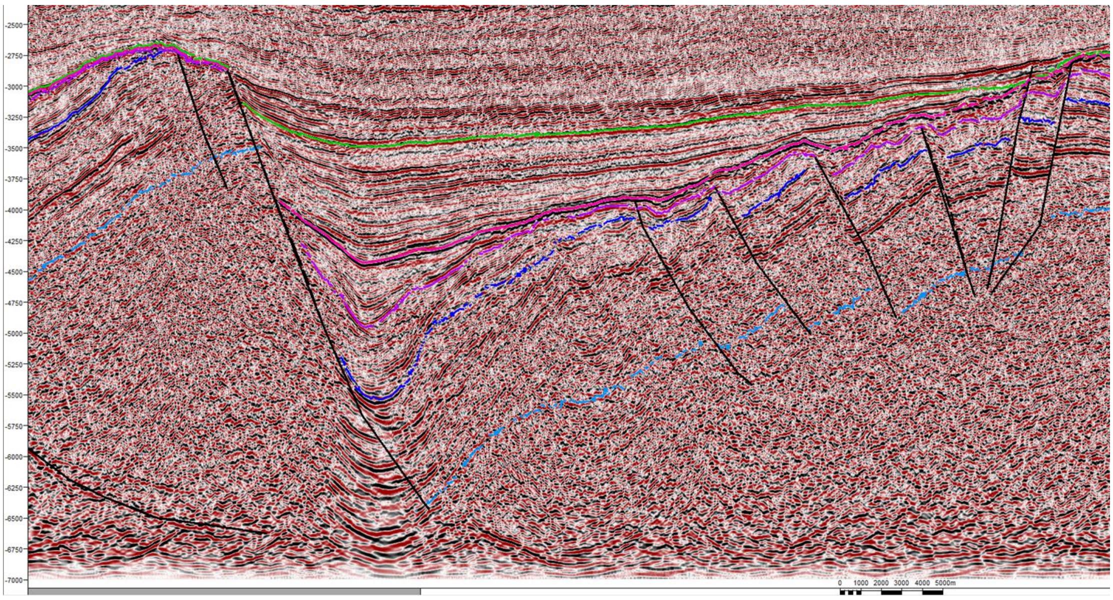
Master Thesis, Department of Geosciences

Structural evolution of the northern North Sea – with links to the adjacent onshore geology

Are Reiakvam



Structural evolution of the northern North Sea – with links to the adjacent onshore geology

Are Reiakvam

Master Thesis in Geosciences

Discipline: Petroleum Geology and -Geophysics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

University of Oslo

10.03.2015

Abstract

As the northern North Sea has experienced multiple tectonic events it is important to investigate each one to gain understanding of their significance and structural impact. This study focuses on the structural development of the northern North Sea, between 60°30'-62°N and 2°30'E to approximately 6°E, taking onshore elements and evolution of the Western Norwegian mainland into consideration for the geological history of the northern North Sea. With the use of 2D-seismic lines and wells one can get a better understanding of the subsurface by studying its geometry and its relation to surrounding areas.

The study area have at least undergone three major extensional periods during Paleozoic-Mesozoic times. The youngest event, the Late Jurassic-extension, was confined primarily within the present-day Viking Graben and Sogn Graben linked to the triple junction-development, caused by the updome of the central North Sea. The development of large grabens as well as structural terraces proximal to the graben axis was controlled by transfer zones, and these were also responsible for the eastward shift of the rift axis. The transfer zone was located at Marflo Spur, possibly assisted by the shear zone feature Marflo Lineament, stretching across both onshore and offshore areas. The Permian-Triassic extensional event involved major fault block development and -rotation of the Horda Platform as well as proto-grabens of the Viking Graben and Sogn Graben. The rift's boundaries are defined by the N-S trending en-echelon faults Øygarden Fault Complex to the east and Hutton Fault to the west. Fault-polarity reversal during this event is associated with the transfer zone protruding from the mainland at 61°N, likely the offshore continuation of the Nordfjord-Sogn Detachment.

The oldest extensional event is likely of Devonian-Carboniferous(?) age, related to the Caledonian denudation in southern Norway. Traces of this event are found mainly on the Western Norwegian mainland with the extensive shear zone, the Nordfjord-Sogn Detachment, and the Devonian basins located above this detachment. The offshore continuation of the detachment can be observed in the northern North Sea; however this feature was not important for the future development of the area as this structure has been cut by younger structures. Even though Devonian sediments have not been detected in any wells on Norwegian territory, it is speculated in a Devonian presence on the Horda Platform.

Preface

This master thesis is a one-year project within the discipline of Petroleum Geology and – Geophysics, at the Department of Geosciences, University of Oslo. The thesis is also a part of the MultiRift project, a collaboration project between University of Oslo, University of Bergen, the University of Manchester and the Imperial College London. The MultiRift project is a Petromaks project funded by the Research Council of Norway and Statoil. The intention of the project is to gain an understanding of pre-existing structural controls on normal fault growth, tectonic geomorphology and sedimentation in multiphase rifts like the northern North Sea.

Acknowledgement

I would like to express my thankfulness toward my supervisor, Prof. Jan Inge Faleide, for giving me this task and opportunity to work with such an interesting and challenging topic. His guidance and time spent on our discussions are very much appreciated. I would also like to give many thanks to Dr. Michel Heeremans for setting of his time and the help-outs with the technical parts of the thesis. Big thanks go to the TGS and Fugro for providing the 2D-seismic lines used in this thesis.

Additionally, I wish to express my sincere gratefulness to all my family, who have always been there for me and always can depend on. Their support and encouragements through bright times and dark times will always be appreciated. Thanks to my nieces and nephews for their joyful and energetic nature, living up anyone's day.

A big shout-out to all my ever-precious friends, both within- and outside the geology-circle, for marvellous times. I would like to thank my friends at room 217 for our conversations and discussions, feedbacks and coffee-breaks. A special thank goes to some others as well.

I lastly want to thank the geology of northern North Sea and the Nordfjord-Sogn Detachment for their structural complexities, without them this thesis would be rather futile and tedious.

Table of Contents

1. Introduction

The North Sea shows many structural complexities that have been imprinted by many important events throughout the geological history. As a feature that was a part of the Caledonian mountain chain to be a present day submarine basin, many structural footprints have been left behind along the path of its geological evolution. Since the North Sea is a very important site for Norway and the beginning of its history of hydrocarbon exploration and -production, the area has been subjected to numerous scientific studies.

The study area of this thesis is confined in the northern part of the North Sea (Figs. 1.1 and 1.2), between 60°30'N and 62°N and from 2°30'E and eastward across the coastal parts of Western Norwegian mainland, approximately to 6°E. The seismic data in this study extends to approximately 4°40'E. The study area includes structural grabens, terraces and highs that have a significant impact on the petroleum system. The Viking Graben trends NNE-SSW, whereas Sogn Graben has a N-S trend. The study area to the south of 61°N is characterised by the wide, sub-platform Horda Platform to the east and the deep Viking Graben to the west, separated by the Lomre Terrace in between. Further north the Lomre Terrace and Viking Graben continues, where the former neighbours the Uer Terrace and the latter with the East Shetland Basin. The Øygarden Fault Complex dominates the easternmost part of study area north from this point as well. As the Viking Graben reaches it northward extent the Sogn Graben becomes apparent about 61°20'N where it widens northward. The graben is confined between the Måløy Fault Blocks to the east and Tampen Spur and Marflo Spur to the west. The study area barely rubs shoulder with Marulk Basin to the northwest. The onshore part of thesis presents the sedimentary Devonian basins, located in Sogn og Fjordane, Norwegian Western mainland (Fig. 1.2). From north to south they are named Hornelen Basin, Håsteinen Basin, Kvamshesten Basin and Solund Basin (Osmundsen and Andersen, 2001; Braathen et al., 2004).

The structural evolution of the North Sea has been extensively investigated and documented (e.g. Badley et al., 1988; Færseth et al., 1995, 1997; Færseth, 1996; Ravnås et al., 2000; Faleide et al., 2010; Bell et al., 2014). Recent work on this topic has been accomplished by Bell et al. (2014). They have studied the structural configuration of the northern North Sea with special emphasis on the Horda Platform and Viking Graben during the Permian-Triassic and Late Jurassic evolution and how they relate to each other. Færseth et al. (1995, 1997) and Færseth (1996) have tried to explain the evolution of the northern North Sea based upon structural grains of the basement rock, formed by the Caledonian orogenic belt and its extensional collapse.

The goal of the thesis study is to investigate and discuss the structural evolution of the basin configurations in northern North Sea with main focus on the time period between Permian and Cretaceous. It will also be studied how structural elements on the mainland may have affected the development of the offshore areas due to the presence of major shear zones related to the Caledonian denudation.

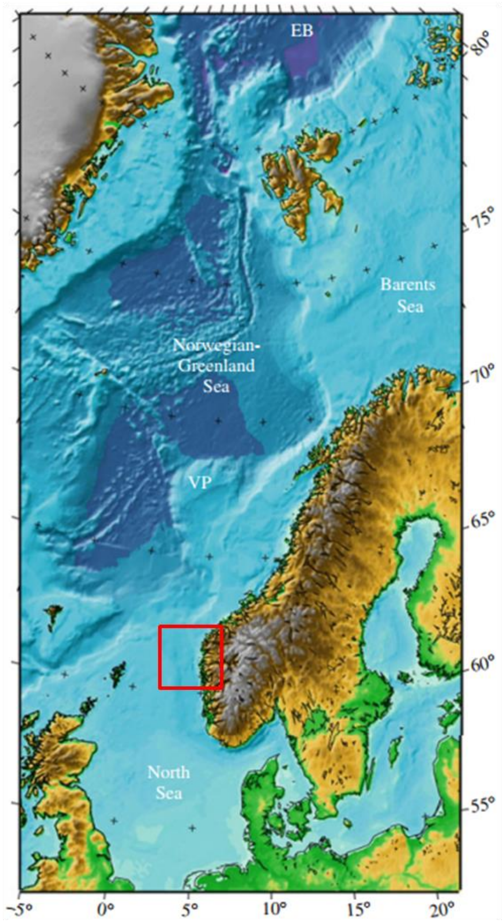


Fig. 1.1 Map of the North Sea and South-Norway with area of study in the red box. Modified from Faleide et al., 2010. EB = Eurasia Basin, VP = Vøring Plateau

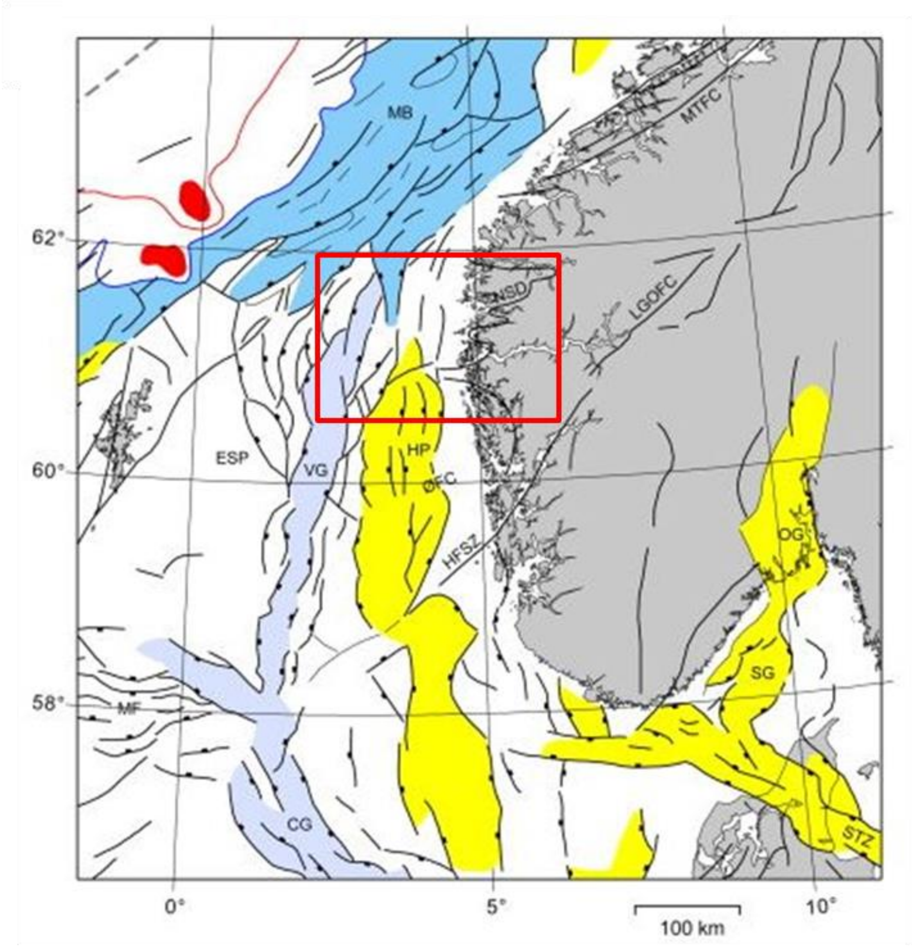


Fig. 1.2 General structural map of the North Sea, study area outlined in red box. Modified from Gabrielsen et al. (2010). ESP = East Shetland Platform, HP = Horda Platform, MB = Møre Basin, OG = Oslo Graben, SG = Skagerak Graben, STZ = Sorgenfrei-Thornquist Zone, MTFC = Møre – Trøndelag Fault Complex, ØFC = Øygarden Fault Complex, HFSZ = Hardengerfjorden Shear Zone, NSD = Nordfjord-Sogn Detachment, LGOFC = Lærdal-Gjende-Olestøl Fault Complex.

2. Geological setting

This chapter will give a general geological development of the Devonian basins on mainland Western Norway and the Late Paleozoic to present evolution of the northern North Sea area. Structural elements found on mainland Norway will first be presented before giving a description of the Devonian basins and their development. Lastly, a short structural evolution of the northern North Sea will be presented, with special emphasis on the Permian-Triassic- and Jurassic - Cretaceous extensional events.

2.1 Structural elements of the mainland, Western Norway

Regional detachments and fault complexes in central Norway played major roles during the extension and denudation of the Caledonides (Andersen, 1998; Braathen et al., 2000), such as the Nordfjord-Sogn Detachment and the Møre-Trøndelag Fault Complex (Braathen et al., 2000). The Nordfjord-Sogn Detachment (NSD) is overall oriented in a N-S trend and it juxtaposes sedimentary rocks in the hanging wall with Devonian footwall eclogites, and the detachment itself consists of mylonite and diverse fault rocks, reflecting structural changes and activity related to the tectonic denudation. Movements in the NSD was generally by creeping in its early stage and earthquake related slip-movements in its later stage (Braathen et al., 2004). The brittle development along the detachment formed the Dalsfjord Fault, a scoop-shaped fault detaching beneath the Kvamshesten Basin, along the mylonites of Nordfjord-Sogn Detachment (Osmundsen et al., 1998) and is likely of a Late Devonian age (Braathen et al., 2004). The detachment is confined approximately between 61-62°N (Færseth et al., 1995) and is associated with a top-westerly directed shearing (Andersen, 1998).

The Møre-Trøndelag Fault Complex is a NE-SW trending sinistral shear zone located parallel to the northeastern coast of Norway (Seranne, 1992; Braathen et al., 2000). The fault complex separates the offshore Møre Basin to the north from the offshore Viking Graben and Sogn Graben to the south (Gabrielsen et al., 1999). As this structure has shown multiple reactivations through time, its tectonic movements has changed from being sinistral in Late Devonian - possibly Early Carboniferous (Seranne, 1992) to dextral and normal dip-slip in Mesozoic. A compressional stage took place in the Cenozoic, causing basin inversion in the Møre Basin, however the northern North Sea was shielded from this event (Grønlie and Roberts, 1989; Gabrielsen et al., 1999).

Another regional structural element, possibly having an onshore-offshore connection, is the Marflo Lineament after Smethurst (2000). It trends NW-SE and has been assigned an origin as early as Precambrium age. It separates the Viking Graben and the Sogn Graben in the North Sea and continues onshore in south-western Norway (Karpuz et al., 1991; Smethurst, 2000). The lineament is a dextral strike-slip feature (Frost et al., 1981), and activity along the onshore part has been registered to be active in modern time Holocene (Karpuz et al., 1991).

2.2 Onshore development of mainland, Western Norway

2.2.1 Caledonian denudation

The Caledonian orogen was at its peak contractional development in the Late Silurian, where nappes were transported east- to top-to-the-ESE above a basal decollement (Andersen, 1998; Fossen, 2000). The denudation of the orogeny evolved through different stages, involving nappe-eduction and the development of major extensional brittle- and ductile shear zones (Fossen and Rykkelid, 1992; Fossen, 1992; 2000; Fig. 2.1). The extension took place in Early-Mid Devonian, and the hinterland-directed movements of the overlying nappes were associated with a westerly to north-westerly directed transport (Norton, 1986; Fossen, 1992; 2000; Fossen and Rykkelid, 1992; Andersen, 1998; Osmundsen et al., 2000; Osmundsen and Andersen, 2001). The formation of the extensional shear zones, the Nordfjord-Sogn Detachment, the Bergen Arc- and the Hardangerfjord Shear Zones, are linked to this denudation stage (Fossen, 2000). There have been suggestions to the cause of the denudation, such as gravitational forces (Andersen, 1998) and plate divergence (Fossen, 1992; 2000). The later stages of the denudation involves the development of the brittle Devonian basins on the present day western mainland (Fossen, 1998; Osmundsen et al., 1998; 2000; Osmundsen and Andersen, 2001).

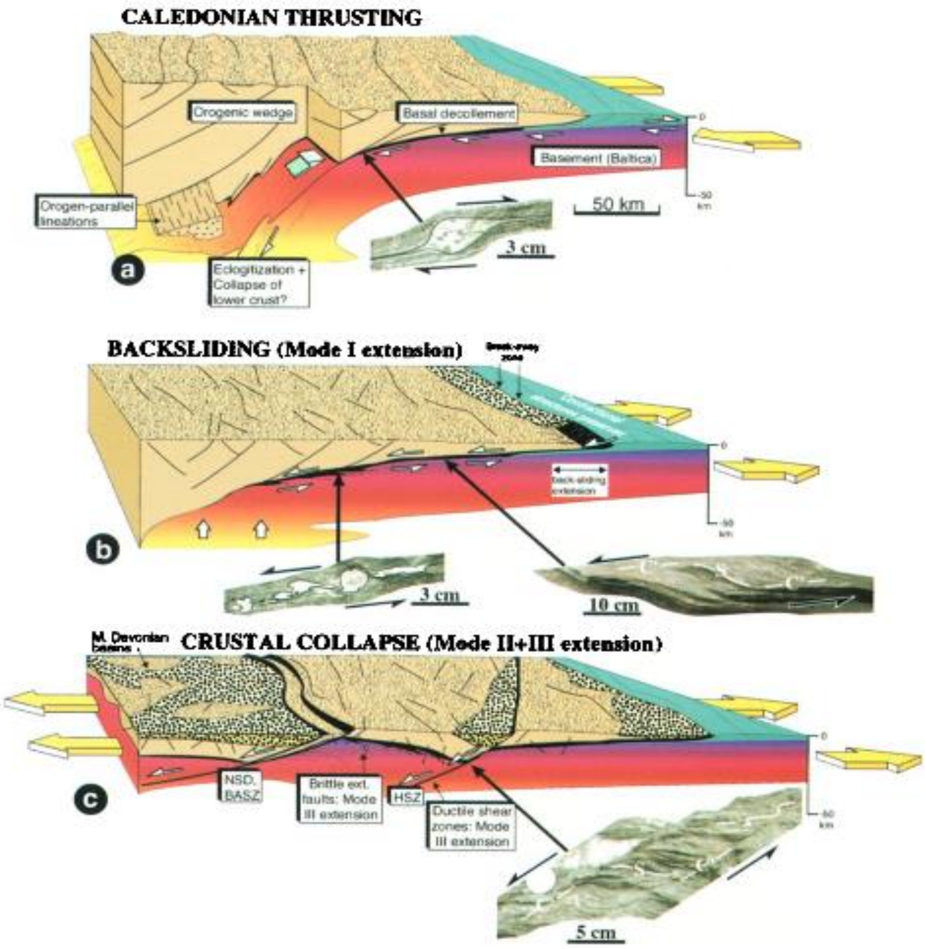


Fig. 2.1 Principal model of the orogenic denudation of the Caledonians. Three stages of extension led to the mountain-collapse, where the first stage involved eduction and the two later stages involve collapse due to ductile and brittle shear zones. The ductile shearing pre-dates the brittle structures. BASZ, Bergen Arc Shear Zone; NSD, Nordfjord-Sogn Detachment. From Fossen (2000).

2.2.2 Onshore Devonian basins

The Devonian sediments are located unconformably atop of the hanging wall Caledonian nappes, as the synclines in the folded hanging wall act as catchments. The anticlines exposes gneisses and eclogites of the Western Gneiss Region. The Devonian continental basins in the western Norway are from the southwest to the northwest; Solund Basin, Kvamshesten Basin, Håsteinen Basin and Hornelen Basin (Osmundsen et al., 1998; Figs. 2.2 and 2.3).

Their basin flanks are low-angled normal faults trending E-W and NE-SW in the synclines and their bases are along the Nordfjord-Sogn Detachment (Wilks and Cuthbert, 1994; Osmundsen et al., 1998; Osmundsen et al., 2000). The basins have half-graben configuration with syn-sedimentary layering dipping E and SE. The Kvamshesten Basin, for instance, is located within a rollover anticline-syncline pair that makes up its basin geometry (Osmundsen et al., 2000). The deposits in the Devonian basins are characterised by alluvial conglomerates and sand along the margins. Toward the centre floodplain deposits associated with axial rivers parallel to the basin margins are present. The alluvial fans are located along the footwalls and the fluvial fans are on the hanging wall (Osmundsen and Andersen, 2001). As the creation of accommodation was high due to subsidence, the basins were filled with thick sedimentary packages. The packages are also observed to be skewed in both a retrogradational and progradational manner, sensitive to varying subsidence rates (Osmundsen et al., 2000). Palaeocurrent data of the river deposits, along with structural configuration, indicate an overall westward extension of the basins (Osmundsen et al., 2000). It is disagreed upon when the folding of the basins took place. As the areas were folded along a N-S compressional axis some have suggested it occurred during the sedimentation (Chauvet and Séranne, 1994; Osmundsen et al., 2000), whereas others suggest it developed after the deposition (Osmundsen et al., 1998). Either scenario, N-S compressional folding led to the development of syncline- anticline pairs where Western Gneiss Region was exposed in the anticlines (Osmundsen et al., 1998).

The Kvamshesten Basin is internally faulted into fault blocks, dipping both NW and NE, and they terminate against the Dalsfjord Fault. The Dalsfjord Fault has been proposed to be a ramp-flat detachment, where the rollover anticline was developed (Osmundsen et al., 1998). The orientations of the basin margins rotate anticlockwise the closer they are to the Møre-Trøndelag Fault Complex. The Solund Basin, located farthest away, has a general NW-SE orientation compared to the Hornelen Basin, located closer to the fault complex, which have an E-W orientation (Osmundsen and Andersen, 2001). Proximal basins south of the Møre-Trøndelag Fault Complex are oriented NE-SW, consistent with the extensional pull to the southwest in a sinistral shear zone (Braathen et al., 2000). With both the Nordfjord-Sogn Detachment and the Møre-Trøndelag Fault Complex being active during the Devonian the western Norway experienced regional extension and rapid denudation, affecting the accommodation space (Seranne, 1992). This explains the syn-rift nature of the alluvial sediments and the trends of the basin margins due to footwall uplift. It is however uncertain on whether the fault complex was active at the same time as the detachment or if it post-dated the detachment (Osmundsen and Andersen, 2001).

The flanks of the Devonian basins have rotated due to the N-S compressional folding. Thus the normal faults became steeper and were reactivated as strike-slip faults (Osmundsen et al, 1998). The denudation has overall been estimated to have occurred in a westward and north-westward direction, with the Solund Basin illustrating a NW-SE extension and Hornelen Basin displaying a ENE-WSW extension (Osmundsen and Andersen, 2001). It has also been shown that extension-direction has changed the tilt of the hangingwall from being SE- to E-dipping in Kvamshesten Basin, indicating a change of extensional-direction from north-west in possibly Early - Middle Devonian to westward directed in Middle Devonian - Early Carboniferous (Osmundsen et al., 1998).

The Western Gneiss Region was exhumed during the denudation of the Caledonian nappes, where Proterozoic orthogneisses have been preserved with little structural deformation. The lower part of the Western Gneiss Region consists of high-grade metamorphic rocks such as eclogites (Andersen, 1998). These are observed in the footwalls of the Devonian basins, located in the anticlines between the basins (Osmundsen and Andersen, 2001).

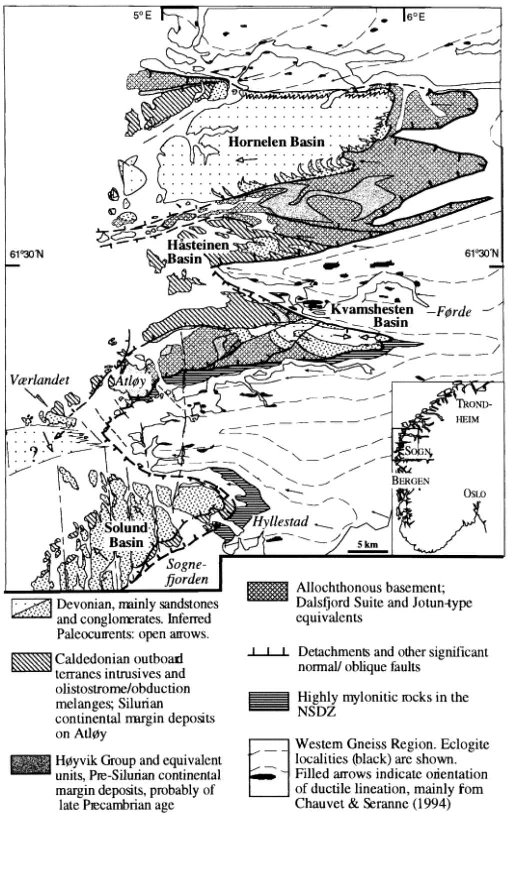


Fig. 2.2 Geological overview of the Devonian Basins, located on the mainland, western Norway. From Osmundsen and Andersen, 2001.

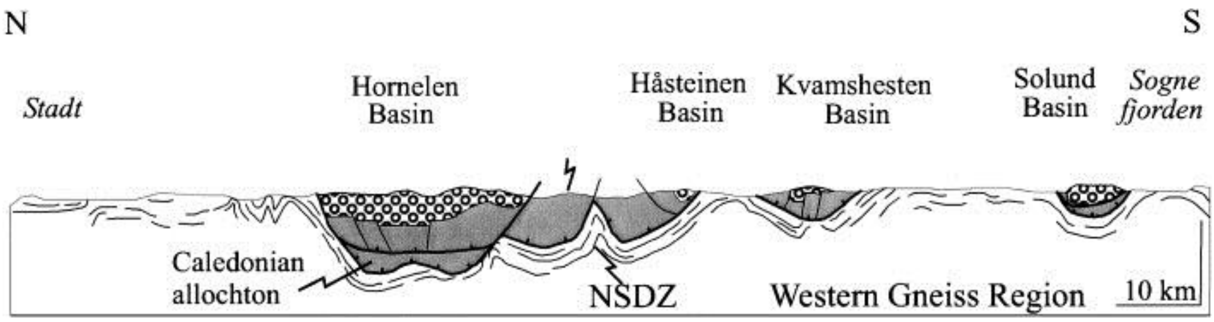


Fig. 2.3 N-S cross section of the Devonian basins, illustrating the underlying Nordfjord-Sogn detachment displaying a folded character. The Devonian basins are confined within the synclines, and the Western Gneiss Region crops out in the anticlines. From Osmundsen and Andersen, 2001.

2.3 Northern North Sea

The northern North Sea stretches from the East Shetland Platform to the west and the Øygarden Fault Complex to the east, and covers an area of 40,000 km^2 (Knag et al., 1995). The area has been influenced by several tectonic events, developing grabens, terraces and sub-platforms (Ziegler, 1990; Færseth et al., 1995, 1997; Færseth, 1996; Faleide et al., 2010, Gabrielsen et al., 2010; Fig. 2.4).

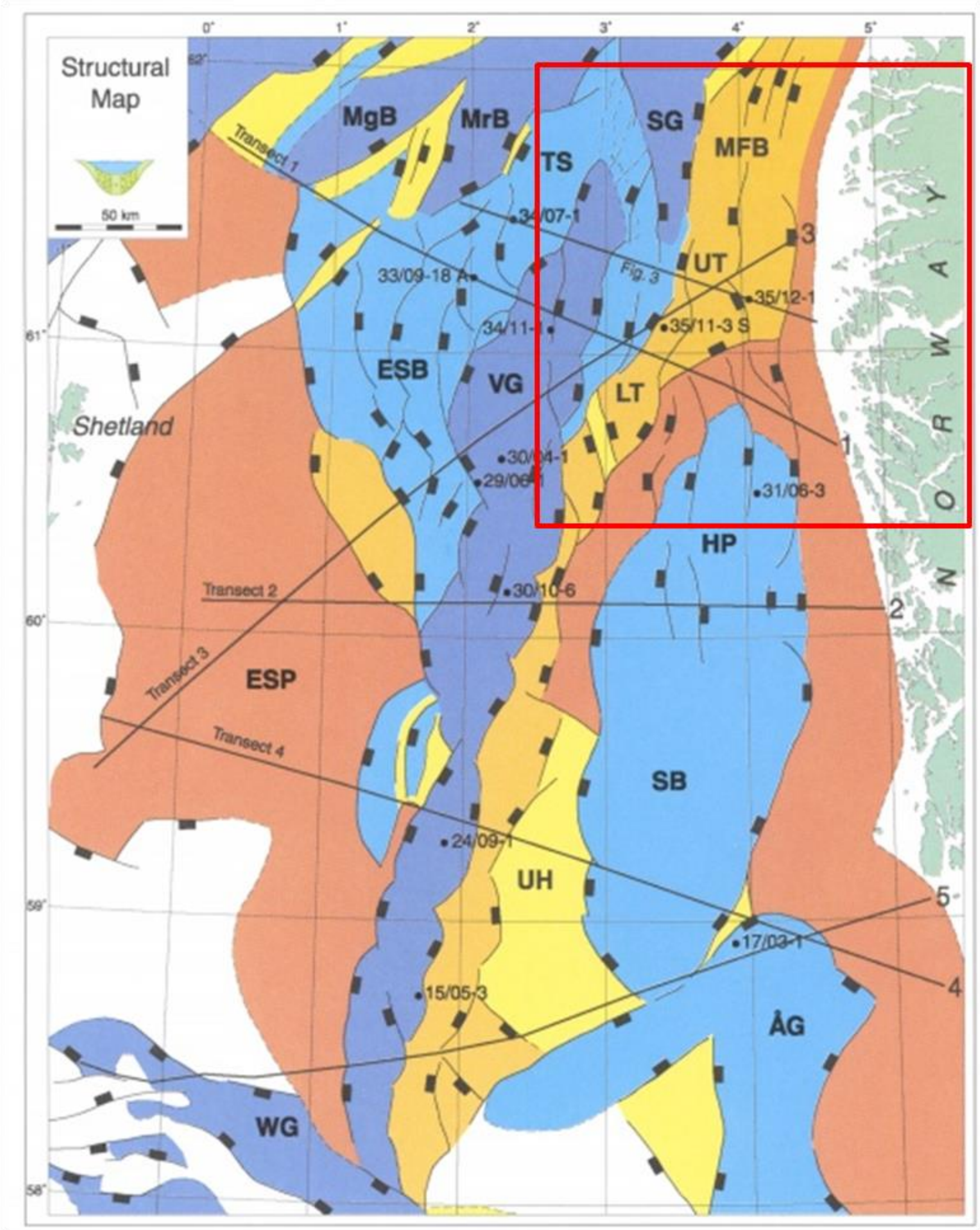


Fig. 2.4 Structural map of the northern North Sea, with encaged study area in red. Modified from Faleide et al., 2002. ESB, East Shetland Basin; ESP, East Shetland Platform; HP, Horda Platform; LT, Lomre Terrace; MFB, Måløy Fault Blocks; MgB, Magnus Basin; MrB, Marulk Basin; SB, Stord Basin; SG, Sogn Graben; TS, Tampen Spur; UH, Utsira High; UT, Uer Terrace; VG, Viking Graben; WG, Witchground Graben; AG,Asta Graben.

2.3.1 Devonian - Carboniferous

The basement of the region is of Caledonian origin. During the Late Devonian the area went from a contractional setting to a strike-slip region between Greenland and Fennoscandia

(Faleide et al., 2010). It is believed that weak zones in the basement, developed during Precambrian and Caledonian orogeny, were areas that would control the future extension in for example the Viking Graben (Gabrielsen et al., 1999). Gabrielsen et al. (1999) also speculated that the same Precambrian and Caledonian deformation style can be found in the basement below the graben. In the boundary of the Devonian and the Carboniferous the lateral shear movements ceased and areal stretching began (Faleide et al., 2010). In Late Carboniferous all faulting activity in the western central part of the Caledonian orogeny had seized (Gabrielsen et al., 2010).

2.3.2 Permian - Triassic

Before the onset of Permian-Triassic rift event the Caledonian domain went from having a crustal thickness of 60 km to just 30-35 km (Sellevoll, 1973; Andersen et al., 1991). The rise of the Variscan orogenic belt in present day Central Europe led to extension in the North Sea due to NW-SE trending strike-slip movements (e.g. Sorgenfrei-Tornquist Zone) associated with orogenic folding. The consequences were rifting and subsidence which affected the entire width of the northern North Sea (Færseth, 1996; Faleide et al., 2010). The Permian-Triassic rifting trended N-S, caused by E-W extension, occupying a 130-150 km wide portion of the North Sea area, bounded by the Øygarden Fault Complex to the east and the Alwyn-Ninian-Hutton alignment to the west in the northern North Sea (Badley et al., 1988; Steel and Ryseth, 1990; Færseth, 1996). The stretching propagated from the north in relation to the Arctic North Atlantic rift system (Gabrielsen et al., 1999). The rift axis has been proposed beneath the present day Horda Platform (Færseth, 1996; Faleide et al., 2010). The Nordfjord-Sogn Detachment from the Devonian was most likely reactivated in conjunction of the development due to the E-W extension matching the orientation of the detachment (Torsvik et al., 1992; Færseth et al., 1995). The Møre-Trøndelag Fault Complex was active in Permian-Early Triassic, and possibly even in Early Carboniferous, separating the northern North Sea and Møre Basin already in this period. Hence slight differences in extensional direction affected these areas (Sturt and Torsvik, 1987; Grønlie and Torsvik, 1989; Gabrielsen et al., 1999).

Extension and subsidence prevailed during the Early Triassic with activity of the master-fault Øygarden Fault Complex on the east side of the Permian-Triassic basin in the North Sea. This fault is a crustal-scale detachment that penetrates all the way down to the lowermost reflective crust apparent in seismic data of the area. It has a planar appearance at the upper part of the crust but becomes more listric downward to the low reflective crust (Gabrielsen et al., 1999). This fault system also affected the East Shetland Basin in the Triassic (Tomasso et al., 2008). The subsequent post-rift episode during the Middle Triassic until Early Jurassic involved subsidence of the northern North Sea by faulting toward the axis of the future Viking Graben. There are however evidence of minor movements against the Øygarden Fault Complex during Late Triassic - Early Jurassic (Steel and Ryseth, 1990; Nøttvedt et al., 1995). Some (Badley et al., 1988; Roberts et al., 1995) however have suggested the post-rift stage terminated later, and was interfered by the renewed rifting in Late Jurassic.

2.3.3 Jurassic - Cretaceous

An important crustal thinning occurred in Middle-Late Jurassic (Ziegler, 1990; Færseth, 1996; Færseth et al., 1997; Christiansson et al., 2000; Faleide et al., 2010; Gabrielsen et al., 2010). This event was not however as extensive as the previous event in the Permian-Triassic (Færseth, 1996). The central part of the North Sea in Middle Jurassic experienced uplift due to high geothermal gradients, leading to volcanic development and exposure of the area which was later eroded (Ziegler, 1990; Faleide et al., 2010). The updoming developed a triple junction, where Viking Graben represent one of the rift arms. As the central North Sea uplifted the northern North Sea subsided in Middle Jurassic (Ziegler, 1990). The prevailing extensional direction during Late Jurassic rifting remain controversial as three stress configurations have been proposed (Færseth, 1996; Bell et al., 2014). Some (Badley et al., 1988) suggest a consistent E-W extension, whereas others propose a continuous NW-SE extension (Færseth, 1996; Bell et al., 2014) or a change of stress field during the Late Jurassic rifting from E-W to NW-SE (Doré and Gage, 1987).

The Middle Jurassic - earliest Cretaceous rift phase comprises two stages of extension and a break in between. The first stage encompasses the late Bajocian-Oxfordian and the latter in Kimmeridgian-mid Berriasian, both stages involving reactivation of N-S trending Permian-Triassic faults and generating new ones, trending NE-SW (Badley et al., 1988; Færseth, 1996; Færseth et al., 1997). The involved fault blocks rotated along the Viking Graben, where their shoulders were uplifted and formed islands (Badley et al., 1988; Rattey and Hayward, 1993; Faleide et al., 2010). Thus Jurassic strata and even parts of the Triassic strata in the upper part of the blocks were eroded away to form an unconformity (Faleide et al., 2010). The rifting however was more distinctive along the western margin of the Viking Graben, making it asymmetric in appearance by the development of en échelon-pattern (Færseth, 1996, Færseth et al., 1997). Some of the Permian faults were reactivated, but new faults trending N-S and NNE-SSW were also generated (Færseth, 1996; Gabrielsen et al., 1999). The Horda Platform however was not largely affected by this rifting due to the Sogn Graben in the north acting as a relay in the rift-system (Færseth, 1996; Bell et al., 2014).

As the active rifting ceased during the Cretaceous thermal cooling of the North Sea gradually happened, leading to subsidence. In the northern North Sea this post-rift evolution is divided into three stages. The initial stage occurred in Early Cretaceous with uneven subsidence where the previously developed structures in the rift basin influenced the basin setting with block rotations and sediment deposition. The next stage during the Cenomanian-late Turonian involved less subsidence rate due to higher sediment supply. In the final stage in early Coniacian-early Palaeocene subsidence ceased completely (Badley et al., 1988; Gabrielsen et al., 2001; Faleide et al., 2010). Though some faulting has occurred in the Sogn Graben area during Early Cretaceous as a reaction to further development of the Møre Basin to the north (Gabrielsen et al., 1999; 2001; Bugge et al., 2001). There has also been evidence of further fault activity in the Møre Basin after Cretaceous, but this seems to had no effect on the Viking Graben, and has been related to the Møre-Trøndelag Fault Complex and presumably its reactivation in the Cenozoic (Gabrielsen et al., 1999).

2.3.4 Cenozoic - present

The seafloor spreading associated with the NE Atlantic began in early Cenozoic with uplifts, related to the Icelandic plume, of the East Shetland Platform, becoming an important source for the depocentres in the Viking Graben area. Uplifting of southern Norway in Eocene-Oligocene caused prograding units to develop in northern North Sea, and continued uplift and sea level fall formed erosion to the north and large depocentres in the southeastern North Sea (Faleide et al., 2010; Gabrielsen et al., 2010). Erosion of the Norwegian mainland continued into the Pliocene, where Late Pliocene uplift developed angular unconformity with the overlying Pleistocene on the eastern margin in the North Sea. The Pliocene-Pleistocene period was characterised by glacial activity, as the sedimentary sequence is partly glacial and partly marine in origin (Faleide et al., 2002, 2010; Gabrielsen et al., 2010). The Holocene deposits are only very thin in the North Sea due to trapping of sediments in the fjords (Faleide et al., 2010).

3. Seismic Interpretation

3.1 Data

The data sets used in this thesis are 2D seismic lines and well data (Fig. 3.1). The 2D lines are provided by TGS and Fugro, and as they originate from different surveys they have varying orientations and quality. Table 3.1 depicts each of these characteristics. The well data consist of eight selected wells; seven of them reaching down to basement. These data combined with the seismic were used to map key surfaces to investigate the sedimentary packages and structural evolution of the eastern flank of northern North Sea.

The general well information along with lithostratigraphic data of each well is summarised in Table 3.2, and has been taken from the Norwegian Petroleum Directorate (NPD). The wells reaching the top basement are 35/3-2, 35/3-4, 35/3-5, 35/9-1, 35/9-2, 36/1-1 along with 36/1-2, and are commonly located on structural highs and rotated fault blocks. All of them are located in the north-eastern side of the study area. The last well, 35/8-3, has been used to correlate the Jurassic- and Cretaceous strata. Their positions are marked as blue points on Fig. 3.1.

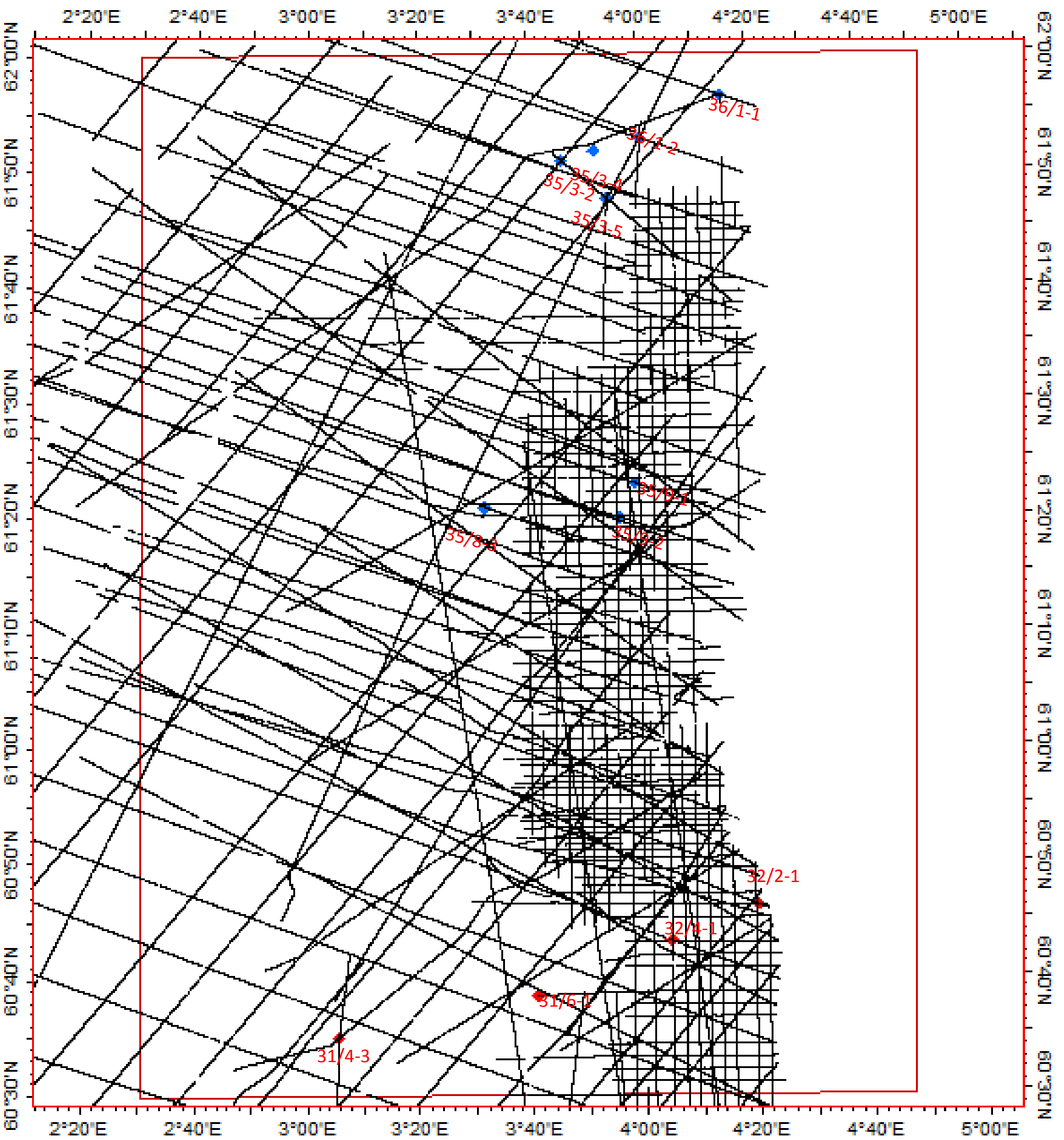


Fig. 3.1 Coverage of seismic data and wells used in the project. The blue wells were included in Petrel, whereas the red wells were not.

Both 35/3-2 and 35/4-3 were drilled on the Måløy Fault Blocks, between the Øygarden Fault Complex and the Sogn Graben. Their total depths are 4400 m RKB and 4089 m RKB, respectively. Well 35/3-5 is located in the same area and its total depth is 4114 m RKB. Wells 35/9-1 and 35/9-2 were developed on the southern part of the Måløy Fault Blocks near the fault boundary of Uer Terrace. Their total depths are 2350 m RKB and 2885 m RKB, respectively. Well 36/1-1 was drilled down to a total depth of 1596 m RKB. It is located in the northern part of the study area on the Måløy Fault Blocks. Well 36/1-2 was entered in the same area, reaching down to a total depth of 3255,6 m RKB (NPD - FactPages).

The well 35/8-3 was used for correlation purposes, and is located within the southern part of Sogn Graben. It was drilled with a total depth of 3944 m RKB, reaching down to the Rannoch Formation of middle Jurassic age (NPD - FactPages).

Additionally, four more wells have been included in this study, but not in Petrel. These are the wells 31/4-3, 31/6-1, 32/2-1 and 32/4-1, all located on Horda Platform (marked as red points on Fig. 4.1). They have mainly been used to gain a better understanding of the sedimentary packages and their ages in the deeper parts of the fault blocks in Horda Platform. These wells have been summarised in table 3.3, and wells 31/6-1 and 32/4-1 have been drilled down to basement.

Data set	**Main orientation(s)**	**Resolution**	**Colour of polarity**
NVGTI-92	NW-SE	Medium	Red White Black
NVGT-88	NW-SE NNE-SSW	Medium-Poor	Red White Black
NSR	NE-SW NWW-SEE	Good	Seismic default
SG8043	NE-SW NNW-SSE NW-SE	Good	Seismic default
GE8601	N-S E-W	Medium	Seismic default
GE8901	N-S E-W	Good	Seismic default
GE8902	N-S E-W	Medium	Seismic default
TE90	N-S E-W	Good	Seismic default
TE93	N-S E-W	Good	Seismic default

Table 3.1. Data sets used in this project and their characteristics.

Age		Lithostratigraphic unit		Wells used in Petrel							
Era	Period	Group	Formation	36/1-1	36/1-2	35/3-2	35/3-4	35/3-5	35/9-1	35/9-2	35/8-3
Cenozoic	Neogene	Nordland Gp.		191	251	297	283	295	384	392	396
	Paleogene	Hordaland Gp.		586	582	975	575	593		573	730
		Rogaland Gp.		650	900	1332	1162	975	588	658	1468
Mesozoic	Cretaceous	Shetland Gp.	JORSALFARE FM	839	1315	1520	1470	1420	1229	1305	1792
			KYRRE FM	888	1335	1665	1561	1500	1280	1385	1960
			TRYGGVASON FM	-	2217	2864	2714	2569	-	-	-
			BLODØKS FM	-	2575	3190	3040	2904	-	-	3122
			SVARTE FM	-	2597	3207	3088	2912	1940	-	3127
		Cromer Knoll Gp.	RØDBY FM	1175		3447		3181	1967	-	3140
			AGAT FM	1218	2815	3528	3345	3219	-	-	-
			SOLA FM	-	-	-	-	3510	-	-	-
			ÅSGARD FM	-	2865	3722	3583	3639	2013	2016	3216
	Jurassic	Viking Gp.		1358	2875	-	3667	3732	2037	2058	3318
		Brent	TARBERT FM	-	-	-	-	-	-	-	-
			NESS FM	-	-	-	-	-	2225	2615	3810
			ETIVE FM	-	-	-	-	-	-	2640	3820
			RANNOCH FM	-	-	-	-	-	2250	2646	3880
			BROOM FM	-	-	-	-	-	-	-	3896
		Dunlin Gp.	DRAKE FM	-	-	3819	3800	3955	2267*	2680	-
			COOK FM	-	-	3920	3963	3999	-	-	-
			BURTON FM	-	-	3946	-	4052	-	-	-
			AMUNDSEN FM	-	-	3975	-	4060	-	-	-
		Statfjord Gp.		-	-	4143	-	-	2312	2754	-
Palaeozoic	Undifferentiated	Basement		1568	3233	4167	4069	4092	2314	2856	-

*Table 3.2. Lithostratigraphic units of study area and their depths (m) in wells used in Petrel-software. These are represented as blue points on Figs 3.1 and 4.1.*Only the depth of lithostratigraphic group. Based on information from NPD - FactPages.*

Age		Lithostratigraphic unit		Wells			
Era	Period	Group	Formation	31/4-3	31/6-1	32/2-1	32/4-1
Cenozoic	Neogene	Nordland Gp.		195	327	377	336
	Paleogene	Hordaland Gp.		843	531	-	-
		Rogaland Gp.		1723	972	-	535
Mesozoic	Cretaceous	Shetland Gp.	JORSALFARE FM	1965*	1232	-	846
			KYRRE FM	-	-	-	849
			TRYGGVASON FM	-	-	-	894
			BLODØKS FM	-	-	-	940
			SVARTE FM	-	-	-	956
		Cromer Knoll Gp.	RØDBY FM	-	1304*	-	1081
			SOLA FM	-	-	620	-
			ÅSGARD FM	-	-	755	1106
	Jurassic	Viking Gp.	DRAUPNE FM	2010	1313	823	1109
			HEATHER FM	-	1335	884	1216
			SOGNEFJORD FM	2018	1352	902	1238
			HEATHER FM	2082	1488	-	1306
			FENSFJORD FM	2136	1518	1012	1366
			HEATHER FM	-	-	-	1595
			KROSSFJORD FM	-	1720	1115	1598
			HEATHER FM	-	1776	-	1645
		Brent	TARBERT FM	2327*	1805*	1187*	-
			NESS FM	-	-	-	1650
			ETIVE FM	-	-	-	1655
			RANNOCH FM	-	-	-	-
			BROOM FM	-	-	-	-
		Dunlin Gp.	DRAKE FM	2411	1835	-	1680
			COOK FM	2448	1962	-	1733
			BURTON FM	-	-	-	1783
			JOHANSEN FM	2543	1981	-	1785
			AMUNDSEN FM	2470	2083	-	1791
		Statfjord Gp.		2702	2111	1228	1816
	Triassic	Hegre Gp.		2879	2156	1247	1832
Palaeozoic	Permian?	Undefined		4450	3978	-	-
		Basement		-	4014	-	3132

*Table 3.3. Summarized lithostratigraphic units and their depths (m) in the wells not used directly in Petrel. These are represented as red points on Fig. 3.1 and 4.1.*Only the depth of lithostratigraphic group. Based on information from NPD - FactPages.*

3.2 Interpretation software and approach

The seismic interpretation tool used in this project was Petrel, which is a software tool developed by Schlumberger (link: http://www.software.slb.com/products/platform/Pages/petrel.aspx). It can be used to display 2D- and 3D-seismic to interpret horizons in order to generate three-dimensional surfaces and maps. Displaying of the data in form of different attributes may be applied to reveal the nature of the surfaces and their interaction with each other. Fault interpretation and -mapping are also possible to be utilized in Petrel.

To be able to view the seismic data it was necessary to load the data that was going to be used in the Petrel software. After this the data were sorted into subfolders within the interpretation folder based on the survey and the orientation of the lines. Wells were later loaded into the project in order to calibrate and confirm each reflection's position. The wells indicate the top of the layers. To map the top layer of the formation one must follow a certain reflection across a line. The use of wells gives a great starting point for which reflection to follow as the appropriate marker in the well intersects the top layer. By following a particular reflector along the line, crosslines will be affected by leaving marks at their lines at the point where the two lines intersect. This will further enhance where the reflector continues in crossing sections.

3.3 Seismic stratigraphy and -boundaries

The successions studied and mapped in this thesis include the Cretaceous, with separation of Early- and Late Cretaceous, Middle- and Late Jurassic and the succession between Middle Jurassic to the top acoustic basement. The latter comprises of at least Permian-Middle Jurassic. The sequences have been mapped by following their sequence boundaries. This has been completed by mapping, stratigraphically downward, base Cenozoic, Late Cenomanian, base Cretaceous unconformity, base Sognefjord Fm., Top Brent Group and finally top acoustic basement. A stratigraphic log and colour code scheme are presented in Fig. 3.2 and Table 3.4 respectively to distinguish the horizons.

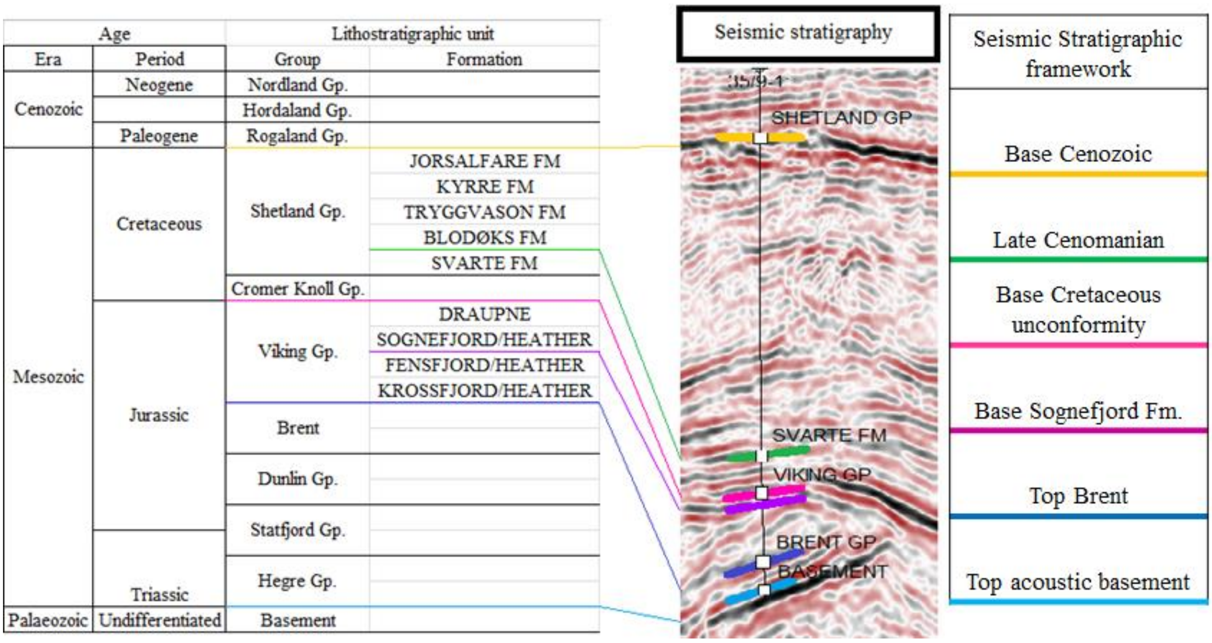


Fig. 3.2 Stratigraphic column for the study area. The seismic section displays the well 35/9-1, and coloured lines crossing it indicate the top of the formation/group used in this study. As these tops correspond to a certain age six horizons have been mapped across the entire study area and have been correlated with the other wells provided in Petrel. Note the lack of Base Sognefjord Fm. in this particular well, and have been placed right below base Cretaceous unconformity.

Reflectors	**Formation**	**Stage (Age)**	**Colour**
Base Cenozoic	Top Shetland Group	Top Maastrichtian (66,0 Ma)	
Late Cenomanian	Top Svarte Formation	Cenomanian (~93,9 Ma)	
Base Cretaceous	Top Viking Group	Top Berriasian (139,4 Ma)	
Late Jurassic	Base Sognefjord/ Heather Formation	Base Oxfordian (163,5 Ma)	
Middle Jurassic	Top Brent	Top Bathonian (166,1 Ma)	
Top Acoustic Basement	?	?	

Table 3.4. Colour codes for each reflectors used in this project with their corresponding label and age.

3.3.1 Top acoustic basement

The top acoustic basement is mostly confined to the lower part of the seismic lines, where the resolution is relatively poor due to a general loss of energy and increased ray scattering with depth. The acoustic basement has been proposed to possibly be of Devonian-Carboniferous origin (Christiansson et al., 2000), or Proterozoic origin related to the Western Gneiss Region, that has been "Caledonized" (Færseth et al., 1995) or Caledonian shear zones (Færseth et al., 1995; Reeve et al., 2014). Two criteria however has been kept in mind while tracing the top acoustic basement. As the acoustic impedance for the basement is higher compared to sedimentary rocks due to the former's higher density and velocity an abrupt impedance contrast is expected to affect the wavelets as they propagate downward from sedimentary rocks to basement rock. This will form a sharp, positive amplitude in a normal polarity setting in the interface between the sedimentary strata and the basement. However, deeply buried sedimentary rocks are well compacted and may therefore have acoustic impedances closer to basement rocks. Hence, the boundary may not be eminent. The other characterisation is the interface's separation of layered and relatively continuous reflections above from distorted reflections below, as the latter is typical for basement rock. However this criteria is not automatically followed to be the acoustic top basement, as the surface is not necessarily equivalent to an actual top basement of metamorphic nature. This will be later discussed in Section 5.2. In the mapping process these criteria have been followed across the entire study area in combination with well tops indicating the top basement of unknown nature. As the well tops used in acoustic basement mapping are located in the northeast of the study area this was the site of lowest uncertainty. In the southeast, in Horda Platform, wells 31/6-1 and 32/4-1, reaching down to basement, are drilled in this area (Fig. 1.1b). The acoustic basement interpretation was based on the criterions set for a top acoustic basement in addition to two published sections of Nøttvedt et al. (1995) and Steel and Ryseth (1990). In the study area the top acoustic basement is located deepest near the graben axis and shallows towards the eastern margin, where it reaches the sea floor. The horizon shallows more abruptly in the northeast, in Måløy Fault Blocks, compared to in Horda Platform.

3.3.2 Top Brent Group

The top Brent horizon, of Middle Jurassic age, was followed as a medium to strong reflection with a negative normal polarity. The top Brent is equivalent to top Tarbert Formation, which consists of sandstones with thin beds of silt, shale and coal along with calcareous bands, making up coarsening-upward sequences (NPD - FactPages). It is a reflection displaying a particular tabular behaviour within faultblocks due to its general pre-rift association (Badley et al., 1988; Ravnås et al., 2000). It has been mapped in the entire region of study, with evidence of discontinuity on crests of rotated fault blocks. The deeper parts of the horizon are confined in the grabens, and become shallower towards the sea floor eastward.

3.3.3 Base Sognefjord Fm.

The base Sognefjord Formation, of Late Jurassic age, is located within syn-rift wedges where the base of the sand-prone formation, of shallow marine origin, indicates larger sediment supply compared to creation of accommodation (Badley et al., 1988; Ravnås et al., 2000). The base Sognefjord Formation is well developed to the southeast in study area, on the Horda Platform, but proximal to the Viking Graben its shale-prone equivalent, the Heather Formation, dominates (Steel, 1993). As some of the wells only display "Intra Heather Fm. SS" without specifying the age of the sands, an assumption the horizon's position was placed at that level. The horizon is a part of the Viking Group which was deposited during the Bathonian-Berriasian rift event (Badley et al., 1988).

3.3.4 Base Cretaceous unconformity

The base Cretaceous unconformity has been based upon the mapping of a surface characterised by toplap truncations below it and onlaps and downlaps above it. This is commonly found in areas that have been exposed to erosion and areas that have subsided, forming a basin geometry to accommodate sediments. The unconformity has also a distinctive reflection signature due to stacked sequences and facies change. The base Cretaceous unconformity separates mostly deformed Jurassic syn-rift strata from unfaulted Cretaceous post-rift strata, but this is not necessarily evident along large faults where the unconformity itself may be displaced. On the platforms the base Cretaceous unconformity behaves as an angular unconformity and in the Viking Graben it has an onlapping nature (Kyrkjebø et al., 2004). In the graben however it was partially difficult to find it due to dragging structures of the Jurassic reflectors along the western master fault, making them behave as apparent onlaps.

3.3.5 Late Cenomanian

The top Svarte Formation corresponds to the Late Cenomanian and the formation is characterised by mudstones and limestones (Bugge et al., 2001; Gabrielsen et al., 2001). The reflection is observed as rather strong with infill-character in local basins, and merges with the base Cretaceous unconformity on local highs. It is also mostly continuous in the northern area of study, explained by the focused subsidence in the particular area in middle Cretaceous (Gabrielsen et al., 2001). The mapping of the reflector has been based upon its behaviour across the study area and well top correlation. Additionally, a seismic profile from Sogn Graben and its eastern flank and another from Måløy Fault Blocks, presented by Bugge et al. (2001) and Jackson et al. (2008), respectively has been used.

3.3.6 Base Cenozoic

The base Cenozoic represents the shallowest interpreted horizon given the scope of study. It is seen as a bright, continuous reflection, separating the Cretaceous post-rift reflectors below from the Cenozoic clinoforms developed above (Kyrkjebø et al., 2001). It corresponds to the top Jorsalfare Formation, a formation which is marl-dominated in the eastern region and shale-dominated to the west (Bugge et al., 2001). It is mainly unfaulted, with the exception in the vicinity of large faults, such as the Øygarden Fault Complex. In the basin it is confined to the same level with slightly bended reflection character. Eastward of the basin the reflector is seen to climb upward in height, forming a flank of the basin, and truncated by an unconformity of Eocene age (Kyrkjebø et al., 2001) or Pliocene-Pleistocene age (Kyrkjebø et al., 2004). The reflection has been correlated by the use of well tops.

3.4 Fault interpretation

Fault interpretation was carried out on large faults that have affected any of the horizons, either by displacement or bending. Displacements are embedded both on the horizons and surrounding reflections. Diffractions from fault planes causes low reflectivity, and will then stand out as areas of low to no visibility, sharply separating generic reflections. In some instances the fault plane itself may give rise to reflection and appears as a noticeable reflection in the seismic. The angle of it depends on the angle of the fault plane, but is commonly low-angle. Interpretation was done by tracing the faults along the line of displacement and line of diffraction and/or reflection, where the latter determines the vertical extent. However caution is to be made when deciding its extent due to data quality and scattering of energy with depth. When labelling the faults they were either labelled the same name used from NPD FactMaps (ex. Øygarden Fault, Tusse Fault) or with a letter (E for east-dipping; W for west-dipping) and a number (ex. E3). Do note during this thesis the fault "Øygarden Fault" will be used for the easternmost fault located on the Horda Platform, south of 61°N, whereas the "Øygarden Fault Complex" includes the eastern marginal footwall of the study area (see Figs. 1.2 and 4.1). Due to the large spacing of seismic lines, many local faults quickly die out, especially along the eastern margin of Viking Graben, hence only the larger ones were able to be mapped over larger distances.

After mapping the faults, polygons of the faults were made to make fault maps. As a fault plane dips it intersects the different surfaces at different lateral positions, as well as the vertical extent varies for each fault. Therefore three fault maps were generated to present the position and extent of each fault; one representing the faults intersecting acoustic basement, one cutting the base Cretaceous surface and finally one representing the faults reaching up to base Cenozoic. The two former fault maps were made to document and highlight faults that are important features in the Permo-Triassic and Late Jurassic extensional events. The latter fault map is intended to signify fault-reactivations. Each fault polygon were assigned solid block line type to highlight their dip orientation.

4. Results

This chapter will present the results obtained from the seismic interpretation in the format of seismic key lines and -sections and maps. The first part of the chapter presents the key lines with enlarged sections to enhance observations, before going detailed into maps generated to gain an overall understanding of the entire study area. Lastly, a few seismic sections will be presented to investigate basement structuring and -anatomy. The locations of the seismic lines are shown in Fig. 4.1.

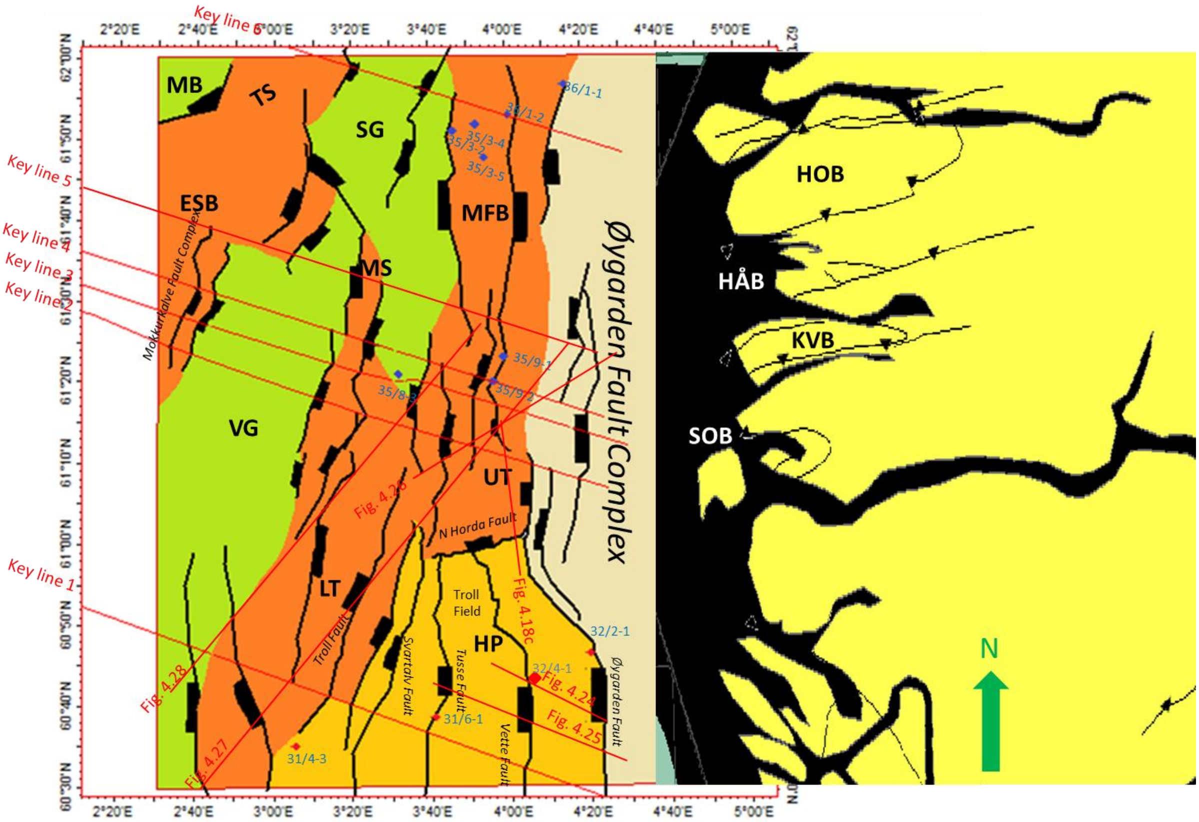


Fig. 4.1. Main structural elements in the study area of northern North Sea, along with Devonian basins located onshore Western Norway. Position of red key lines and blue wells used in this thesis are presented as well. Abbreviations: ESB – East Shetland Basin; HOB – Hornelen Basin; HP – Horda Platform; HÅB – Håsteinen Basin; KVB – Kvamshesten Basin; LT – Lomre Terrace; MB – Marulk Basin; MFB – Måløy Fault Blocks; MS – Marflo Spur; SG – Sogn Graben; SOB – Solund Basin; TS – Tampen Spur; VG – Viking Graben. Map of mainland modified from NPD – FactMaps.

4.1 Key seismic lines

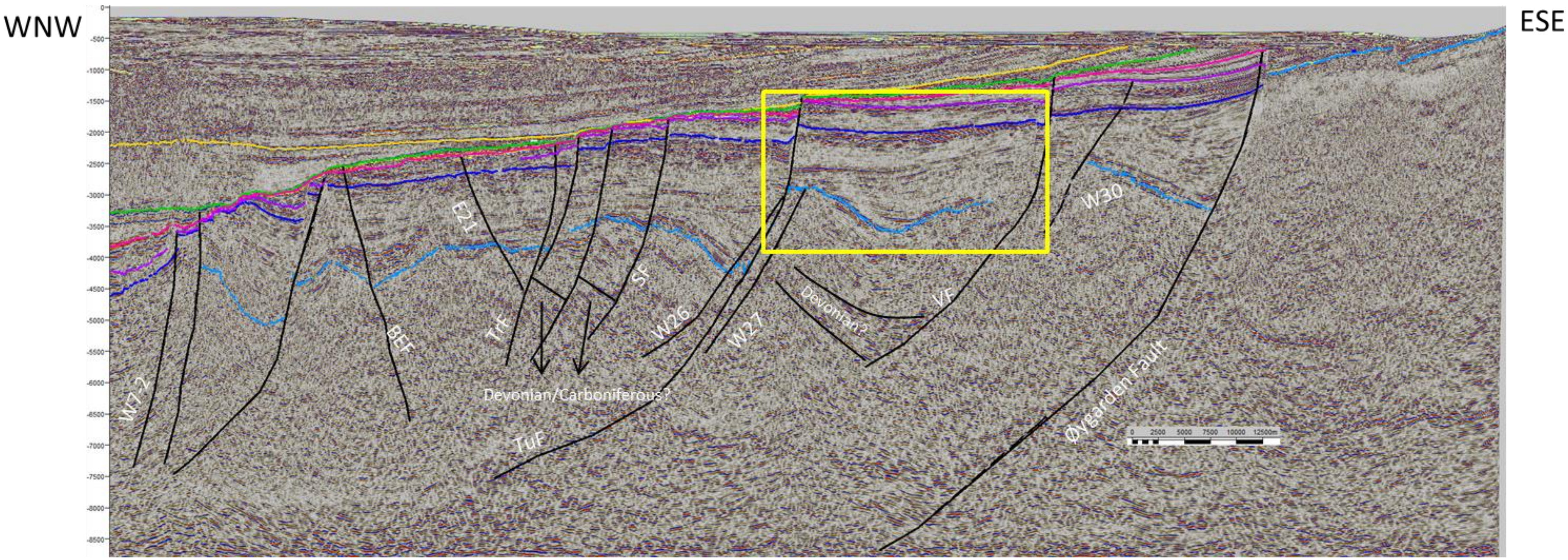
Selected seismic profiles from the region will be presented, from south north to show representative structures and distribution of sedimentary sequences. Key line 2, 3 and 4 have closed spacing, and this is to highlight drastic changes of the study area occurring in the site. This section will give a description of each profiles to understand the structures present in more detail.

4.1.1 Key seismic line 1

This profile (Fig. 4.2), a WNW-ESE trending line located just north of 60°30'N, crosses the Øygarden Fault Complex, the Troll Field on Horda Platform and eastern Viking Graben (Fig. 4.1). This key line indicates three mega fault blocks, separated by the Øygarden-, Vette- and Tusse faults, on the Horda Platform with relatively continuous, but slightly eastward tilted Jurassic and Cretaceous reflections. In the westernmost section, transitioning to the Viking Graben, the horizons change dip to a westerly character. Each mega block is separated by large listric faults that are penetrating into the deeper parts of the profile as well extending upward, affecting the Base Cenozoic reflection. In each mega block minor curved faults are present, making a tabular appearance at Jurassic level. They offset the Jurassic horizons, but do not extend further than the base Cretaceous unconformity. On top of these mega blocks parts of base Sognefjord Formation is eroded. Wedging between base Cretaceous unconformity and top Brent is however evident along the larger faults, with the Sognefjord Formation within these wedges.

The top acoustic basement horizon is seen being affected by the large listric faults displacing it along the three easternmost, listric faults. The easternmost fault, the Øygarden Fault, tilts the acoustic basement horizon in the hanging wall. In this hanging wall a wedge geometry is observed above the top acoustic basement horizon, with the reflectors rotating anticlockwise, becoming sub parallel to the top Brent horizon. From here the reflectors are stacked up to the top Brent horizon. However a few reflections seem to onlap from the crests of the basement blocks, suggestive of a near or at base level exposure (enlarged section of Fig. 4.2). The ages between the basement and top Brent make up at least Triassic, with the Hegre Group, and Early Jurassic, with Statfjord Formation, as indicated by well 32/2-1 and 32/4-1, positioned in same easternmost hanging wall block. Upper Palaeozoic and Triassic sediments have been suggested to exist in this area by Christiansson et al. (2000) and Odinsen et al. (2000b). Well 31/4-3, proximal to the Troll Fault, also confirms this with the presence of both the Triassic

Hegre Group and Early Permian sediments (NPD - FactPages). Noteworthy is also the westward thinning of reflection package between top acoustic basement and top Brent horizon abutting the Vette and Tusse faults. Westward the package remains rather constant in thickness. It is interesting to note that along the west-dipping Tusse-, Vette- and Øygarden faults and the east-dipping Brage East Fault the displacement of the top acoustic basement is larger compared to the offset of top Brent along the same faults, indicating reactivation(s) of pre-existing faults. This is not apparent with the west-dipping fault W7-2 as the throw of acoustic basement is similar to that of the Jurassic horizons, indicating new fault generation of Late Jurassic age. The positive relief structure between Brage East Fault and Tusse Fault forms a low-relief accommodation zone (Rosendahl, 1987), acting as a graben axis. There are also some faults located proximal of Tusse Fault and Vette Fault, which do not intersect base Cretaceous and form minor basement fault blocks (ex. W26, W27 and W30). The westernmost basement fault, W26, merges with Tusse Fault, whereas the central basement fault, W27, terminates at top acoustic basement level. The easternmost basement fault, W30, shows a larger displacement of top acoustic basement compared to practically non-displacement of top Brent, indicating a fault generation in Permian-Triassic and reactivation in Jurassic times. Below the top acoustic basement however some wedged features from the Troll Fault and eastward to Vette Fault down to ~6 s TWT reflections are apparent. The footwall of the Troll Fault these do not match any reflections above to be multiples. Likewise with the hanging wall of Vette Fault indicating a wedge in the lower part.



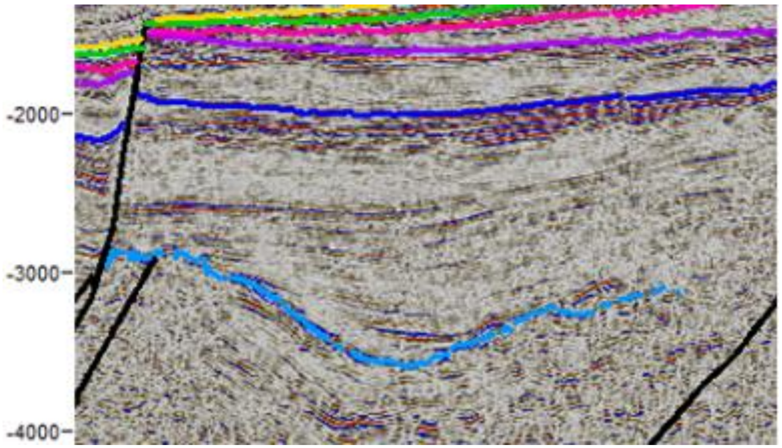


Fig. 4.2. Key line 1 across Horda Platform and Lomre Terrace (see Fig. 4.1 for location), showing mega fault blocks delineated by large listric faults. These faults show larger displacement of top acoustic basement compared to the Jurassic- and Cretaceous horizons above, indicating a pre-Jurassic origin that have later been reactivated. The concave top acoustic basement near Troll Fault may signify a pre-existing graben axis from the Permo-Triassic extensional event. The enlarged section show onlapping reflections onto the top acoustic basement. Abbreviations: BEF - Brage East Fault; SF - Svartalv Fault; TrF - Troll Fault; TuF – Tusse Fault; VF – Vette Fault

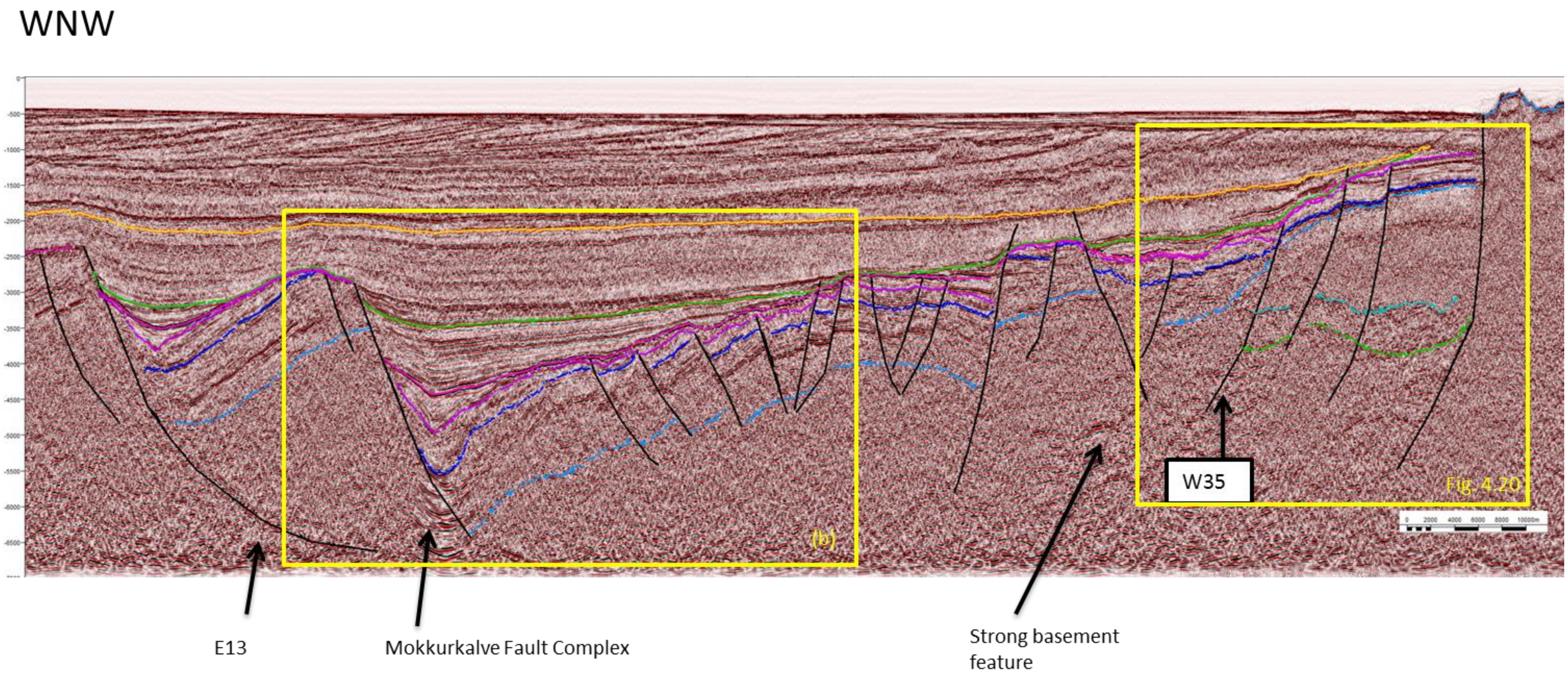
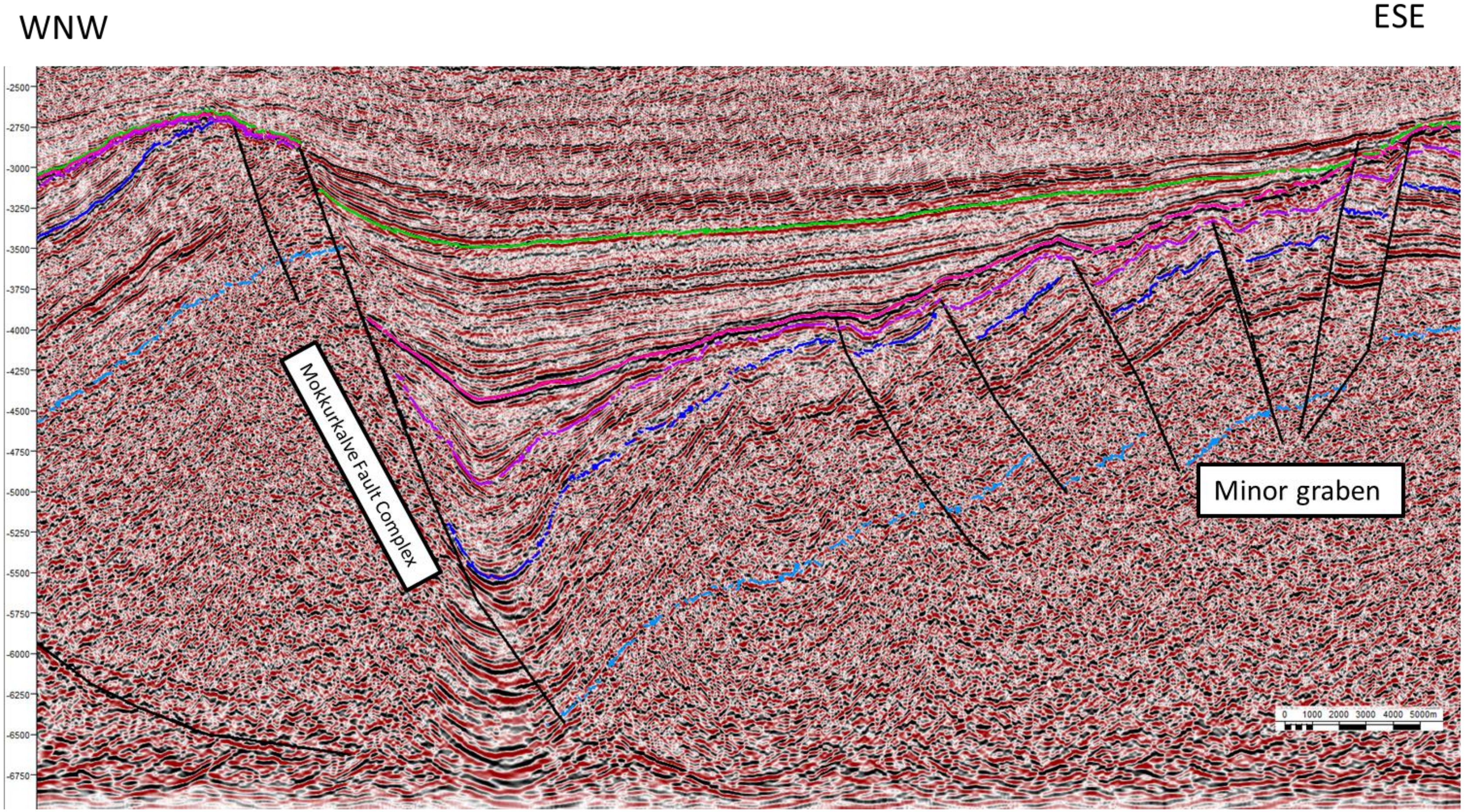


Fig. 4.3a. Key line 2 across Øygarden Fault Complex, Uer Terrace, Marflo Spur, Viking Graben and East Shetland Platform (see Fig. 4.1 for location). The Viking Graben displays an asymmetric behaviour along Mokkurkalve Fault Complex, and an a symmetrical graben is developed in the Uer Terrace, proximal to Øygarden Fault Complex. Both grabens display a Jurassic thicknening, and the Viking Graben shows in addition Cretaceous thickening. The Cretaceous sequences are thickest in the Viking Graben, and thins laterally towards the margins. The faults in between these grabens display both west-dipping and east-dipping polarities, forming fault blocks and horsts.



b. Enlarged section of Viking Graben and its eastern margin from key line 2. Thickening of both Jurassic and Early Cretaceous sequences along the western fault boundary, the Mokkurkalve Fault Complex, indicate active extension and creation of accommodation space in these periods. Adjacent faults however terminate at the base Cretaceous unconformity, in addition they dip away from the Viking Graben axis and toward the minor graben development on the eastern margin. Across this minor graben the fault polarity changes.

4.1.2 Key seismic line 2

This line crosses the Øygarden Fault Complex, Uer Terrace, parts of Marflo Spur, the northern Viking Graben and the East Shetland Basin (Fig. 4.3a; see Fig. 4.1 for location). The line is oriented WNW-ESE, and presents a complex fault block system, displaying both easterly and westerly polarity. The profile indicates one major asymmetric graben, the Viking Graben, and a more or less symmetrical graben in the Uer Terrace, separated by tabular fault blocks and horsts in between. The symmetrical graben is delineated by a large horst to the west and large, closely spaced west-dipping faults to the east. This graben shows signs of Jurassic growth and possibly even Triassic growth. Larger spacing between the Cretaceous horizons above the graben, compared to that above the flanks, indicate a site of higher accommodation. The merging of base Cretaceous, Late Cenomanian and base Cenozoic on the eastern flank indicate prevailing erosion during Cretaceous. Evidence of Cretaceous reactivation of the flanks are also apparent. The acoustic basement has been largely affected by the western boundary fault, Mokkurkalve Fault Complex, of the Viking Graben. As the interpretation of the horizon is uncertain beneath the graben, the marked area displays a thicker unit between it and top Brent compared to the same unit in the western flank. The top acoustic basement is generally continuous in the eastern flank and in Marflo Spur, with some offsetting of the horizon equal to that of the Jurassic horizons. Two intra-basement horizons, Basement A and -B, are included as well to the east, beneath the top acoustic basement. These will be elaborated further in section 4.5.

From the enlarged section (Fig 4.3b) the Viking Graben displays an asymmetrical shape with the deepest point located along its western boundary fault, the Mokkurkalve Fault Complex. It is evident that the Jurassic horizons and the base Cretaceous horizon form a wedge, thickening along this western master fault. Drag-folding is also present along the fault plane. The fault also offsets the Late Cenomanian in addition accommodating for more reflection packages above, indicating continued faulting through Late Cretaceous time. The margins of the graben mark thinning of the wedges between Late Jurassic and Cretaceous horizons, due to the rift unconformity forming at latest Jurassic-earliest Cretaceous (Nøttvedt et al., 1995) and with the Late Cenomanian horizon merging with the base Cretaceous horizon, implying the unconformity persisted in Early Cretaceous. The base Cenozoic horizon drapes the whole profile with minor topographic shallows above the margins of the Viking Graben. It is suggesting the area was submerging at that time with the largest subsidence rate in the graben. Eastward from the graben axis minor fault blocks are observed, decreasing in lateral size toward a minor graben development. These fault blocks are displacing the Jurassic horizons, but not the base Cretaceous unconformity, which suggest they were eroded and were inactive in Early Cretaceous. It is interesting to note that although the Viking Graben is asymmetrical the tabular fault blocks are dipping away from the main graben axis, and is instead dipping toward the minor graben. On the other side of the minor graben the dip polarity changes.

4.1.3 Key seismic line 3

This key line is oriented WNW-ESE, crossing the Øygarden Fault Complex, northern Uer Terrace, southern tip of Sogn Graben, Marflo Spur, northern Viking Graben and East Shetland Basin (Fig. 4.4a; see Fig. 4.1 for location). Along with the standard horizons used, intra-basement A and -B is also present beneath the top acoustic basement, located to the east. The westward extents of these intra-basement-horizons were however challenging to follow. The central part of the key line shows a sub-platform with opposing structural polarities across it, delineating multiple internal horsts and grabens.

It illustrates large west-dipping and east-dipping faults facing each other across the graben. The west-dipping faults, W22 and W37, appear to be planar, whereas the westernmost east-dipping faults, Mokkurkalve Fault Complex and E13, have a planar upper part and a listric lower part. Nearly all the faults extend into the basement, evident with the displacement of the top acoustic basement as well as Basement A and -B to the east. They additionally cut into the Cretaceous sequence with the exception of fault W23 only cutting through the base Sognefjord Fm. The easternmost fault W24 is seen penetrating the Quaternary section near the seafloor. It is also noted that the faults making the southern tail of Sogn Graben, E17 and W3, show a larger displacement between top acoustic basement and top Brent, compared to that between the other horizons.

In the enlarged section of key line 3 (Fig. 4.4b) the sequences between common horizons overall thin eastward, with top Brent horizon amalgamating with the top acoustic basement and likewise for the Cretaceous horizons and base Cenozoic. Base Sognefjorden Fm. is seen partially truncated by the base Cretaceous unconformity on the fault block crests. The horizon however seems to diverge with top Brent until they become parallel eastward. In the central part of the enlarged section of key line 3 the sequence between top Brent and top acoustic basement is spotted to be wedge shaped, with thickening along the E6 and E7 faults. The former wedge shows evidence of local displacement of top Brent with internal domino style, tilting the horizon eastward.

4.1.4 Key seismic line 4

The line trends NWW-SEE across the Øygarden Fault Complex, northern Uer Terrace, southern part of Sogn Graben, Marflo Spur, northern part of Viking Graben and East Shetland Basin (Fig. 4.5a; Fig. 4.1 for location). Well 35/9-2 is also present, drilled down to the basement. The basement has been identified as a Caledonian basement (NPD - FactPages).

Figure 4.5b presents the northern Uer Terrace. It illustrates two sets of large faults, offsetting the basement, with opposite polarities; west- and east-dipping. The west-dipping faults are located adjacent to the Øygarden Fault Complex, W10-3, W23 and W24. Nearly all faults cut across the Late Cenomanian horizon and even further into the Upper Cretaceous. The easternmost W24-fault cuts up to near present-day sea floor, forming the footwall as a basement high. The two fault sets form local horst and graben structures, where the acoustic basement is seen to be downfaulted into depressions by two opposing faults. The westernmost depression has been more displaced along the E7- fault, evident with the thickening of Late Jurassic- and Early Cretaceous packages, drag folding and tilt of strata. The eastern graben however seems to be symmetrical with equal displacement along both the E6- and W10-3 faults. It is noteworthy that the west-dipping faults east of this graben are steeper than the E6- and E7 faults, with evidence of west-tilted strata in the eastern fault blocks. The base Cretaceous unconformity truncates the Upper Jurassic sediments, and the Late Cenomanian reflection coincide with the unconformity on the fault block crests, indicating Late Cenomanian subaerial exposure. Amalgamation of the base Cretaceous unconformity and the Late Cenomanian horizon on the eastern margin indicate Late Cenomanian subaerial exposure of it as well. Late Jurassic sediments are either very thin or absent due to erosion, whereas the thickest parts remain in the local graben. The sequence between the top Brent and base Cretaceous unconformity shows minor thinning eastward to E6, but it has preserved thickness to the east of the same fault. The base Cenozoic horizon covers the entire basin, and shows a low-angle, west-dipping character. The westward divergence of it and the Late Cenomanian horizon indicate a differential basin subsidence. The thin units between top acoustic basement and top Brent, in addition to lack of pre-Jurassic sediments in well 35/9-2 (NPD - FactPages) imply a large hiatus, including the Permian and Triassic periods. It is however interesting to observe a wedging of this unit along the E7 fault, indicating tectonic activity before the deposition of top Brent Group.

The enhanced section of the western part of key line 4 (Fig. 4.5c) is positioned across the southern tail of the Sogn Graben, Marflo Spur and northern Viking Graben. The section illustrates a fairly deep Viking Graben and a shallow Sogn Graben separated by west-dipping fault blocks. The Sogn Graben and the west-dipping blocks are on the same level and form an easterly intra-platform margin relative to the Viking Graben. The faults confined to this platform reaches up to the base Cretaceous unconformity. What is noteworthy is the symmetrical appearance and change of tilt of the Viking Graben in the north compared to that in the south (compare this section of key line with key line 2, Fig. 4.3b). The graben centre consists of small fault blocks with displaying opposite fault polarity, where the west-tilted blocks are outnumbered by the east-tilted. The former are also confined along the western boundary fault of the graben, Mokkurkalve Fault Complex. The Jurassic sequence is thin in the Viking Graben with indication of wedging along the flanks of it. Studying the Lower Cretaceous package it is observed to be rather thin across the intra-platform and expands westward in the Viking Graben. The westward expansion is also seen in the Upper Cretaceous package above (key line 4.5a). The eastern boundary fault of Sogn Graben, fault W3, displays a thickening across it between top acoustic basement and top Brent, a possible indication of a pre-Jurassic package confined at deeper level.

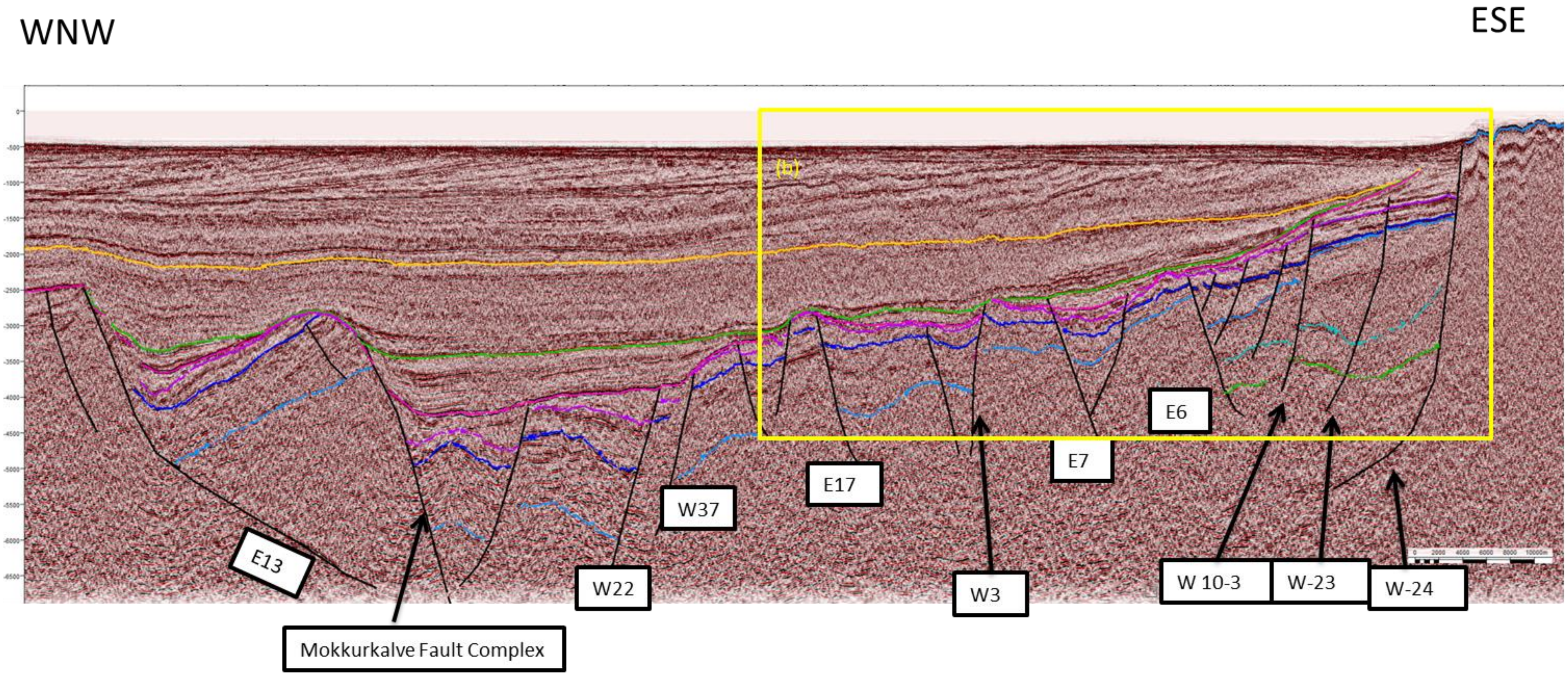
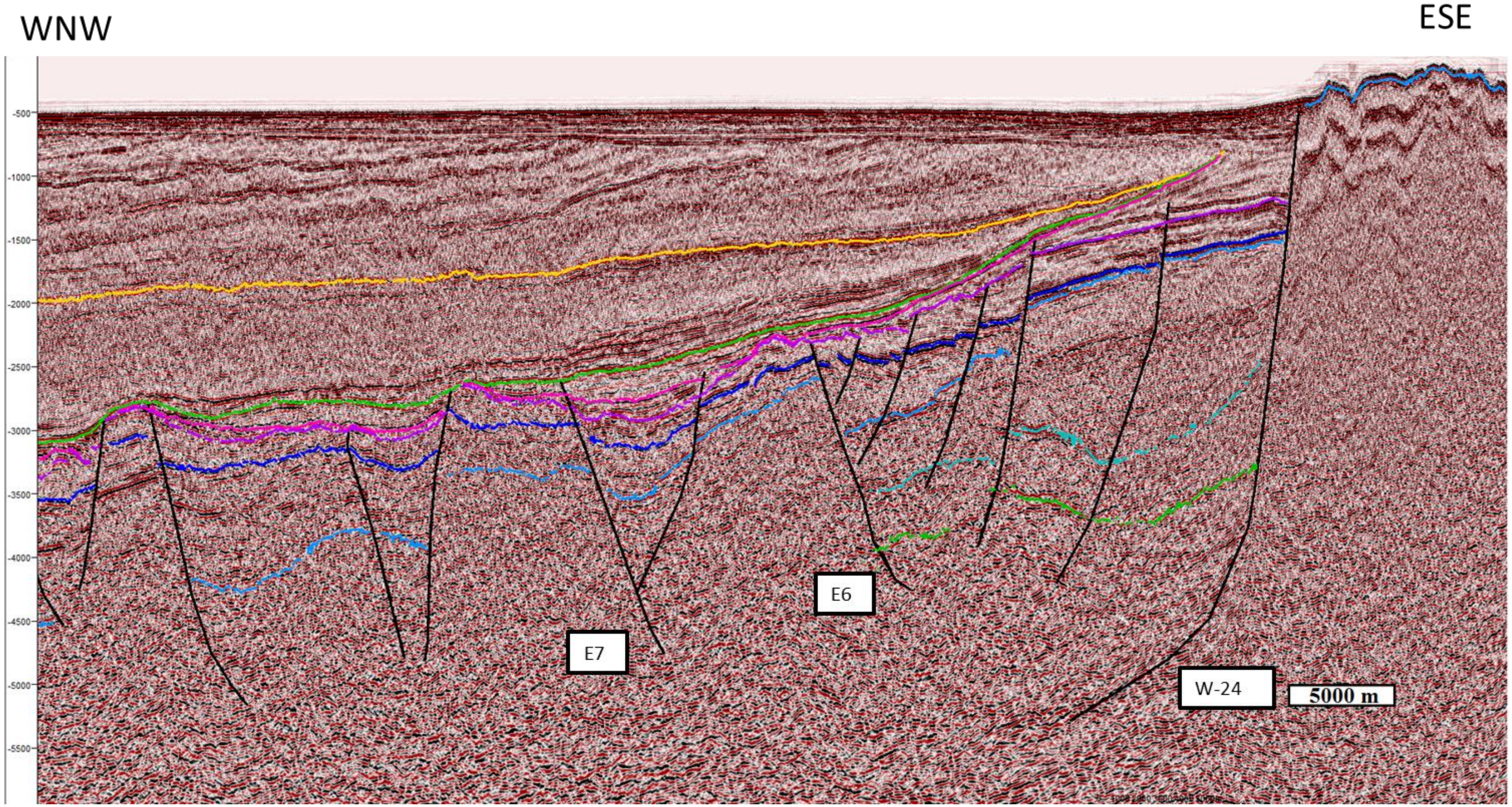


Fig. 4.4a. Key line 3 across Øygarden Fault Complex, Uer Terrace, Marflo Spur, Viking Graben and East Shetland Basin (see Fig. 4.1 for location). It displays faults showing complex both westward and eastward polarities, more or less alternating across the sub platform of Marflo Spur. Intra-basement A and –B are included in the easternmost side of this key line.



b. Enlarged section of eastern margin of key line 3. The Jurassic horizons and the Late Cenomanian horizon form thin units across the sub platform, but some Jurassic wedging is apparent along E7. The Late Cretaceous sequence thins eastward as well. Wedging between top Brent and top acoustic basement is evident along both faults E6 and E7. The length of the scale box represents 5000 m.

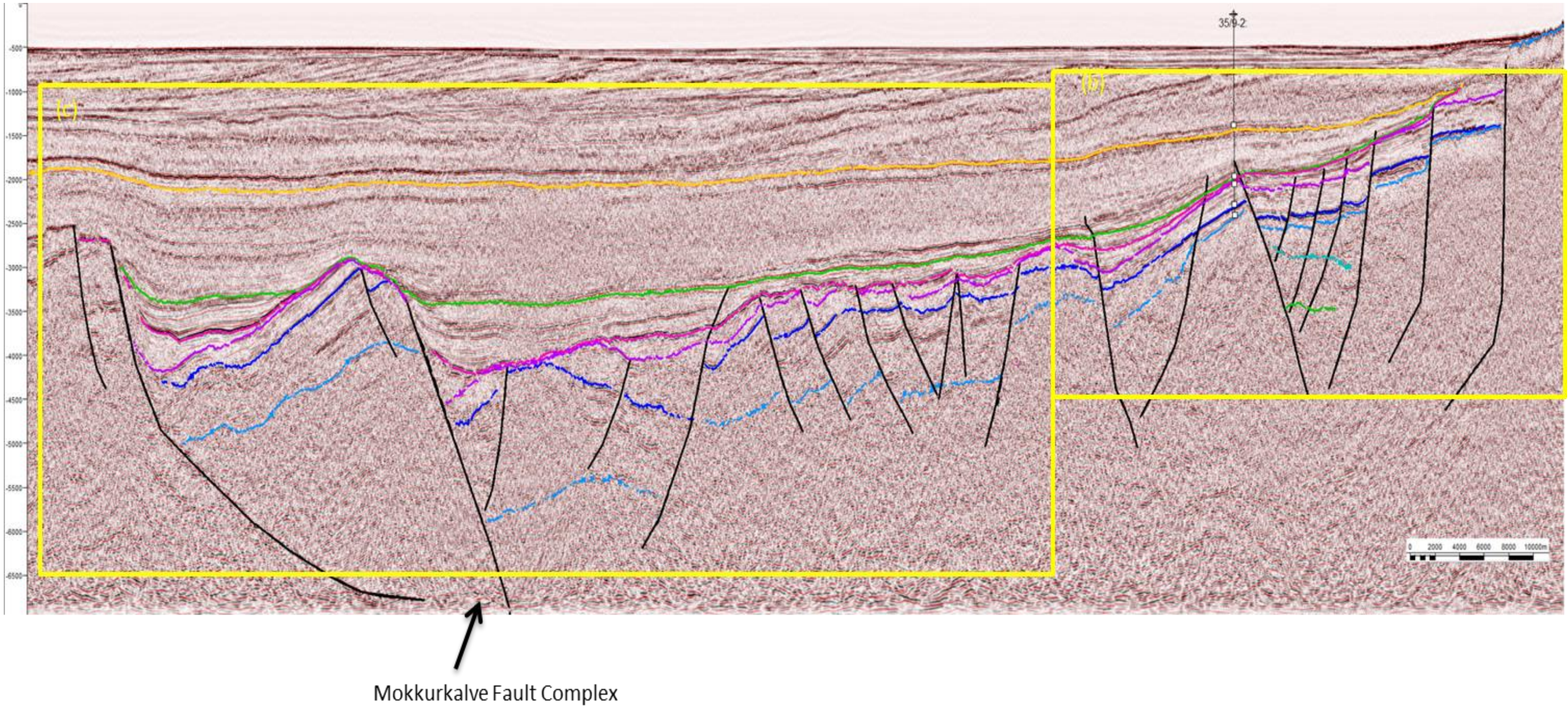
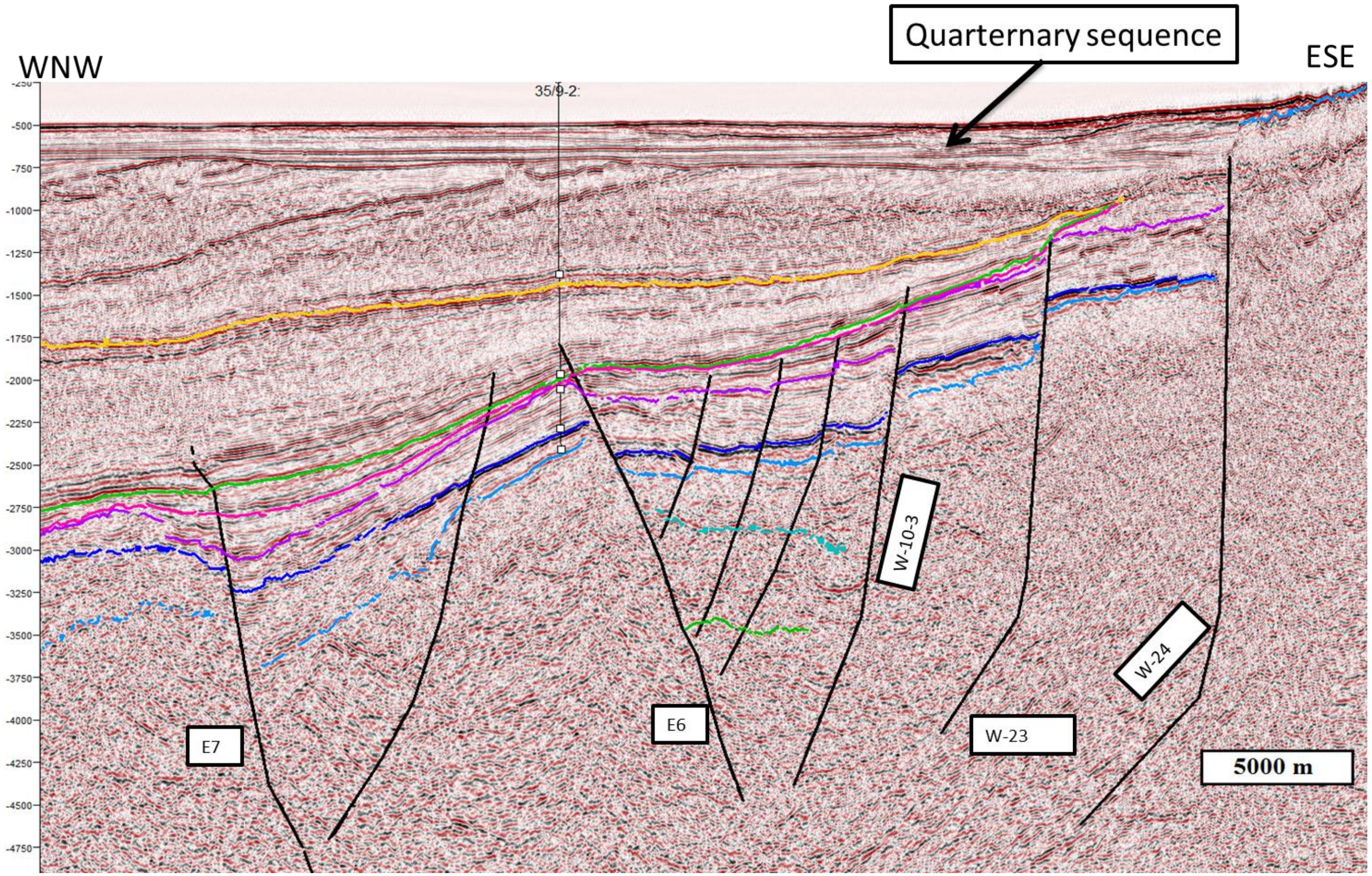
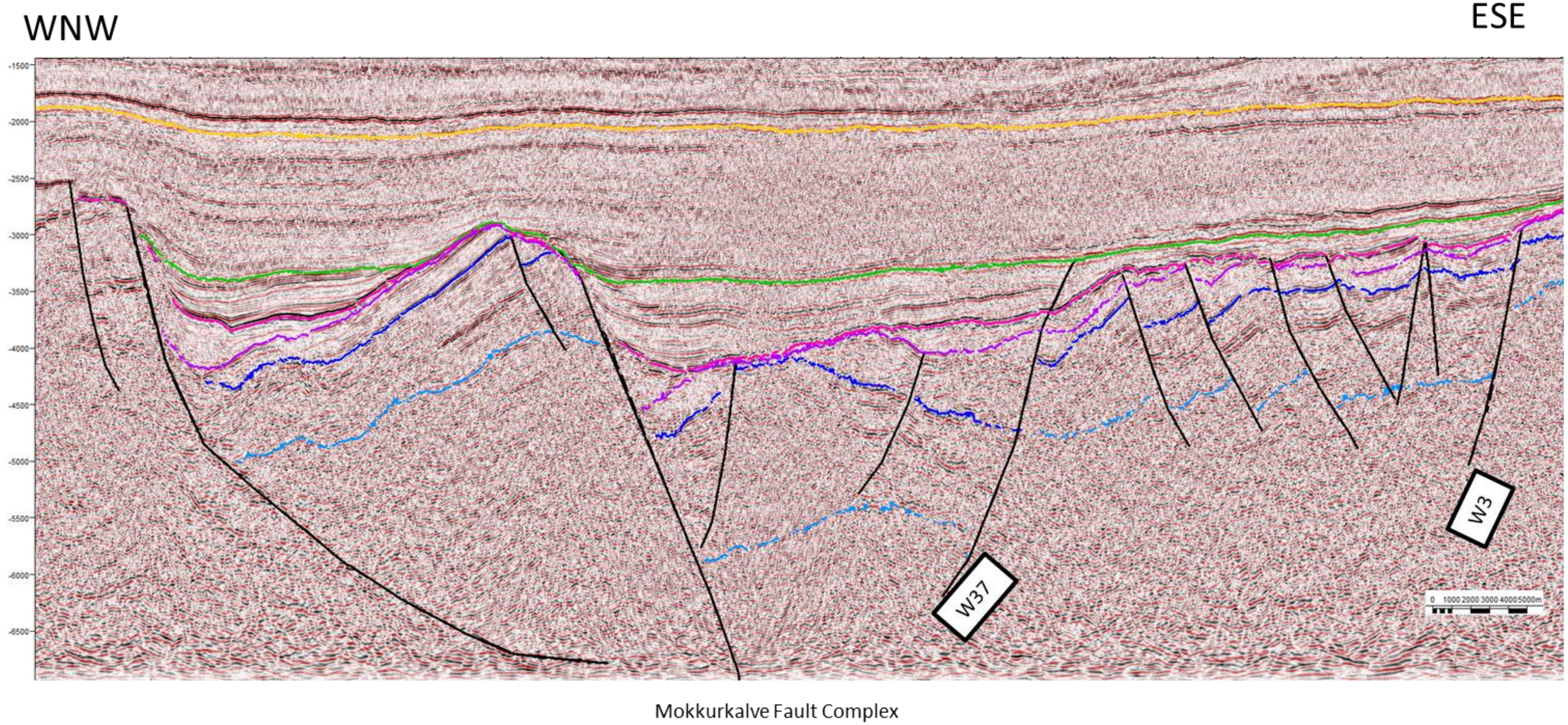


Fig. 4.5a. Key line 4 crossing the Måløy Blocks, southern Sogn Graben, Marflo Spur, northern Viking Graben and East Shetland Basin (see Fig. 4.1 for location). Well 35/9-2 reaches down to basement.



b. Enlarged section of eastern margin of key line 4, highlighting horst and graben structures. The well reaches down to basement and indicates it is overlain by Jurassic sediments. The Jurassic and base Cretaceous horizons display a sequence-thickening in the eastern graben, bounded by E6 and W10-3. Wedging of this sequence is also apparent along E7, but also a wedge between acoustic basement and top Brent is also present along the same fault, indicating faulting prior to the Late Jurassic extensional event. The Cretaceous sequences thin eastward, and are truncated by the Quarternary sequence at the top. The length of the scale box represents 5000 m.



c. Enlarged section of the Viking Graben from key line 4, displaying a more symmetrical character between Mokkurkalve Fault Complex and W37, forming Jurassic wedges along both faults. Displacement along W37 overrides that of Mokkurkalve Fault Complex due to larger wedge along W37. Note also thicknening of sequence between top Brent and top acoustic basement along Mokkurkalve Fault Complex. The W3-fault represents the eastern boundary of Sogn Graben, and it also display thickening of sequence between top Brent and top acoustic basement.

4.1.5 Key seismic line 5

The key line 5 has a NWW-SEE trend, crossing the parts of Øygarden Fault Complex, Måløy Fault Blocks, southern Sogn Graben, Marflo Spur and East Shetland Basin (Fig. 4.6a; see Fig. 4.1 for location). The centre of the profile consists of mainly east-dipping faults, delineating fault blocks of different sizes, tilting the reflections westward. The fault blocks are noted to be affected by the unconformity of the base Cretaceous due to their smooth appearances as well as the termination of the faults on the East Shetland Basin. The Måløy Fault Blocks and Sogn Graben stand out as half-grabens, separated by a narrow horst. These are observed to wedge along their western flanks in all sequences from pre-top Brent to Early Cretaceous. The west-dipping faults in Øygarden Fault Complex and on East Shetland Basin exhibit Upper Cretaceous wedging along the hanging wall. The Lower Cretaceous sequence across Sogn Graben and Marflo Spur thickens and thins laterally toward east and west. The easternmost margin is marked by the thinnest sequences with a shallow acoustic basement. It is also registered the faults intersecting the into the Early Cretaceous sequence in this area and at the narrow horst. At the top the Late Cretaceous sequence is seen to drape the entire basin with eastward thinning.

From the enlarged section (Fig. 4.6b) the southern Sogn Graben is observed as a large half graben with wedging along the east-dipping E3-fault. The wedge encompasses the three lowermost sequences used in this study; pre-top Brent, Late Jurassic and Early Cretaceous. Internally the half-graben contains small east-dipping faults, terminating at base Cretaceous unconformity, where E33 offsets the sequences along E3, with evidence of more pronounced Late Jurassic wedging. The Sogn Graben terminates against the west-dipping W4-fault, the latter expressing westward thickening of the pre-top Brent- and Late Jurassic sequence. Fault E2 to the west of Marflo Spur however only indicates Late Jurassic wedging.

4.1.6 Key seismic line 6

This profile crosses the Øygarden Fault Complex, well 36/1-2 on the Måløy Fault Blocks, the northern part of Sogn Graben and Tampen Spur to the west (Fig 4.7a; Fig. 4.1 for location). It is aligned on a WNW-ESE trend, and the key seismic line displays the Sogn Graben to the west and the Måløy Fault Blocks to the east. The Sogn Graben exhibits a generally symmetrical behaviour with large faults along the flanks of it. These faults are seen to offset the Jurassic horizons, the base Cretaceous unconformity and reach up to pre-Cenomanian levels. The Sogn Graben is confined to an approximate depth of 6 s TWT on base Cretaceous level, and Lower Cretaceous sediment-packages dominate the infill. Due to the resolution of the NVGT-88 lines and poor imaging at such depths difficulties arose to map the top acoustic basement in the graben and along its flanks. On the Måløy Fault Blocks however the basement is shallow with thin Jurassic- and Cretaceous units (Fig. 4.7b). The horizons show a grabenward dip, where the Jurassic horizons display a tabular fashion, whereas the Cretaceous horizons have a more smoother appearance. The lack of displacement of the base Cretaceous unconformity in addition to thinning and merging of Jurassic units on the fault block crests indicate the fault blocks were eroded and minor fault activity on the Måløy Fault Blocks in Early Cretaceous. It is interesting to note the Jurassic and Cretaceous horizons converges toward each other eastward to the Western Norwegian Mainland. The base Cenozoic reflector is observed as a continuous reflection with a flat character, dipping westward. The Late Cenomanian reflector also displays the latter similarity, indicating a westward tilting in Cenozoic time.

The faults of the Måløy Fault Blocks display an interesting antithetic pattern compared to the flanks of the Sogn Graben, the former dipping eastward. The faults separating the blocks are seen to penetrate deeply into the basement, and their tilt increases eastward toward the Norwegian mainland. Well 36/1-2 drilled in the central fault block reaches down to basement. It has here been determined as gneissic rock (NPD-FactPages).

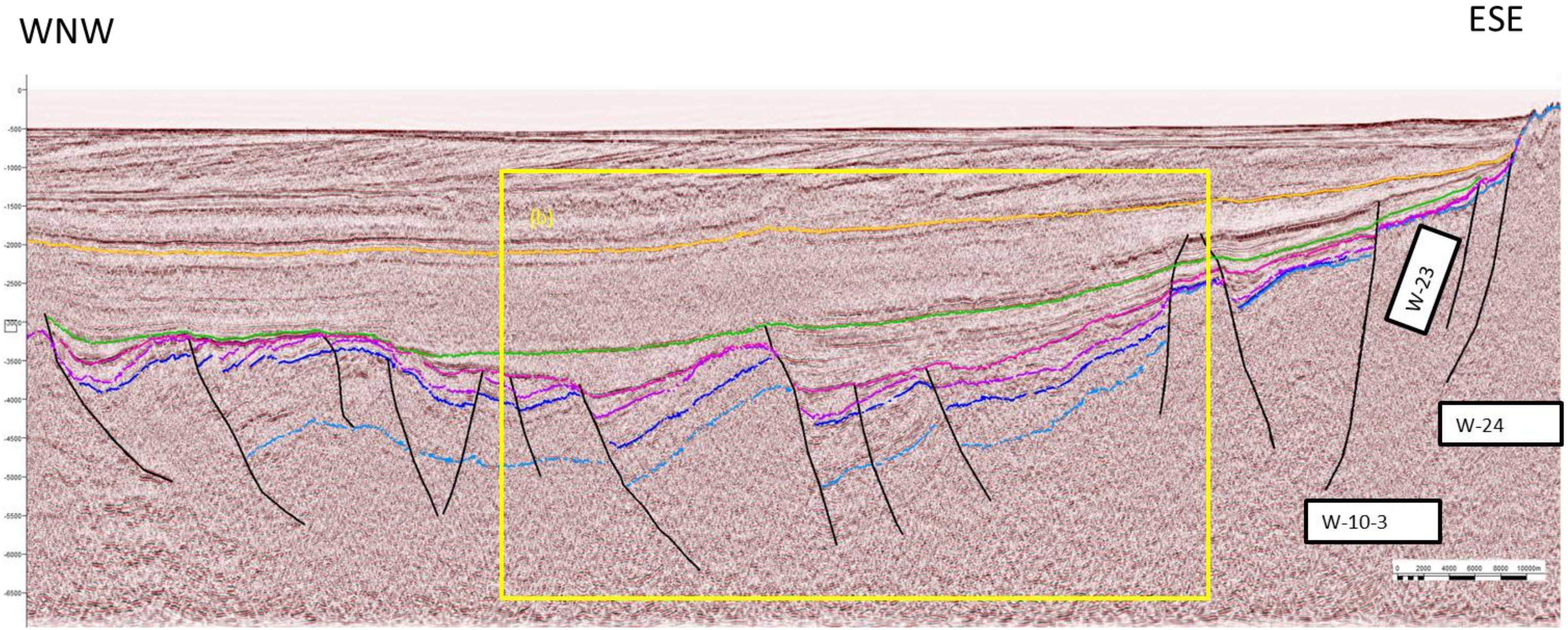
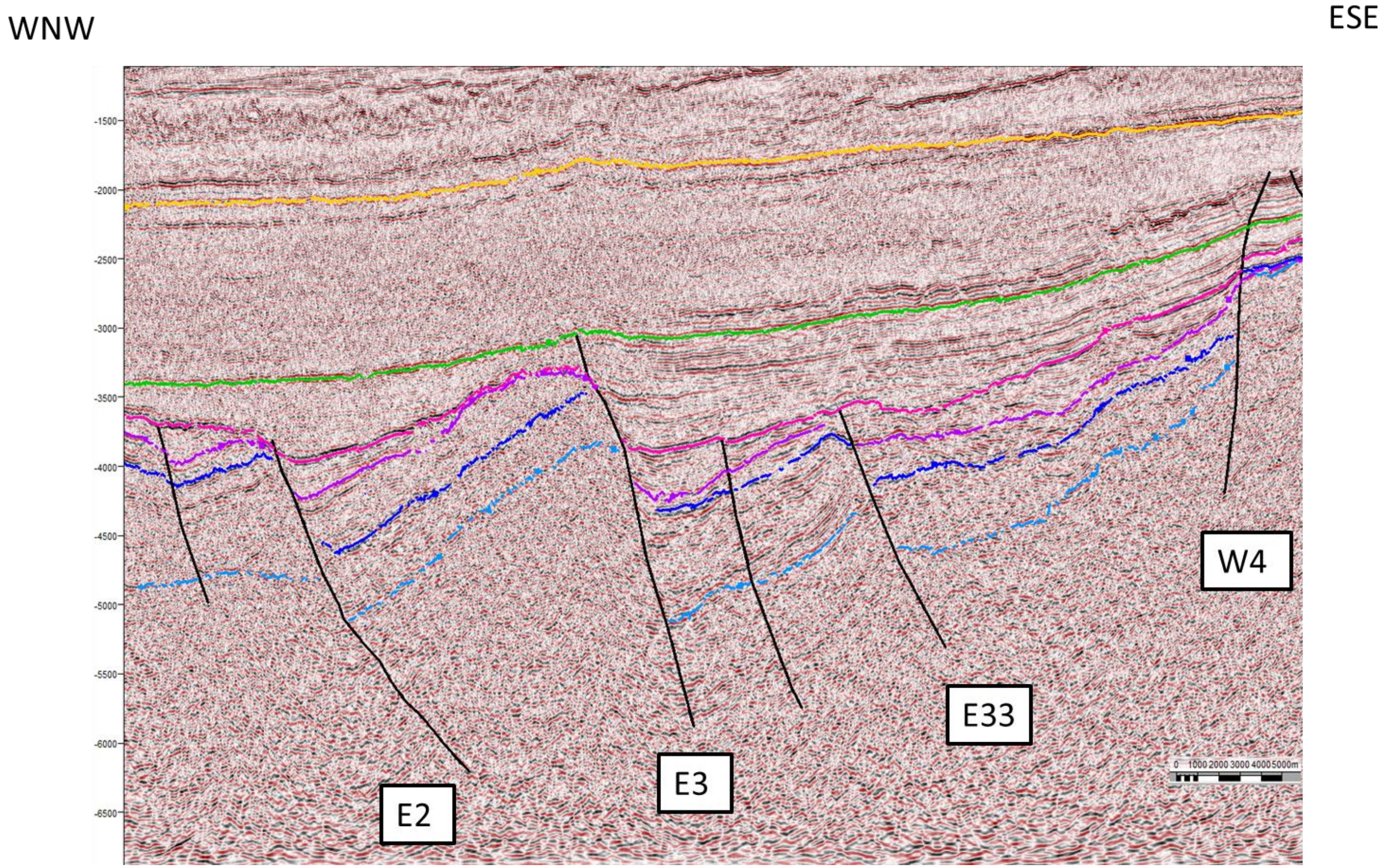


Fig. 4.6a. Key line 5 across the Øygarden Fault Complex, Måløy Fault Blocks, Sogn Graben, Marflo Spur and East Shetland Basin (see Fig. 4.1 for location). The key line illustrates a west-dipping system from Øygarden Fault Complex to Marflo Spur, with change of fault polarity across the protruding horst in eastern margin. The horst further separates the Sogn Graben from a minor half-graben.



b. Enlarged section from key line 5, highlighting the half-graben configuration of Marflo Spur and southern Sogn Graben. It wedges along both E3 and E33, terminating at W4, where westward growth is apparent. The eastward wedging encompasses the pre-Top Brent sequence, Late Jurassic sequence and Early Cretaceous sequence. The western fault block, delineated by E2 and E3, display only Late Jurassic.

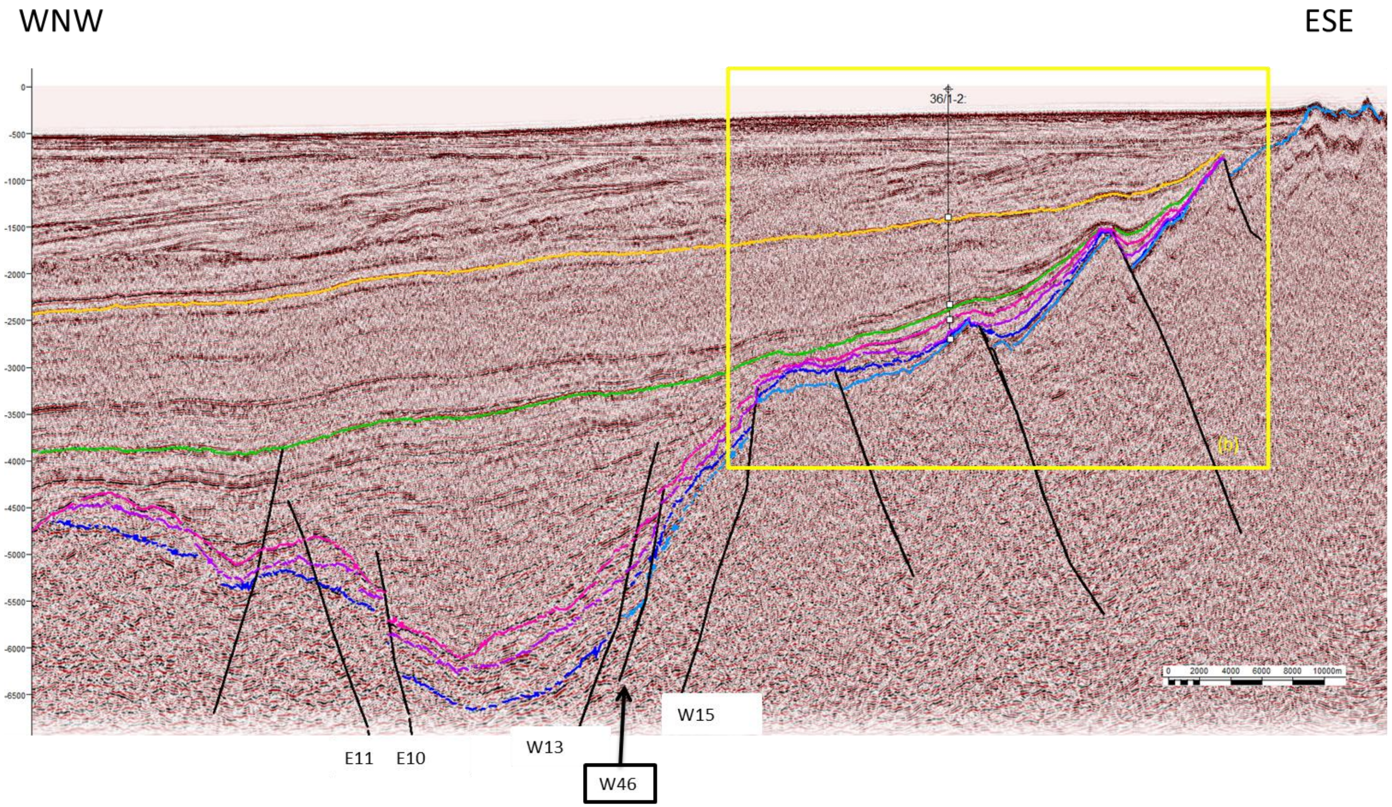
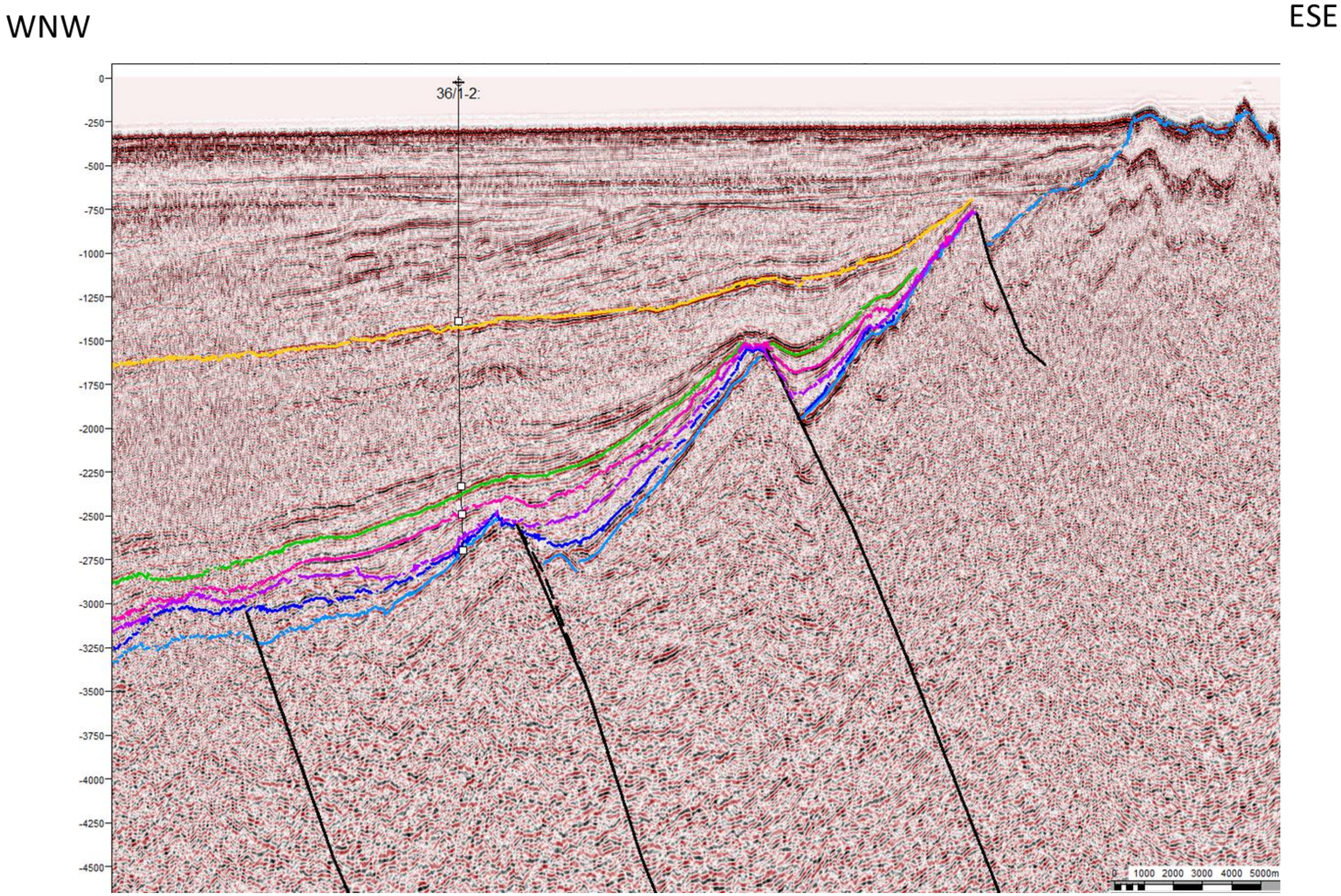


Fig. 4.7a. Key line 6 crossing Måløy Fault Blocks, with well 36/1-2 present and Sogn Graben (see Fig. 4.1 for location). The transition from eastern margin to Sogn Graben decreases sharply from ~3 s TWT down to ~6 s TWT at base Cretaceous level. The Sogn Graben has been deeply downfaulted by both the east-dipping and west-dipping boundary faults. Eastward the faults only display an east-dipping polarity. The basement is shallow on the margin, and thin units of Jurassic and Early Cretaceous sediments are present, whereas the graben is dominated by Early Cretaceous infill. Late Cretaceous sequence drapes the entire profile.



b. Enlarged section of Måløy Fault Blocks from key line 6. Thin Jurassic sequences directly overlie the basement, but some wedging is still prominent along the east-dipping fault planes. The Cretaceous sequences are strongly affected by the fault blocks by bending the Cretaceous horizons.

4.2 Fault maps

Fault maps have been generated at three separate levels to map faults intersecting a certain horizon. The levels used are faults at top acoustic basement, base Cretaceous and base Cenozoic, highlighting both the vertical and lateral extent of each fault at each level.

The fault map representing faults crossing the top acoustic basement (Fig. 4.8) shows large faults trending ENE-WSW, with predominantly west-dipping polarity. The west-dipping faults are mainly located on the Horda Platform and Øygarden Fault Complex, southern Viking Graben and eastern flank of Sogn Graben, whereas the major east-dipping faults are located on western margin of Viking Graben and the Måløy Fault Blocks. However the fault at the northern boundary of Horda Platform, the N-Horda-Fault, located at approximately 61°N (see Fig. 4.1), trends in a WNW-ESE direction and dips toward NNW. Smaller faults display both east- and west-dipping polarities and are more scattered across the centre of the study area. These minor faults display a mainly NW-SE trend, but some also trend NNE-SSW, similar to the larger faults. Although this fault map only expresses the downward extent of the faults, some additional west-dipping faults, proximal to Tusse Fault and Vette Fault, do not reach up to base Cretaceous. These indicate an older origin, and in key line 1, (Fig. 4.2) they correspond to the faults in the acoustic basement (faults W26, W27 and W30).

The fault map illustrating the base Cretaceous level is presented in Figure 4.9, and share many similarities with the fault map at top acoustic basement level, with the exception of the minor, west-dipping faults affecting only the acoustic basement. A majority of the faults represent the upward extent and their point of termination at the base Cretaceous unconformity.

The base Cenozoic fault map (Fig. 4.10) however shows a much more reduced number of faults. They are only found on the Horda Platform and along the Øygarden Fault Complex. As these faults are related to the same faults presented in previous mentioned fault maps they therefore indicate fault reactivations in Early Cenozoic.

A final composite map illustrating the latest activity of each fault is shown in Figure 4.11.

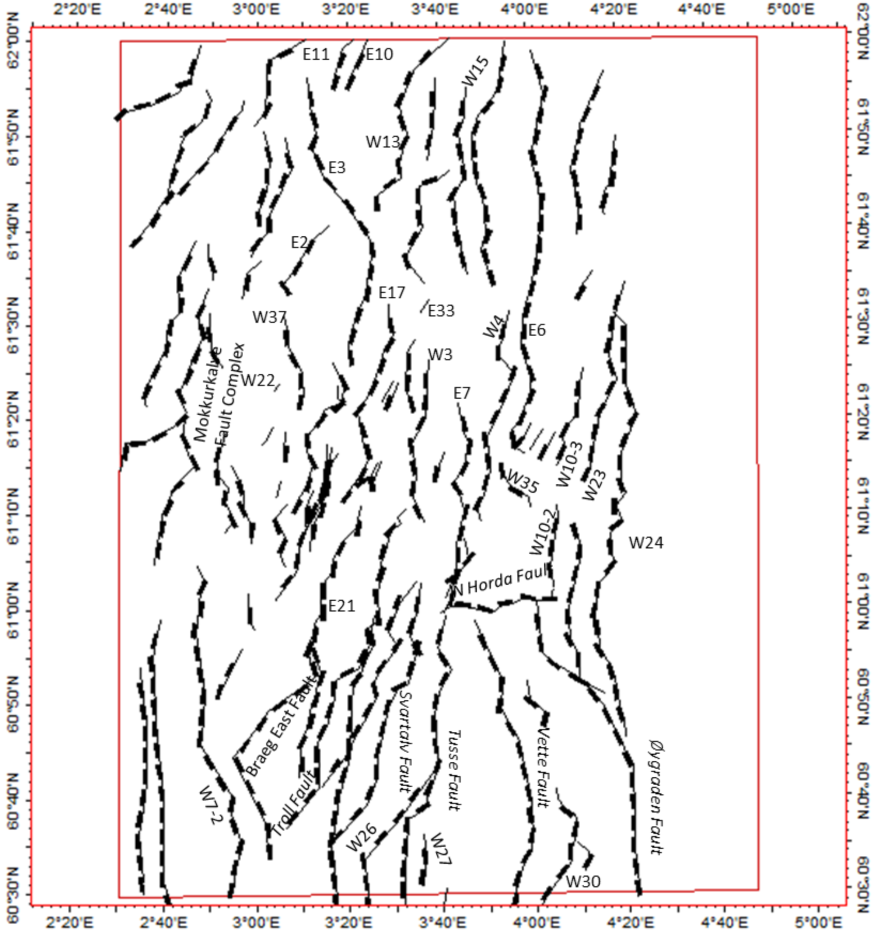


Fig. 4.8. Fault map at top acoustic basement level.

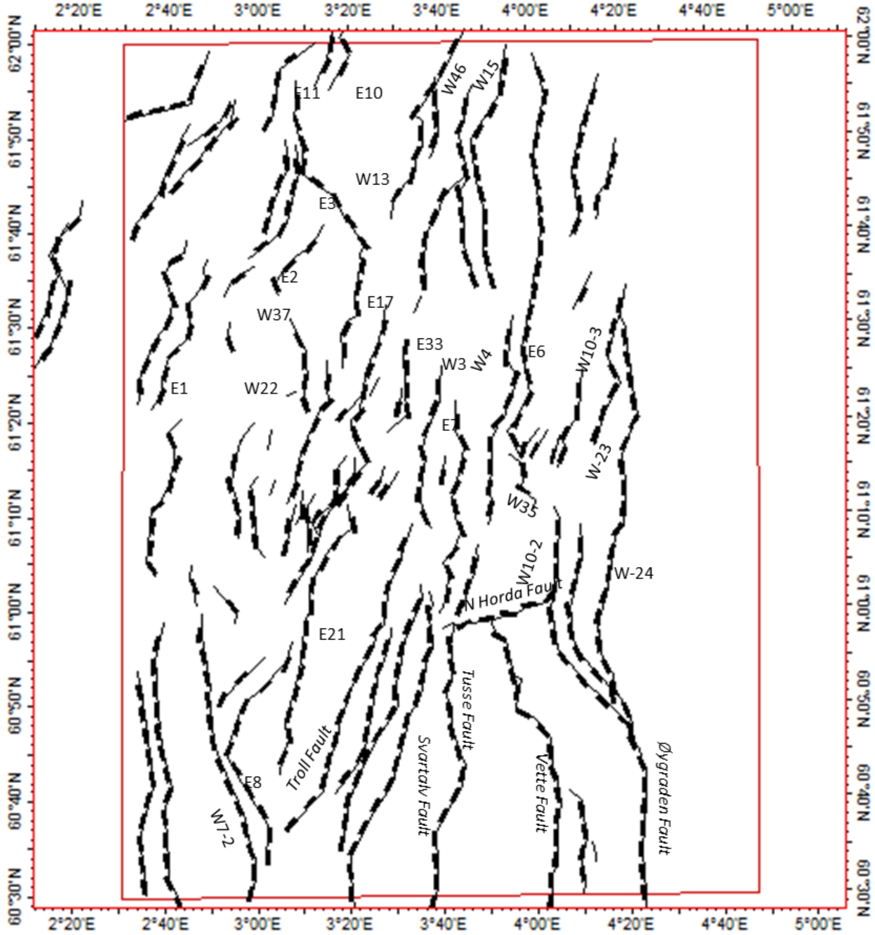


Fig. 4.9. Fault map at base Cretaceous unconformity level.

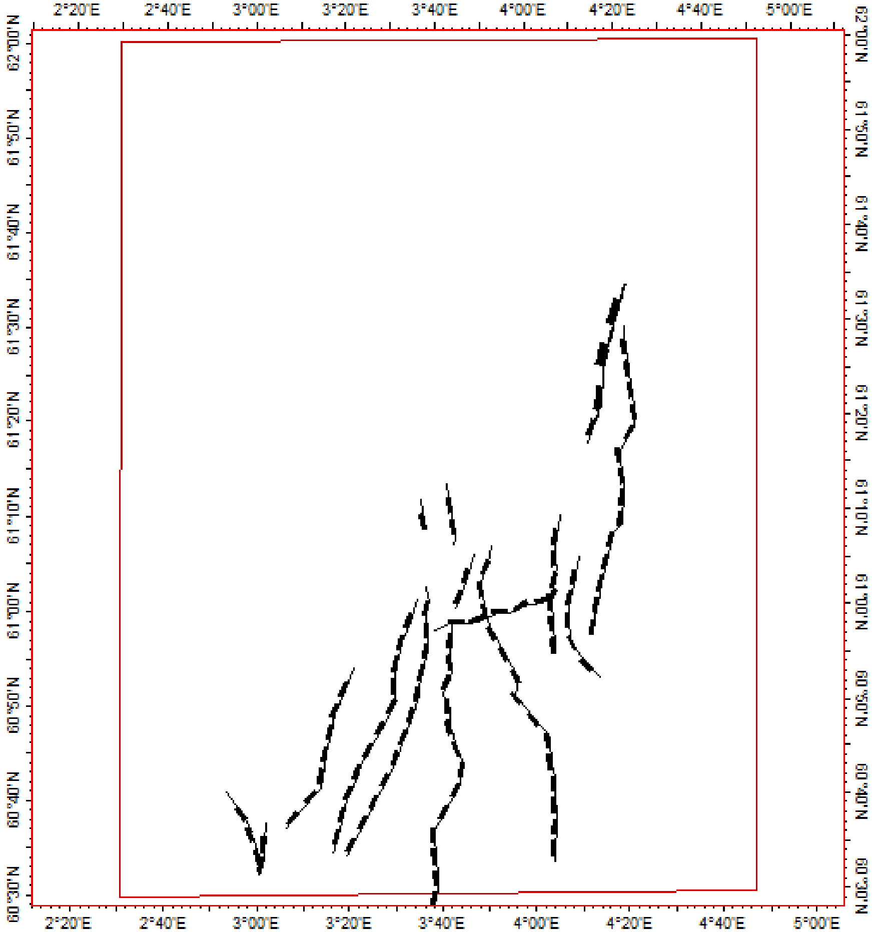


Fig. 4.10. Fault map at base Cenozoic level.

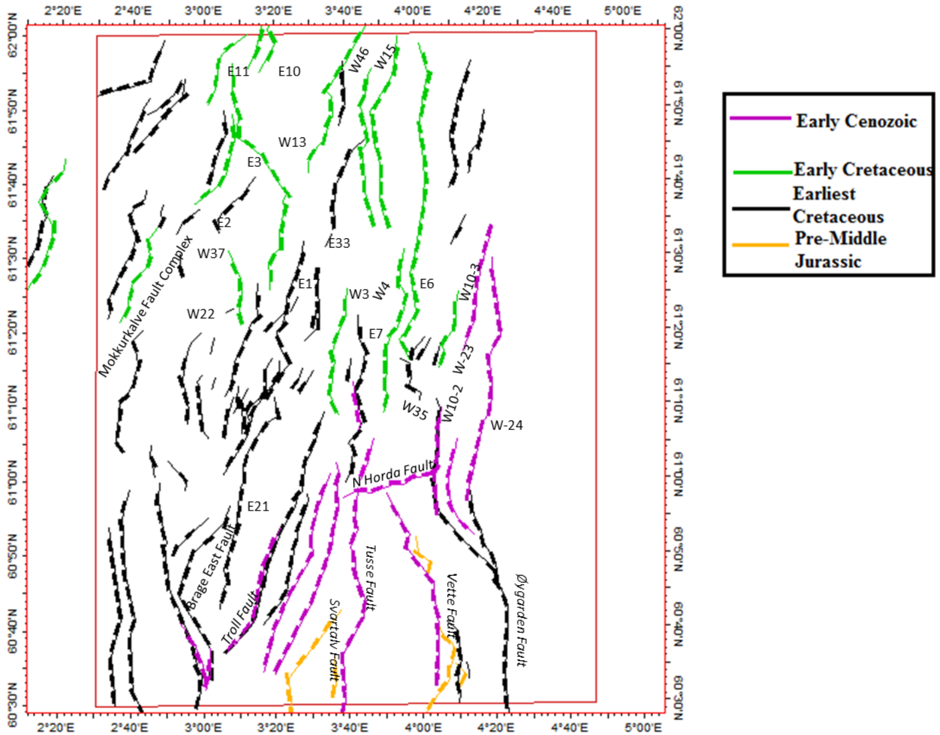


Fig. 4.11. Composite fault map, denoting each of the faults latest activity. See colour description for time.

4.3 Regional time-structure maps

Time-structure map for each interpreted reflectors will be presented and described in order to gain a better understanding of the individual reflector's behaviour across the region as well as their relationship to each other. The contours are set with an interval of 500 ms TWT on all maps, with the exception of Late Cenomanian which has been set to a 400 ms TWT-interval and base Cenozoic with a contour interval of 200 ms TWT. This has been done in order to amplify details of these rather smooth surfaces. As the Petrel software interpolates the areas between the 2D-seismic lines during surface generation smoothening occurs to assume the reflection's continuity. Seismic profiles with low resolution tend to have distorted and spiky reflection appearance that can result in local scars of the generated surface where the lines are oriented. A smoothening technique was therefore performed by the use of Petrel software by using different numbers of iterations to smooth the surfaces. This number varies for each surface, dependant on how uneven each surface appeared. The top acoustic basement, top Brent, base Sognefjord Fm. and base Cenozoic had hundred smoothening iterations, whereas base Cretaceous and top Svarte Fm. were applied seventy and fifty iterations, respectively. Notice the colour bar for each map differs in scale. For comparison the surfaces have also been combined with the fault maps to strengthen the understanding of the paleobathymetry, thus each surface was merged with the appropriate fault map level.

4.3.1 Top Acoustic Basement

The top acoustic basement horizon has been mostly interpreted in the eastern part of the northern North Sea along with the grabens and their western adjacent areas. Figure 4.12a displays the time-structure map of the top acoustic basement in the seismic data. The top acoustic basement horizon has a maximum elevation of -101 ms TWT, and the surface generated from it has been cropped above this value. The map shows a general deepening of the basement westward, with the deepest areas confined in the Viking Graben to the west and in Sogn Graben to the northwest of the study area. In the east, proximal to the Norwegian Western mainland, a prominent basement platform is evident north of 60°50'N, being much shallower compared to the acoustic basement south of 60°50'N; about 2,5 s TWT in the north compared to 4 s TWT in the south. The abrupt deepening to the south can be explained by the presence of the Øygarden Fault (Fig. 4.12b). The Horda Platform, Lomre Terrace and Uer Terrace, along with the Shetland Platform display a relatively uniform basement depth (~4 s TWT) with shallower local areas, but deepening proximal to the Viking Graben. The time-structure map also shows a general shallowing trend of the basement northward from Horda Platform to Måløy Fault Blocks. The basement between Viking Graben and Sogn Graben, in their linkage between Marflo Ridge and Tampen Spur, lie shallower compared to that in the grabens.

4.3.2 Top Brent

The top Brent surface has been mapped across the whole study area in the northern North Sea (Fig. 4.13a). The time-structure map shows a general deepening of top Brent towards the centre of the region. The deepest areas are located within and parallel to the Viking Graben and Sogn Graben; ~ 6 s TWT and ~ 7 s TWT, respectively, and to the west in Marulk Basin. The most significant abrupt change of depth is located along the flanks of the Sogn Graben and the western part of Viking Graben, with the latter imposed by the Mokkurkalve Fault Complex. The map displays the change of depth decreasing away from the grabens, with the contour spacing increasing eastward from the Viking Graben to Horda Platform and from Sogn Graben to the Måløy Fault Blocks. As with the time-structure map of top acoustic basement, this map too depicts a shallower area in the linkage between Sogn Graben and Viking Graben. It is interesting to note a trough adjacent to the Western Norwegian mainland just north of 61°N with a NW-SE trend. This trough is approximately positioned and trending the same direction as the southern part of Sogn Graben as well as the northeastern flank of the Marflo Spur. This surface is clearly intersected by faults, both minor and major faults (Fig. 4.13b).

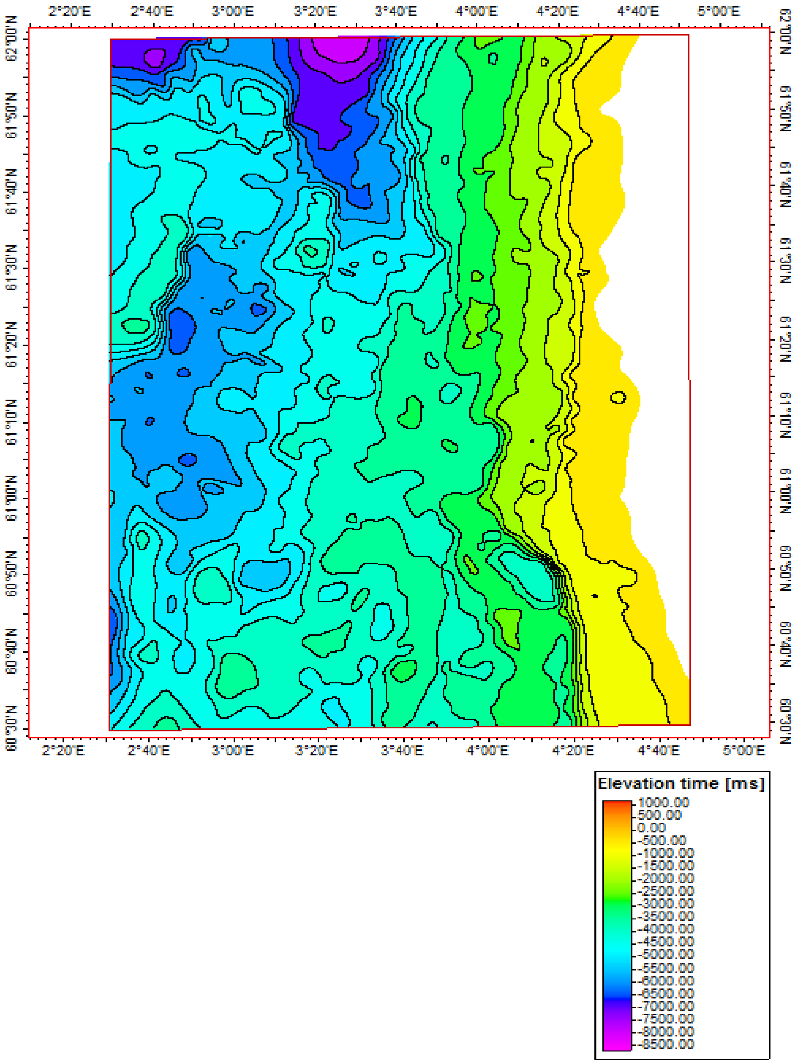
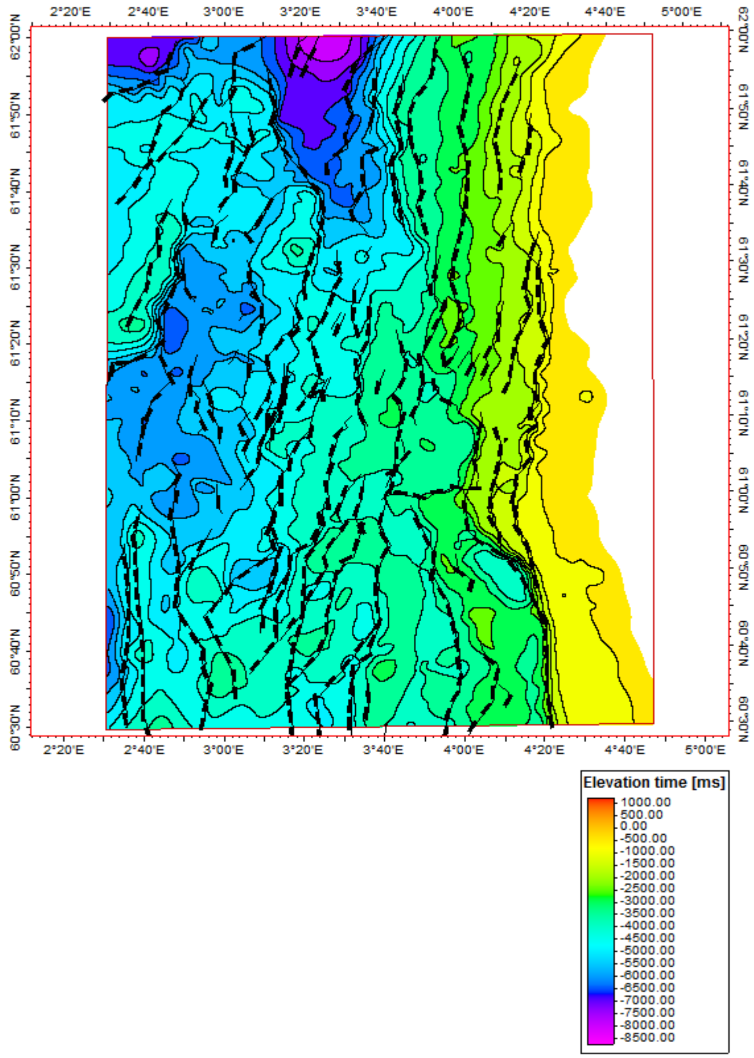


Fig. 4.12a. Time-structure map of top acoustic basement



b. Time-structure map of top acoustic basement with fault traces at top acoustic basement level.

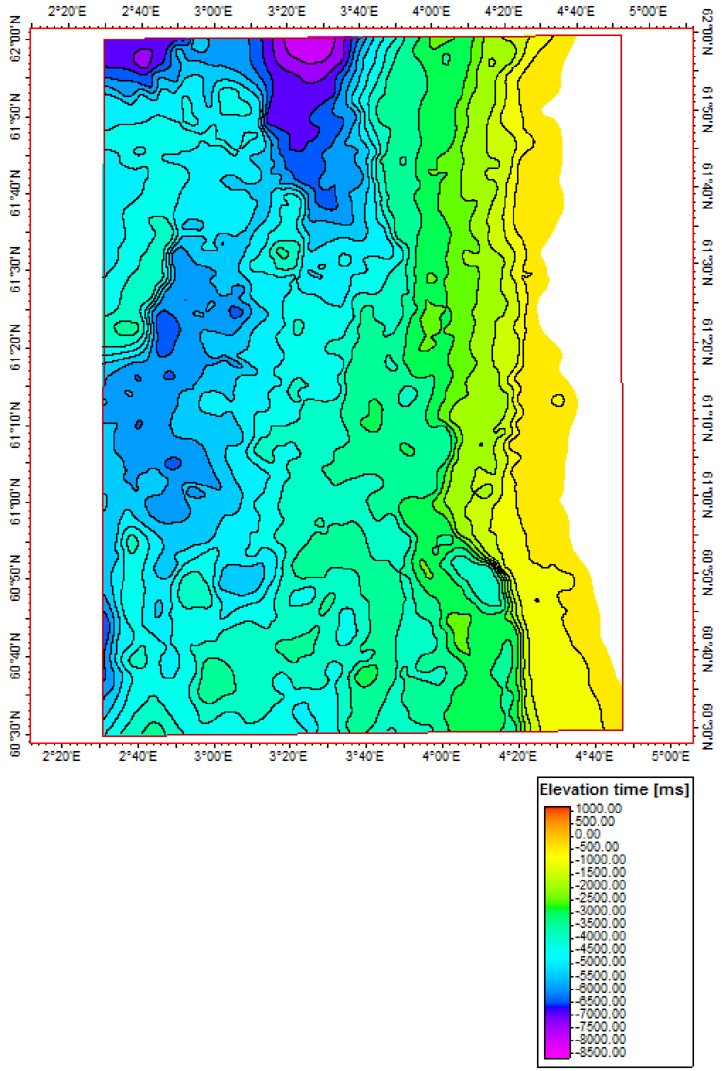
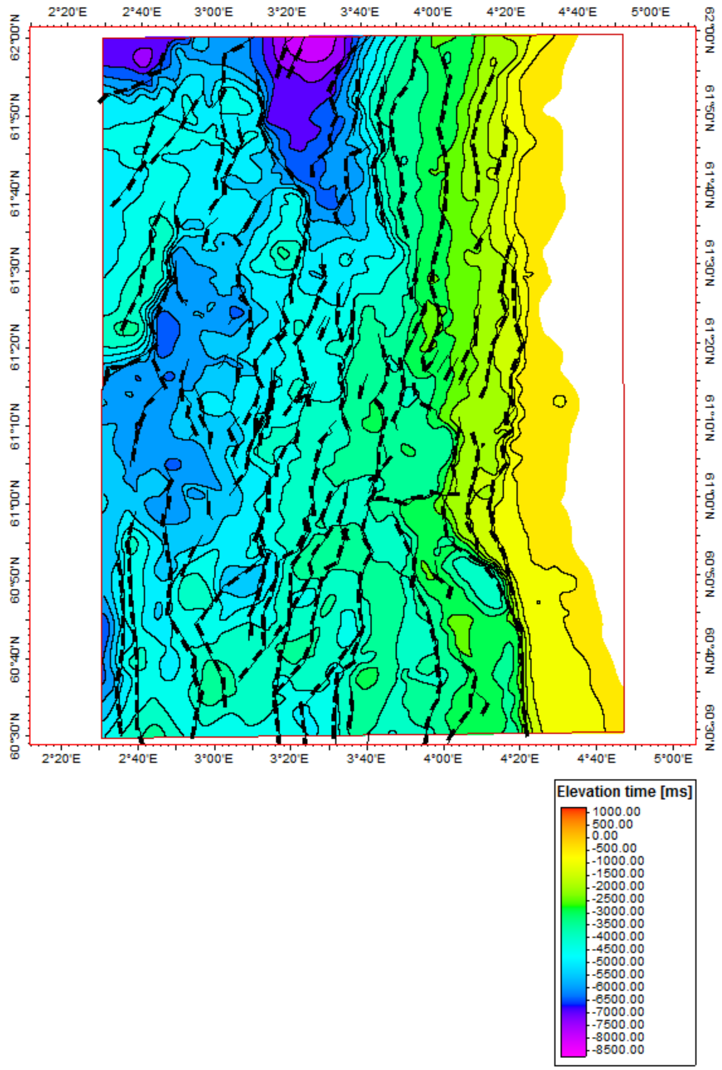


Fig. 4.13a. Time-structure map of top Brent.



b. Time-structure map of top Brent with fault traces at base Cretaceous level.

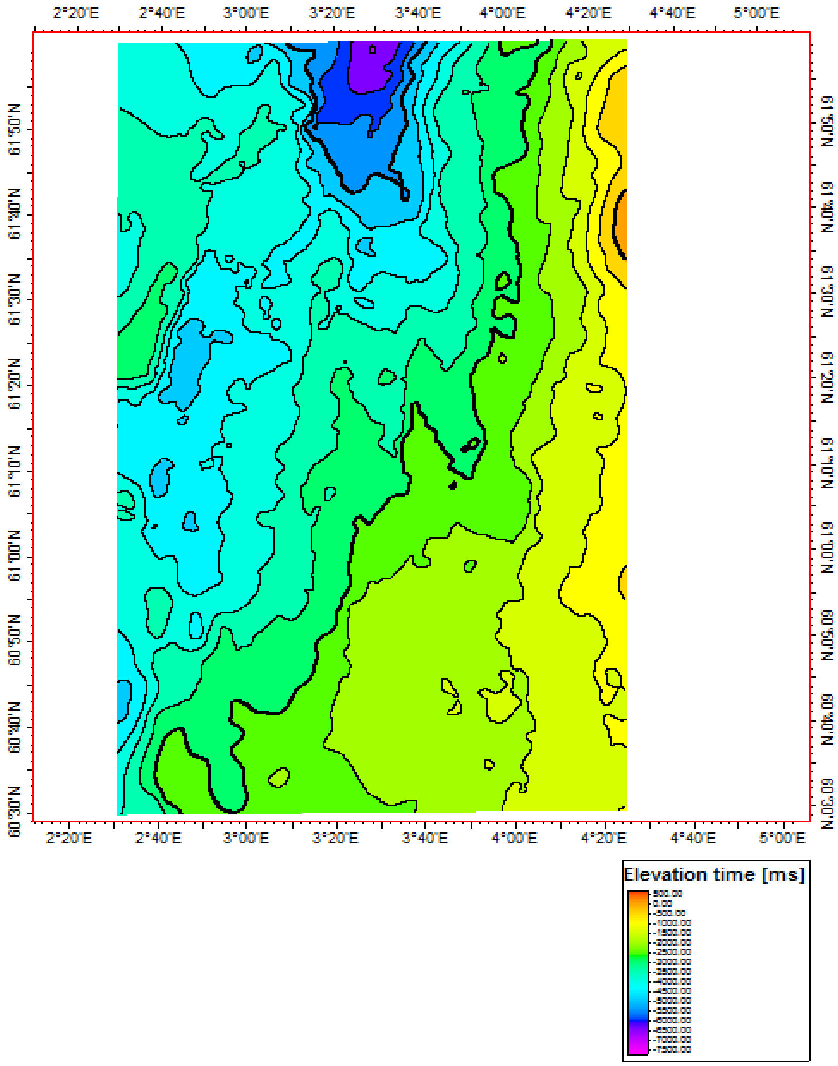
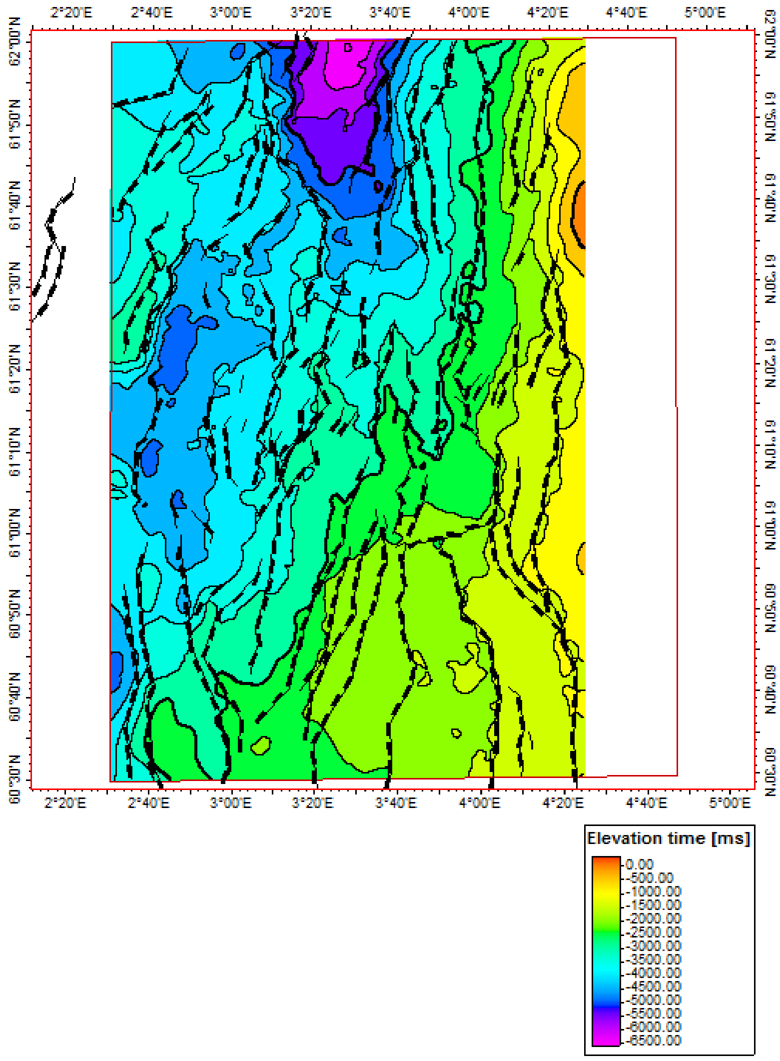


Fig. 4.14a. Time-structure map of base Sognefjord Fm..



b. Time-structure map of base Sognefjord Fm. with fault traces at base Cretaceous level.

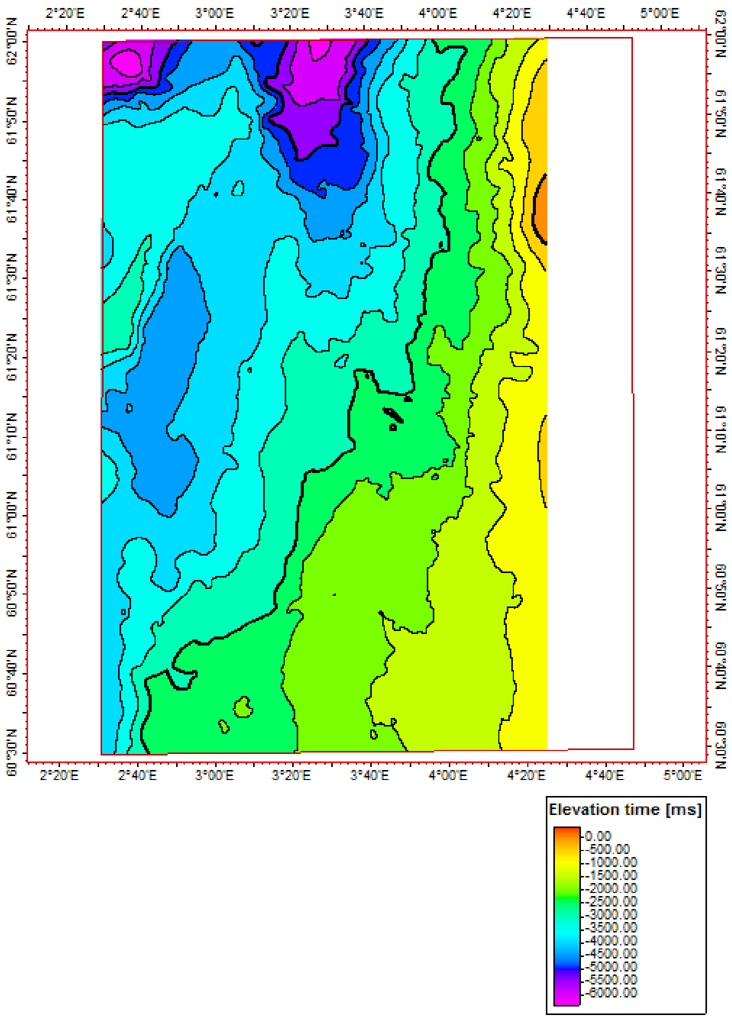
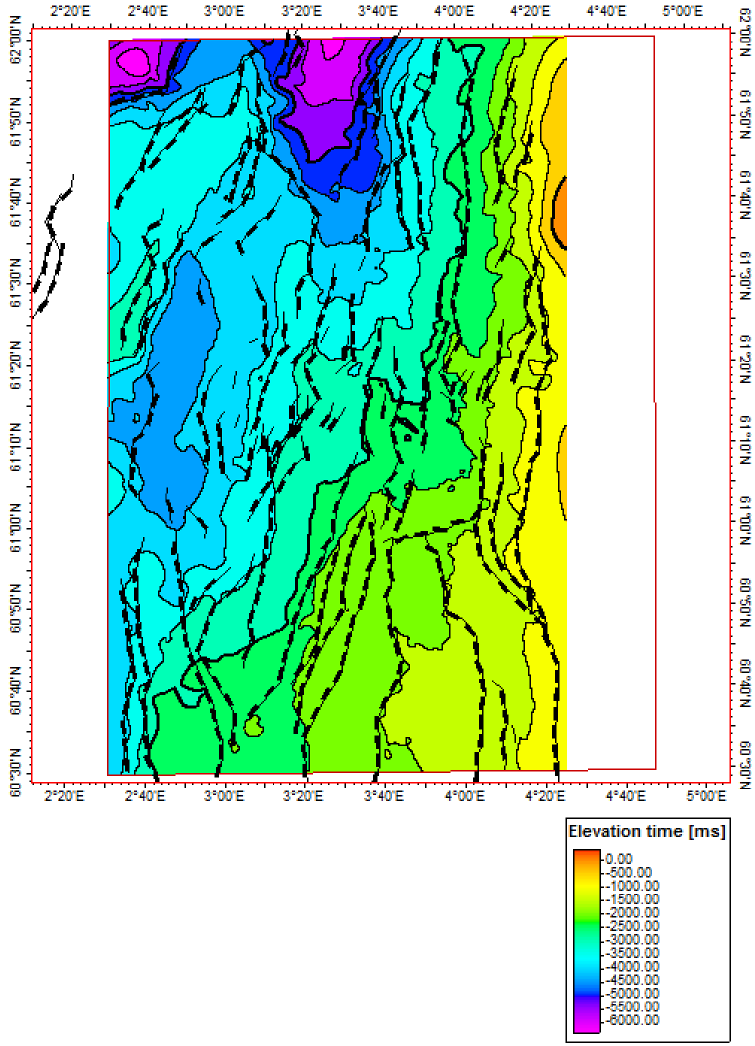


Fig. 4.15a. Time-structure map of base Cretaceous unconformity.



b. Time-structure map of base Cretaceous unconformity with fault traces at base Cretaceous level.

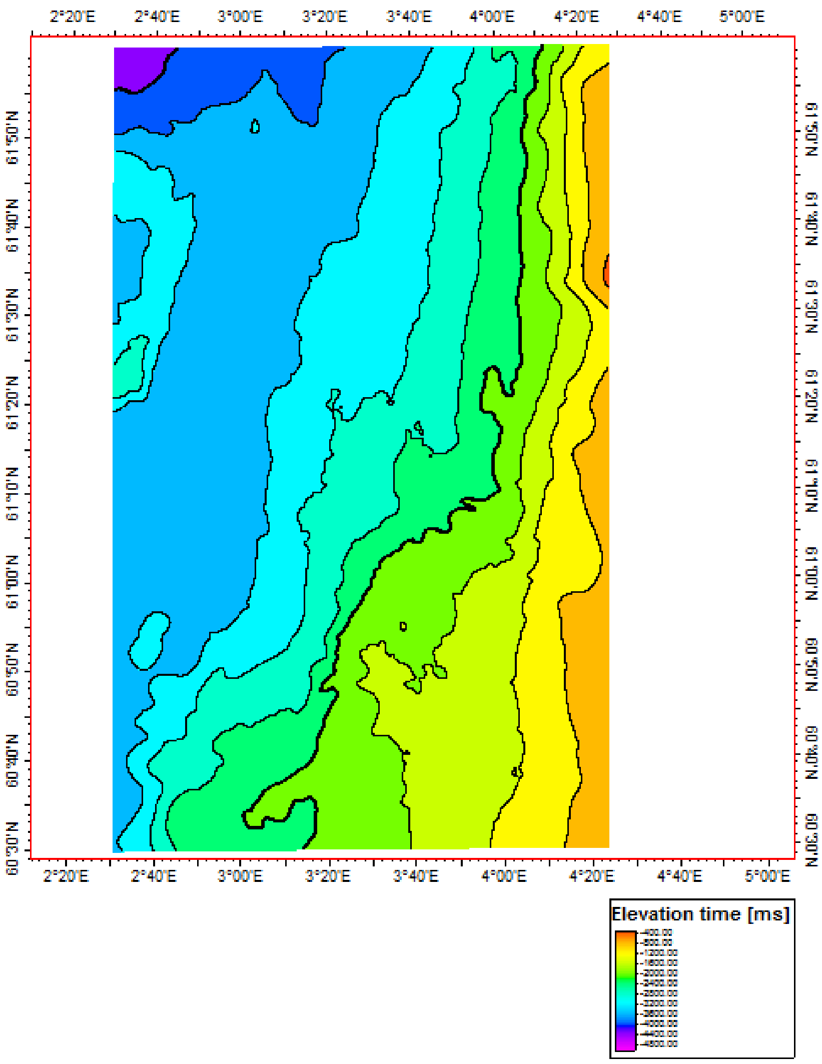
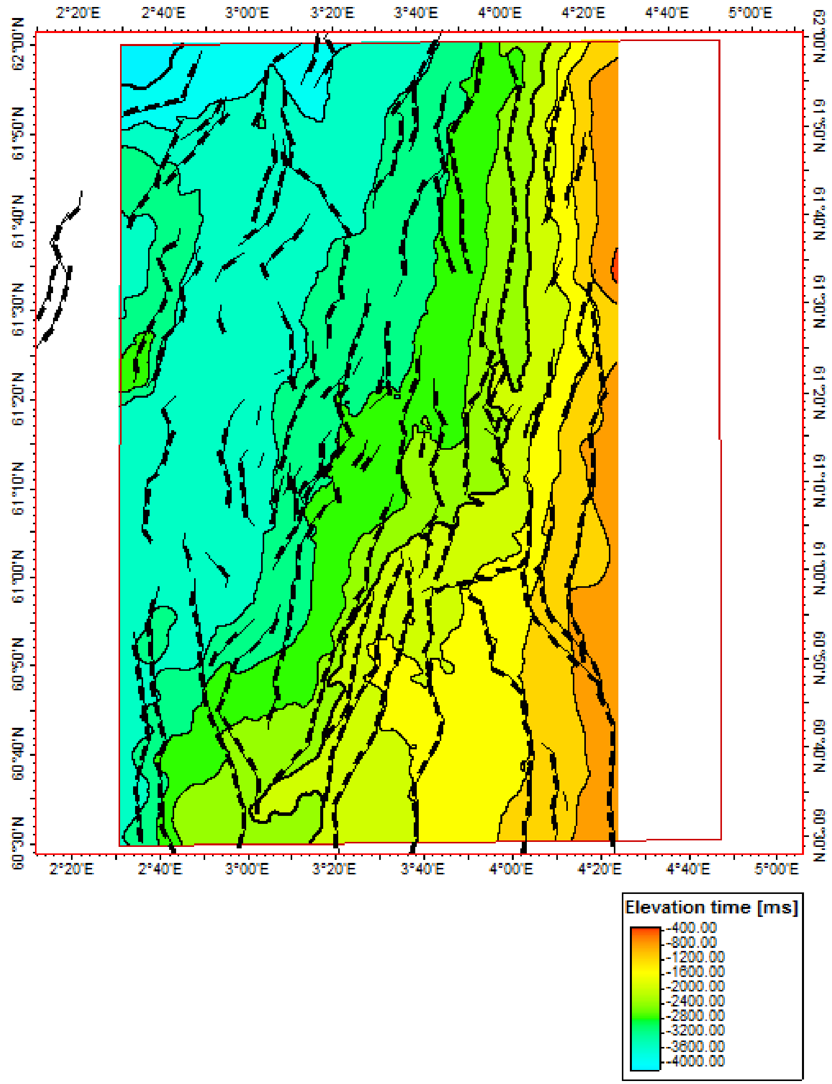


Fig. 4.16a. *Time-structure map of Late Cenomanian.*



b. Time-structure map of Late Cenomanian with fault traces at base Cretaceous level.

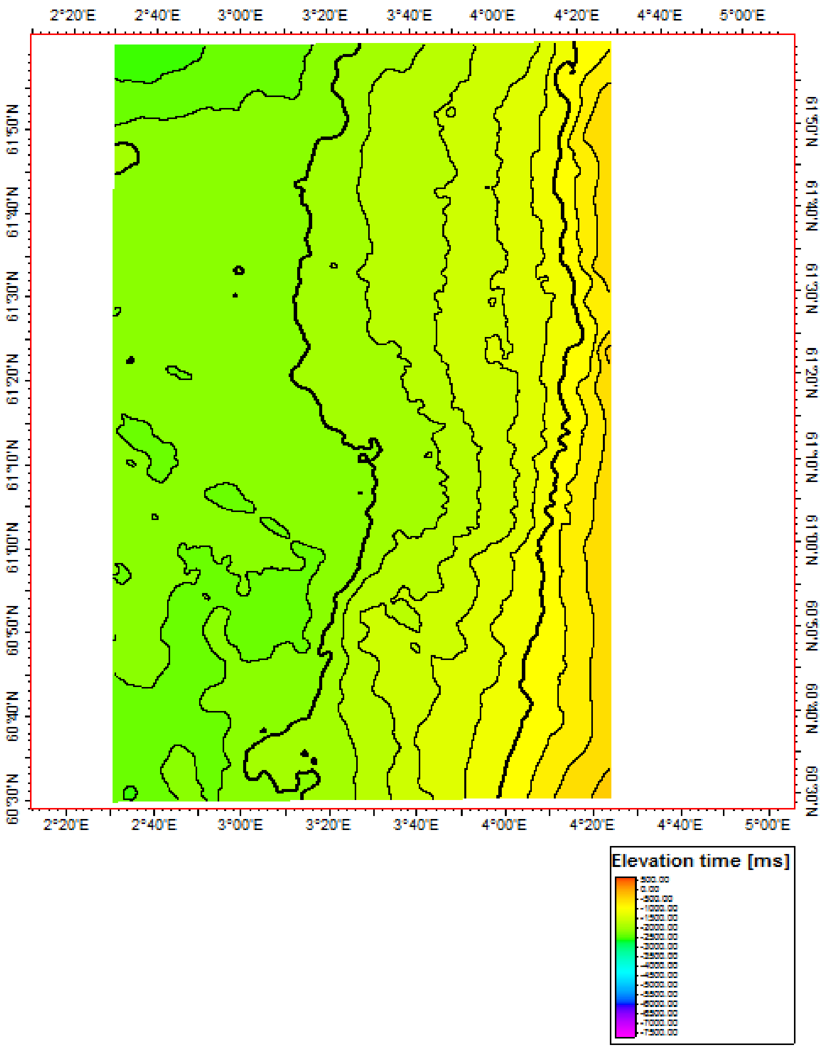
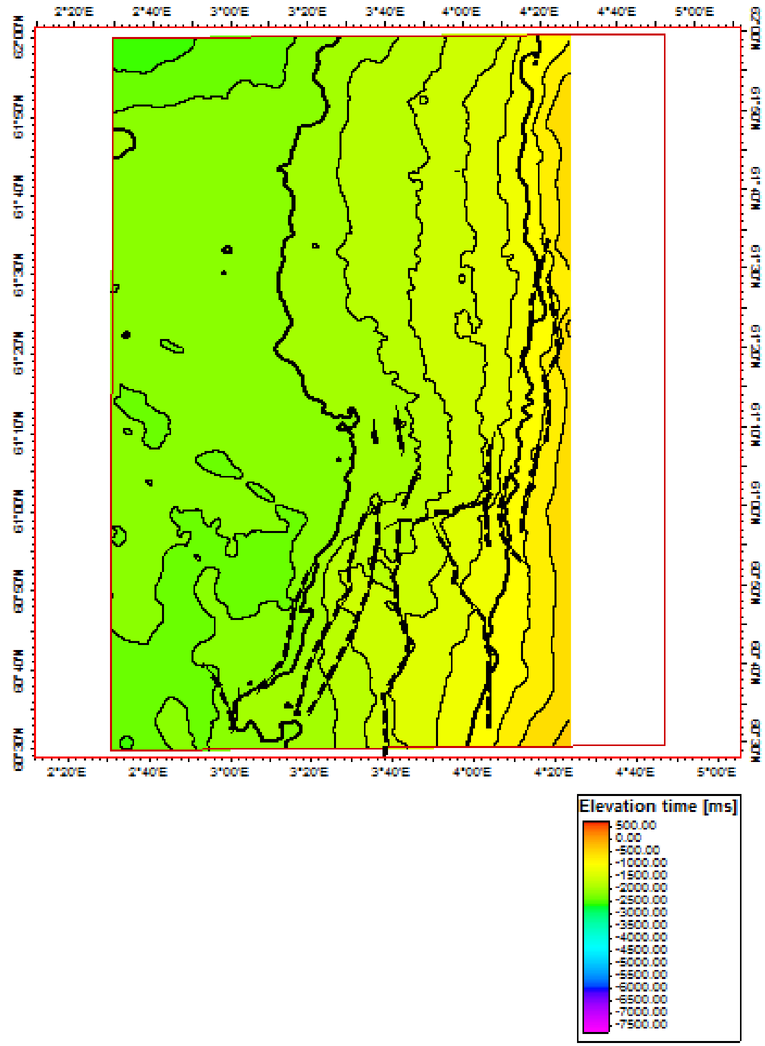


Fig. 4.17a. Time-structure map of base Cenozoic.



b. Time-structure map of base Cenozoic with fault traces at base Cenozoic level.

4.3.3 Base Sognefjord Fm.

The time-structure map of base Sognefjord Fm. share many similarities with the top Brent time-structure map (Fig. 4.14a). It also depicts a surface which has a sharp depth transition from the western margin of the Viking Graben and Sogn Graben into the grabens, as well as the region with the overall shallowing eastward towards the mainland. The reflection in the Horda Platform and Uer Terrace is generally low-dipping and shallows eastward. In the Måløy Fault Blocks however the contours are comparably denser, indicating a more steeper terrain. The trough noted in the top Brent time-structure map is also present in the base Sognefjord surface with the same characteristic trend. The integrated fault map illustrate that faults are intersecting the surface and shaping it (Fig. 4.14b).

4.3.4 Base Cretaceous unconformity

The Base Cretaceous unconformity has been mapped in the study area with emphasis to the east of the grabens, the grabens themselves as well as the western flanks of the grabens. It is clear that the study area deepens towards the grabens, with the deepest part in the Sogn Graben (Fig. 4.15a). The most prominent change of depth are along the western flank of the Viking Graben as well as the flanks of the Sogn Graben (Fig. 4.15b). Areas of Horda Platform and Måløy Fault Blocks however show an eastward shallowing, where the latter having a steeper gradient towards the mainland. The deeper basin to the west of Sogn Graben corresponds to the Marulk Basin (Fig 4.1).

4.3.5 Late Cenomanian

The reflection of Late Cenomanian age is mostly apparent in the Cretaceous infill of the basins, defined by the Base Cretaceous Unconformity, and generally follows this unconformity outside the basins along their margins. It has been mapped across the grabens, on the eastern side of the study area, as well as on the western margins of the grabens. The time-structure map shows an increase in two-way travel time towards the centre of the basin with the deepest areas following the same trend of NNE-SSW as the grabens (Fig. 4.16a). It is however not a clear distinction anymore between the Viking Graben and the Sogn Graben, and the deepest parts are more continuous over a wider area with smaller depth range in the map. There is a shallowing trend eastward with slope gradient increasing, confirmed by the decreasing contour spacing towards the mainland. The map also indicates a smaller contour spacing in the Horda Platform at about 3°20'E.

4.3.6 Base Cenozoic

The base Cenozoic reflection has been mapped across the entire study area and is the uppermost horizon that has been mapped. This reflection represents the top of the Cretaceous post-rift sedimentary infill, and extends across regionally and is relatively uniform. Its corresponding time-structure map confirm this observation with a small depth range in the whole region and the deepest contours are covering a wide area (Fig. 4.17a). Still one can see that the deepest parts are bounded to areas positioned above the grabens, though this is vague due to the depression's wide coverage. A steadily easterly increase in slope gradient is present, as seen in the other Cretaceous time-structure maps. It is also notable that there are closer contour spacing on Horda Platform at 3°20'E as noted in the Late Cenomanian time-structure map. The same surface with integrated base Cenozoic fault map is presented in Fig. 4.17b.

4.4 Time-thickness maps

Time-thickness maps (TWT) were generated between selected surfaces in order to obtain a better understanding of the sediment distribution of each seismic sequence in the study area. These will later be used in the discussion to relate them to geological evolution. The surfaces used to perform this task are the top acoustic basement-, top Brent-, base Cretaceous unconformity-, Late Cenomanian- and base Cenozoic surfaces. After generation they were all subjected to a hundred iterations of smoothening to make them less distorted. Furthermore, as there is no possibility to have negative thickness, all areas exceeding the zero-value were replaced with zero. Areas affected by this are located in the easternmost study areas, where Petrel extrapolates the surfaces outside of the basin, giving rise to negative thicknesses. Note the scale of the colour bar and the contour interval varies for each map. The latter will be emphasised in each section. Likewise with the time-structure maps, a combined map from both the time-thickness map and the proper fault map is presented to enhance the relationship between structures and seismic stratigraphy. The isochore contours have been obliterated to avoid fault trace camouflage.

4.4.1 Top Brent to top acoustic basement

The contour interval set for this map is 300 ms TWT. The thickness distribution in the region shows a general south-westward thickening between the top acoustic basement reflection and the top Brent reflection (Fig. 4.18a). The thinnest parts are indicated in orange and are confined to the eastern part of the region, the Måløy Fault Blocks and the footwalls of the Øygarden Fault Complex. These areas display an approximate zero thickness which is also evident from the seismic profiles in the area (e.g. key line 6; Fig. 4.7a). The thicker parts are confined south of 61°N, but a blue-purplish part is also seen to the north in Viking Graben, in the Sogn Graben curving to the south-east of Marflo Spur. In the former, the thickening also curves south-eastward and assumes the shape of a half-graben. The southern thick units contain some elongated areas of thinner units located within, trending NW-SE and NE-SW. When applying the top acoustic basement fault map onto the time-thickness map it is evident the major listric faults on Horda Platform correspond to the thicker units (Fig. 4.18b). As the units decreases in thickness away from the faults before abruptly expand again across the faults, it indicates a wedging geometry between them, thus indicating a fault generation predating the Middle Jurassic.

The observation of wedging in the minor graben, along fault E6, from key line 3 (Fig. 4.4b) represents also a feature paralleling the N-S trending fault further to the east. Wedging is also apparent along the E7-fault in key profile 3 and 4 (Fig. 4.4b and 4.5b, respectively). This also applies to the faults delineating the western Viking Graben, fault Mokkurkalve Fault Complex (see key line 4; Figs. 4.5a and c), and western Sogn Graben, fault E3 (see key line 5; Fig. 4.6), matching that of the thickened pattern mentioned earlier. This illustrate however the minor importance of the eastern fault boundaries of the grabens north of 61°N during this time period. Although the Marflo Spur consists of east dipping faults of Permo-Triassic origin, the west dipping fault, W3, in key line 3 and 4 (Figs. 4.4 and 4.5) also indicates it originated in the same period due to thicker pre-top Brent unit in the hanging wall compared to the footwall. This suggests an antithetic development, forming a minor graben. Noteworthy is also the northern fault boundary of Horda Platform, N-Horda-Fault, separating the thick depocentres on Horda Platform to the south from the thin units to the north. The central parts of the map illustrate however an intermediate transition where sediment-accommodation was larger between two facing, opposite-dipping faults. Additionally, the area includes a south-dipping fault, possibly showing thickening of pre-top Brent sequence along it. However due to scarce data coverage in this particular area, tracing this fault was difficult and has therefore not been included further in the study (Fig. 4.18c, see Fig. 4.1 for location of seismic section).

4.4.2 Base Cretaceous unconformity to top Brent (syn-rift sequence)

As many fine details are present a small contour interval of 200 ms TWT has been applied to enhance local thickness variations in the region. This map shows a general thickening in the whole basin, but with slighter thinning on the Tampen Spur than on Horda Platform (Fig. 4.19a). The thickest units are restricted to the grabens as is evident with the lateral transition from yellow to green-blue colours. The thinnest units are mainly located to the east of the study area, approximately north of 61°N in the footwalls of Øygarden Fault Complex and the Måløy Fault Blocks. Applying the fault traces (Fig. 4.19b) the obvious development of the grabens have occurred along their fault boundaries. Thin units are also detected on narrow areas between opposing faults proximal to the Viking Graben, paralleling it. However some of the faults have been active on the rest of the study area with signs of minor thickening along them. This is especially evident on Horda Platform along its major listric faults (see for example key line 1; Fig. 4.2) and its northern fault boundary, the N-Horda-Fault. This is also true for the Måløy Fault Blocks, but with thinner wedges (key line 6; Fig. 4.7a). This time-thickness map also implies a structural development of the Marulk Basin to the northwest. It is interesting to note when comparing Marflo Spur in this isochore map with the isochore map between top acoustic basement and top Brent that it has a larger thickness in this particular case than the other.

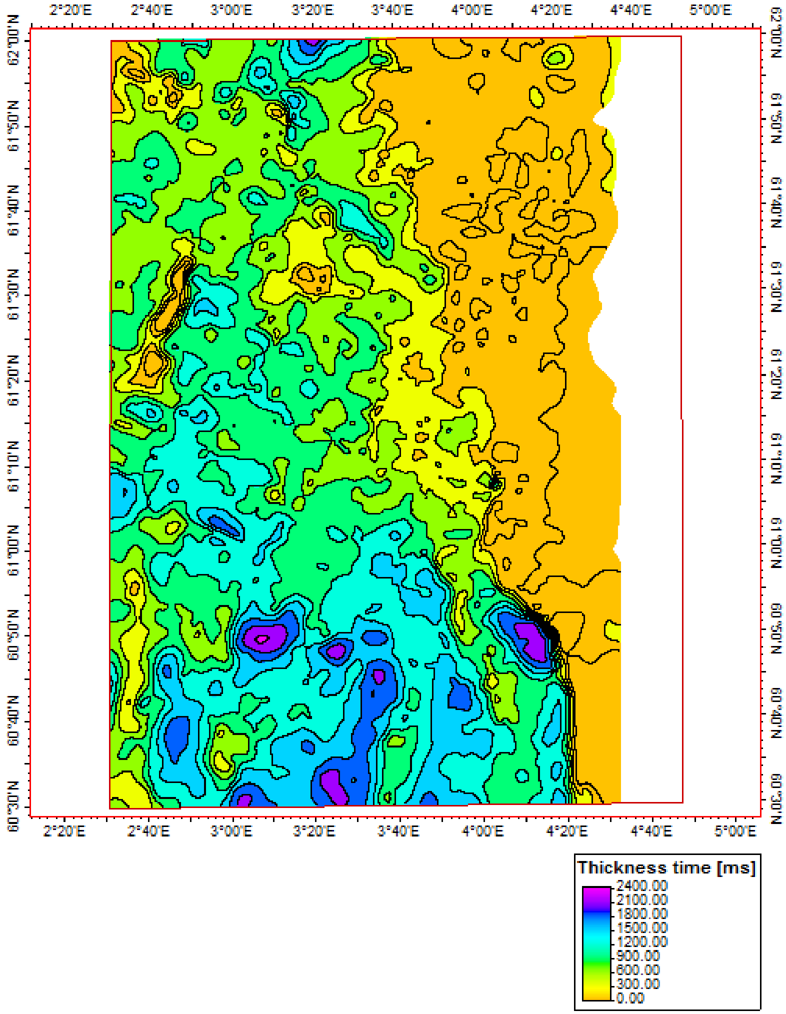
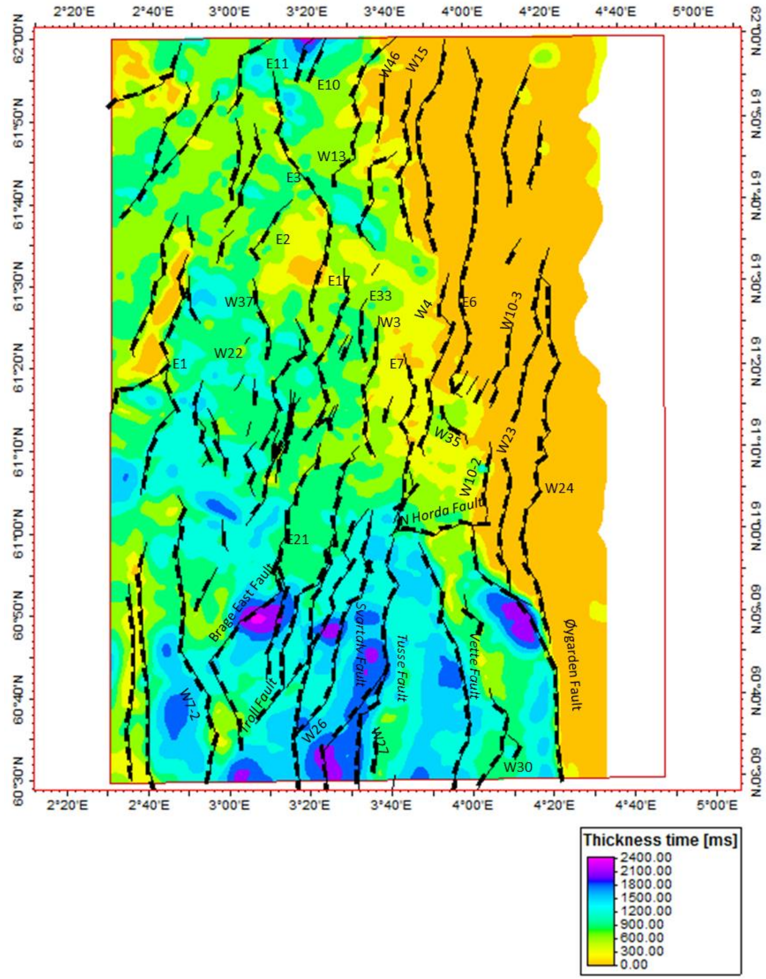
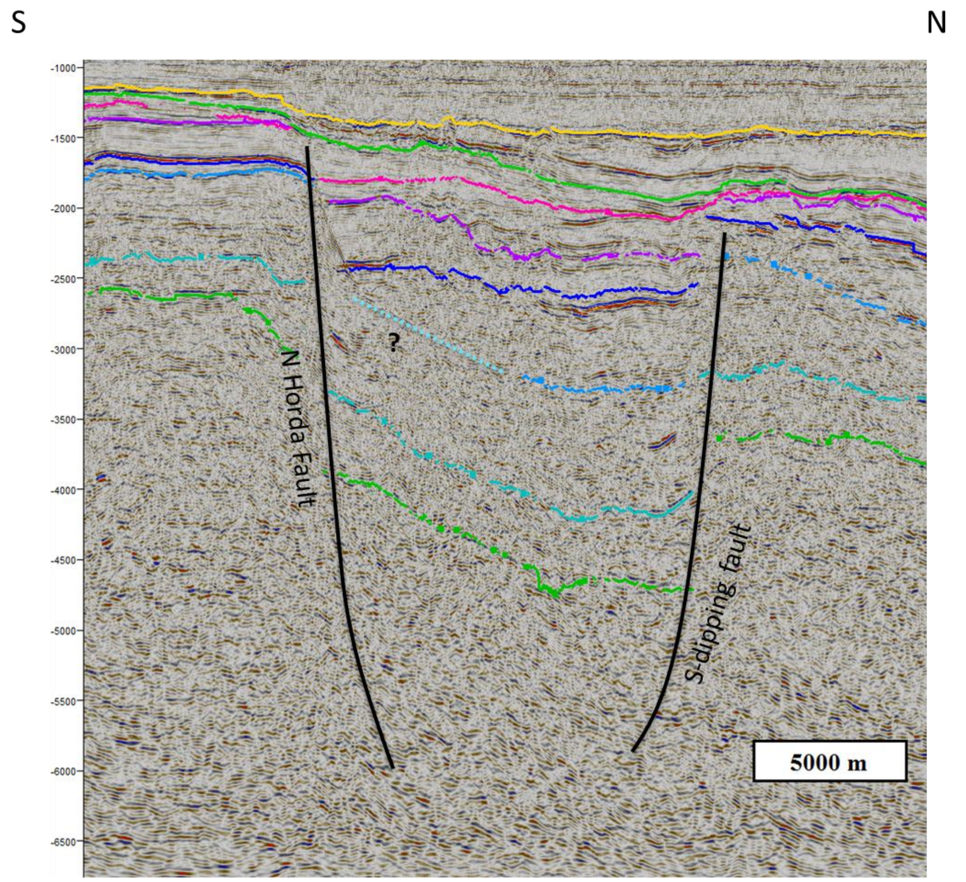


Fig. 4.18a. Time-thickness map between top Brent and top acoustic basement.



b. Time-thickness map between top Brent and top acoustic basement with integrated top acoustic basement fault traces.



c. Section crossing the N-Horda-Fault (see Fig. 4.1 for location), revealing a south-dipping fault, offsetting the Jurassic and pre-top Brent sequences. Due to the width of seismic data spacing in this area, the coverage was too scarce to follow it. The lowermost sequence thickens across it and with the proposed extrapolation of top acoustic basement-horizon it may be wedge-shaped toward N-Horda-Fault, indicating an activity along it before Middle Jurassic. The length of the scale box represents 5000 m.

4.4.3 Late Cenomanian to base Cretaceous unconformity (early post-rift sequence)

The time-thickness map, with a contour interval of 200 ms TWT, between the Late Cenomanian reflection and the base Cretaceous unconformity displays the largest time-thicknesses in the grabens where they reach up to ~0,8 TWTs and ~2,4 TWTs in the Viking Graben and Sogn Graben, respectively (Fig. 4.20a). The thicknesses decrease rather rapidly towards the flanks of the grabens, indicated by both the colour transition from blue-green to uniform yellow-orange, and the denser contours. *When reviewing key profile 3, 4 and 6 (Figs. 4.4, 4.5 and 4.7, respectively) this is observed with the thick Early Cretaceous package in the grabens whereas it thins drastically eastward.* It is evident in the Horda Platform and Uer

Terrace to the east and on the western boundary of the Viking Graben show narrow, elongated areas of thinner spots trending along an approximate N-S axis. From the applied fault map (Fig. 4.20b) the thickening in the grabens have distinctively occurred along their fault boundaries. The faults on Horda Platform and East Shetland Basin were of minor importance, but some accommodation were formed, see for example key line 1 (Fig. 4.2). But the northern fault boundary of Horda Platform, the N-Horda-Fault generated more space during this period. As fault boundaries of the Sogn Graben extend into the Early Cretaceous from key line 6 (Fig. 4.7) it may be deemed that some of the accommodation space was fault-controlled, as seems to match with the applied fault map.

4.4.4 Base Cenozoic to Late Cenomanian (late post-rift sequence)

A contour interval of 300 ms TWT has been applied on the time-thickness map between base Cenozoic and Late Cenomanian (Fig. 4.21a). This period represents the middle and late stage of the post-rift evolution (Gabrielsen et al., 2001). The map exhibits a larger time distance in the centre compared to the margins of the region, with the former being the largest in the central northern part. The individual graben segments themselves are no longer recognisable, and appear as one large depression. South of 61°30'N the contours converge from the central parts towards the eastern margin and become rather constant close to the mainland. North of this latitude the contours climb rather continuously towards the mainland. The applied fault map (Fig. 4.21b) indicates that faults in the Øygarden Fault Complex and the large, listric faults on Horda Platform were reactivated in Early Cenozoic. The fault-displacements on Horda Platform were not significant to withstand erosion, but the northernmost Øygarden Fault Complex seems to have had some effects on the boundary between it and Uer Terrace.

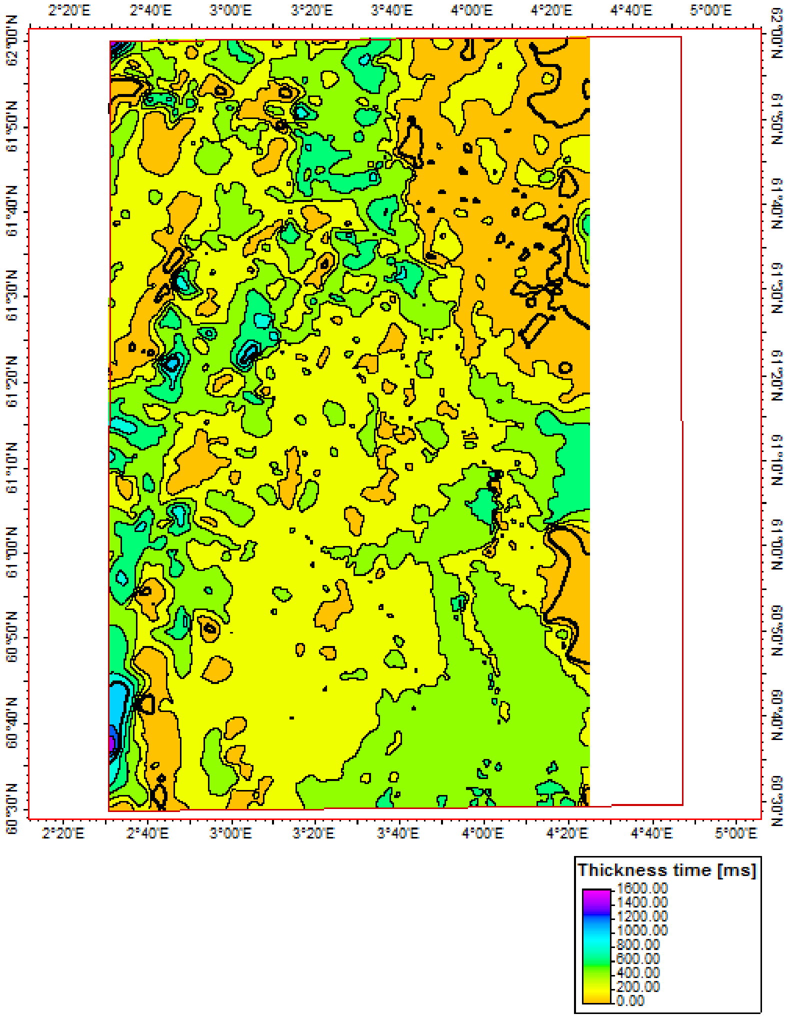
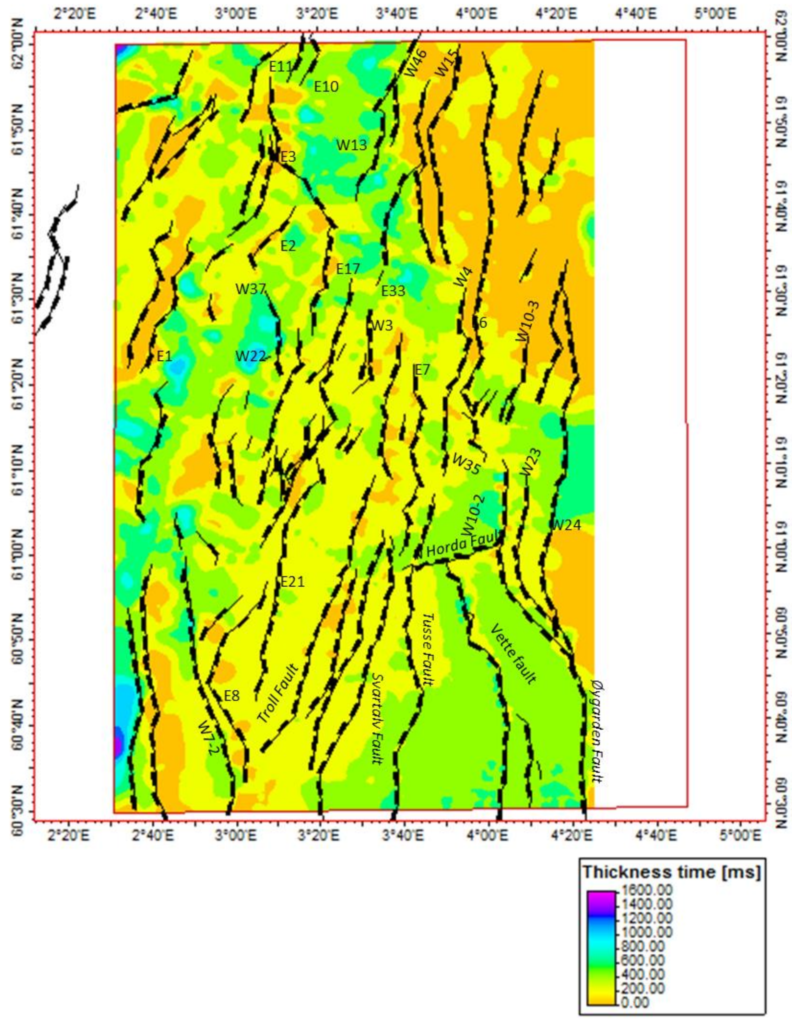


Fig. 4.19a. Time-thickness map between base Cretaceous unconformity and top Brent.



b. Time-thickness map between base Cretaceous unconformity and top Brent with integrated base Cretaceous fault traces.

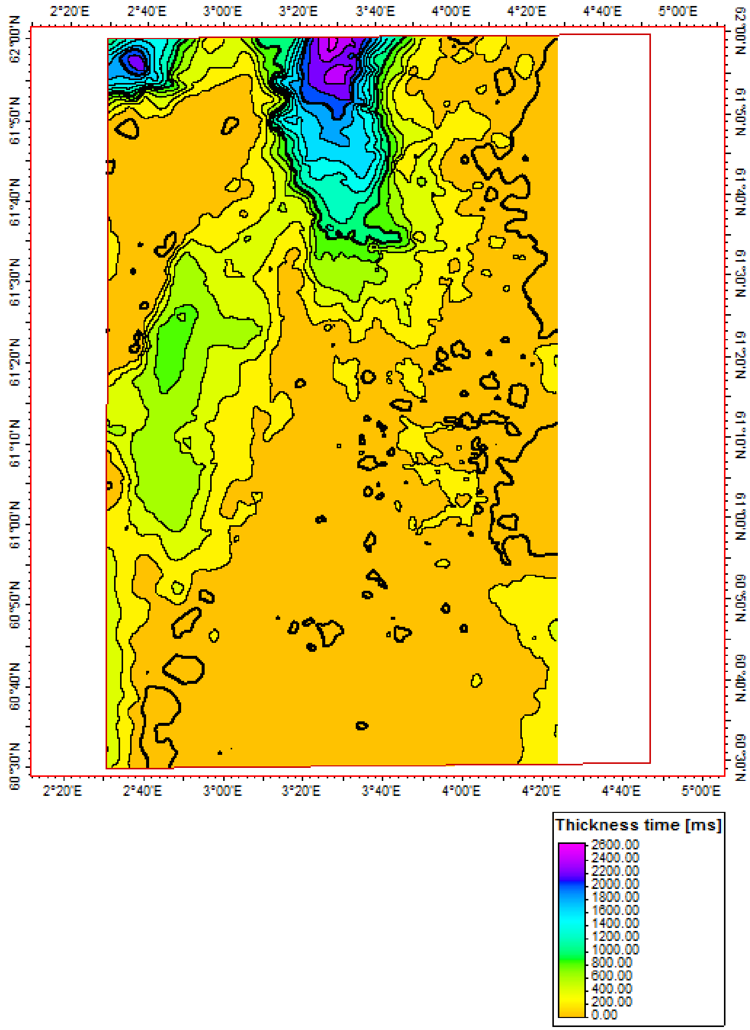
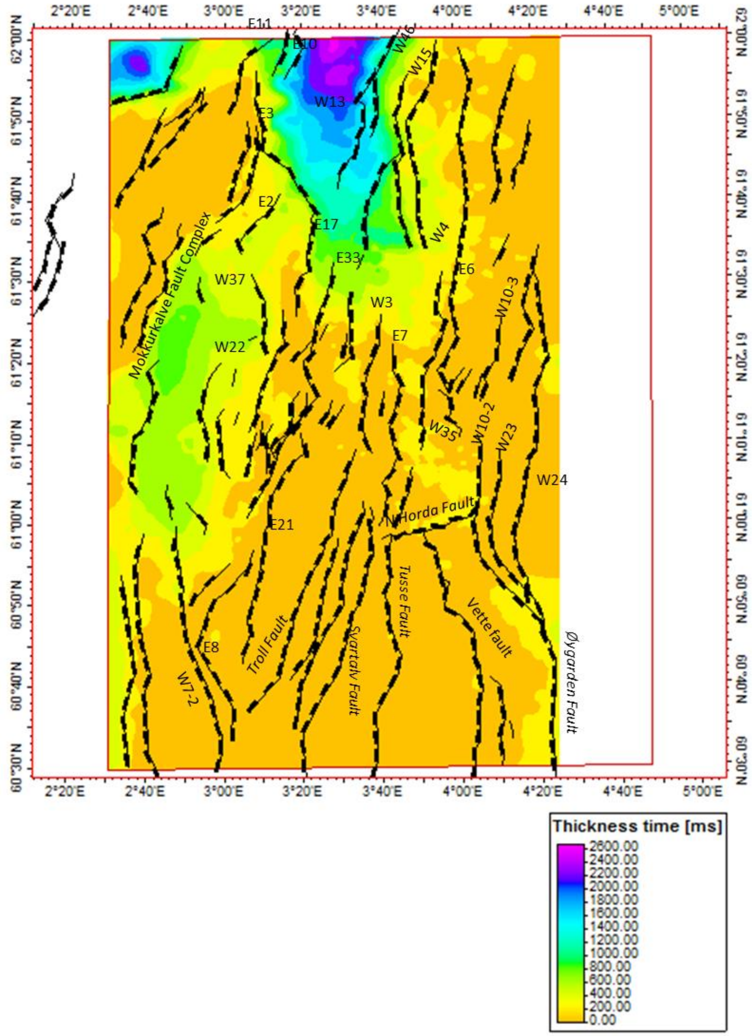


Fig. 4.20a. Time-thickness map between Late Cenomanian and base Cretaceous unconformity.



b. Time-thickness map between Late Cenomanian and base Cretaceous unconformity with integrated base Cretaceous fault traces.

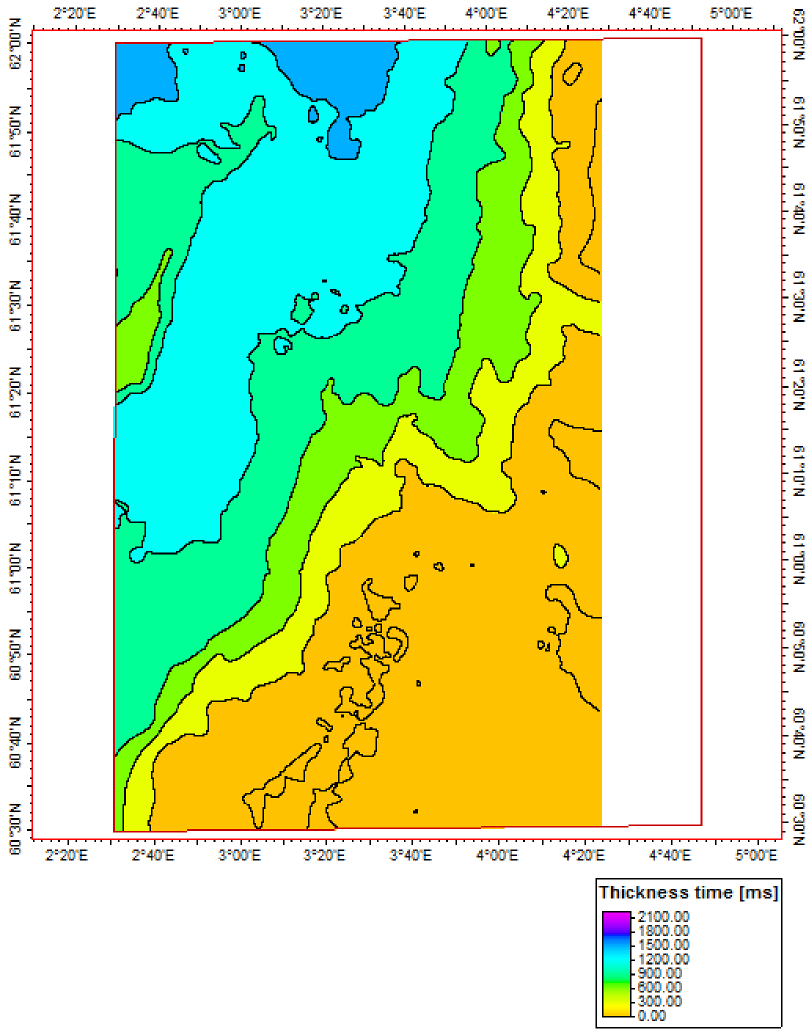
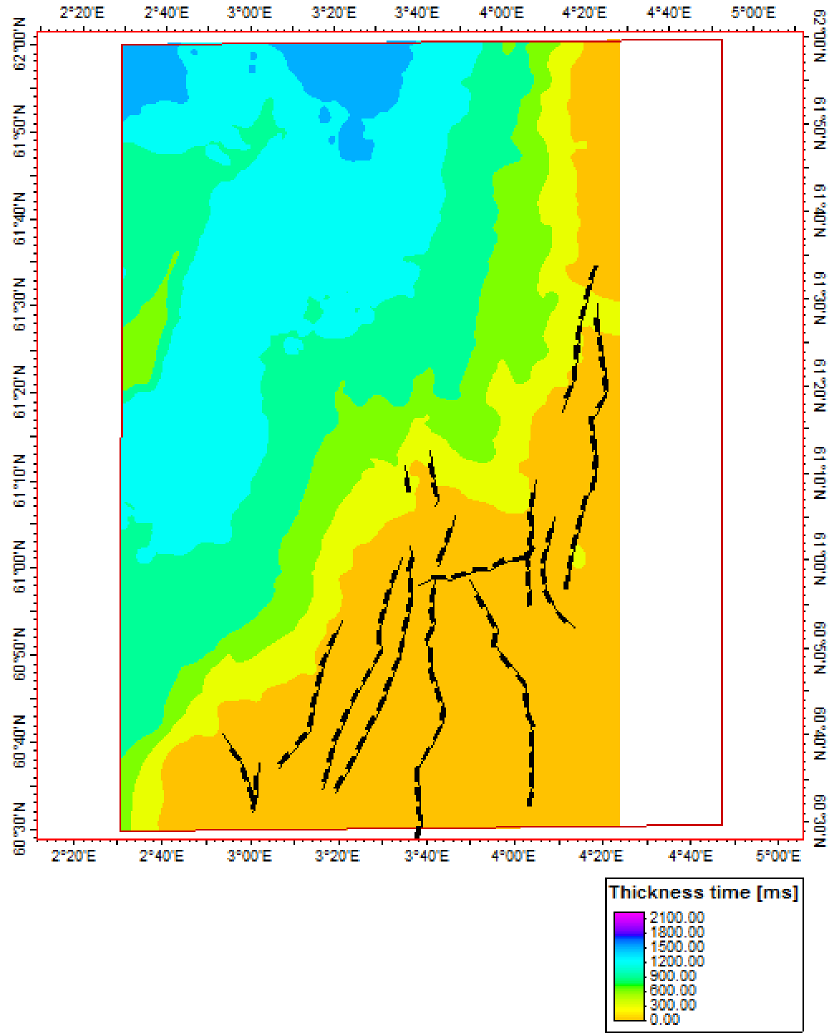


Fig. 4.21a. Time-thickness map between base Cenozoic and Late Cenomanian.



b. Time-thickness map between base Cenozoic and Late Cenomanian with integrated base Cenozoic fault traces.

4.5 Reflections/structures below top acoustic basement

Key lines 2 and 3 display a wedge-shaped unit along the W24-fault below the top acoustic basement (Figs. 4.3a and 4.4b) when the top Brent-horizon is flattened (Fig. 4.22). The wedge top is defined by the top acoustic basement horizon itself and the base by the east-tilted intra-basement A, and contain a rather distorted signature in between. The unit below the base of this wedge, defined by intra-basement B, shows clearer reflectors that are more continuous. This unit also seems to display a wedging character with westward decreasing distance between intra-basement A and B. They both appear to merge with the top acoustic basement and cut westward by the west-dipping W35-fault. But they do not seem to be affected by the next two easternmost faults, W10-2 and W23, when displayed with a flattened top Brent horizon (Fig. 4.22). As both these wedges where difficult to follow they seem however to not extend further south than to 60°55'N (Fig. 4.23). Figure 4.24 (see Fig. 4.1 for location) also illustrates a sub-acoustic basement wedge with growth along the Øygarden Fault. The wedge however do not seem to extend across the entire fault block and do not reach the crest of the fault block. Figure 4.25 (see Fig. 4.1 for location) shows one of the faults affecting only the basement with it being rather low angle to be a regular normal fault.

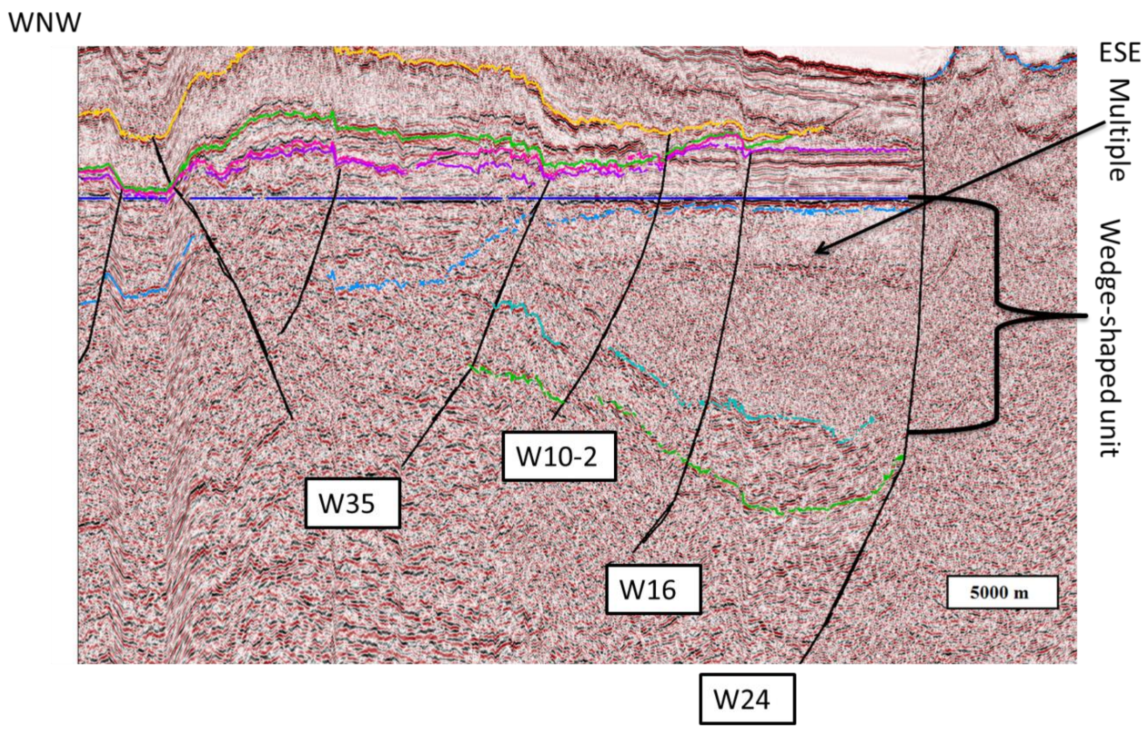


Fig. 4.22. Flatten section of top Brent-horizon in the eastern margin of key line 2. Note the large wedge-shaped unit along W24 between intra-basement A and top acoustic basement. The length of the scale box represents 5000 m.

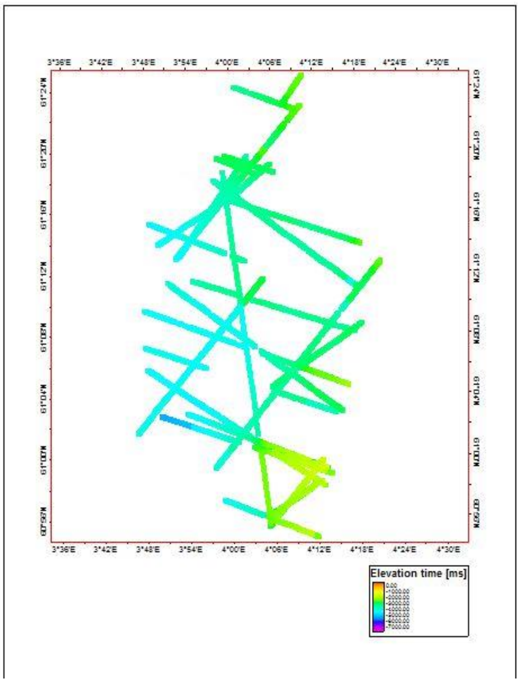


Fig. 4.23. Horizon map of the extent of interpreted intra-basement A and –B. Their southward extent do not seem to go further than 60°55’N. However their westward extent was challenging to determine.

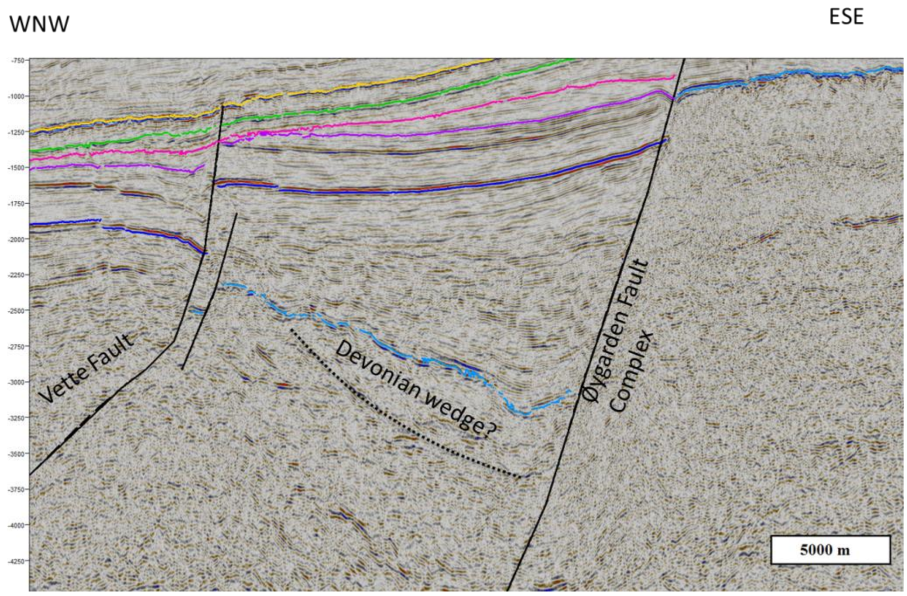


Fig. 4.24. Section crossing the easternmost hangingwall fault block of Øygarden Fault Complex (see Fig. 4.1 for location), highlighting a possible Devonian wedge beneath top acoustic basement. Basement rock has been confirmed on the crest of the fault block by the well 32/4-1, proximal to this section. The length of the scale box represents 5000 m.

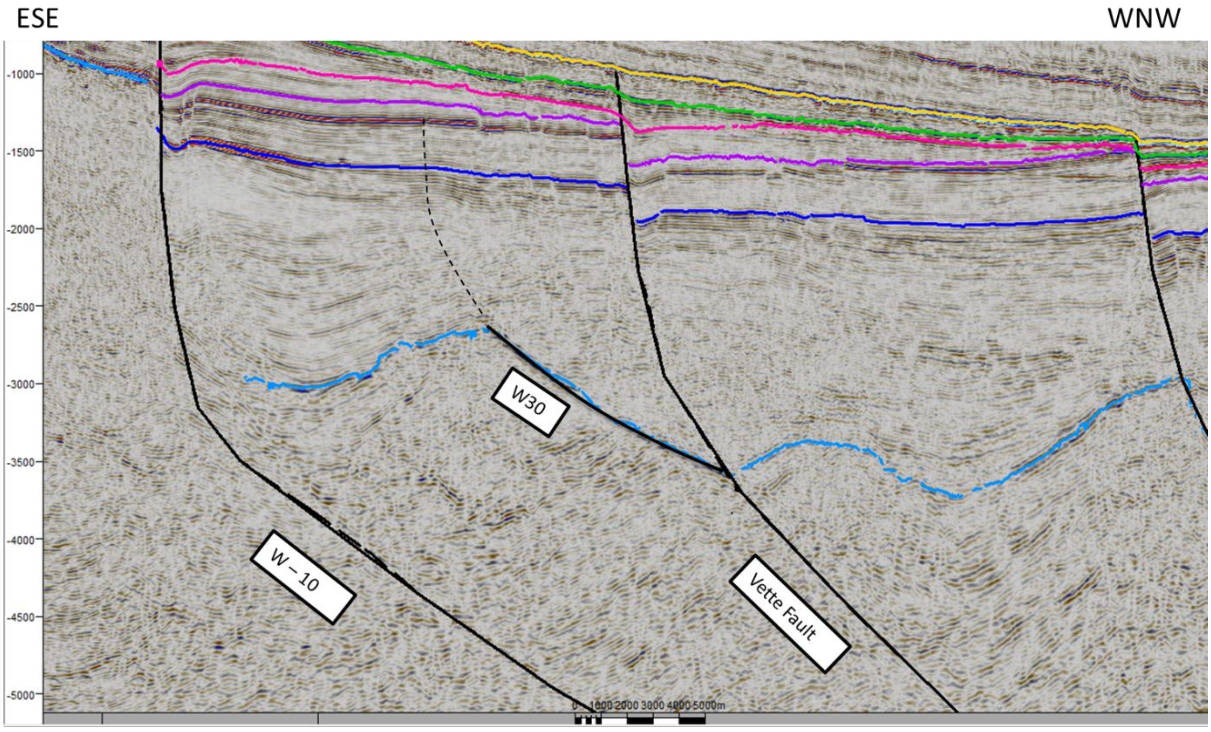


Fig. 4.25. Section crossing the Horda Platform, illustrating a low angle fault (W30) apparently only affecting the basement. See Fig. 4.1. for location.

In profile SG8043-205A (Fig. 4.26), three lateral SW-dipping reflectors terminate at the top acoustic basement horizon in the southern part of the Måløy Fault Blocks. Their dip-angle decreases rapidly toward southwest, becoming close to flat-lying, making them similar to each other. The surrounding reflectors beneath top acoustic basement appear to follow the shape of their trend, as the steepest parts are located to the northeast of area, and progressively decreases in dip angle south westward. It is however notable the lower part of the profile, ~5000 ms TWT and downward, shows lower angle compared to the upper part, as the reflection pattern in the latter seems to downlap and merge toward the underlying low-dipping part. Interestingly, when asserting the intra-basement horizons A and -B they correspond to the dipping reflections. The lower basement-segment indicates SW-dipping reflections to the north-east in Øygarden Fault Complex, that truncate the steep reflections. Figure 4.27a illustrate the segments on a larger scale across Uer terrace and Lomre Terrace in a NE-SW trend (see Fig. 4.1 for location of section). In its zoomed section (Fig. 4.27b) intra-basement A and -B, within the same depth as that presented in Figure 4.26, appear to merge across fault W35. When using the full section the south-western part of it also contain SW-dipping reflections in the basement, but becoming more low-dipping, and may represent a continuation of those observed to the north-east (Fig. 4.27a). A possible offset may exist further south-west, perhaps due to the presence of fault-E21. Undulating reflections are also present within this section above the feature.

Figure 4.28 presents a complex intra basement with tilted and bended reflection pattern. As the profile extends from Måløy Fault Blocks in the northeast to central Viking Graben in southwest the basal reflections seems to shift polarity from a south-western dip to north-eastern character. They meet in the middle of the profile, forming a V-shaped structure. Above the intersection high amplitude, undulating reflectors evident as they terminate against the V-shaped structure. The structure is also seen possibly truncating the lowermost reflections due to its steeper flanks.

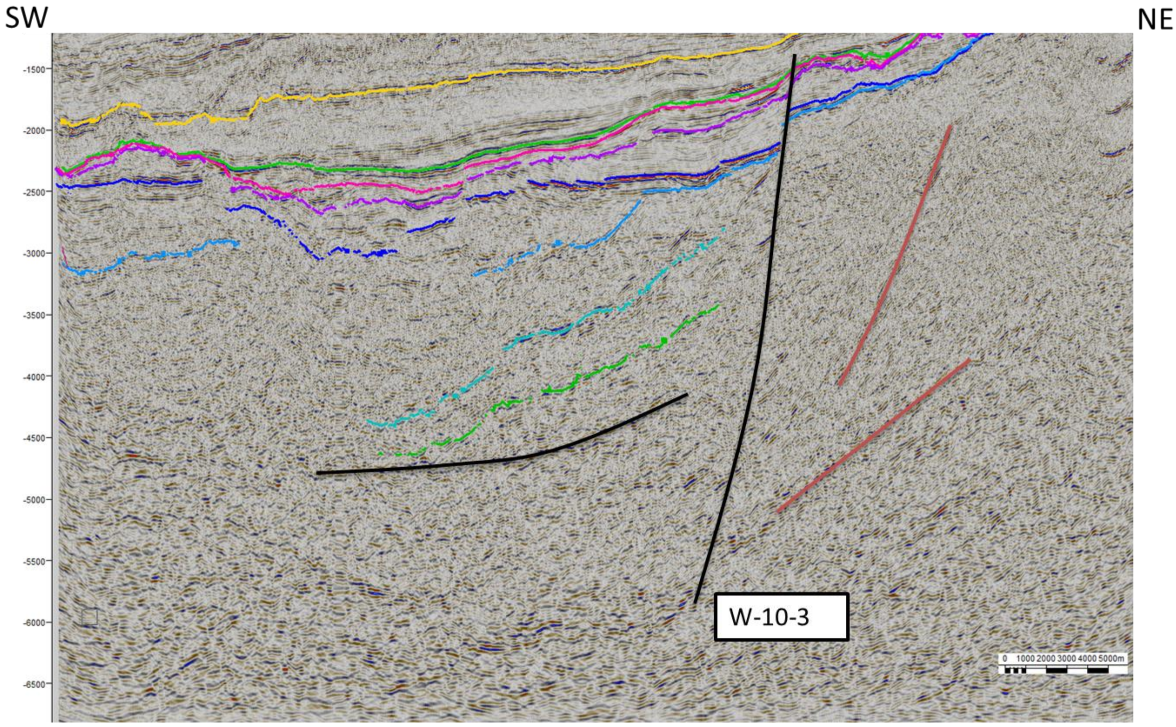


Fig. 4.26. Section crossing the southern Måløy Fault Blocks (see Fig. 4.1 for location). The arrows indicate the generalised behaviour of the intra-basement reflection patterns on each side of the black line. This separation flattens at about 4,5-5 s TWT. The upper reflections are parallel to the intra-basement A and –B, and become gradually low-angled and terminates by the black line. The lower reflections are steep to the east, but decrease in angle quickly westward.

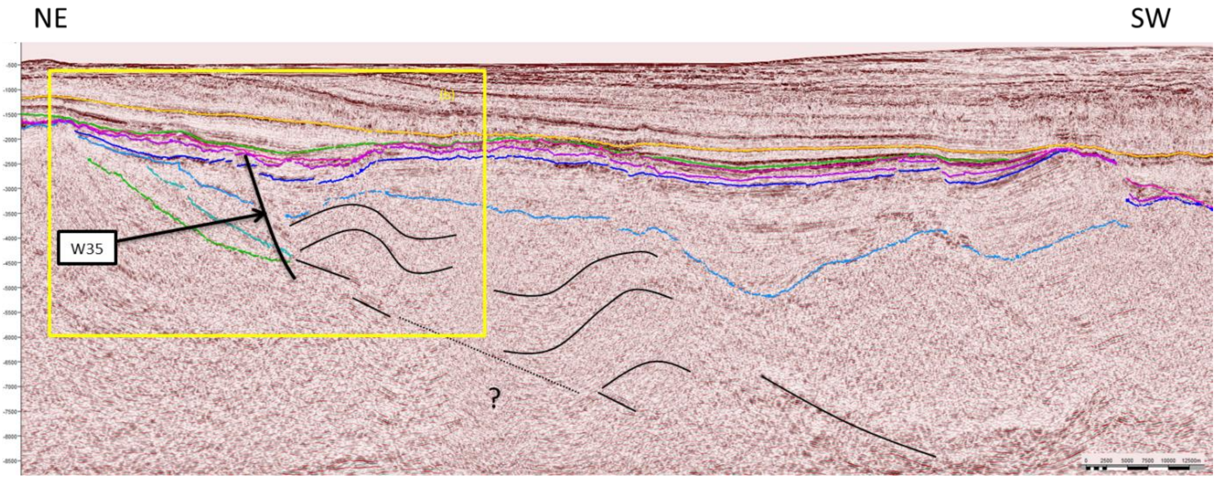
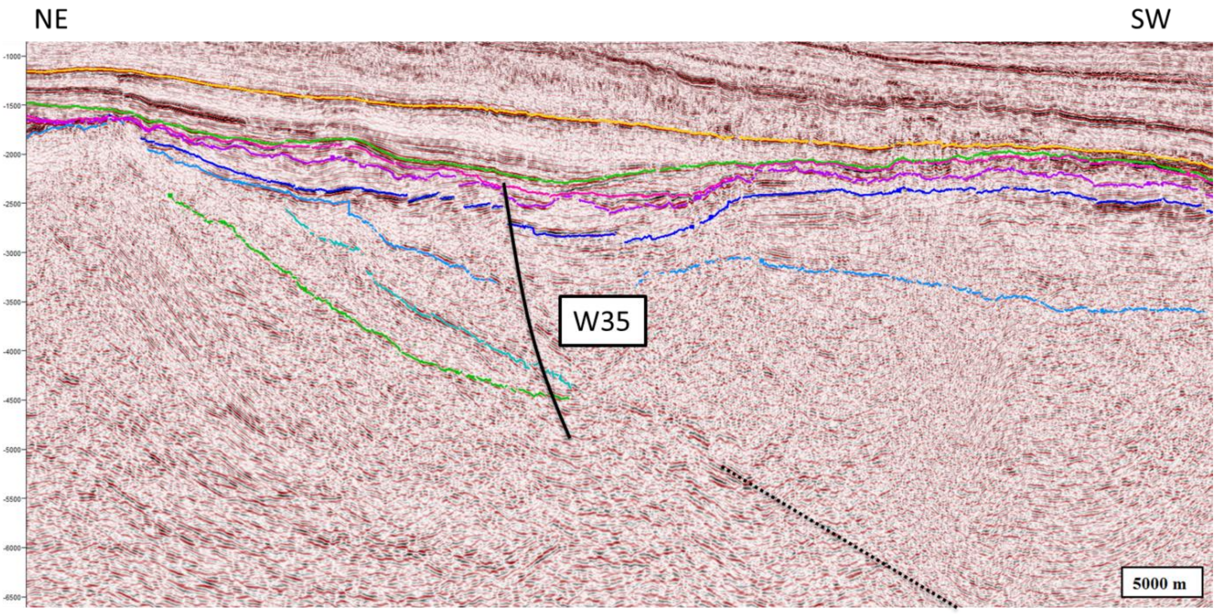


Fig. 4.27a. Section trending NE-SW across Uer Terrace and Lomre Terrace (see Fig. 4.1 for location). Intra-basement A and –B appear to merge together to a south-west dipping feature at a depth of approximately 4.5-5 s TWT. The feature separates undulating reflections above from more straight reflections below. The south-westward continuation is speculative.



b. Enlarged section of Figure 4.27a, highlighting the convergence of intra-basement A and –B, probably continues as a feature beneath W35. The length of the scale box represents 5000 m.

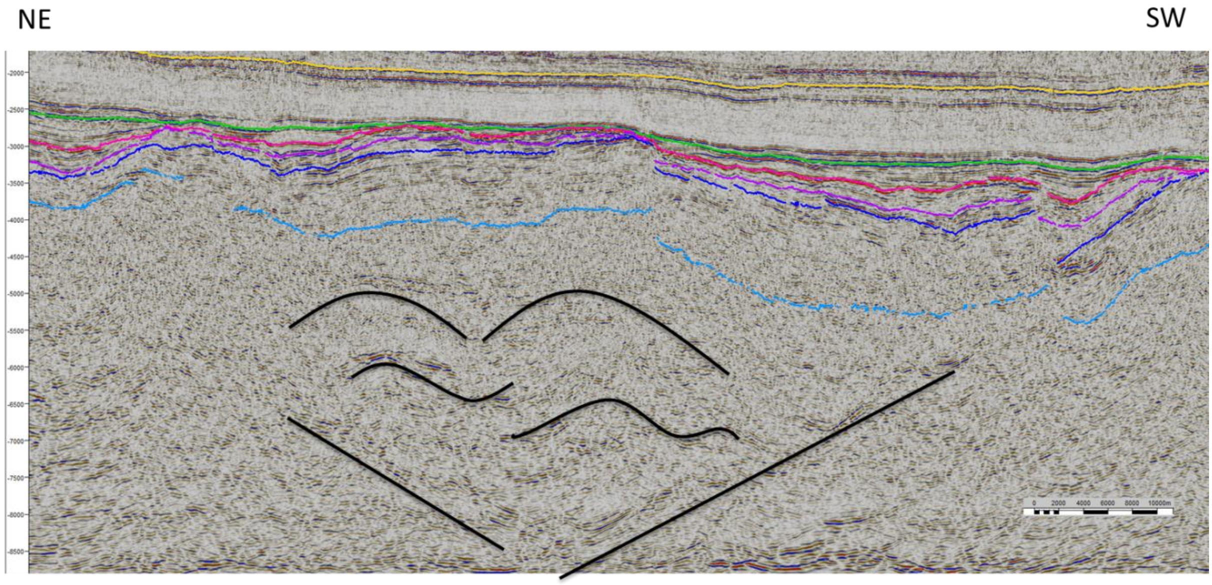


Fig. 4.28. NE-SW trending section across Måløy Fault Blocks and central Viking Graben (see Fig. 4.1 for location). The lowermost reflective basement indicate a V-shape structure, separating undulating reflections above from straight reflections below. The V-shape is also seen possibly truncating the lowermost reflections due to its steeper flanks.

5. Discussion

In section 5.1 each rift event will be discussed, starting with the youngest event, the Late Jurassic - earliest Cretaceous, and next with the older event, the Permian - earliest Triassic extensional event. For each rift event it will be discussed timing of rifting, direction of extension and the amount of extension (the β-factor). Timing of rifting will be based on investigating the fault geometries and sedimentary growth along the faults. This can be done in both section view (using key lines) and map view (time-thickness maps). By studying the growth sequences timing of tectonic activity can be derived. With the use of fault geometries one can study the fault segmentations and - patterns associated with each extensional event. This can further be used to constrain extensional directions associated with each rifting periods. The β-factors for each event will be presented through literature treating basin modelling of the North Sea. Lastly a relationship between the two events will be discussed to investigate how the younger event behaved in the study area that has already been affected by the previous event.

In section 5.2 intra-basement structures and Devonian basin configuration will be discussed based on onshore-offshore correlations. Intra-basement structures may reveal structures that likely was not generated by the Late Paleozoic - Mesozoic extensional events, thus may be related to syn- or post-Caledonian origin. These structures may further be explained by features found or related to onshore geology.

5.1 Main rift events

5.1.1 Characteristics of the Late Jurassic - earliest Cretaceous rift architecture

From key line 2 (Fig 4.3a) the Viking Graben is pronounced with the asymmetrical character and largely displaced horizons along the western boundary fault, the Mokkurkalve Fault Complex. This wedging along the western boundary signify a faulting focus along the Viking Graben. The sharp dragging of horizons along fault planes indicate immediate deformation due to faulting (Schlische, 1995; Twiss and Moores, 2007). It is clearly indicated the largest offset is along the Mokkurkalve Fault Complex, with thickening of the Jurassic sequence and the reflections in the graben, beneath the base Cretaceous unconformity, appear to dip westward. Obviously there was an active rifting event comprising the Late Jurassic. The upper part of the Viking Group, comprising the earliest Cretaceous has not been mapped in this study, but it has been documented that the Late Jurassic rifting event continued into the earliest Cretaceous; Berriasian (Badley et al., 1988; Gabrielsen et al., 1990; Ziegler, 1990).

The eastern flank of the Viking Graben is interpreted to have developed in Late Jurassic due to syn-rift growth along the W22 and W37 faults from key line 3 and 4 (Figs. 4.4a and 4.5c, respectively). As they form a local low on the Jurassic surfaces they represent an eastern boundary of the Viking Graben. With the prominent Late Jurassic wedge it displays the localised strain confined in the graben development even in the northern part of the Viking Graben. This is also supported by the β-factor modelled in the area by Odinsen et al. (2000b). They have estimated the Late Jurassic β-factor to 1,42 in northern Viking Graben, whereas to the east of the graben, in the Horda Platform, the factor is decreased to 1,08, indicative of a minor extension. This also seems to be in accordance with the estimated β-factors by Roberts et al. (1993). But it has also been determined by other authors a much lower β-factor ranging 1,15-1,2 in this part of Viking Graben (Giltner, 1987; Badley et al., 1988). Crustal modelling by Rüpke et al. (2008) also suggest a similar factor, but their estimation of the mantle-thinning factor suggests a factor of ~1,4. As the β-factor has been measured to be larger to the south, outside of the study area ($\beta = 1{,}53$), compared to that in the northern graben (Odinsen et al., 2000b) it may be deemed a northward dying of extensional effects in the graben. This is evident of the northward extent of the graben (see for example Fig. 4.13a and b).

The Sogn Graben displays an area of extensive fault focusing, indisputable with the time-structure maps and Late Jurassic time-thickness map (Fig. 4.19a). The northern part show a symmetrical graben (key line 6; Fig. 4.7a), whereas to the south it is asymmetric, wedging along the E3-fault (key line 5; Fig. 4.6). The northern part indicate a Late Jurassic development of the eastern margin, with Jurassic wedging along the W13-fault. This is further indicated from Figure 4.19b. Southward this becomes more neglectable, and appears as one large half-graben developed along the eastern boundary, represented by the southward dying of the west-dipping boundary faults. This is in dispute with Færseth (1996) as he indicates the faulting was occupied only along the western flank of the Sogn Graben. It must be emphasised though that the general poor seismic resolution of the northern part of study area rises uncertainties in the interpretation at such depths. However, Færseth and thesis author, along with other authors (Faleide et al., 2010, Fossen et al., 2010), agree upon the western flank also experienced active faulting and Sogn Graben representing the north-eastern site of Jurassic extension in northern North Sea. The β-factor for Sogn Graben has been estimated to 1,22-1,29 from the transect of Roberts et al. (1993, their fig. 7), and it is obvious from the key lines presented that the Sogn Graben was the easternmost site in study area experiencing the Jurassic extension heavily.

The Cretaceous post-rift sequences are focused in the grabens, with Sogn Graben being the most prominent (Figs. 4.20 and 4.21). As the sites of most active faulting generate more accommodation space they are also the areas displaying most subsidence during post-rift stage (Nøttvedt et al., 1995). Bugge et al. (2001) claimed that the Late Jurassic extension continued into the Barremian with evidence of fault-related intra-basinal footwall uplifts. The graben's proximity to the Møre-Trøndelag-Fault-Complex to the north was likely affected by the dilatation of the fault complex in Aptian-Albian time (Gabrielsen et al., 1999; 2001). The thinning to the east, as observed in the Early Cretaceous time-thickness map (Fig. 4.20), is an indication of little subsidence in the platform areas and in Marflo Spur, the junction between the grabens. This enhances the distribution of the Jurassic extension as it was localised in the areas of Viking Graben and Sogn Graben and minor in adjacent areas. The amalgamation of Late Cenomanian with the base Cretaceous in the east of study area may signify a shallow basin with a low or above palaeo-base level. The observation of a slightly thicker Lower Cretaceous unit in the northern Måløy Fault Blocks is interpreted to be related to the proximity of the strongly subsiding Sogn Graben.

Two scenarios arise; an active uplifting stage taking place between Late Cenomanian and base Cenozoic, except for Horda Platform, or too minor subsidence of the platform areas to escape erosion during early post-rift stage. In the latter scenario eustatic variations will affect the deposition of Cretaceous formations. Uplift of Lomre Terrace and Horda Platform has taken place in Early Cretaceous, according to Gabrielsen et al. (2001, their fig. 4a). It is of an early post-rift character which the infill follows the bathymetric remnants formed by the syn-rift event (Prosser, 1993; Gabrielsen et al., 2001). The elongated, very shallow, spotted pattern observed in northern and western Horda Platform may indicate areas that were subaerial exposed during the entire Early Cretaceous period. These areas were a part of a shoal- and archipelago-system which divided the northern North Sea into multiple sub-basins (Gabrielsen et al., 2001). Some of the major faults were also reactivated, cutting up through intra-Late Cretaceous and even base Cenozoic, as observed by the fault map at base Cenozoic level (Fig. 4.17b).

The time-thickness map of Late Cenomanian - base Cenozoic (Fig. 4.21) reflects the subsidence pattern during the late post-rift stage, with deepening of the entire area and shallowing of the eastern margins. All key lines, except key line 1, display the reflections within this sequence as saucer-shaped with basinward tilting near the margins, as an expected late post-rift signature (Nøttvedt et al., 1995; Gabrielsen et al., 2001). Although the middle and upper parts of this sequence remain continuous the lower part, near Late Cenomanian, is seen to be slightly affected by the underlying bathymetry (see for example eastern margin in key profile 6, Fig. 4.7b), probably as an effect of the marginal uplifts as a result of continued faulting in Early Cretaceous. This is in agreement with the studies done by Gabrielsen et al. (2001) and Kjennerud et al. (2001).

The intra-mega fault blocks from key line 1 (Fig. 4.2) are separated by faults responsible for two periods of sedimentary thickening along them. As some of them have been active during Permian-Triassic extensional event (for example the Øygarden Fault, see discussion below), yet they displace the Jurassic horizons further up, they must have been reactivated during the Late Jurassic rifting event, as suggested by others (Færseth, 1996; Odinsen et al, 2000a; Whipp et al., 2014). These faults are speculated to be of Permian-Triassic origin, and later reactivated.

5.1.2 Characteristics of the Permian - earliest Triassic rift event

The observed thick sequence between the top Brent surface and the top acoustic basement surface in the mega fault blocks on the Horda Platform indicate a large deposition unit of pre Middle Jurassic age. From key profile 1, as the lower part of the sequence thickens along the west-dipping fault planes and thins on the fault block crests (Fig. 4.2) it indicates syn-rifting sequences. This is especially prominent along the Øygarden master fault. With the well 31/4-3 present on Horda Platform, Early Permian sediments have been confirmed in this area (NPD, FactPages). The faults separating the mega fault blocks are oriented in a N-S trend, suggesting a bidirectional extension in E-W of Permian age. This fault trend has been widely recognised by many authors (e.g. Badley et al., 1988; Gabrielsen et al., 1990; Steel and Ryseth, 1990; Whipp et al., 2014). N-S trending onshore dikes, dated to Permian (Fossen, 1998) and cataclasites on Nordfjord-Sogn Detachment of Permian age (Eide et al., 1997; Braathen et al., 2004) match the trend of these offshore structures and are likely features related to this event. Færseth et al. (1995) and Færseth (1996) also claim this to be of Permian - Triassic character.

The reflections onlap onto the top wedge units, with gradual overlapping of the entire Horda Platform. When studying the tilt of the overlaps it is evident these reflectors tilt basinward, typical of a post-rift stage (Prosser, 1993; Nøttvedt et al., 1995). Verification of Triassic sediments from wells located on the Horda Platform (Fig. 4.1; Table 3.3), penetrating past top Brent, enhances a post-rift subsidence of Triassic age. Although this event is estimated to be of Early Triassic - mid-Early Jurassic (Gabrielsen et al., 1990; Steel, 1993), it has been proposed a continuation until Bathonian (Badley et al., 1988), and even into Upper Jurassic in the Horda Platform (Roberts et al., 1995). This can possibly be inferred from the two easternmost mega fault blocks in key line 1 (Fig. 4.2), where the Jurassic horizons and the base Cretaceous appear as continuous, stacked overlaps, vertical distance between them is more or less constant and are subparallel with the reflections beneath top Brent. Additionally, no sign of reflection truncation, suggesting unconformities, are present. Thus the fault blocks could accommodate sediments during Jurassic. Northward to about 61°20'N in Fig. 4.19, in Øygarden Fault Complex, the observed Late Jurassic thinning is not necessarily fault related, and hence may match a subsiding basin margin. Since the Late Jurassic sediments on the Horda Platform consist of sandy deposits of the Viking Group (Steel, 1993; Ravnås et al., 2000), the sediment supply must have been larger than the rate of subsidence, and hence may signify a ceasing post-rift subsidence. This idea has also been suggested by Steel (1993). Other explanations may be that the accommodation creation is induced by compaction (Nøttvedt et al., 1995) or late-rift rotations (Ravnås et al., 2000).

The proposed low-relief accommodation zone between the Brage East Fault and Tusse Fault supports the notion of a classic rift with both sides of the rift axis experiencing marginward tilting (Nøttvedt et al., 1995). The rather low-dipping set of reflections along with the acoustic basement, indicate they were not particularly affected by rotation of the extensional event. It may therefore match a centre of extension; a rift graben, of Permian-Triassic age, located within the Horda Platform. This idea has also been recognised by other authors (Færseth et al., 1995; Færseth, 1996; Faleide et al., 2010), however this is in dispute with Badley et al. (1988, their fig. 7a) and Lepercq and Gaulier (1996) who proposed a Triassic - Early Jurassic rift axis closer to present day Viking Graben. An estimation of crustal stretching (β-factor) of the Permian-Triassic rifting in Horda Platform has been conducted by others. It has been modelled to a factor of 1,4 (Roberts et al., 1995), 1,33 and 1,39 approximately 61°N and 60°10'N, respectively (Odinsen et al., 2000b). Lepercq and Gaulier (1996) on the other hand modelled the β-factor to be 1,8 in present day northern Viking Graben. Rüpke et al. (2008) have also modelled it to be about 1,7-1,95 across the northern Viking Graben and East

Shetland Basin, where it sharply lowers west of the Hutton Fault. The mantle stretching factor is estimated to be 1,5 in northern Viking Graben (Rüpke et al, 2008).

The general lack of pre-top Brent sediments in the north-eastern part of study area, north of 61°N, is an interesting feature in the time-thickness map between top acoustic basement and top Brent (Fig. 4.18). In addition all the wells in the area (Table 3.2) indicate a lack of pre-Jurassic sediments, and the Jurassic sediments unconformably overlie the top basement (see example key line 6b, Fig. 4.7b). This means there is a hiatus present stretching from at least Permian till base Jurassic, and some wells, e.g. 36/1-1 and 36/1-2, contain a time-gap between Permian and Late Jurassic.

South of 61°N is the Horda Platform, Lomre Terrace and southern Viking Graben area with the thickest mega-sequence, as discussed above. As the age of the syn- and post-rift sediments corresponds to the age of the hiatus it seems likely to determine that the northern side must have experienced uplift and the southern side subsidence, as the latter became a site for accommodation. Hallam and Sellwood (1976) and Nøttvedt et al. (1995) described unconformities related to a rift initiation, where the area affected by doming forms a proto-rift unconformity. Another erosional aspect is described by Kusznir and Ziegler (1992); the process of isostatic rebound related to active rifting. They explained that topographic highs formed during active rifting are prone to erosion and unloading, allowing the area to be uplifted, thus eroded furthermore. Low-density, diapiric melts formed by the hotter asthenosphere intruding the crust may also attribute to increased isostacy due to density contrasts between the melts and mantle (Turcotte and Emerman, 1983; Kusznir and Ziegler, 1992; Ziegler, 1992). These processes combined may form a region wide, break-up unconformity (Nøttvedt et al., 1995). The sum of erosion by these processes may explain the hiatus prevailing north of 61°N, implying this is the site of the Permian-Triassic updoming.

Considering the fact that some of the wells in this area indicate the top basement is of Caledonian composition or older (NPD, FactPages), may point out how deep and extensive the erosion was if Devonian rocks were present at that time. The proposed antithetic fault in the Marflo Spur, fault W3, may also have played a role in separating the Permian-Triassic basin to the west from the proposed updomed area to the east (Fig. 4.18b). Since the transition just north of 61°N, approximately N-Horda-Fault, separates the eroded areas from the thick Permian-Triassic depocentres in Horda Platform (Fig. 4.18) it likely has acted as an axial conduit. As half-grabens interfere with each other the drainage patterns, sediment yield and -

distribution are greatly affected; major fluxes will be located in and running parallel to interbasinal interference zones between the half-grabens (Gawthorpe and Hurst, 1993; Gawthorpe and Leeder, 2000). Antithetic, non-overlapping half-grabens facing each other give rise to the broadest interference zones (Paul and Mitra, 2013). This further explains the thick deposits found on the Horda Platform. Since this particular site just north of 61°N does not illustrate any particular growth along the N-Horda-Fault, it may indicate it did not exist as a fault in Permian-Triassic times. However the N-Horda-Fault probably had the role as a transfer zone as it separates the east-dipping faults to the north and west-dipping faults to the south. This is an expected behaviour due to interaction of non-overlapping, fault trends located parallel to the prevailing extensional direction (Paul and Mitra, 2013).

The east-shrinking sequence between top acoustic basement and top Brent along western fault boundary of Viking Graben (Fig 4.18), thinning to the north at about 61°30'N, seems to match the east-dipping Visund Fault and Sogn Graben Fault by Færseth (1996; Fig. 5.1). His Sogn Graben Fault appears to be a conjoined fault of the east dipping faults E3, E11 and possibly E10. His Brage East Fault seems also to partially match the interpreted Brage East Fault, even though the interpreted fault appears to curve north-eastward and intersect through the thickened sequence in Fig. 4.18b. The latter is likely an effect of the fault trace design from the fault intersecting the hanging wall at basement level rather than at top Brent level. The Mokkurkalve Fault Complex, E3 and E11 to the north coupled with the west-dipping faults to the south make up the geometry of an en echelon-fault set, trending N-S, where the curved parts face each other. Badley et al. (1988) and Færseth (1996) remarked the east-dipping faults north of 61°N as internal faults within the Permian-Triassic rift as the Alwyn-Ninian-Hutton alignment, with Hutton as its northern delineation, outside the study area (Færseth, 1996; Fig. 5.1), has been determined the rift's western boundary fault (Steel and Ryseth, 1990; Yielding et al., 1991). As the Møre-Trøndelag Fault Complex was active during Permian-Triassic with a dextral strike-slip movements (Gabrielsen et al., 1999) it is likely the effects of N-S trending structures in the Northern North Sea terminated against it. Southward, outside the study area, the structural trend prevailed toward the central North Sea (Færseth, 1996; Fig. 5.1). Odinsen et al. (2000b) have modelled from their transects the Permian-Triassic β-factor to be largest in the northern Viking Graben, same area as the position of the western Viking Graben fault, Mokkurkalve Fault Complex, an indication of significant thinning. Thickness estimations of early-middle Jurassic groups show large thicknesses in this location, reflected by thermal subsidence (Badley et al., 1988). It is therefore reasonable to believe this fault is proximal to the then Permian-Triassic rift axis.

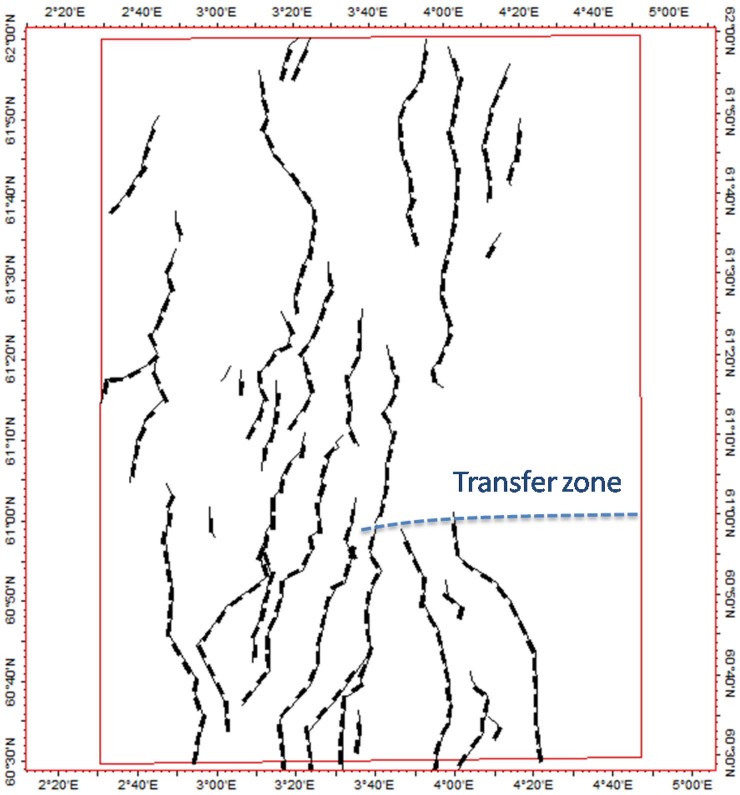


Fig. 5.1. Map of proposed faults that were active during Permian-Triassic rifting event in the study area. The west-dipping faults are mainly located south of the proposed transfer at 61°N, being synthetic to the Øygarden Fault. North of 61°N the faults dip eastward, synthetic to the Hutton Fault in East Shetland Basin, outside the study area.

The minor wedges in Uer Terrace and Måløy Fault Blocks are likely to have been conjugated with the larger east-dipping Viking Graben fault, Mokkurkalve Fault Complex, and E3 along the Sogn Graben to the west of these areas. The Permian reactivation of the Nordfjord-Sogn Detachment on the Norwegian mainland (Eide et al., 1997; Braathen et al., 2004) was also a probable feature of this extensional event. These will further highlight the eastward extent of fault block progradation and deformation by the east-facing half-grabens of Permian-Triassic age.

5.1.3 Relationship of the two rift events

It has been presented two late Palaeozoic - Mesozoic extensional phases taking place in the northern North Sea, where the latest event seems to have exploited previous developed faults and zones of weakness. This is evident by Jurassic reactivation of faults generated in Permian-Triassic and Jurassic locus in Viking Graben and Sogn Graben, features of the Permian-Triassic rift event. Some synthetic faults proximal to the Late Jurassic graben axis however are antithetic to the adjacent Permian-Triassic, east-dipping faults near the northern delineation of the Viking Graben reflecting new fault generation. As the development of the Viking Graben was linked to the triple junction formed in the Central Graben, strain concentrations develop to form narrow rifting (Ziegler, 1990; Dyksterhuis et al., 2007; Bell et al., 2014). Heat from the increased volcanic activity to the south may also have contributed to weakening of the crust in the rift arm (Corti et al., 2003; Bell et al., 2014). These factors suggest it was probably easier to form new faults with reverse polarity. Other Permian-Triassic faults have been reactivated in Late Jurassic with evidence of Jurassic displacement, but their overall offset decrease marginward from the graben axis, with the fault reactivations on Horda Platform being the most minor due to its distal position relative to the locus. The N-S trending faults in Horda Platform only affecting the basement can be speculated to be of a Permian-Triassic origin or older due to their matching trend and polarity with the overall fault set in the area (see key line 1, Fig. 4.2). However due to their inactivity in the Late Jurassic rifting event it, the faulting was thus concentrated on the larger, listric faults on the Horda Platform.

The interaction of the older and younger structures form local horsts and grabens with likely Jurassic fault terminations against the Permian-Triassic faults (see for example key line 4b; Fig. 4.5b). An additional fault map illustrating proposed timing of each fault's origin, is presented in Fig. 5.2. The Permian-Triassic extension had a wider effect on the North Sea than the Jurassic event (Færseth et al., 1995; Færseth, 1996; Ter Voorde et al., 2000) with the former boundaries defined by the Øygarden Fault Complex to the east and the Hutton Fault, northern part of Alwyn-Ninian-Hutton Alignment, to the west (Færseth, 1996; Fig. 5.1). The en echelon-configuration of the Permian-Triassic boundaries defines the behaviour of the large faults adjacent to the boundary faults with a northward polarity-shift from westerly to easterly azimuth across 61°N. These will interact with each other to form structural highs and

-lows, depending upon how they relate to one and other (Rosendahl, 1987). Their style depends on distance, orientation and dip-polarity of half-grabens interacting, proximity to rift axis, change of strain- and subsidence-locus, distribution of displacement, pre-existing crustal weaknesses (e.g. foliations, lineaments) (Rosendahl, 1987) and volcanism that may significantly alter the rheological properties of the lithosphere (Corti et al., 2003; Bell et al., 2014).

The polarity-shift of major faults across 61°N in eastern study area is interpreted to reflect a Permian-Triassic en echelon-configuration, with the faults separating the Måløy Fault Blocks being synthetic to the Sogn Graben's western boundary fault, E3 and E11, and Hutton Fault in the westernmost Permian-Triassic basin, whereas the faults on Horda Platform are synthetic to the Øygarden Fault. The shift from a southern thickening in Permian-Triassic (Fig. 4.18b) to a northward thickening in Late Jurassic (Fig. 4.19b) along N-Horda-Fault indicate it acted as an interbasinal transfer zone (Gawthorpe and Hurst, 1993). Færseth et al. (1995; 1997) and Færseth (1996) suggested this zone is as an offshore continuation of the Nordfjord-Sogn Detachment extending from Solund Basin due to its matching trend and position with the basin on the mainland. Smethurst (2000) also seems to agree with this, but has instead linked the continuation with Dalsfjord Fault or Nordfjord-Sogn Detachment in Kvamshesten Basin.

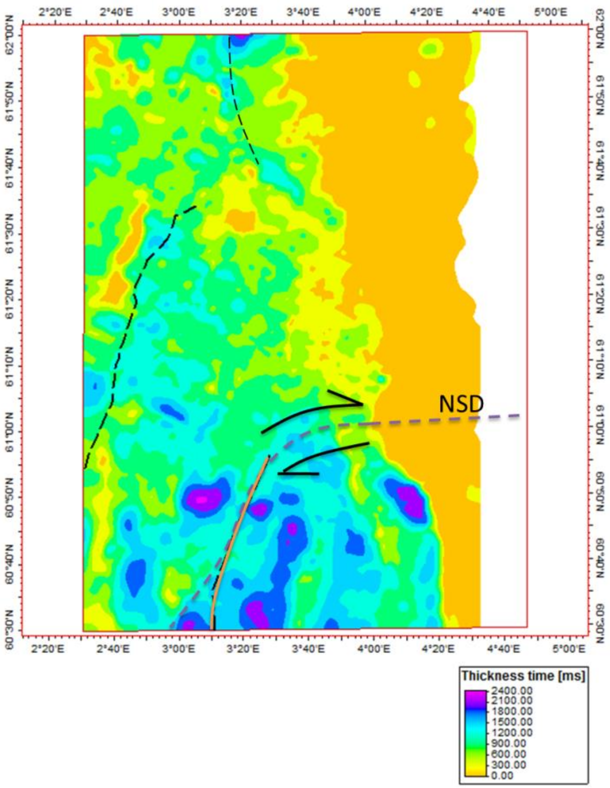
The symmetrical development of the Viking Graben northward indicates an eastward migration of graben axis. It is suggested that it terminate approximately near the E2-fault, adjacent to Marflo Spur. The graben axis is then shifted south-eastward along the Marflo Spur and into the southern Sogn Graben. Northward from here the graben axis also migrates eastward into the more symmetrical part of the Sogn Graben. The Late Jurassic step over of graben axis at Marflo Spur is interpreted to be associated with a transfer zone (Fig. 5.2b). When the width of the grabens is smaller than the distance between their graben axes a ridge is expected to develop between the grabens. Moreover this ridge may be curved in map view due to the relationship of the stress fields of the approaching grabens (Fossen et al., 2010). As the eastern flank of the Marflo Spur is the E3-fault, delineating the southern Sogn Graben (e.g. Fig. 4.15b), curving westward to the north and the northward dying of Viking Graben, represented by W37-fault, it is proposed that Marflo Spur represents such an interbasinal ridge. The fault block to the north-west, delineated by fault E2, of this ridge is also likely a part of this transfer zone, activated during the same extension.

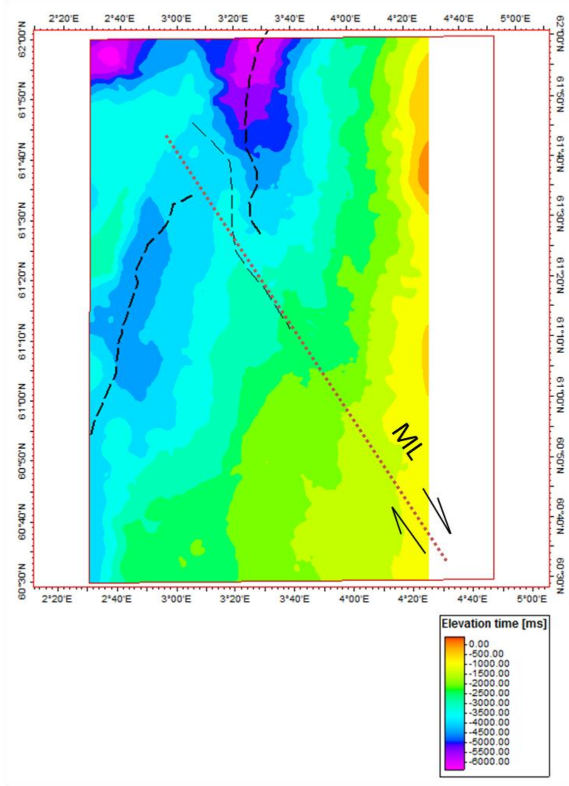
Færseth et al. (1997) denoted the continuation of the Nordfjord-Sogn Detachment with a NE-SW trend from the northern flank of Hornelen Basin, separating the northern Viking Graben and Sogn Graben near the Visund Fault Block. They suggested the Jurassic fault trend is en-echelon relative to the underlying N-S and NE-SW structural grain developed by the Nordfjord-Sogn Detachment. The fault maps however do not suggest any NE-SW trending transfer fault relaying the Sogn Graben and Viking Graben, but indicate however a transfer zone crossing the Marflo Spur with a NNW-SSE trend. This may also explain the prevailing NNW-SSE trough , defined somewhat of the N-S faults, across Uer Terrace and Måløy Fault Blocks in all the time-structure maps, except Base Cenozoic. The regional-scale transfer zone acts as a NNW-SSE trending anticline, separating the grabens and defines synclines. An explanation for the lack of the proposed NE-SW trending transfer fault south of Sogn Graben may be scarce coverage, given the large data-spacing in this area.

The Marflo Lineament, a basement feature proposed by Smethurst (2000), trending NNW-SSE across the mainland, Uer Terrace and south of Marflo Spur may also match this transfer zone. As it is speculated in being a dextral shear zone of Precambrian origin (Frost et al., 1981; Karpuz et al., 1991) this lineament is seen cutting the transfer zone in Marflo Spur (Fig. 5.2b). It has further been suggested by Smethurst (2000) to have acted on the stepover of graben axis as this matches a right-lateral displacement. It is interesting to note the lineament's orientation along some of the fault tips, especially in regard to the west-dipping faults and the minor NE-SW trending faults generated by the Late Jurassic rifting. Dextral shearing may give rise to sinistral directed dilatation, forming extensional structures, such as normal faults (Twiss and Moores, 2007), thus northwest dipping faulting may occur. These effects could possibly also have partially assisted the northward expansion of Øygarden Fault Complex from 61°N to 61°35'N. Additionally it seems to delineate the northern Viking Graben as west-dipping faults begin to dominate in this site. Additionally, since the N-Horda-Fault is proposed to have behaved as a transfer zone in Permian-Triassic times, its proximity to the lineament may have assisted the N-Horda-Fault to become an active fault in Late Jurassic. It may also be speculated whether it had any effect during the Permian-Triassic extension, but due to lack of rotation of fault tips proximal to lineament in map view may indicate a very small to neglectable significance. A NW-SE extensional direction, thought to be the prevailing extension (Færseth et al., 1996; Bell et al., 2014), may however account for its apparent revival in Late Jurassic.

From the time-thickness map between top acoustic basement and top Brent in Horda Platform the arcuate parts of the Svartalv Fault and Brage East Fault face each other with a topographic high intervening in between (see key line 1, Fig. 4.2). As the facing faults have to compete for the same area the geometrical configuration may therefore end with a topographic accretion in the middle, forming a low-relief accommodation zone (Rosendahl, 1987). Tomasso et al. (2008) have illustrated that East Shetland Basin had west-dipping faults in the Permian-Triassic, the same polarity as the listric faults on the Horda Platform, due to diachronous fault development, where the west-dipping faults propagated westward. The west-dipping faults separating the Lomre Terrace and Viking Graben (e.g. W7-2) may indicate a pre-Jurassic activity (Fig. 4.18b). Færseth (1996) indicated the Brage East Fault is the westernmost extent of the Permian-Triassic faulting, and that the offshore continuation of Nordfjord-Sogn Detachment crosses the low-relief accommodation zone (Fig. 5.2a) to delineate the southern part of Brage East Fault outside the study area. The detachment, according to Færseth (1996) further separates the surrounding structural terraces from the platform. This is especially clear with the N-Horda-Fault in the northern part of platform. With evidence of Triassic basin development during Permian-Triassic rifting in the Horda Platform and the minor deformation of same the site, even though the surrounding areas (Lomre and Uer terraces) downfaulted in Late Jurassic, it may be inferred a controlling feature along the platform. It is therefore suggested that the transfer zone, compatible with that proposed by Færseth (1996), may be an offshore continuation of the Nordfjord-Sogn Detachment (Fig. 5.2a).

The south-westward continuation of the Nordfjord-Sogn Detachment from 61°N to 60°30'N is plausible due to the continued overlap between the arcuate parts of the Øygarden Fault and the Hutton Fault (Fig. 5.3). The configuration will lead to a NE-SW oriented dextral shearing character of the transfer zone, thus maintaining an opposite fault polarity on each side of the transfer zone. This transfer would then cause westward shift of basin axis, as seen in Fig. 5.2a. The extent of its continuation outside of the study area is however speculative. Færseth (1996) and Færseth et al. (1997) suggested it to reach south-westward toward the flank of East Shetland Platform at approximately 60°N. This scenario however crosses a southward continuation of the east-dipping fault segment close to East Shetland Basin, thus does not act as a separation of fault polarities. It may therefore remain southward along the Horda Platform toward Utsira High (Fig. 5.3).





5.2 *a. Proposed basin axes (black, stippled lines) and axis of low-relief accommodation zone (orange, filled line) in the Permian-Triassic extensional event. The transfer zone separating the Triassic basins to the south-east from the thin unit to the north-east is interpreted to be an offshore-continuation of the Nordfjord-Sogn Detachment (NSD). This transfer zone continues toward south-west in the southern study area.*

b. Proposed graben axes (thick, black stippled line) and transfer zone (thin, black stippled line) in the Late Jurassic extensional event. The surface used is the base Cretaceous. The transfer zone trends in a N-S to NW-SE direction, and crosses the Marflo Spur. The red dotted line represents the Marflo Lineament (ML), after Smethurst (2000), possibly being a transfer zone in the Late Jurassic. This feature seems to match good with the proposed transfer zone, thus indicating it may have played a role in the shift of the Late Jurassic basin axis.

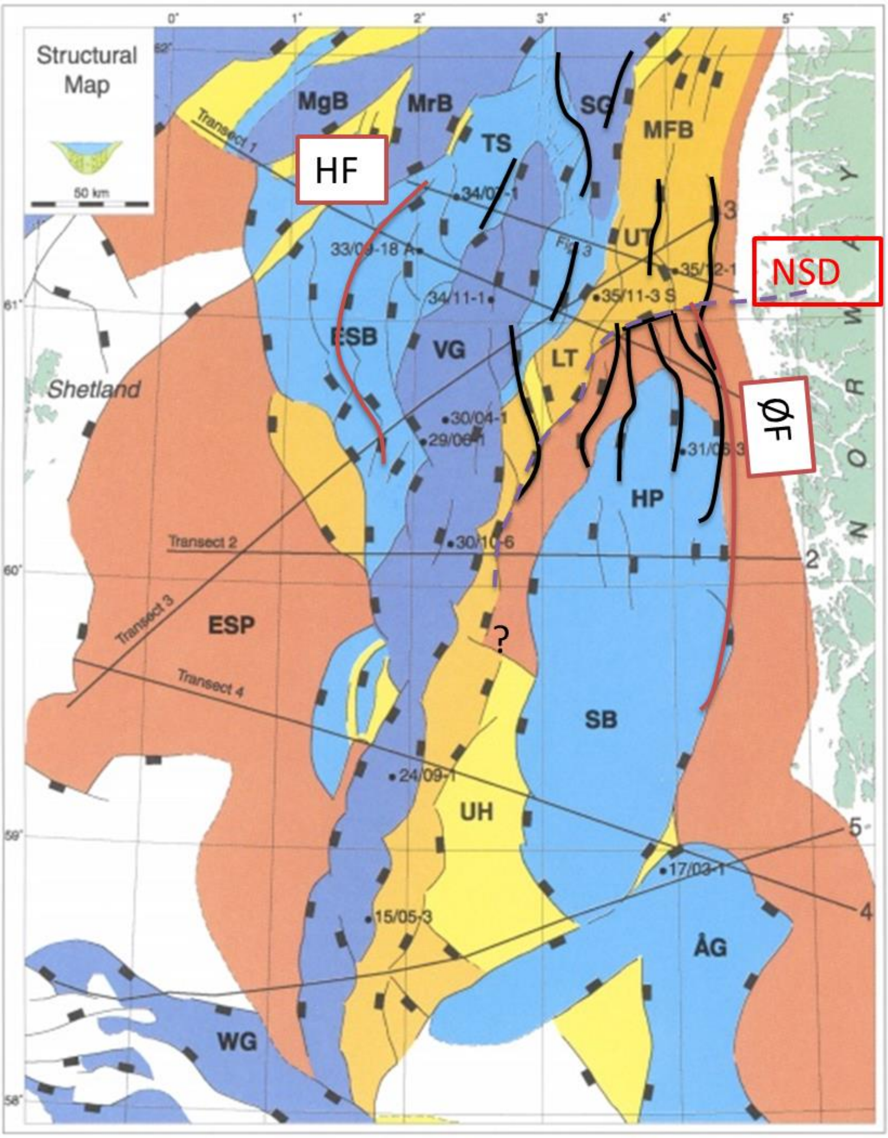


Fig. 5.3. Regional map of the northern North Sea with the suggested offshore continuation of the Nordfjord-Sogn Detachment. As the transfer zone between the fault tips of the Hutton Fault to the west and Øygarden Fault to the east will follow an expected NE-SW trend, the detachment will likely be along the Horda Platform, as this site has been greatly influenced by it during the Late Paleozoic-Mesozoic extensional events. A further southward-directed extent of it, along SW-Horda Platform, is suggested. Modified from Faleide et al. (2002).

5.2 Basement and Devonian basin configuration - onshore-offshore correlations

The presented seismic sections of the intra-basement reflections from section 4.5 give some ideas regarding their anatomy. The wells reaching the basement indicate gneisses to the north-east in the study area and a Caledonian basement at about 61°20'N in Uer Terrace (NPD - FactPages, -FactMaps; Fig. 4.1). The northernmost basement is probably a part of the Western Gneiss Region as found to the north of the Devonian basins on the mainland (Osmundsen and Andersen, 2001). The presented basement sections are likely of a Caledonian character. This seems to be in agreement with intra-basement reflections displaying different angles in the different segments (Figs. 4.26 and 4.27). The undulating patterns are interpreted as folded segments or nappes due to their lateral kilometre-size. This would further suggest the feature the nappes are located above may represent a low-angle detachment, or a reactivated thrust. The feature also extends to the strong reflection found in the eastern horst in key line 2 (Fig. 4.3a), illustrating a gentle dip westward. This is consistent with a westward continuation of the Nordfjord-Sogn Detachment, due to its latitudinal position and westerly, low-dipping character (Osmundsen et al., 1998; Osmundsen and Andersen, 2001).

Reeve et al. (2013) have interpreted the reflections in Fig. 4.26 as mylonite zones, trending NW-SE along a northern flank of Solund Basin. As the ductile shear movements of the Nordfjord-Sogn Detachment are evident with the basal mylonites onshore along the Devonian basins (Andersen, 1998; Osmundsen and Andersen, 2001; Braathen et al., 2004), it may be deduced an offshore continuation of it. The SW-dipping feature in Fig. 4.28 probably represents a westward continuation of it. The segments from Figure 4.26 show this from an another angle, highlighting the detachment being offset by the Øygarden Fault Complex. The reflection pattern in the footwall of the Øygarden Fault Complex however may be mere acoustic artefacts by the faults. While the deeper extent of the faults are difficult to determine it appears from the key lines 2, 3 and 4 (Figs. 4.3, 4.4 and 4.5, respectively) that the curved parts of the Øygarden Fault Complex seem to be shallower than that in key line 1 (Fig. 4.2), hence matching a southward underlying detachment feature. But they all seem to detach beneath the speculated detachment, thus suggesting they may detach into another detachment. The NE-dipping feature from Figure 4.28 could match the offshore continuation of the Nordfjord-Sogn Detachment suggested by Færseth (1996, fig. 3) proximal to the Brage East Fault, due to its position in the study area, and its southward curve. Do note this feature is only clearly visible on this seismic line.

Extrapolating the section in Figure 4.27 north-eastward to the mainland it intersects the northern flank of the Hornelen Basin, suggesting a continuation of the detachment along it. It has been denoted the offshore continuation of the Møre-Trøndelag Fault Complex, trending NE-SW (Gabrielsen et al., 1999) and the anticlockwise rotation of the Hornelen Basin proximal to this fault complex and Devonian WSW-extension of this basin (Osmundsen and Andersen, 2001). Hence, it may be that the Nordfjord-Sogn Detachment follows this and bends toward south-west in the offshore areas from the mainland. Færseth et al. (1997) speculated in a southward curving of the detachment past eastern Tampen Spur, based upon the Jurassic fault trend, NE-SW, controlled by the detachment's underlying structural grain. It has also been interpreted that basal detachments in Gullfaks and Visund in the same area detaches into Devonian or Caledonian shear zones (Fossen et al., 2000). A conflicting scenario arises however as this crosses the proposed transfer zone at 61°N-latitude, active during Permian-Triassic rifting, delineated by the southern part of Nordfjord-Sogn Detachment. It is not apparent from Fig. 4.27a however how the detachment behaves further south-westward due to low resolution of the seismic data. With the Mesozoic fault W35 (Fig. 4.27b) appearing to cut through the proposed mylonites and yet it dips toward south-west in map view (Fig. 4.7) may indicate prevailing pre-existing weakness zones. This may be a result of weak zones due to a NW-SE structural grain (Færseth et al., 1995) or mechanical weaknesses in the contact zone between two lithologies (Twiss and Moores, 2007).

The wedging in the Øygarden Fault Complex, abutting fault W24 (Fig. 4.24), indicates growth along the fault plane earlier than Permian. As the base of the wedge, delineated by the intra-basement A- and B reflections, may be inferred as proposed mylonite zones the wedge above may be assigned a Devonian age due to association of the Devonian sedimentary growth in the extensional basins (Andersen, 1998; Osmundsen et al., 2000; Osmundsen and Andersen, 2001) neighbouring the fault complex. Moreover, the basins were not affiliated with brittle structuring until Late Devonian (Braathen et al., 2004), thus ascribing this the maximum age of the W24. The extent of these intra-basement reflections are to the west of Kvamshesten Basin and Solund Basin, accentuating its extensional character. The Kvamshesten Basin displays Devonian sediments onlapping the detachment that has been cut by the Dalsfjord Fault, with an easterly and south-easterly tilt of strata (Osmundsen et al., 1998). The internal NE- and NW-dipping normal faults, detaches into the Dalsfjord Fault, originated by a westward directed extension (Osmundsen et al., 1998; 2000), thus matching the trend of W24. However, the dispute between these faults is that the proposed mylonites are displaced and rotated along W24, whereas on the mainland these are only cut along by the basal fault. An explanation may be that the basal fault behaves as a ramp-fault (Osmundsen et al., 1998), thus westward portions of it may either continue as a straight, diagonal fault or forming a new ramp. In either scenario the basal fault can cut within the lower part or beneath the mylonitic shear zone, forming fault blocks above it. A less complicated alternative is a post-Devonian development, possibly of Carboniferous origin, due to cooling and continued earthquake rupturing of the mainland area (Braathen et al., 2004). As only wedging is apparent along W24, unaffected by the faults W10-2 and W16, the easternmost fault of Øygarden Fault Complex was the only one being active. The possible termination of the wedge against W35 may dictate it was active as well, as it is the only fault displaying a SW-dip in the eastern area.

Presence of Devonian strata is likely confined at least eastern part of the study area due to the proximity of the Devonian basins on mainland. Furthermore, since the basement has been uplifted in Permian-Triassic times to the north-east, exposing Caledonian basement and gneisses to erosion, indicated by the wells, it is likely that Devonian sediments were preserved in the south-eastern part of study area. Devonian sediments have been speculated to exist in the deeper levels of the Horda Platform (Christiansson et al., 2000; Whipp et al., 2014; Bell et al., 2014). From key line 1 (Fig. 4.2) the areas below top acoustic basement, the tilted reflections may represent Devonian or Carboniferous strata as these are not multiples. The wedging between top acoustic basement and top of the tilted sequence likely represents Permian-earliest Triassic, thus the strata below must be older. The deep wedging along the Vette Fault may be speculated in a Devonian syn-rifting. As this wedge is small the Vette Fault may be deemed as a minor fault in the Devonian where later rift events have exploited the fault, developing it further. The Øygarden Fault in key line 1 however does not seem to display any pre-Permian wedging and this may be due to it being too far south from the Devonian basins. Figure 4.24 is more proximal and shows a possible wedging character along the Øygarden Fault of tentative Devonian age. The crest of the fault block have been proven to be of basement rock from well 32/4-1 (Table 3.3), thus suggesting the Devonian wedge thins out before reaching the crest. As minor fault blocks exist within the mega fault blocks of the Horda Platform, the low-angle fault in Fig. 4.25 may represent a fault delineating one of these fault blocks (see also minor basement fault block next to Tusse Fault in Fig. 4.24). The low-angle nature of it may be due to fault block rotation of Permian-Triassic age, thus suggesting this fault may be older, possibly Devonian-Carboniferous(?). Due to poor seismic resolution at such depths however limits the visibility and confidence of the structural- and the seismic stratigraphic interpretation.

6. Conclusion

The northern North Sea has undergone a complex structural evolution to develop its remarkable geometry.

- As a response to the Permian-earliest Triassic E-W directed extensional event the area developed N-S trending fault systems where the polarity was separated by a transfer zone, deduced to represent the offshore continuation of the Nordfjord-Sogn Detachment. The rifting was confined between Øygarden Fault and Hutton Fault.
- The same extensional event likely caused uplift of the north-eastern part of the study area, causing large depocentres to develop in the Horda Platform and northern Viking Graben, through the transfer zone at 61°N. The transfer zone was also responsible for the westward shift of basin axis in study area.
- The Late Jurassic - earliest Cretaceous rifting event was focused on a narrower part of the study area; the Viking Graben to the south and the Sogn Graben to the north. The margins were only slightly affected, but the Lomre Terrace and Uer Terrace were formed during this event. The Sogn Graben also developed into a symmetrical graben northward.
- The Late Jurassic graben axes are separated by the transfer zone, making up the Marflo Spur. The basement lineament, Marflo Lineament, may also have affected the graben axis-step over. With nearly all the minor faults terminating at base Cretaceous unconformity a Cretaceous post-rift subsidence took place, drowning all the bathymetric remnants of the Late Jurassic-earliest Cretaceous rifting event. Apparently only the large faults on Horda Platform and Øygarden Fault Complex, especially those of Permian-Triassic origin, have shown to be active in Cenozoic.
- With the proximity of the Nordfjord-Sogn Detachment it have influenced the offshore basement structuring, and vice versa as offshore structuring have affected the detachment. With some parts of the Øygarden Fault Complex displaying a probable Late Devonian - Carboniferous origin the complex has likely been developed in conjunction with the brittle E-W extensional deformation of Nordfjord-Sogn Detachment. Future extensional events seem to cut through the detachment.
- Due to the offshore study area's proximity and probable influence of the mainland Devonian basins, Devonian-Carboniferous(?) sediments may be located in the Horda Platform.

7. Reference list

Andersen, T. B. 1998. Extensional tectonics in the Caledonides of southern Norway, an overview. *Tectonophysics*, 285**,** 333-351.

Andersen, T. B., Jamtveit, B., Dewey, J. F. & Swensson, E. 1991. Subduction and eduction of continental crust: major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. *Terra Nova,* 3**,** 303-310.

Badley, M. E., Price, J. D., Dahl, C. R. & Agdestein, T. 1988. The structural evolution of the northern Viking Graben and its bearing upon extensional modes of basin formation. *Journal of the Geological Society*, 145**,** 455-472.

Bell, R. E., Jackson, C. A.-L., Whipp, P. S. & Clements, B. 2014. Strain migration during multiphase extension: Observations from the northern North Sea. *Tectonics*, 33**,** 1936-1963, doi: 10.1002/2014TC003551.

Braathen, A., Nordgulen, Ø., Osmundsen, P.-T., Andersen, T. B., Solli, A. & Roberts, D. 2000. Devonian, orogen-parallel, opposed extension in the Central Norwegian Caledonides. *Geology,* 28(7)**,** 615-618.

Braathen, A., Osmundsen, P. T. & Gabrielsen, R. H. 2004. Dynamic development of fault rocks in a crustal-scale detachment: An example from western Norway. *Tectonics,* 23, doi: 10.1029/2003TC001558.

Bugge, T., Tveiten, B. & Bäckström, S. 2001. The depositional history of the Cretaceous in the northeastern North Sea. *In:* Martinsen, O. J. & Dreyer, T. (eds.) *Sedimentary Environments Offshore Norway - Palaeozoic to Recent.* Amsterdam: Norwegian Petroleum Society Special Publications, 10, 279-291.

Chauvet, A. & Séranne, M. 1994. Extension-parallel folding in the Scandinavian Caledonides: implications for late-orogenic processes. *Tectonophysics,* 238**,** 31-54.

Christiansson, P., Faleide, J. I. & Berge, A. M. 2000. Crustal structure in the northern North Sea: an integrated geophysical study. *In:* Nøttvedt, A. et al. (eds.) *Dynamics of the Norwegian Margin.* London: Geological Society, Special Publications, 167, 15-40.

Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P. & Sokoutis, D. 2003. Analogue modelling of continental extension: a review focused on the relations between the patterns of deformation and the presence of magma. *Earth-Science Reviews,* 63**,** 169-247.

Doré, A. G. & Gage, M. S. 1987. Crustal alignments and sedimentary domains in the evolution of the North Sea, North-east Atlantic Margin and Barents Shelf. *In:* Brooks, J. & Glennine, K. W. (eds.) *Petroleum geology of North West Europe.* London, Graham and Trotman, 2, 1131-1148.

Dyksterhuis, S., Rey, P., Müller, R. D. & Moresi, L. 2007. Effects of initial weakness on rift architecture. *In:* Karner, G. D., Manatschal, G. & Pinheiro, L. M. (eds.) *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup.* Geological Society, London, Special Publications, 282, 443-455.

Eide, E. A., Torsvik, T. H. & Andersen, T. B. 1997. Absolute dating of brittle fault movements: Late Permian and late Jurassic extensional fault breccias in western Norway. *Terra Nova,* 9**,** 135-139.

Faleide, J. I., Bjørlykke, K. & Gabrielsen, R. H. 2010. Geology of the Norwegian continental shelf. *In:* Bjørlykke, K. (ed.) *Petroleum Geoscience.* Berlin: Springer Verlag, 467-499.

Faleide, J. I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R. H., Jordt, H., Fanavoll, S. & Bjerke, M. D. 2002. Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. *In:* Doré, A. G., Cartwright, J. A., Stoker, M. S., Turner, J. P. & White, N. (eds.) *Exhumation of the North Atlantic*

Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society, London, Special Publications, 196, 235-269.

Fjeldskaar, W., ter Voorde, M., Johansen, H., Christiansson, P., Faleide, J. I. & Cloetingh, S. A. P. L. 2004. Numerical simulation of rifting in the northern Viking Graben: the mutual effect of modelling parameters. *Tectonophysics*, 382**,** 189-212.

Fossen, H. 1992. The role of extensional tectonics in the Caledonides of south Norway. *Journal of Structural Geology,* 14(8/9)**,** 1033-1046.

Fossen, H. 1998. Advances in understanding the post-Caledonian structural evolution of the Bergen area, West Norway. *Norsk geologisk tidsskrift,* 78**,** 33-46.

Fossen, H. 2000. Extensional tectonics in the Caledonides: Synorogenic or postorogenic? *Tectonics,* 19(2)**,** 213-224.

Fossen, H., Odinsen, T., Færseth, R. B. & Gabrielsen, R. H. 2000. Detachments and low-angle faults in the northern North Sea rift system. *In:* Nøttvedt, A. & al., e. (eds.) *Dynamics of the Norwegian Margin.* Geological Society, London, Special Publications, 167, 105-131.

Fossen, H. & Rykkelid, E. 1992. Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance. *Geology,* 20**,** 737-740.

Fossen, H., Schultz, R. A., Rundhovde, E., Rotevatn, A. & Buckley, S. J. 2010. Fault linkage and graben stepovers in the Canyonlands (Utah) and the North Sea Viking Graben, with implications for hydrocarbon migration and accumulation. *AAPG Bulletin,* 94(5)**,** 597-613.

Frost, R. T. C., Fitch, F. J. & Miller, J. A. 1981. The Age and Nature of the Crystalline Basement of the North Sea Basin. *In:* Illing, L. V. & Hobson, G. D. (eds.) *Petroleum Geology of the Continental Shelf of North-West Europe.* London: Institute of Petroleum, 43-57.

Færseth, R. B. 1996. Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea. *Journal of the Geological Society,* 153**,** 931-944.

Færseth, R. B., Gabrielsen, R. H. & Hurich, C. A. 1995. Influence of basement in structuring of the North Sea basin, offshore southwest Norway. *Norsk geologisk tidsskrift,* 75**,** 105-119.

Færseth, R. B., Knudsen, B. E., Liljedahl, T., Midbøe, P. S. & Søderstrøm, B. 1997. Oblique rifting and sequential faulting in the Jurassic development of the northern North Sea. *Journal of Structural Geology,* 19(10)**,** 1285-1302.

Gabrielsen, R. H., Faleide, J. I., Pascal, C., Braathen, A., Nystuen, J. P., Etzelmuller, B. & O'Donnell, S. 2010. Latest Caledonian to Present tectonomorphological development of southern Norway. *Marine and Petroleum Geology,* 27**,** 709-723.

Gabrielsen, R. H., Færseth, R. B., Steel, R. J., Idil, S. & Kløvjan, O. S. 1990. Architectural styles of basin fill in the northern Viking Graben. *In:* Blundel, D. J. & Gibbs, A. D. (eds.) *Tectonic evolution of the North Sea rifts.* Oxford: Clarendon Press, 158-179.

Gabrielsen, R. H., Kyrkjebø, R., Faleide, J. I., Fjeldskaar, W. & Kjennerud, T. 2001. The Cretaceous post-rift basin configuration of the northern North Sea. *Petroleum Geoscience,* 7**,** 137-154.

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

Gawthorpe, R. L. & Hurst, J. M. 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. *Journal of the Geological Society, London*, 150**,** 1137-1152.

Gawthorpe, R. L. & Leeder, M. R. 2000. Tectono-sedimentary evolution of active extensional basins. *Basin Research,* 12**,** 195-218.

Giltner, J. P. 1987. Application of extensional models to the Northern Viking Graben. *Norsk Geologisk Tidsskrift,* 67**,** 339-352.

Grønlie, A. & Roberts, D. 1989. Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag fault zone, Central Norway. *Journal of structural geology,* 11(3)**,** 295-305.

Grønlie, A. & Torsvik, T. H. 1989. On the origin and age of hydrothermal thorium-enriched carbonate veins and breccias in the Møre-Trøndelag Fault Zone, central Norway. *Norsk Geologisk Tidsskrift,* 69**,** 1-19.

Hallam, A. & Sellwood, B. W. 1976. Middle Mesozoic sedimentation in relation to tectonics in the British area. *Journal of Geology,* 84**,** 301-321.

Jackson, C. A.-L., Barber, G. P. & Martinsen, O. J. 2008. Submarine slope morphology as a control on the development of sand-rich turbidite depositional systems: 3D seismic analysis of the Kyrre Fm (Upper Cretaceous), Måløy Slope, offshore Norway. *Marine and Petroleum Geology,* 25**,** 663-680.

Karpuz, M. R., Gabrielsen, R. H., Engell-Sørensen, L. & Anundsen, K. 1991. Seismotectonic significance of the 29 January 1989 Etne earthquake, SW Norway. *Terra Nova,* 3**,** 540-549.

Kjennerud, T., Faleide, J. I., Gabrielsen, R. H., Gillmore, G. K., Kyrkjebø, R., Lippard, S. J. & Løseth, H. 2001. Structural restoration of Cretaceous-Cenozoic (post-rift) palaeobathymetry in the northern North Sea. *In:* Martinsen, O. J. & Dreyer, T. (eds.) *Sedimentary Environments Offshore Norway - Palaeozoic to Recent.* Norwegian Petroleum Society Special Publications.

Knag, G. Ø., South, D. & Spencer, A. M. 1995. Exploration trends in the northern North Sea (60–62° N). *In:* Hanslien, S. (ed.) *Petroleum Exploration and Exploitation in Norway.* Elsvevier, Amsterdam: NPF Special Publication, 4, 115-134.

Kusznir, N. J. & Ziegler, P. A. 1992. The mechanics of continental extension and sedimentary basin formation: A simple-shear/pure-shear flexural cantilever model. *Tectonophysics,* 215**,** 117-131.

Kyrkjebø, R., Gabrielsen, R. H. & Faleide, J. I. 2004. Unconformities related to the Jurassic–Cretaceous synrift–post-rift transition of the northern North Sea. *Journal of the Geological Society, London,* 161**,** 1-17.

Kyrkjebø, R., Kjennerud, T., Gillmore, G. K., Faleide, J. I. & Gabrielsen, R. H. 2001. Cretaceous-Tertiary palaeo-bathymetry in the northern North Sea; integration of palaeo-water depth estimates obtained by structural restoration and micropalaeontological analysis. *In:* Martinsen, O. J. & Dreyer, T. (eds.) *Sedimentary Environments Offshore Norway - Palaeozoic to Recent.* NPF Special Publications, 10, 321-345.

Lepercq, J.-Y. & Gaulier, J.-M. 1996. Two-stage rifting in the North Viking Graben area (North Sea): inferences from a new three-dimensional subsidence analysis. *Marine and petroleum geology,* 13(2)**,** 129-148.

Norton, M. G. 1986. Late Caledonide extension in western Norway: A response to extreme crustal thickening. *Tectonics,* 5(2)**,** 195-204.

Nøttvedt, A., Gabrielsen, R. H. & Steel, R. J. 1995. Tectonostratigraphy and sedimentary architecture of rift basins, with reference to the northern North Sea. *Marine and Petroleum Geology,* 12(8)**,** 881-901.

NPD, FactMaps: Norwegian Petroleum Directorate. Available: http://gis.npd.no/factmaps/html_20/ (last visited: 19.02.2015)

NPD, FactPages: Norwegian Petroleum Directorate. Available: http://factpages.npd.no/factpages/Default.aspx?culture=en (last visited: 19.02.2015)
Odinsen, T., Christiansson, P., Gabrielsen, R. H., Faleide, J. I. & Berge, A. M. 2000a. The geometries and deep structure of the northern North Sea rift system. *In:* Nøttvedt, A. et al. (eds.) *Dynamics of the Norwegian Margin.* London: Special Publication, 167, 41-57.
Odinsen, T., Reemst, P., Van Der Beek, P., Faleide, J. I. & Gabrielsen, R. H. 2000b. Permo-Triassic and Jurassic extension in the northern North Sea: results from tectonostratigraphic forward modelling. *In:* Nøttvedt, A., et al. (eds.) *Dynamics of the Norwegian Margin.* London: Geological Society, Special Publications, 167, 83-103.
Osmundsen, P. T. & Andersen, T. B. 2001. The middle Devonian basins of western Norway: sedimentary response to large-scale transtensional tectonics? *Tectonophysics,* 332**,** 51-68.
Osmundsen, P. T., Andersen, T. B., Markussen, S. & Svendby, A. K. 1998. Tectonics and sedimentation in the hangingwall of a major extensional detachment: the Devonian Kvamshesten Basin, western Norway. *Basin Research,* 10**,** 213-234.
Osmundsen, P. T., Bakke, B., Svendby, A. K. & Andersen, T. B. 2000. Architecture of the Middle Devonian Kvamshesten Group, western Norway: sedimentary response to deformation above a ramp-flat extensional fault. *In:* Friend, P. F. & Williams, B. P. J. (eds.) *New Perspective on the Old Red Sandstone.* Special Publications: Geological Society, London, 180, 503-535.
Paul, D. & Mitra, S. 2013. Experimental models of transfer zones in rift systems. *AAPG Bulletin,* 97(5)**,** 759-780.
Prosser, S. 1993. Rift-related linked depositional systems and their seismic expression. *In:* Williams, G. D. & Dobb, A. (eds.) *Tectonics and Seismic Sequence Stratigraphy.* Geological Society Special Publication, 71, 35-66.
Rattey, R. P. & Hayward, A. B. 1993. Sequence stratigraphy of a failed rift system: the Middle Jurassic to Early Cretaceous basin evolution of the Central and Northern North Sea. *In:* Parker, J. R., ed. Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, (215-249) Geological Society of London.
Ravnås, R., Nøttvedt, A., Steel, R. J. & Windelstad, J. 2000. Syn-rift sedimentary architectures in the Northern North Sea. *In:* Nøttvedt, A., et al. (eds.) *Dynamics of the Norwegian Margin.* London: Geological Society, Special Publications, 167, 133-177.
Reeve, M. T., Bell, R. E. & Jackson, C. A.-L. 2014. Origin and significance of intra-basement seismic reflections offshore western Norway. *Journal of the Geological Society,* 171**,** 1-4, doi: 10.1144/jgs2013-020
Roberts, A. M., Yielding, G., Kusznir, N. J., WALKER, I. & Dorn-Lopez, D. 1993. Mesozoic extension in the North Sea: constraints from flexural backstripping, forward modelling and fault populations. *In:* Parker, J. R., ed. Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, (1123-1136) Geological Society of London.
Roberts, A. M., Yielding, G., Kusznir, N. J., Walker, I. M. & Dorn-Lopez, D. 1995. Quantitative analysis of Triassic extension in the northern Viking Graben. *Journal of the Geological Society, London,* 152**,** 15-26.
Rosendahl, B. R. 1987. Architecture of continental rifts with special reference to East Africa. *Annual Review of Earth and Planetary Sciences,* 15**,** 445-503.
Rüpke, L. H., Schmalholz, S. M., Schmid, D. W. & Podladchikov, Y. Y. 2008. Automated thermotectonostratigraphic basin reconstruction: Viking Graben case study. *AAPG Bulletin,* 92(3)**,** 309-326.
Schlische, R. W. 1995. Geometry and origin of fault-related folds in extensional settings. *AAPG Bulletin*, 79(11)**,** 1661-1678.

Sellevoll, M. A. 1973. Mohorovičić discontinuity beneath Fennoscandia and adjacent parts of the Norwegian Sea and the North Sea. *Tectonophysics,* 20**,** 359-366.

Seranne, M. 1992. Late Paleozoic kinematics of the Møre-Trøndelag Fault Zone and adjacent areas, central Norway. *Norsk Geologisk Tidsskrift,* 72**,** 141-158.

Smethurst, M. A. 2000. Land–offshore tectonic links in western Norway and the northern North Sea. *Journal of the Geological Society, London,* 157**,** 769-781.

Steel, R. 1993. Triassic–Jurassic megasequence stratigraphy in the Northern North Sea: rift to post-rift evolution. *In:* Parker, J. R., ed. Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, (299-315) Geological Society of London.

Steel, R. & Ryseth, A. 1990. The Triassic—early Jurassic succession in the northern North Sea: megasequence stratigraphy and intra-Triassic tectonics. *In:* Hardman, R. F. P. & Brooks, J. (eds.) *Tectonic Events Responsible for Britain's Oil and Gas Reserves.* London: Geological Society, Special Publications, 55, 139-168.

Sturt, B. A. & Torsvik, T. H. 1987. A late Carboniferous palaeomagnetic pole recorded from a syenite still, Stabben, Central Norway. *Physics of the Earth and Planetary Interiors,* 49**,** 350-359.

Ter Voorde, M., Færseth, R. B., Gabrielsen, R. H. & Cloething, S. A. P. L. 2000. Repeated lithosphere extension in the northern Viking Graben: a coupled or decoupled rheology? *In:* Nøttvedt, A., et al. (eds.) *Dynamics of the Norwegian Margin.* London: Special Publications - Geological Society, 167, 59-81.

Tomasso, M., Underhill, J. R., Hodgkinson, R. A. & Young, M. J. 2008. Structural styles and depositional architecture in the Triassic of the Ninian and Alwyn North fields: Implications for basin development and prospectivity in the Northern North Sea. *Marine and Petroleum Geology,* 25**,** 588-605, doi: 10.1016/j.marpetgeo.2007.11.007

Torsvik, T. H., Sturt, B. A., Swensson, E., Andersen, T. B. & Dewey, J. F. 1992. Palaeomagnetic dating of fault rocks: evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjord Fault, western Norway. *Geophysical Journal International,* 109**,** 565-580.

Turcotte, D. L. & Emerman, S. H. 1983. Mechanisms of active and passive rifting. *Tectonophysics,* 94**,** 39-50.

Twiss, R. J. & Moores, E. M. 2007. *Structural Geology,* 2nd edition, New York, WH Freeman and Company, 736 pp.

Whipp, P. S., Jackson, C., Gawthorpe, R. L., Dreyer, T. & Quinn, D. 2014. Normal fault array evolution above a reactivated rift fabric; a subsurface example from the northern Horda Platform, Norwegian North Sea. *Basin Research,* 26**,** 523-549, doi: 10.1111/bre.12050

Wilks, W. J. & Cuthbert, S. J. 1994. The evolution of the Hornelen Basin detachment system, western Norway: Implications for the style of late orogenic extension in the southern Scandinavian Caledonides. *Tectonophysics,* 238**,** 1-30.

Yielding, G., Badley, M. E. & Freeman, B. 1991. Seismic reflections from normal faults in the northern North Sea. *In:* Roberts, A. M., Yielding, G. & Freeman, B. (eds.) *The Geometry of Normal Faults.* Geological Society, London: Special Publications, 56, 79-89.

Ziegler, P. A. 1990. Tectonic and palaeogeographic development of the North Sea rift system. *In:* Blundell, D. J. & Gibbs, A. D. (eds.) *Tectonic Evolution of the North Sea Rifts.* Oxford: Clarendon Press, 1-36.

Ziegler, P. A. 1992. Geodynamics of rifting and implications for hydrocarbon habitat. *Tectonophysics,* 215**,** 221-253.