-2000 ms TWT) by the Klakk Fault Complex compared to the Trøndelag and the Froan Basin which show thinner sediment strata (<100 ms TWT) separated by the Vingleia Fault Complex and the Bremstein Fault Complex. Therefore thickness variation on this thickness map may indicate tectonic activity during this time interval which shaped the Halten Terrace present structure.

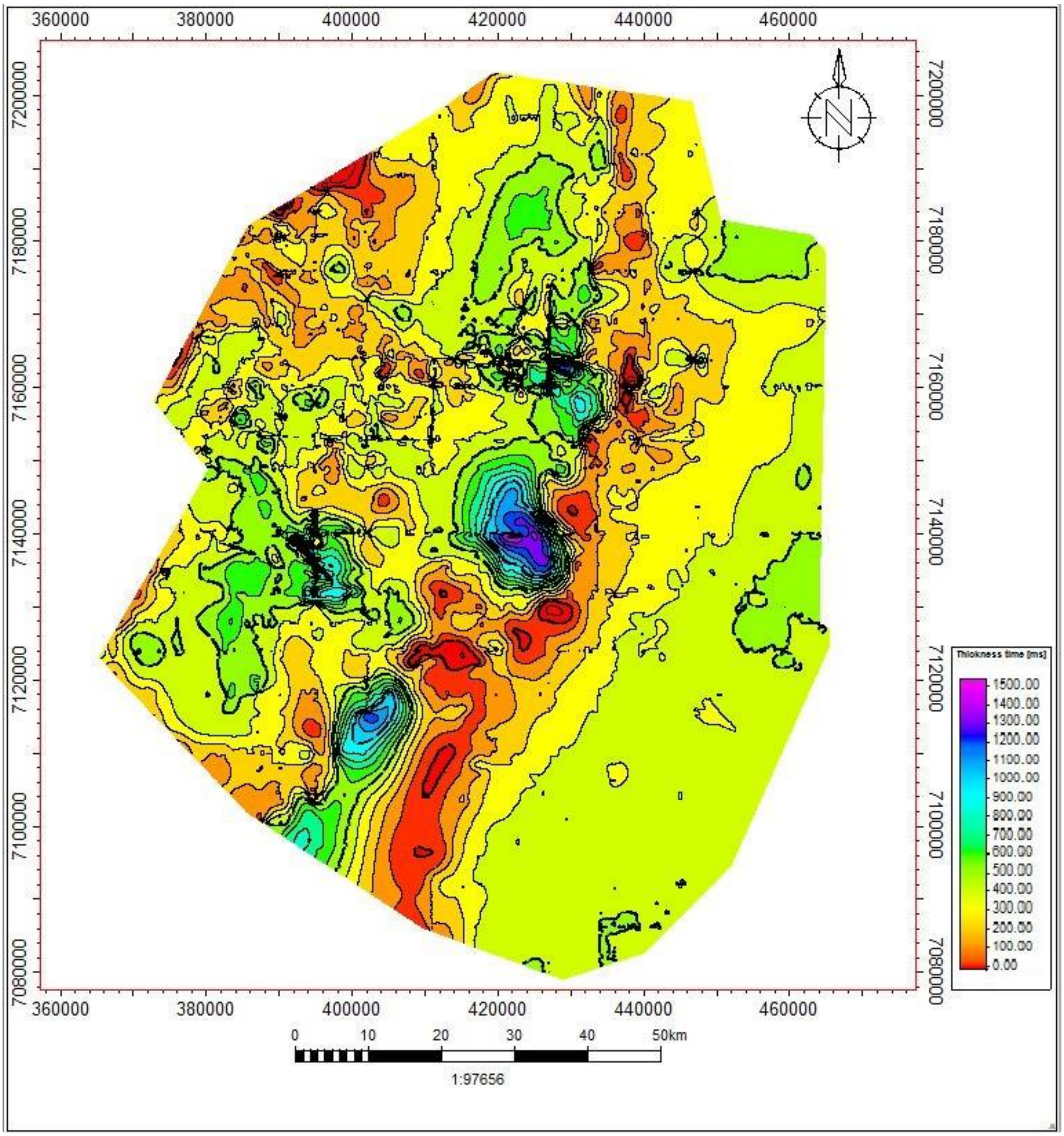


Figure-3.38: Base Cretaceous–Top Tilje presents the deep depocenters immediate to the main fault in the northeast and the Njord dome structure to the southwest forming a local graben.

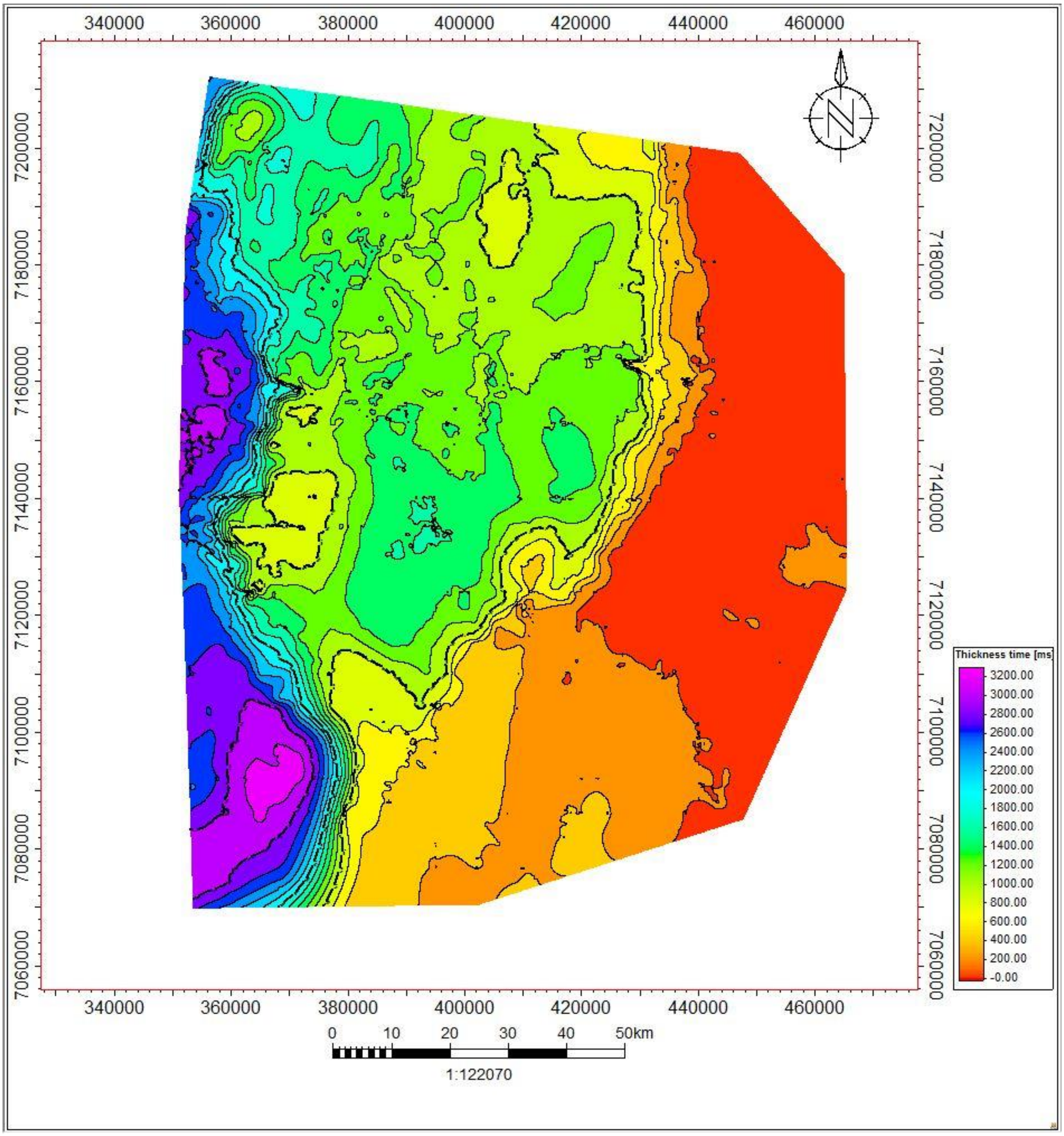


Figure-3.39: Base Tertiary–Base Cretaceous time-thickness map showing the shape of the Halten Terrace bounded by the Klakk Fault Complex in the west and by the Vingleia Fault Complex in east.

4. Discussion

This chapter focuses on discussion of the structural style, geometry and evolution of the Vingleia Fault Complex. Special emphasis is given to the structural style and evolution of the Vingleia Fault Complex (Fig. 4.6). Timing of tectonic events (Figs. 4.9 & 4.10) and structural evolution relationships between the Halten Terrace, Rås Basin, Froan Basin, Frøya High and the Trøndelag Platform will be discussed based on data and observation presented and described in the previous chapter and in relation to literature studies done in the study area. In this thesis, the discussion focuses on the following points:

- Fault geometry, style of deformation, strike and dip variations along and across the Vingleia Fault Complex as well as the segmentation and evolution of the Vingleia Fault Complex.
- The role of the evaporite unit in modifying structural style and geometry of deformation in the study area such as extensional forced folds, fault propagation folds, basement-involved and basement-detached normal faults resulted from the modifying influence of evaporite unit.
- Geological evolution of the study area.

There is a clear fault geometry variation along the four segments of the Vingleia Fault Complex. Segment-I with NW-SW strike and located in the northeast part of the study area shows a listric fault geometry, whereas segment-II located in the central part with W-E strike is characterized by a pronounced ramp-flat-ramp fault geometry. This ramp-flat-ramp fault geometry of segment-II diminishes both southwest (segments III and IV) and northeast wards (segment-I). Therefore the above interpretation agrees with the findings of (Ehrlich and Gabrielsen, 2004) and Osmundsen & Ebbing (2008) that described the central segment, along the Njord area as ramp-flat-ramp fault geometry and segments I and III shows much less rotated hangingwall block than segment II do (Fig. 4.6).

Segment-III with NE-SW strike and located southwest of segment-II is characterized by listric fault geometry, whereas segment-IV located at the southern end of the study area shows ramp-flat-ramp fault geometry with wider flat and gently dipping upper and lower ramp. It shows a much less rotated hangingwall block than segment-II.

In segment-II the hangingwall fault complex is strongly deformed and shows a prominent anticline, bounded to the NW by a couple of steeply dipping antithetic accommodation faults (Figs. 4.5 a & b). These locally populated faults around the Njord structure shows circular pattern in the Tilje Formation and Base Cretaceous Unconformity fault maps (Figs. 3.32 & 3.34). Generally, the Vingleia Fault Complex shows smaller heave and throw along segments III and IV compared the central and northeastern located segments-I and II (Fig. 3.13).

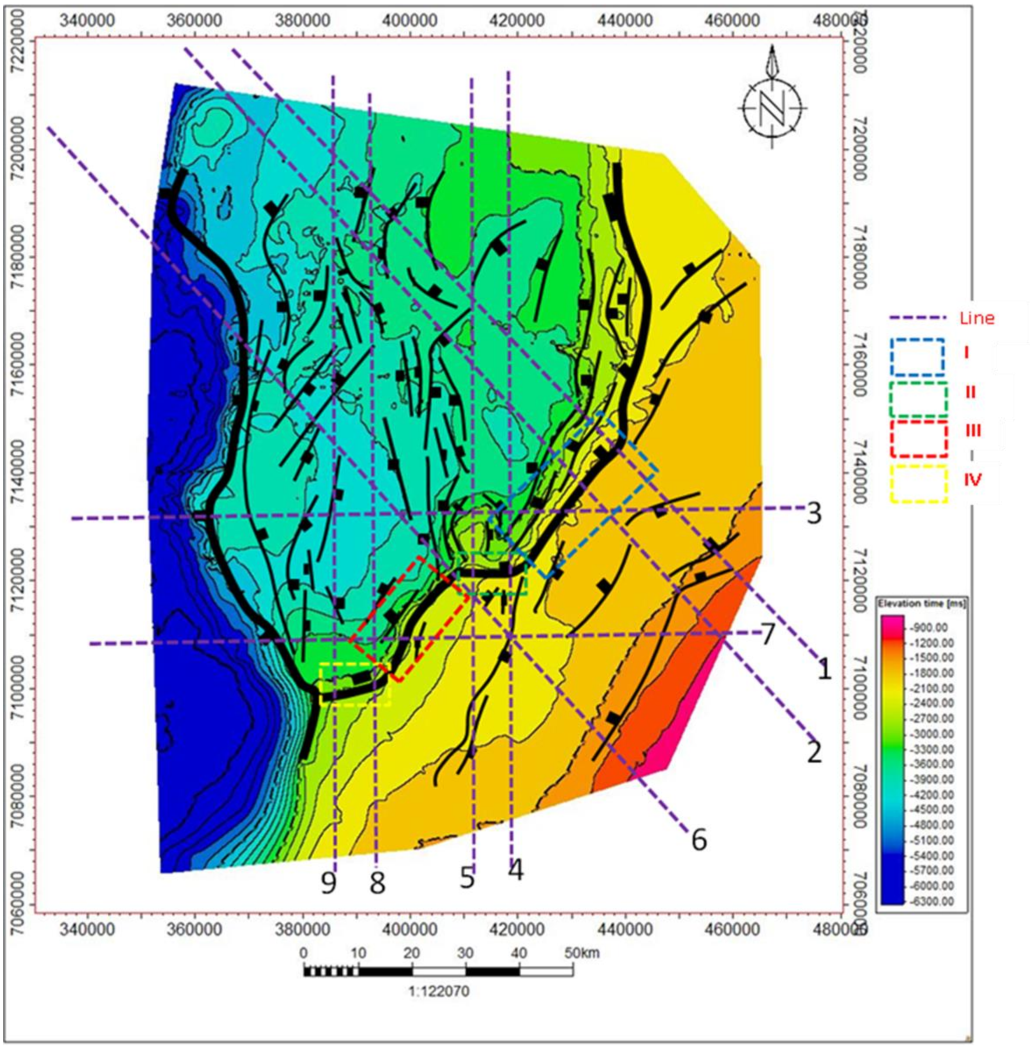


Figure-4.1: Time-structure map of the Base Cretaceous Unconformity stratigraphic level. The figure shows location of key profile-3 (Fig. 4.2) and the four segments. Key profile-3 crosses the large rollover structure around the Njord Field.

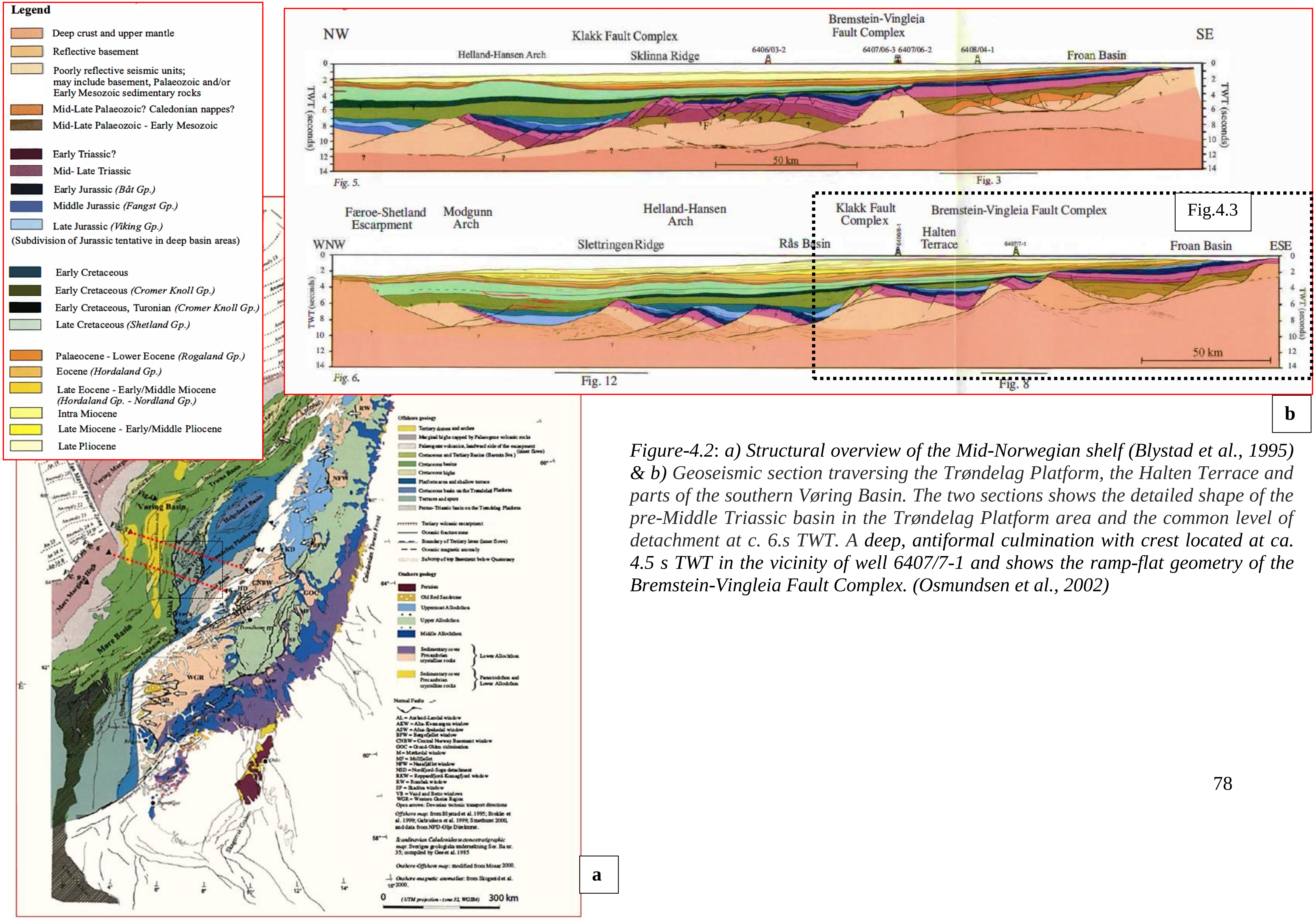


Figure-4.2: a) Structural overview of the Mid-Norwegian shelf (Blystad et al., 1995) & b) Geoseismic section traversing the Trøndelag Platform, the Halten Terrace and parts of the southern Vøring Basin. The two sections shows the detailed shape of the pre-Middle Triassic basin in the Trøndelag Platform area and the common level of detachment at c. 6.s TWT. A deep, antiformal culmination with crest located at ca. 4.5 s TWT in the vicinity of well 6407/7-1 and shows the ramp-flat geometry of the Bremstein-Vingleia Fault Complex. (Osmundsen et al., 2002)

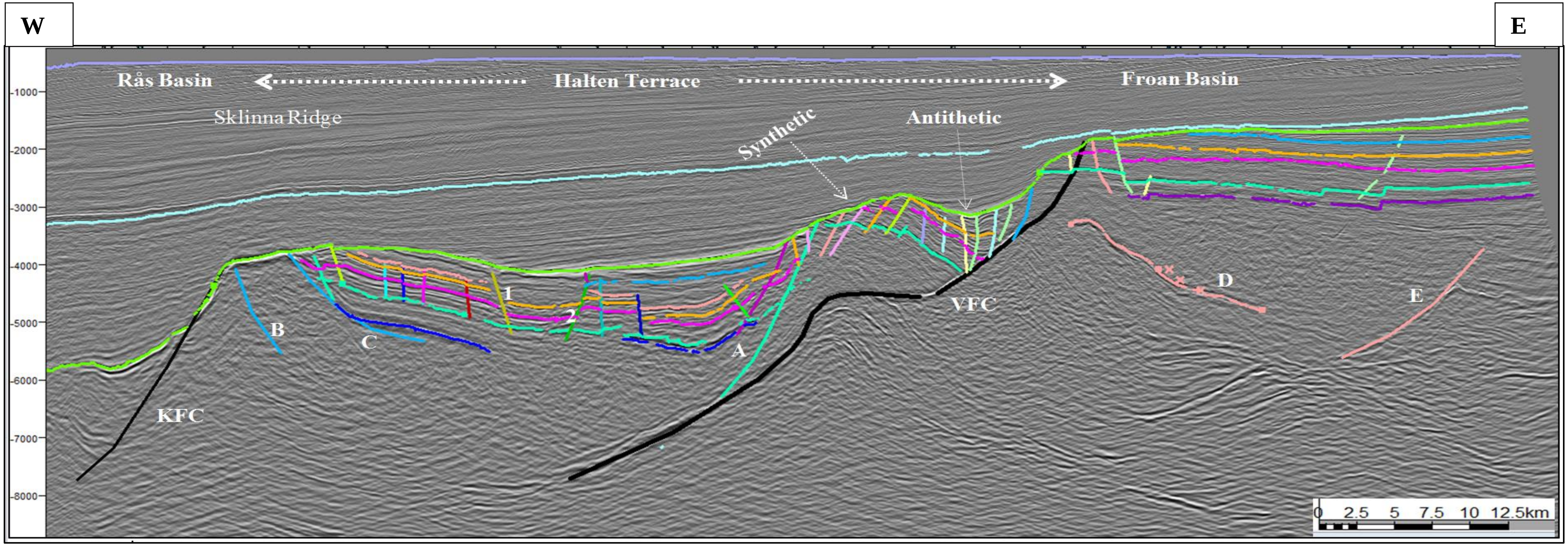


Figure-4.3: Key profile-3 (segment-I), W-E oriented along the Njord structure in comparison with Figure 4.2 above and the structural analysis made by Osmundsen et al. (2002); Ehrlich & Gabrielsen, (2004) and Osmundsen et al.(2008) reflects the geological setting and fault geometry of the study area. The Vingleia Fault Complex around the Njord structure showing general ramp flat ramp fault geometry, basin flank detachment fault. A culmination occurs in the footwall at 5 s TWT marked by white dome shaped. Faults D and E marks a deep structure where fault–D is dipping toward east whereas fault-E dipping to the opposite of fault-D, west ward. The depocenters within the Halten Terrace is bounded by the Klakk Fault Complex and the Sklinna Ridge in the west and the Vingleia Fault Complex in the east. The rollover structure above the culmination form a structural high and matches to the observed structural high in the time structural map of the selected stratigraphic levels (chapter 3) of the study area.

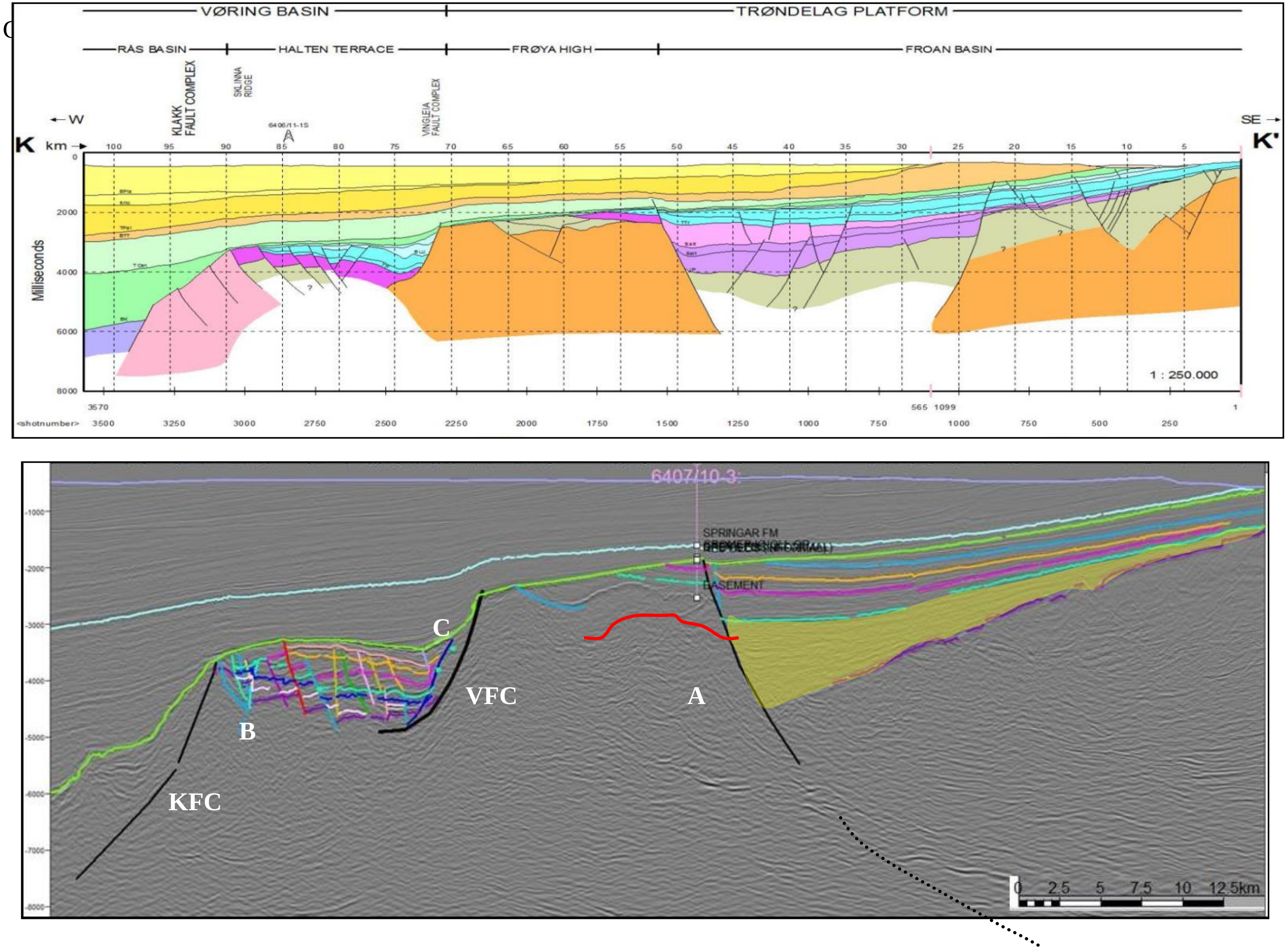


Figure-4.4: *Comparison of profile-7 (segment-III) (lower, with profiles KK' from Blystad et al. (1995 (upper).Location of profile-7 in fig.4.3 above and location as well as legend of profile KK' is show in chapter-2. The boundary fault between the Frøya High and the Froan Basin (fault-A) was active through much of the Triassic time as can be seen by the marked expansion of the Triassic sequence in the hangingwall (yellow colored syn rift deposits).*

4.1 Fault classification, geometry and structural analysis

As Gibbs (1983) defined, listric faults are faults curving towards a mid-crustal detachment within a zone of brittle-ductile transition (Figs. 4.5 a & b). The Triassic evaporite unit in the study area act as a detachment layer and the listric normal faults observed to detach within this layer, examples key profile-2, segment-I (Fig 3.17) and profile-7 , segment-III (Fig. 3.27). Roll-over structures are related to listric faults, developed due to space problem during fault movement causing local contraction (Gibbs, 1983; Ehrlich & Gabrielsen, 2004).

Crustal-scale faults with pronounced ramp-flat-ramp fault geometry are observed in the study area, Figures. 4.5b & 4.6 and profiles 1, 3, 4, 5 & 6 shows the ramp-flat-ramp geometry of the master fault, as argued by Grunnaleite & Gabrielsen (1995); Ehrlich & Gabrielsen (2004). In profile-1 (Fig. 3.16), the Triassic evaporite unit acts as a detachment layer where the flat of the fault is located. This unit could introduce an important sub-horizontal rheological heterogeneity into the upper crust. Therefore this weak layer might have reactivated a pre-existing listric fault to form a ramp-flat-ramp fault geometry (Fossen et al., 2000; Odinsen et al., 2000; Ehrlich & Gabrielsen, 2004) whereas on profiles 3, 5 & 6 (Figs. 3.18, 3.21 & 3.23) the flat of the master fault lays above an antiformal culmination where the evaporite unit has less effect can be explained as to represent an extensional dome in the crystalline basement (Osmundsen et al., 2002; Osmundsen & Ebbing, 2008).

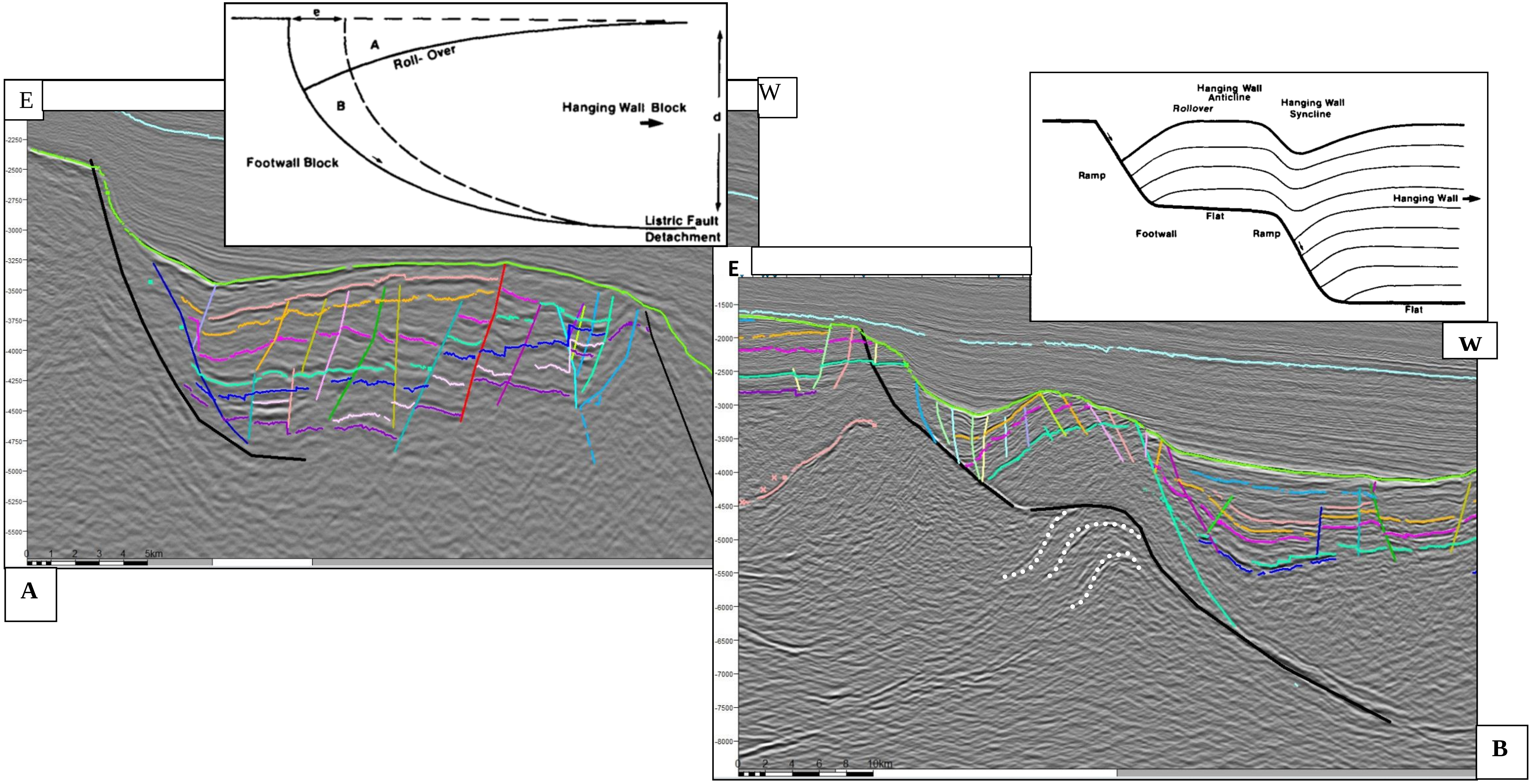


Figure-4.5: (A) Comparison the analog structure from Gibbs (1984) within the study area key profile-7 (segment-III), E-W oriented and the main fault (Black colored, VFC) shows listric fault geometry detached at the Triassic evaporate layer. Antithetic faults to the main fault dominates the fault geometry and the rollover anticline matches with the analog model.(B) Ramp flat-ramp-fault geometry showing folds in the hanging wall produced above footwall ramps and flats (Gibbs, 1984) comparison with key profile- 3, segment-I, ***E****-W oriented section showing the ramp-flat-ramp geometry where the rollover structure is above the flat of the ramp flat ramp fault and the white colored culmination observed to correlated to the basement.*

4.1.1 Structural style, fault segmentation and geometrical deformation of the Vingleia Fault Complex and its evolution

The structure and geometry of the Vingleia Fault Complex (Fig. 3.14) varies from north (segment-I) to south (segment-IV). In the northern and southern parts (segment I & III), the Vingleia Fault Complex is interpreted as a listric fault with a relatively simple geometry at depth but segments II & IV located at the central and the southern part of the study area shows a ramp-flat-ramp fault geometry. According to Ehrlich & Gabrielsen (2004) the development of the Vingleia Fault Complex and deformation of the hangingwall fault block adjacent to the fault complex are characterized by slow, extensional displacement and structural styles such as ramp-flat-ramp faults geometry, extensional horses, extensive roll-over folding, varying strata rotation, synthetic and antithetic faults and characteristic fault bending. Therefore the four segments of the Vingleia Fault Complex shows a unique and complex fault geometry (Ehrlich and Gabrielsen, 2004).

Segment-I located in the northern part shows variation of the fault geometry along the three profiles and this could be related to the role of the evaporite unit in deforming the structure of the master fault. Profiles 1(Fig. 3.16) and 3, (Figs. 3.17 & 4.3) shows ramp-flat-ramp fault geometry of the segment, whereas profile-2 show listric fault geometry. In the northeast part of the segment within profile-2 the evaporite layer is observed to be a thick unit and decouples the upper layer from basement. Therefore the master fault is detached on this unit with ramp-flat-ramp fault geometry. Key profile-2, (Fig. 3.17), characterized by listric fault geometry shows a distinct wedge shaped sediment infill between the Garn Formation and the Base Cretaceous Unconformity stratigraphic levels. This is a characteristic feature of a syn-rift sediment deposition, whereas the onlap truncation of the seismic reflections between the Base Cretaceous Unconformity and Base Cenozoic stratigraphic levels characterizes a post-rift sediment deposition. The same observation is documented in profile-3 but in this profile the evaporite unit is strongly deformed and is not observed within the rollover structure. The presence of a culmination which acts as detachment at the flat of the master fault could explain the development of the ramp-flat-ramp (Ehrlich and Gabrielsen, 2004).

Segment-II is W-E oriented and the three key profiles 4, 5 and 6 shows the ramp-flat-ramp fault geometry of the segment with wider flat and steeper upper and lower ramp around the central part of the study area, around the Njord area. This ramp-flat-ramp fault geometry diminishes both southwest ward (segments-III and IV) and northeast ward (segment-I) (Ehrlich and Gabrielsen, 2004). In key profiles 3, 4, 5 and 6 (Figs. 3.18, 3.20, 3.21 & 3.23) a distinct rollover folding above the flat of a ramp-flat-ramp fault geometry of the Vingleia Fault Complex is recognized and the observation along these profiles, particularly along key profile-3 matches to the Osmundsen et al. (2002), Ehrlich & Gabrielsen (2004) and Osmundsen & Ebbing (2008) interpretations around the well 6407/7-1.

This rollover folding was mapped as elevated area on time-structure map of the Åre and Tilje formations (Figs. 3.29 & 3.30). The fold is bounded by locally populated, basin and land-ward dipping smaller extension faults (Figs. 3.29, 3.30, 3.31 & 3.32). Complex hangingwall folding is a geometrical consequence of the ramp-flat-ramp fault geometry (Fig. 4.5b), where a flat and ramp exist in the footwall a duplex geometry can result with a floor and roof fault (Gibbs, 1984). In Ehrlich & Gabrielsen, (2004) the cause for the large amplitude of the anticline is explained as to be related to the ramp-flat-ramp geometry of the fault, perhaps modified by halokinesis associated with Triassic salt. Such a structure implies strong footwall directed rotation of the inner part of the forced anticline and the rotation depends on the fault-plane geometry and length of the flat (Ehrlich & Gabrielsen, 2004).

The E-W strike observation of segment-II, agrees with Ehrlich & Gabrielsen (2004) who states that the segment links segment-I (northeast) and segment-III (southwest) through direct mutual linkage of the tip lines of the master fault (Fig. 4.6). An initial en-echelon arrangement of two separate fault strands of the Vingleia Fault Complex, in increased strain caused the development of a connecting release fault in an E-W direction. The presence of a culmination within the three profile which acts as detachment at the flat of the master fault could explain the development of the ramp-flat-ramp. The observation of the strong fault plane reflection along the three key profiles 4, 5and 6 which can be traced to 9 s TWT under the Halten Terrace (Figs. 4.2 & 4.4) agree to previous published interpretation (Brekke, 2000; Osmundsen et al., 2002; Ehrlich & Gabrielsen, 2004; Osmundsen & Ebbing, 2008).

Segment-III strikes NE-SW and is located south of the Njord field. The two profiles 6 and 7 (Figs. 3.23 & 3.24) exhibit the change in fault geometry of the Vingleia Fault Complex from ramp-flat-ramp to listric. This observation matches with Ehrlich and Gabrielsen, (2004) observation that the southwest segment shows listric fault geometry with a much less rotated hangingwall block.

Segment-IV strikes W-E and terminates to the southwest, where it meets the Klakk Fault Complex and the Sklinna Ridge. The two profiles 8 and 9 show a ramp-flat-ramp fault geometry detached on the evaporite unit and shows a much less rotated hangingwall block than segment-II (Ehrlich and Gabrielsen, 2004). But sedimentary strata in the hangingwall were strongly deformed.

The observation of ramp- flat- ramp fault geometry within segment-II and northern end of segment-I (profile-1, Fig. 3.16) agrees with the results of Ehrlich & Gabrielsen (2004) who states, that the establishment of the ramp-flat-ramp fault geometry was triggered by the salt layer movement along the master fault geometry in Early Triassic. The observation of a flat-ramp-flat fault geometry above a culmination within the segment-II (Fig. 4.3) could possibly be influenced by basement in homogeneities and is marked by a magnetic/gravity anomaly (Fig. 4.7) (Osmundsen and Ebbing, 2008); Breivik et al., 2011)

Model III in Gabrielsen & Clausen (2001) using experimental model displays the segment linkage development at 14% of extension and this phenomenon is related to the geometry of the basement and the nature of ductile detachment layer where the flat is generated. The observation of the culmination below the flat of the master fault at around 4.5 s TWT is explained by Osmundsen et al. (2002), Ehrilich & Gabrielsen (2004) and Osmundsen & Ebbing (2008) as convex-upward, elongated fault plane culmination (Figs. 4.5b & 4.3) marked by white line. Generally key profiles 8 & 9 (Figs. 3.26 & 3.27) marks a ramp-flat-ramp fault geometry characterized by steeper dip and detached below the Triassic evaporite unit.

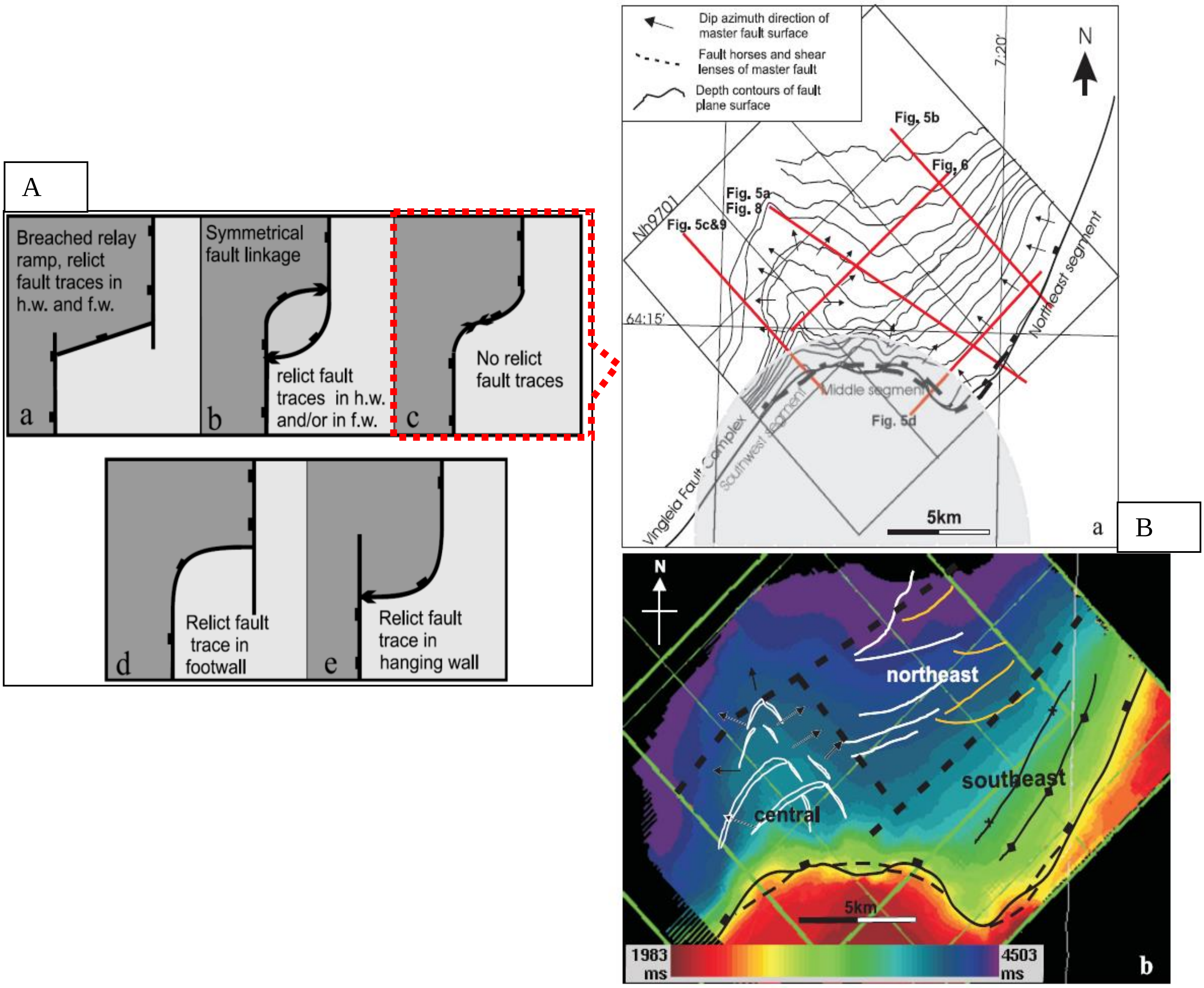


Figure-4.6: (A) Alternative scenarios for linkage of the master fault segment. a, Breached relay ramp with relict fault trace in the hanging and footwall . b, Hard link between propagating faults. c, Hard linking by merging of the tip lines of the approaching faults. d, and e, Faults developing relict fault traces in either hanging or footwall. Form the five-scenario; merging of the tip line of the approaching faults scenario describes the segment linkage between segment-I and III through segment-II (B) Structural map and Time map of the master fault surface showing the outline of the fault geometry (Ehrlich & Gabrielsen, 2004.)

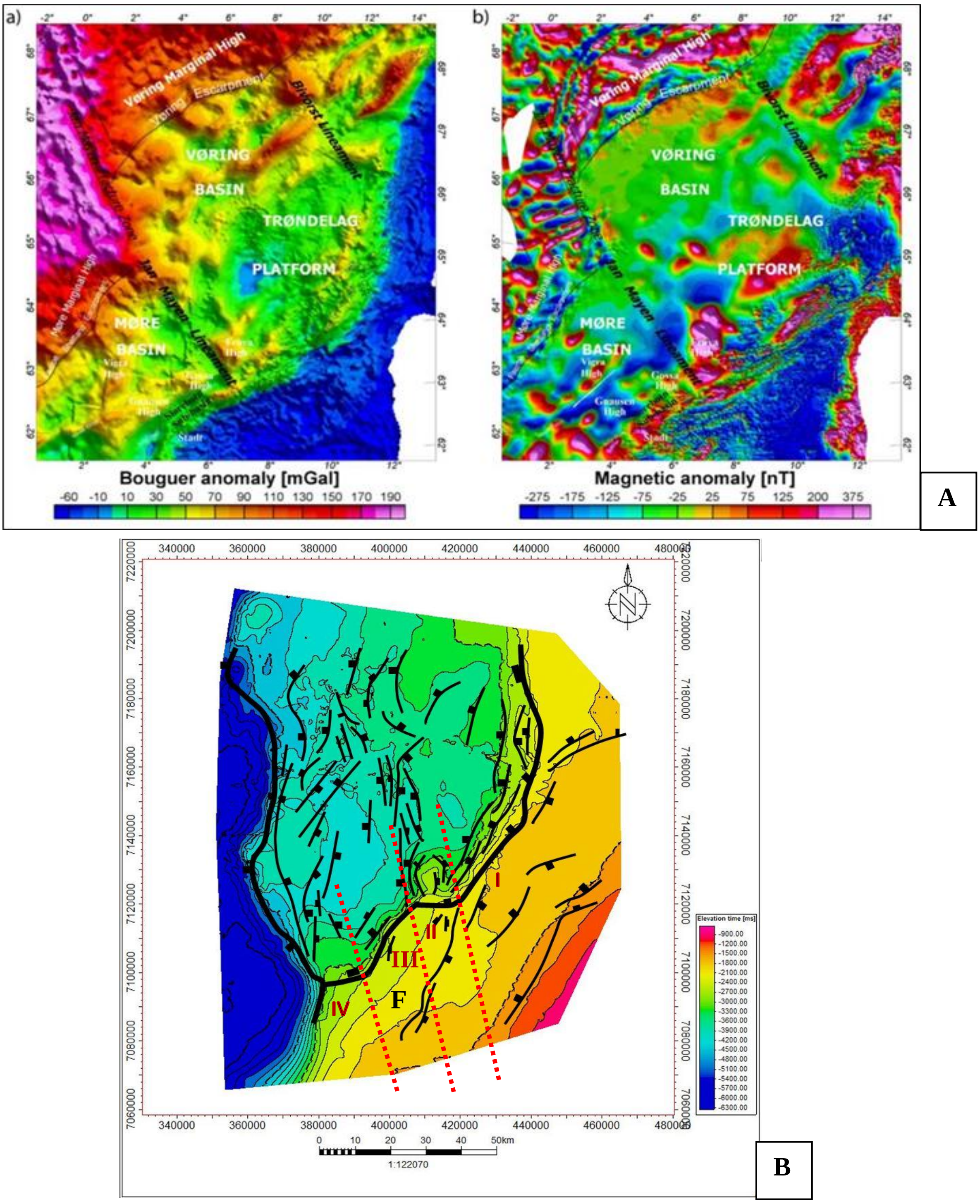


Figure-4.7: (A) Bouguer anomaly and magnetic anomaly maps of the Mid- Norwegian continental margin showing the strong gravity and magnetic field anomaly in the Frøya High (After Olesen et al. 2007). (B) Time-structure and fault map at the Base Cretaceous to show the structural and geometry of the Vingleia Fault Complex. Numbers from 1 to 4 shows fault segmentation, separated by the red broken line. Frøya High is bounded by two major faults, Vingleia Fault Complex to the west and fault-A (Fig. 4.2 above) and forming structural high as shown in (Fig. 4.4) with area of strong magnetic field.

Extensional forced folds are folds whose overall shapes and trends are controlled by shapes and trends of underlying forcing members (Stearns, 1978). In this thesis, the Triassic evaporite unit, acting as detachment (dashed line), commonly are present between folded strata and underlying fault blocks. These folds area formed, because the Triassic evaporite unit behaves in a ductile manner to the underlying forcing members, decoupling overlying strata from underlying faulted strata and basement. Features related to the above structural style (Figs. 4.8a & b) are identified at different positions along the study area. The Triassic unit in key profile-1 (Fig. 3.16) was observed as to be a detachment layer, decoupling the upper strata from the underling basement.

Structural style resulting from the modifying influence of salt layer have been interpreted as extensional forced folds, fault propagation folds, basement-involved and basement-detached normal faults (Withjack et al., 1989, 1990; Pascoe et al., 1999; Corfield & Sharp, 2000; Stewart et al., 1996 and Richardson et al., 2005). On the hangingwall this evaporite layer separates faults a & c confined to the pre-evaporite strata and these above the evaporite unit, faults b, e, f & g. Features related to extensional forced folds and basement detached normal faults (Withjack et al., 1989; Stewart et al., 1996; Richardson et al., 2005) were observed (Figs. 4.8a & b). Profile-4, (Figs. 3.20 & 4.8b) shows an interpreted extensional forced fold (dotted line) and the Triassic evaporite layer (colored in yellow) displaced by upward propagating, basement involved normal fault.

The observed master fault in profiles 4, 6 & 7 (Figs. 3.20, 3.23 & 3.24) is related to a basement-detached normal fault where the fault plane seismic reflectivity can be traced below ca. 9 TWT. As Withjack et al. (1989), Pascoe et al. (1999), Corfield & Sharp, (2000), Stewart et al. (1996) and Richardson et al. (2005) discussed, basement-detached normal faults are upward propagating faults and are directly linked to the basement structure (Figs. 4.8a & b)

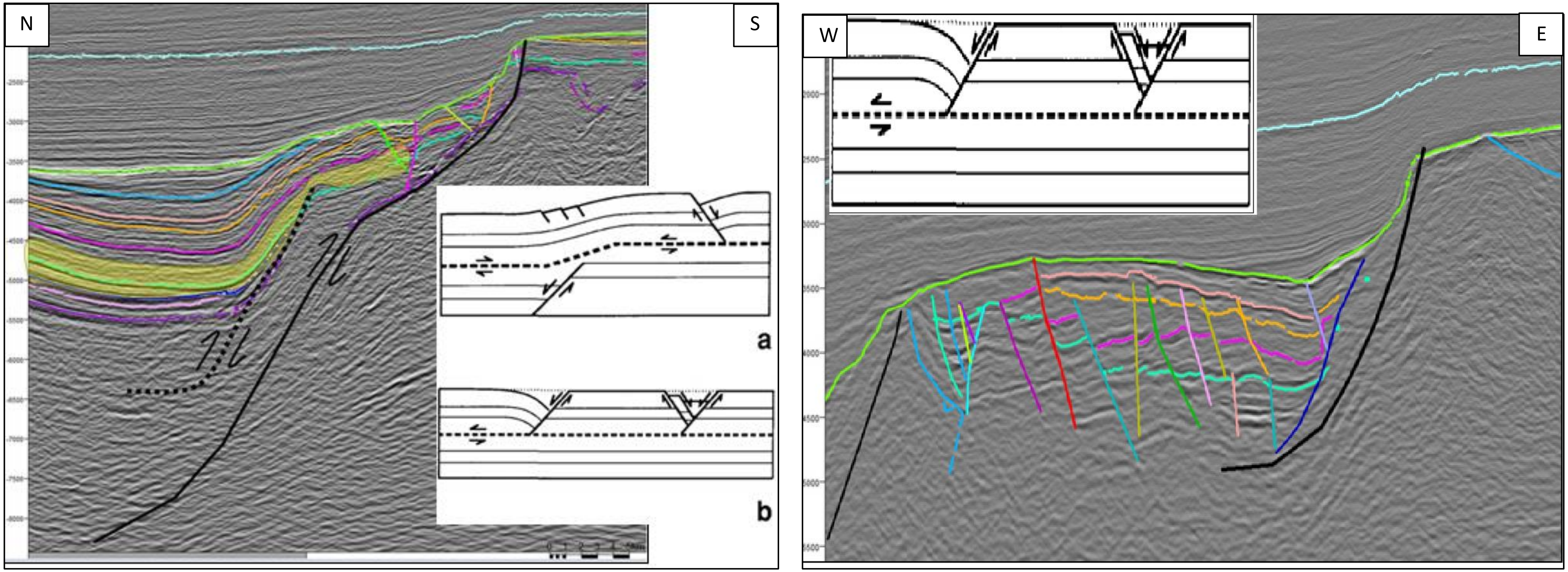


Figure-4.8: (A) Schematic cross sections showing (a) an extensional forced fold and (b) basement-detached normal fault (Withjack et al., 1989). Seismic profile showing extensional forced fold and basement- involved fault blocks, Key profile-4 (segment-II), the yellowish colored sediment strata is the proposed Triassic evaporite unit. (B) Seismic key profile- 7 (segment-III) W-E strike orientation show basement-detached normal faults (listric fault).

4.2 Geological evolution

The geological evolution of the study area (Figs. 4.9 & 4.10) in relation to the regional tectonic events is described below covering the three main tectonic phases, the Late Palaeozoic-Early Mesozoic phase, the Late Jurassic-Early Cretaceous phase, and the Late Cretaceous-Cenozoic phase. Time-structure, fault and time-thickness maps will be used to illustrate the geological development of the study area through time.

4.2.1 Late Paleozoic-Early Mesozoic phase

The basement, pre- Devonian was the oldest stratigraphic level confirmed in the study, where well data from well 6407/10-3 located wthin the Frøya High confirms the presence of fractured granitic basement at TD of 2958.5 m and the strong nature of the seismic reflectivity at 2.5 s TWT can be related to the well data findings. Faults D & E below the Froan Basin (Fig. 4.3), marks a deeper structure**.** Fault-D is dipping land-ward, whereas fault-E dipping basin-ward and this indicates a buried deeper structure below the Triassic evaporite stratigraphic level and over-printed by younger tectonic events. This observation is supported by the Osmundsen et al. (2002) and Osmundsen & Ebbing (2008) interpretations that the Froan Basin is characterized by Permian deposits with southeast facing half-graben geometry.

Triassic sediments, undifferentiated Late to Middle Triassic Red Beds are documented by some of the selected well data (Table-2) and the seismic data also show strong seismic reflectivity, where these Late Triassic sediment units are present (Figs. 4.9 a & b). This strong seismic reflectivity pattern was followed on mapping the evaporite unit in the study area. The time- thickness maps between Top Triassic evaporite-A unit-Top Åre Formation and Top Åre-Top Tilje formations of the Late Triassic to Early Jurassic and Early to Middle Jurassic stratigraphic levels respectively (Figs. 3.36, 3.37, 3.38 and 3.39) shows the presence of the Vingleia Fault Complex during this tectonic phase (Fig. 4.9). Dorè et al. (1997), Gabrielsen et al. (1999), Osmundsen et al. (2002), Faleide et al. (2008) and Osmundsen & Ebbing (2008) argued that the reactivation of Late Paleozoic to early Mesozoic faults may have influenced the development of the Jurassic rift system of the study area and the older structures are overprinted by younger tectonism and thick sedimentary strata.

4.2.2 Late Jurassic-Early Cretaceous phase

The wedge shaped sediment infill toward the Vingleia Fault Complex of the Melke and Spekk formations could indicate a syn-rift tectonic event. Late Jurassic to Cretaceous rifting is characterized by intracontinental rifting and caused c. 50-70 km of crustal extension (Skogseid et al., 2000; Faleide et al., 2010).The Base Cretaceous Unconformity stratigraphic level in the seismic data shows a major unconformity surface and marks tectonic break transition period to post-rift sedimentation (Fig. 4.10a). The time-thickness map (Fig.3.38), between the Top Tilje Formation to Base Cretaceous stratigraphic levels (Middle Jurassic to Early Cretaceous) represents the above phase where thickness variation of sediment along the hangingwall and the footwall along the Vingleia Fault Complex may indicate fault movement (Figs. 4.9 & 4.10). According to Færseth & Lien (2002) the Cretaceous sedimentation represents a post-rift subsidence stage in a setting characterized by tectonic quiescence whereas Tsikalas et al. (2012) explains the extension event during Aptian composite tectonic phase, where continued extension in early Cretaceous resulted in deep burial of overprinted Jurassic domains and rapid maturation of Jurassic source rocks.

4.2.3 Late Cretaceous-Cenozoic phase

The Base Cretaceous to Early Paleocene time-thickness map (Fig. 3.39) displays the features bounding the Halten Terrace and the sediment thickness variation of deposition related to rift-episode that formed a more than 300 km wide zone associated with lithospheric thinning and post-breakup subsidence (Figs. 4.10a & b) (Blystad et al., 1995; Dorè et al., 1997; Brekke, 2000; Skogseid et al., 2000; Faleide et al., 2010). The Rås Basin is characterized by thicker sedimentary units separated from the Halten Terrace by the Klakk Fault Complex which is intermediate in sediment thickness, whereas the Trøndelag Platform and the Froan Basin separated by the Vingleia-Bremstein fault complexes are characterized by thinner sedimentary strata. According to Blystad et al. (1995), Grunnaleite & Gabrielsen (1995) and (Faleide et al., 2010) the Late Cretaceous rifting phase shaped the Halten Terrace to the present structure with faulting associated with the Bremstein and Vingleia fault complexes.

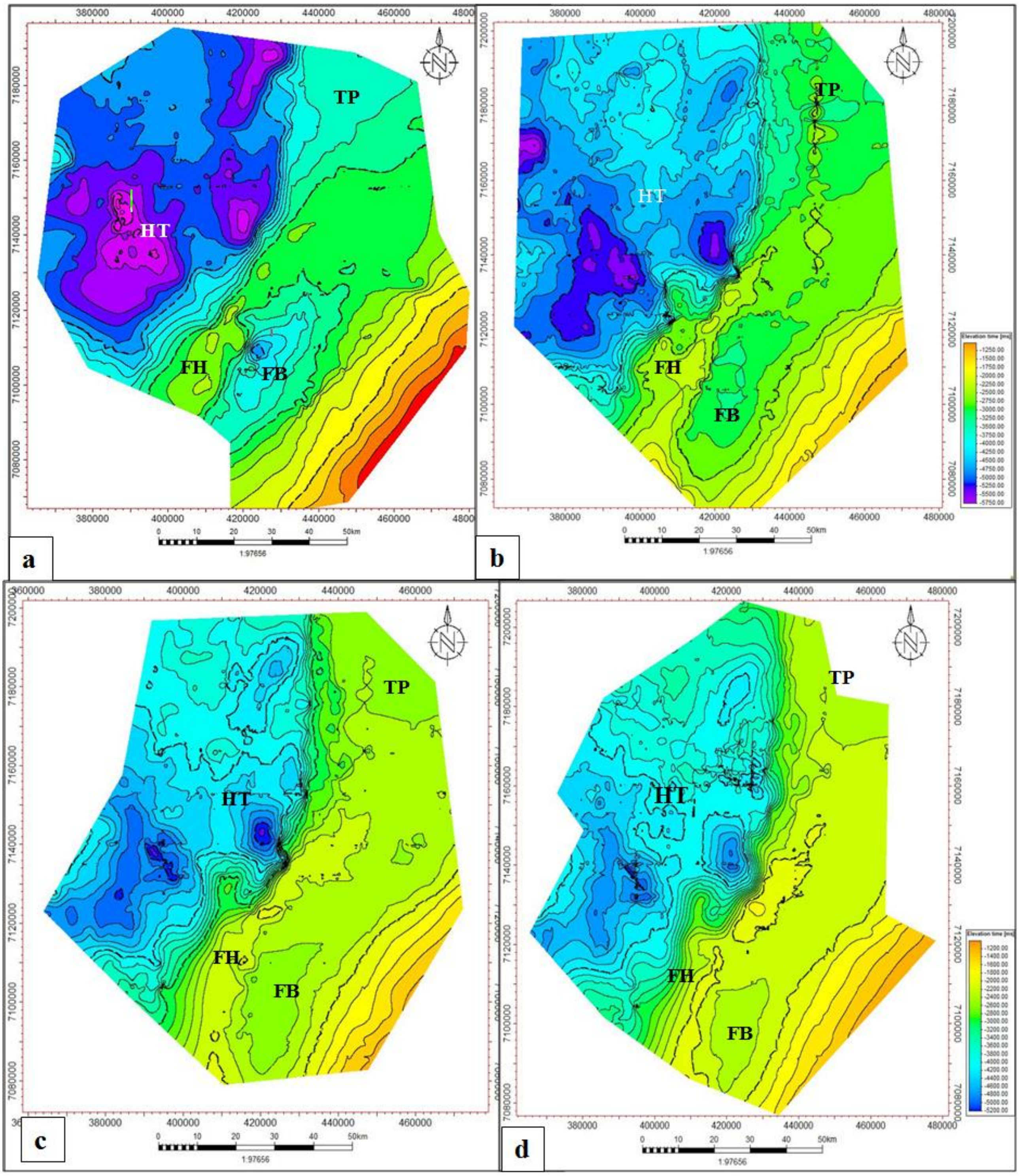


Figure-4.9: Time-structure map (a), Base Triassic evaporite-B (b),Top Triassic evaporite-A (c),Top Åre Formation (d), Top Tilje Formation, stratigraphic levels. The Vingleia Fault Complex appears the major feature in the entire four time-structure map that delineates the Halten Terrace from the Trøndelag Plat form, Frøya High and the Froan Basin. The Froan Basin separated from the Frøya High by a major normal fault, east dipping and the west-dipping fault separating from the main land. HT: Halten Terrace, FH: Frøya High, FB: Froan Basin, TP: Trøndelag Platform.

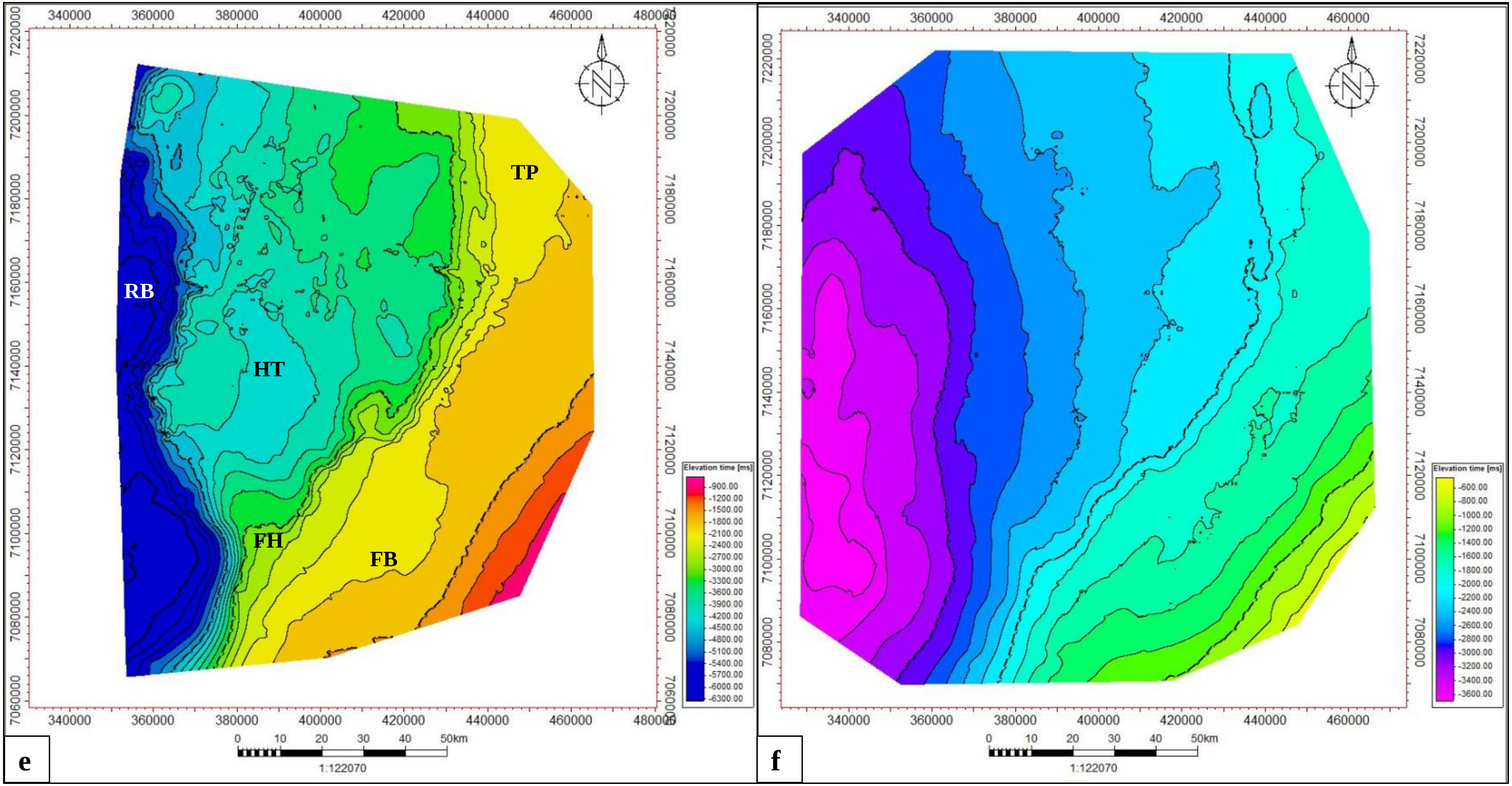


Figure-4.10: Time-structure map, continuation from the above, (e) Base Cretaceous Unconformity shows most of the structures bounding the Halten Terrace and pockets of depocenter developed to a single depocenter. (f) Base Cenozoic stratigraphic level shows west-deeping sedimentary sequence and a major change in tectonic event. HT: Halten Terrace, FH: Frøya High, FB: Froan Basin, TP: Trøndelag Platform, RS: Rås Basin.

5. Conclusion

The Vingleia, Bremstein and Klakk fault complexes and the Kya Fault Zone are the main structural elements of the study area. At the Base Cretaceous Unconformity stratigraphic level, the Klakk Fault Complex is characterized by wider heave zone and larger fault throw than does the Vingleia Fault Complex. The Vingleia Fault Complex on the other hand shows wider heave and throw in the northeastern part compared to the southern part of the study area.

The four segments of the Vingleia Fault Complex show variable fault geometry and style of deformation. Segments I and III are characterised by listric fault geometry where the evaporite unit is the detachment layer. Segments II and IV show a characteristic ramp-flat-ramp fault geometry and a pronounced rollover structure above the flat was a distinct observation along the two segments. The basement and the evaporite layer have strong influence in modifying the shapes of these faults. Therefore the Vingleia Fault Complex shows changes in strike and dip direction across the study area. The Vingleia Fault Complex was reactivated in different tectonic periods. Faults which terminate on the Triassic evaporite unit from bottom (blind faults) form fault propagation folds, whereas faults (normal faults) displacing the evaporite unit are characterized by basement-involved faults.

The study area consist two sets of fault generation, particularly in the northern part. One set of faults are populated above the evaporite unit and terminate from top at the evaporite unit whereas the second set of faults are populated below the evaporite unit and terminates from the base at the evaporite unit. Therefore this leads to conclude that the area could have been subjected to several tectonic events or these sets of fault can be generated in the same tectonic events.

The evaporite unit is thicker and slightly deformed away from the master fault, whereas thinner and strongly deformed towards the Vingleia Fault Complex. This leads to the conclusion that the evaporite movement and salt related deformation has strongly affected the structural style and fault geometry in the study area.

The three tectonic phases, Late Palaeozoic-Early Mesozoic phase, Late Jurassic-Cretaceous phase, and Late Cretaceous-Cenozoic phase decribes the geological evolution of the study area . Well and seismic data confirms the presence of fractured granitic basement of the pre-Devonian in age, particularly along the Frøya High. The time-thickness maps between Top Triassic evaporite-A unit-Top Åre Formation and Top Åre-Top Tilje formations of the stratigraphic levels respectively shows the presence of the Vingleia Fault Complex during this tectonic phase.

During the Late Jurassic-Early Cretaceous phase, the Base Cretaceous Unconformity stratigraphic level in the seismic data shows the major unconformity surface and tectonic subsidence. Thickness variation of sediment along the hangingwall and the footwall along the Vingleia Fault Complex may indicate thermal contraction and followed by tectonic subsidence. During Late Cretaceous-Cenozoic phase the Rås Basin and the Halten Terrace is characterized by thick and intermediate in sedimentary thickness respectively, whereas the Trøndelag and the Froan Basin are characterized by thinner sediment strata.

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