Permian-Triassic tectono-stratigraphic evolution of the Stord Basin, northern North Sea.

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Abstract

The Stord Basin is one of the less explored areas of the northern North Sea, hence the Permian-Triassic tectono-stratigraphic evolution of the basin is not well known. This MSc thesis aims to use available 2D seismic and well data covering the Stord Basin to investigate the evolution of the multiphase rift-basin, with focus on the Permian-Triassic rifting phase. The study is based on seismic interpretation of deep (9 s TWT) 2D seismic lines. Different methods were used to investigate the tectono-stratigraphy in the Stord Basin. Generation of thickness maps allows to illustrate stratigraphic units and indicate fault activity. Creation of throw-length (T-x) plots illustrate the map-view growth history. Heave and throw calculations have been used to evaluate the strain distribution in the Stord Basin through time. The major Permian-Triassic faults are found to have a more curved appearance at depth and consist of multiple sub-segments. Most of the displacements along the faults were obtained during the first Permian-Triassic rifting phase. Evidence of inter-rifting has been further investigated in this thesis. The influence of pre-existing Devonian shear zones on later Permian-Triassic faults' orientation and geometry has also been investigated. The Utsira Shear Zone and the Hardangerfjord Shear Zone have affected the orientation and geometry of later Permian-Triassic faults in their proximities. The shear zones roughly divide the Stord Basin into a structural domain. Analyses of surface and thickness maps have resulted in the determination of the Permian-Triassic rift succession into syn-tectonic and post-tectonic. The collected results have been used to make an evolutionary model of the Stord Basin from the initial Permian-Triassic rifting to the present day configuration.

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Content

1. Introduction

The Norwegian Continental Shelf has been intensively studied the last decades, accumulating great knowledge of the North Sea Rift. The areas of interest to the petroleum industry along the Viking Graben are especially well explored. Little interest has been given the Stord Basin in the past, hence the literature on the basin is somewhat sparse. This rift basin in the northern North Sea is covered by 2D deep (9 ms TWT) seismic reflection data sets of varying quality and a substantial part of the sedimentary succession is still unknown due to lack of well data. A major 3D survey of the Horda Platform and northern Stord Basin is currently being collected, demonstrating that there is an increasing interest for the area.

Previous work has found that the Stord Basin is a Permian-Triassic, N-S trending, well-defined rift basin (Steel and Ryseth, 1990, Faerseth et al., 1995). The basin is located between the Utsira High and the Stavanger Platform, bound to the west and east by the Utsira High Fault Complex and the Øygarden Fault Complex, respectively (Faerseth et al., 1995, Odinsen et al., 2000). The Stord Basin is roughly divided into a structural domain by the Utsira High Shear Zone in the northwest and Hardangerfjorden Shear Zone in the south (Fossen et al., 2016).

The Stord Basin is mentioned in many regional studies, but it is rarely the main target. Biddle and Rudolph (1988) focused on the early Tertiary interval of the Stord Basin, however, this is much younger than the time span considered in this study. The Øygarden Fault Complex has been analysed in multiple regional studies and is well known (Odinsen et al., 2000, Bell et al., 2014). Cenozoic inversion structures have been investigated and multiple studies have looked at the effect pre-existing structures, like older faults and shear zones, have on the development of later faults (Faleide et al., 2002, Maerten et al., 2002, Fazli Khani et al., 2015, Fazli Khani and Back, 2015, Fossen et al., 2016). Having a thorough understanding on how structures influence each other is useful, not only when looking into unexplored areas, but also to gain greater knowledge of the geology in a rift setting. Triassic petroleum plays in the North Sea has received more attention during the last years. The Permian-Triassic Stord Basin might therefore be of particular interest for the petroleum industry, either for exploration or CO_2-storage.

Rift models tend to describe one rift phase (Gawthorpe and Leeder, 2000), which does not take into account the multi-rift development, where one must consider rifting to be somewhat determined by the initial setting, and not intact crust. McKenzie (1978) have proposed a rift model including a first rift event followed by post/pre-rift and a second rift event. Although this is a well-used model for the North Sea, it does not fully explain the complexity observed in the Stord Basin. Subsidence-induced faulting during post/pre-rift must also be considered (Beach et al., 1987).

This thesis aims to better understand the Permian-Triassic rifting phase in the Stord Basin, particularly to identify the syn-rift and post-rift depositional pattern and the structural evolution of the Stord Basin. Furthermore, this study looks at the fault kinematics of the bounding faults and the intra-basin faults, and aim to gain knowledge on the relative fault activity within the Permian-Triassic interval in the Stord Basin. An evolutionary model for the Stord Basin are proposed at the end of the results. To achieve the research goals, a number of methods have been used.

Interpreting and creating structural maps of the stratigraphic succession was the first step and laid the basis for further work. The thickness maps are vital to indicate the temporal fault activity of the Stord Basin, by looking at the geometries of each interpreted package. Furthermore, a fault analysis was conducted by creating throw-length plots to depict the spatial fault activity. Where it was possible, the Permian-Triassic rifting phase was isolated in the plots, as the main focus of this thesis is the first rifting phase. Both heave and throw measurements have been displayed in map view to gain perspective on the distribution of strain through time in the Stord Basin. Restoration, stretching calculations and defining the expansion index has been performed for one cross-section, in an attempt to enlighten the Permian-Triassic rifting phase of the Stord Basin. An evolutionary model of the Stord Basin will be proposed.

This thesis is aiming to describe the Permian-Triassic tectono-stratigraphic evolution of the Stord Basin offshore Norway. It is part of the MultiRiftProject, which is a collaboration between the University of Bergen, University of Oslo, Imperial College London, University of Manchester and Statoil ASA. The main objective of this joint project is to "Develop a fundamental understanding of how pre-existing structures in both basement and cover influence the evolution of normal faults and associated topographic development and depositional systems" (MultiRiftProject, 2016). This thesis contributes to the MultiRiftProject by investigating the possible influence of pre-existing, deep basement structure on later fault development in the Stord Basin, and furthermore by exploring the overall tectono-stratigraphic evolution of the Stord Basin, northern North Sea. The North Sea Rift is a product of multiple extensional phases, which makes understanding the possible effects of pre-existing structures very important.

2. Geological framework

The study area is located offshore the west coast of Norway in the North Sea (Fig. 2.1). The North Sea is a rift with a complex geological history. From Permian through Late Jurassic time, the basement rocks have been extended in multiple pulses (Ziegler, 1975, Erratt, 1993, Roberts et al., 1995). The North Sea is considered a failed rift in connection with the opening of the Atlantic Ocean (Naylor et al., 1974). Compaction and multiple phases of extension has been vital in shaping the geology of the North Sea rift to what it is today, with a vast number of Mesozoic sedimentary Basins (Ziegler, 1992).

The Stord Basin is located east of Utsira High in the northern parts of the North Sea Rift (Fig 2.1 a, b). The basin formed mainly as a result of the Permian-Triassic rifting, while the effects from Late Jurassic rifting was limited. Both rifting phases set the area under E-W extension (Bartholomew et al., 1993, Faerseth, 1996, Cowie et al., 2005) . This resulted in a series of rotated fault blocks separated by normal faults (Fig. 2.1c, d). The Permian-Triassic rifting phase and the mainly Late Jurassic rifting phase are the immediate causes to the North Sea Rift’s creation and geometry. This includes the formation of the Stord Basin, which has an N-S to NNW-SSE trend along the west coast of Norway (Biddle and Rudolph, 1988). The structural evolution of the Northern North Sea will be described in the following sub-chapters.

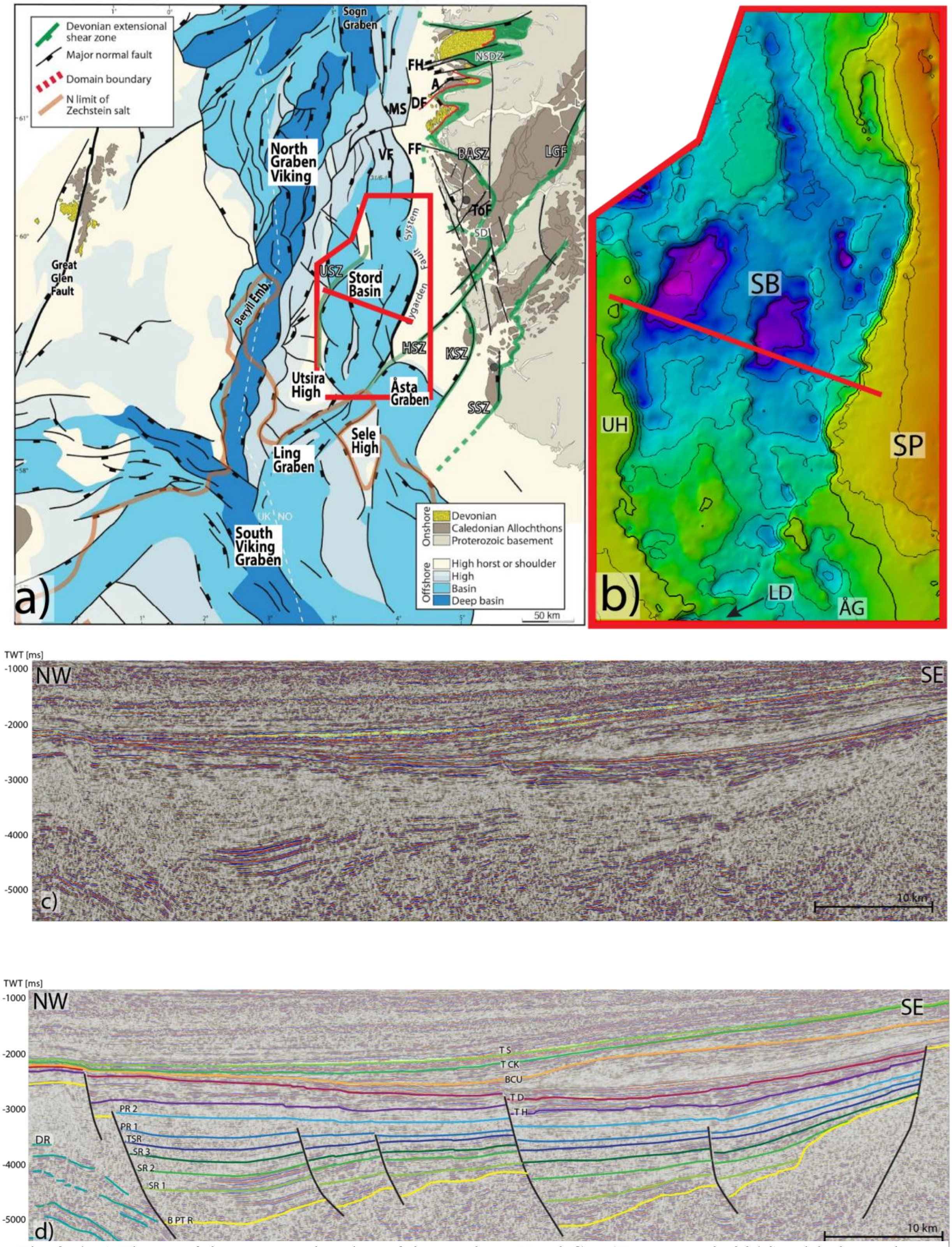


Fig. 2. 1. a) Figure of the structural setting of the northern North Sea (Fossen et al., 2016), with the study area marked in red. b) Close up of the study area with the Base Permian-Triassic Rifting surface displayed and with the location of seismic line marked in red and major structures labelled; SB:Stord Basin, UH:Utsira High, SP:Stavanger Platform, ÅG:Åsta Graben. c) Seismic line NSR09-41153 crossing the Stord Basin from UH to SP. d) Interpretations illustrated atop the seismic line NRE09-41153. Abbreviations of horizons from base to top is as follows; B PT R: Base Permian-Triassic rifting surface, SR 1-3: Syn-Rift horizons 1-3, TSR: Top Syn Rift, PR 1-2: Post-Rift horizons 1-2, TH:Top Hegre, TD:Top Dunlin, BCU:Base Cretaceous Unconformity, TCK:Top Cromer Knoll and TS:Top Shetland.

2.1 Caledonian Orogeny

The moving direction of plate tectonics changed from divergent to convergent in Late Cambrian time. This resulted in the continent-continent collision between Laurentia and Baltica, secondarily also involving Avalonia, in mid-late Silurian time and the subsequent closing of the Iapetus Ocean (Fig. 2.2) (Fossen, 1992, Dewey and Strachan, 2003, Riber et al., 2015). The convergent history culminated in oblique sinistral, continent-continent collision, where the Baltica margin in West Norway was subducted beneath the Laurentian (Greenland) margin (Fossen, 1992, Dewey and Strachan, 2003). This caused the thrusting of nappes south-eastwards onto the Proterozoic Baltic, forming an orogenic wedge (Coward, 1990, Fossen, 1992, Fossen, 2010a). The nappes are separated from the Baltic basement by a weak Caledonian décollement zone of micaceous rocks (Fossen, 1992). The continental collision caused severe thickening of the crust, with depth estimates exceeding 100 km (Faerseth, 1996). On a global scale, this was the time of the formation of the supercontinent Pangea.

The basement rocks of the Proterozoic Baltic Shield were highly deformed in the coastal areas and the North Sea during the Caledonian orogeny and the following Devonian extensional deformation (Fossen, 1992). The basement is heterogeneous and is made up by magmatic and metasedimentary rocks (Slagstad et al., 2011).

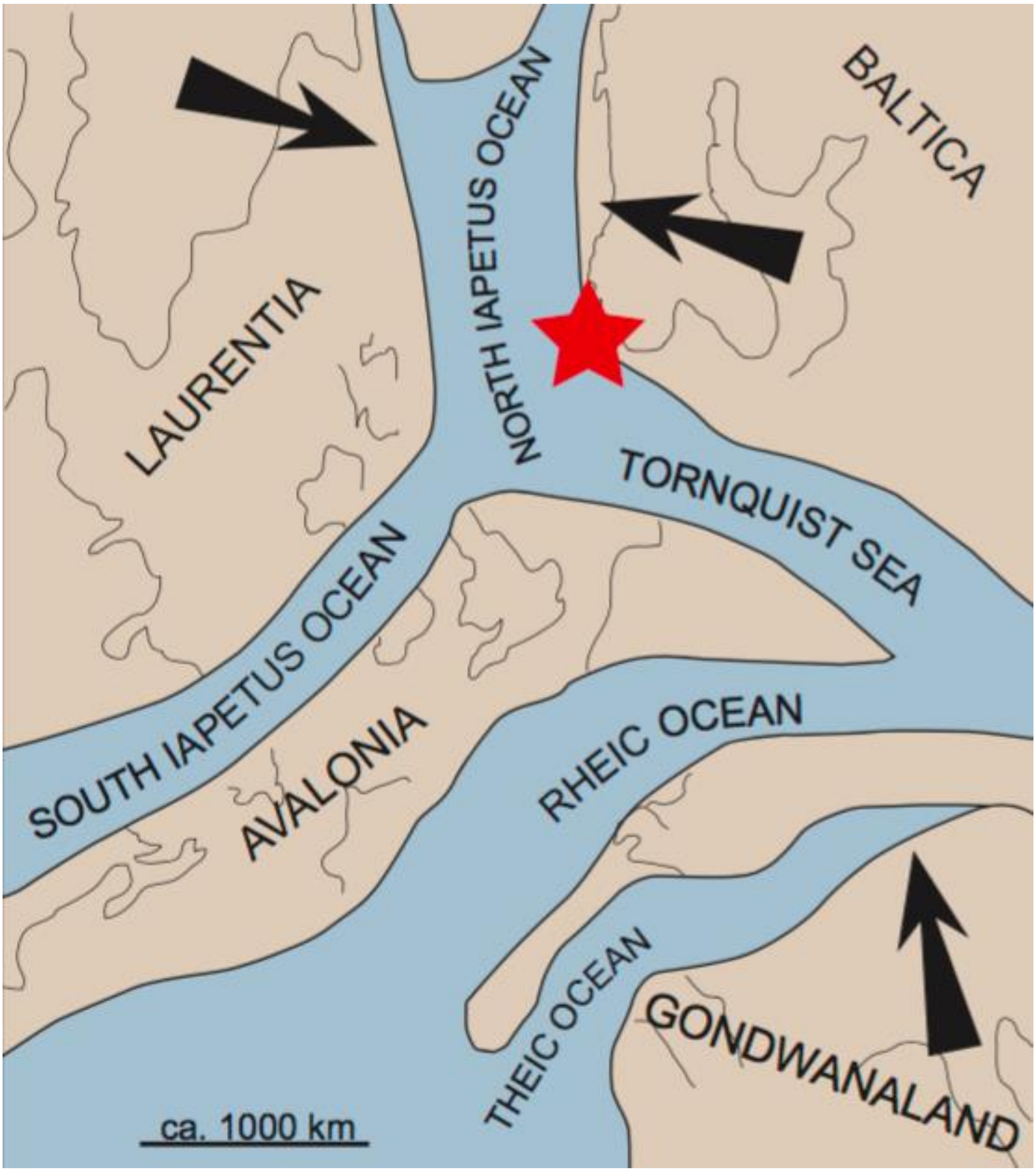


Fig. 2. 2. Plate configuration in mid-late Silurian times, illustrating the convergence of Baltica and Laurentia. The present coast lines are outlined and the red star covers the study area in the northern North Sea. The figure was collected from Riber et al. (2015), who modified it from Rey et al. (1997).

2.2 Orogenic collapse

Extensional collapse and NW-SE extension initiated in Lower Devonian time and lasted to late Carboniferous (Fossen et al., 2016). Intracontinental stretching affected a wide area of the orogeny (Odinsen et al., 2000). The area of extension is gradually more localized for each of the succeeding major rifting phases.

Most of the extensional structures were active in the interval 400-380 Ma (Ziegler, 1975, Fossen, 2010a) . The change to extensional regime lead to roughly 20 km of backsliding of the orogenic wedge by extension along the basal Caledonian décollement zone towards the (W)NW, named Mode I extension (Fig. 2.3a) (Fossen, 1992, Fossen, 2010a). Mode II faulting continued the extension following the cessation of Mode II movement. Mode II caused primarily the formation of shear zones, which cut through the Caledonian décollement zone, hence at a higher angle than the Mode I (Fig. 2.3b). This resulted in multiple Devonian shear zones onshore, extending offshore. An example of a Mode II shear zone is the Hardangerfjord Shear Zone (HSZ), which reactivated post-Devonian despite non-preferential orientation (Fossen et al., 2016). The extensional HSZ transects the Proterozoic Basement onshore and have been identified at lower crustal levels offshore (Hurich and Kristoffersen, 1988, Fossen and Hurich, 2005). Magnetic maps show that the Hardangerfjord Shear zone continues offshore along the Ling Depression, directly south of the Stord Basin (Fossen and Hurich, 2005). Another Devonian shear zone is the Nordfjord-Sogn Detatchment Zone, which is 5-6 km thick with over 50 km displacement (Fossen, 2010a). A package of east-dipping basement reflections along the eastern boundary of Utsira High and further north has recently been mapped and is interpreted as a Mode II shear zone (Fossen et al., 2016).

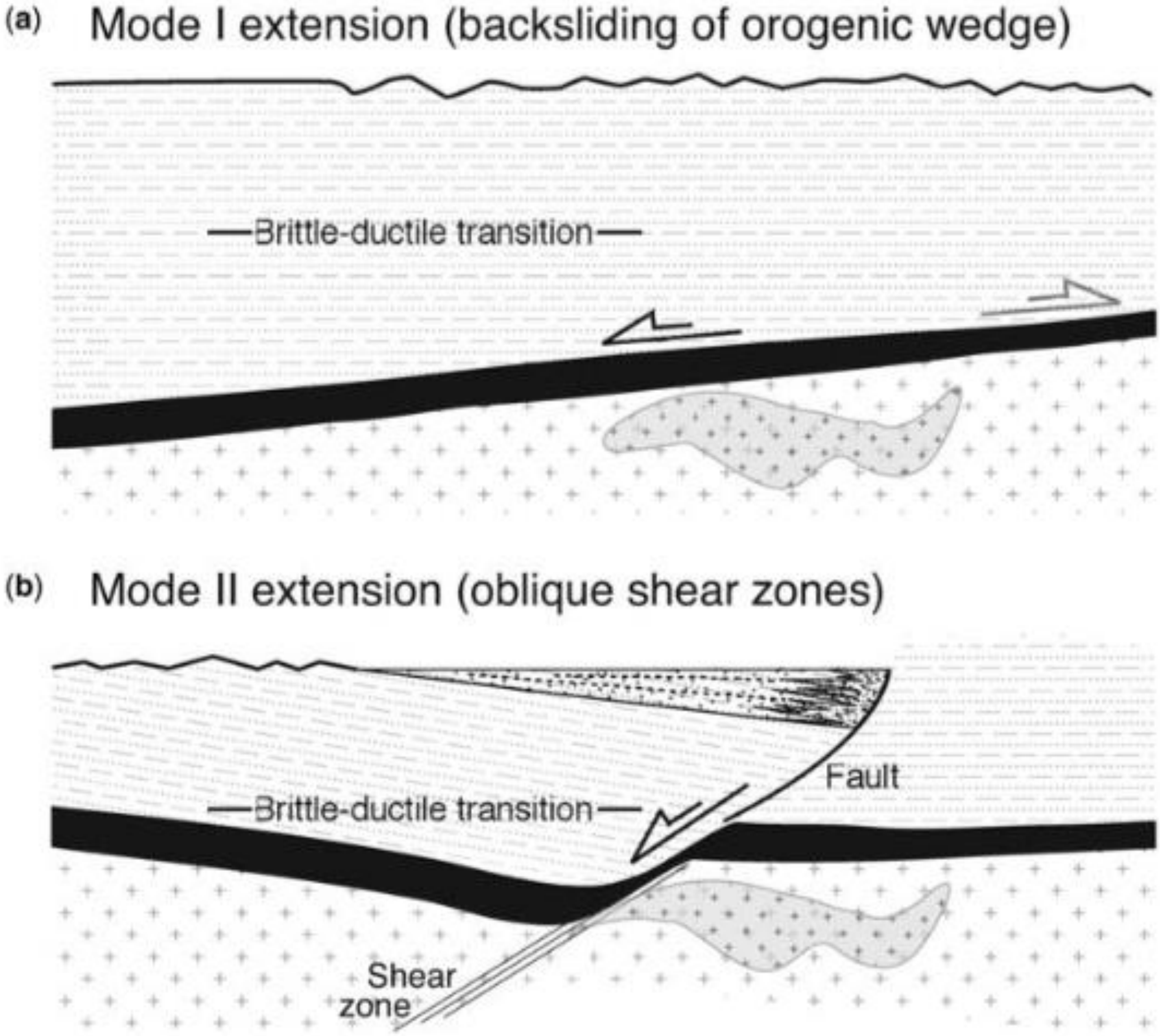


Fig. 2. 3. Figure shows the characteristics of the two-staged orogenic collapse by first a) Mode I extension along a décollement zone, followed by b) Mode II extension cross-cutting and rotating the Mode I at a higher angle. Mode II cause the formation of Devonian shear zones below the brittle-ductile transition, while brittle (Mode III) faults forms at shallower depths. Figure from Fossen (2010a).

2.3 Permian-Triassic rift phase

The onset of Permian-Triassic rifting in the Northern North Sea Rift has not been unambiguously defined, but it is assumed to have started somewhere in early-late Permian time and lasted into the Middle Triassic (Nottvedt et al., 1995, Odinsen et al., 2000). This marks the beginning of the intra-craton rifting stage leading to breakup of the supercontinent Pangea (Ziegler, 1975, McKenzie, 1978, Ziegler, 1993, Doré, 1992). The crust was around 32 km

(Faerseth, 1996) or 40 km thick (Fossen et al., 2016) at the time of rift initiation. The fact that dikes off SW Norway have a mainly N-S direction combined with the predominantly N-S Permian-Triassic faults, have been used to deduce the Permian-Triassic rifting extension direction to be E-W (Faerseth, 1996, Fossen and Hesthammer, 1998). The massive rifting caused differential movement and facilitated major accumulation of sediments (Doré, 1992). Some Permian-Triassic faults align with the NNW striking Devonian extensional grain, which might have been a controlling factor for the fault strikes (Faerseth, 1996, Faerseth et al., 1995).

The Permian-Triassic rifting created a 300-400 km wide rift zone from the Horda Platform in the east to the Hutton Fault, Shetland Platform in the west (Ziegler, 1992, Christiansson et al., 2000), which is more localized than the extension during orogenic collapse (Odinsen et al., 2000). The rift-axis was located beneath the Horda Platform (Christiansson et al., 2000). The stretching factor during the Permian-Triassic was 1.3-1.4, and the extension was distributed on a large number of mainly N-S trending faults (Yielding et al., 1992, Faerseth, 1996). The combination of tilting and deep erosion during the Permian-Triassic rifting led to structural highs with exposed basement rocks (Faerseth et al., 1995, Nottvedt et al., 1995). By the end of Permian-Triassic rifting, the crustal thickness was reduced 11-13 km and the sediment thickness varied throughout the northern North Sea (Faerseth, 1996).

The Permian-Triassic rift phase caused the formation of a series of major fault blocks that were progressively tilted and covered by rift basin fill (Steel, 1993). The rotated fault blocks are characteristic for rift systems and are for example found in the Horda platform and Stord Basin (Fig. 2.1c, d). The stratigraphic geometries in rifted basins are strongly affected by the interaction and activity of rift faults (Dawers and Underhill, 2000). Accommodation space is created by normal faults in a rift setting and the stratigraphy records the activity of the fault through time.

During Permian-Triassic rifting, a large number of basement faults with several kilometres offsets were established (Odinsen et al., 2000). The Øygarden Fault Complex (ØFC), sometimes referred to as Øygarden Fault System (Fossen et al., 2016), is an example of a Permian-Triassic fault system, which obtained a large offset in that first rifting. It was most likely formed by lateral linkage of several fault segments (Odinsen et al., 2000). The ØFC strikes mainly N-S over more than 300 km and was active during most of Permian-Triassic rifting (Christiansson et al., 2000). This major fault system bounds the Stord Basin towards the east.

Rotliegend continental sandstones were deposited early during Permian-Triassic rifting, but have not been identified in the Stord Basin. Some of the Permian basins were marine due to a combination of hanging-wall subsidence and the Permian transgression (Ziegler, 1978). During sea-level high stands the Zechstein salt was deposited, limited to the extents of the Permian ocean. A regression lead to a change in environment in the northern North Sea from marine in Permian to continental in Triassic (Ziegler, 1978).

In the period after Permian-Triassic rifting, the North Sea was dominated by thermal subsidence until it again was set under an extensional regime (Odinsen et al., 2000). The subsidence was eventually eliminated by Middle Jurassic thermal doming as a result of the thinned crust (Glennie, 1998). Compaction of the Permian-Triassic rift sediments and the residual thermal anomalies gives overestimates of the subsidence.

The northern North Sea Basin evolved from a narrow rift basin of linked opposing half-grabens in early Triassic to a broad, open basin in the post-rift period from middle Triassic and out (Steel, 1993, Faerseth et al., 1995). The structural framework of the Permian-Triassic rift set the structural setting for further development in the northern North Sea.

2.4 Late Jurassic-Early Cretaceous rift phase

The second major rift phase initiated in the Late Jurassic and continued into Early Cretaceous time (Odinsen et al., 2000). The rift axis shifted from the Horda Platform westward to the Viking Graben. The extension was localised on major faults dipping towards the rift axis in the Viking Graben (Cowie, 1998). Crustal thinning and subsequently uplift and rotation of fault blocks enabled the deposition of large amounts of sediments. Transgression in the Jurassic flooded the North Sea and facilitated the deposition of deltaic successions. The Viking Formation in the Stord Basin contains similar deltaic deposits as the Brent Formation in the Horda Platform (Halland, 2011). The deltaic successions are enveloped by the erosional Base Cretaceous Unconformity.

The Viking Graben does not align with the Caledonian grain or earlier sedimentary basins (Ziegler, 1992). This indicates that Permian-Triassic rifting, though having some control of later rifting, was not the main controller in Viking Graben.

2.5 Geological framework of the Stord Basin

The Stord Basin is located offshore Norway on the continental shelf and is of Permian-Triassic origin (Fig. 2.1). The rift basins width varies from 30-80 km at the (acoustic) basement level and it is about 190 km long. It contains a substantial amount of Permian-Triassic sediments. The faults in the Stord basin range from a N-S trend to NE-SW trend, have planar geometries and rotate fault block in some cases (Faerseth, 1996, Odinsen et al., 2000). The Stord Basin roughly constitutes one structural domain, limited by the Utsira Shear Zone in the east and north, and the Hardangerfjord Shear Zone to the south (Fossen et al., 2016). The Stord Basin stabilized in the middle stage of Late Jurassic time and became tectonically a part of the Horda Platform, which consist of the entire area from Åsta Graben to Ure Terrace and Måløy Slope in the eastern flank of Viking Graben. The Permian Sea did not cover the Stord Basin, which is believed to have developed as a continental rift basin during the Permian-Triassic rifting phase.

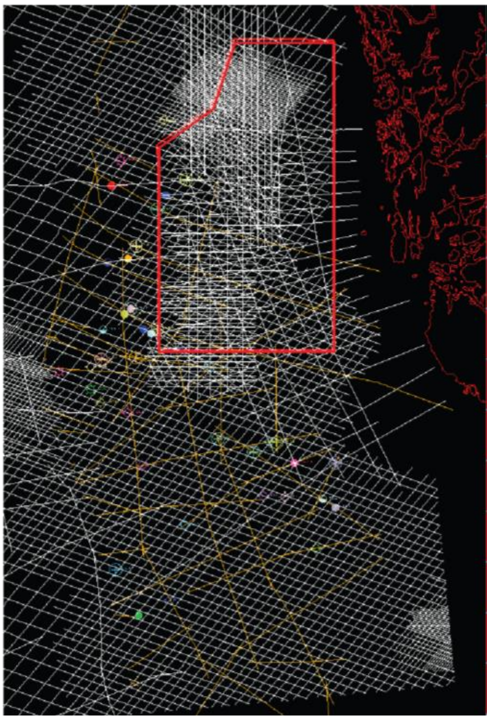
3. Data and methods

This thesis is based on seismic interpretations in the Petrel software. The seismic data and well data used in this thesis will be presented, followed by sub-chapters of software and principles of seismic interpretation in Petrel. An explanation of fault kinematics is provided before the chapter is rounded off by looking into the principles of restoration and stretching.

3.1 Seismic data

2D deep, 9 seconds two-way time (TWT) seismic reflection data have been used in this study, which allow to images both the upper and middle crust of the study area.

Multiple seismic surveys have been available in this project. The surveys contain 2D seismic lines, which allow for deep (9 s) imaging on a regional scale. Fig. 3.1 shows the seismic dataset and the study area in the offshore south-west Norway, tied wells and a table of the available seismic surveys.



Survey name	Well names		
		16/2-3	17/12-2
NSR04	7/4-2	16/2-7	17/12-3
NSR05	7/8-3	16/2-9	17/4-1
NSR06	7/9-1	16/2-9_S	18/10-1
NSR07	8/3-2	16/3-4	18/11-1
NSR08	8/4-1	16/4-1	25/10-2
NSR09	9/1-1_S	16/4-2	25/11-1
CP07	9/2-1	16/5-1	25/3-1
GNRS91	9/2-2	16/6-1	25/4-1
CNST82R88	9/4-3	16/7-2	25/4-5
SBGSR94	15/6-11_A	16/7-3	25/4-6_S
HRTRE00	16/1-5	16/8-2	25/6-1
HPS98	16/11-1_S	17/11-1	25/8-1
CNST86	16/2-11	17/12-1	25/9-1
			26/4-1
			31/5-2

Fig. 3. 1. Overview pictures from the Petrel project. The left hand picture displays the total area, Northern North Sea. The middle picture is a close up of the Stord Basin with its survey lines and wells. To the right is the list of 2D surveys available in this project.

3.2 Well data

Well data have been crucial to interpret the marker horizons. Exploration wells were added throughout the project where wells were needed and check shots available. Check shot for the wells were obtained by using Discos and NPD's website. The distribution of wells is controlled by areas of interest to the petroleum industry and is thus unevenly distributed throughout the study area. It is therefore important to carefully extrapolate the interpretations to areas with little or no well control, for instance the Stord Basin.

3.3 Software

Petrel software was used to conduct the seismic interpretations. Adobe Illustrator was used to make and edit figures.

3.3.1 PETREL version 2013

The University of Bergen have licences to the Petrel seismic interpretation software on a number of their computer labs. The standard modules included in the licences have been sufficient to complete this project. The Blueback Petrel plugin tools "Extend 2D seismic" and "Make 2D seismic" was used to extend certain seismic lines and make new lines. The extension leaves a grey background where crossing interpretations may be displayed. The same goes for the new-made lines. This was used actively in the fault analysis as these "artificial" lines could enable the measurements to be done with smaller increments and more or less perpendicular to the fault compared to the existing crossing lines.

3.3.2 Adobe Illustrator CS6 and CC2015

Adobe Illustrator CS6 is graphics software which allow for making figures of different complexity. It is vector-based and was used to make figures.

3.4 Seismic interpretation

Horizon interpretations have been done by tracing either positive amplitudes (peaks) or negative amplitudes (troughs) in the seismic data (Fig. 3.2). Zero crossings have not been interpreted. Peaks are displayed as red, troughs as blue and zero crossings are shown as thin white bands.

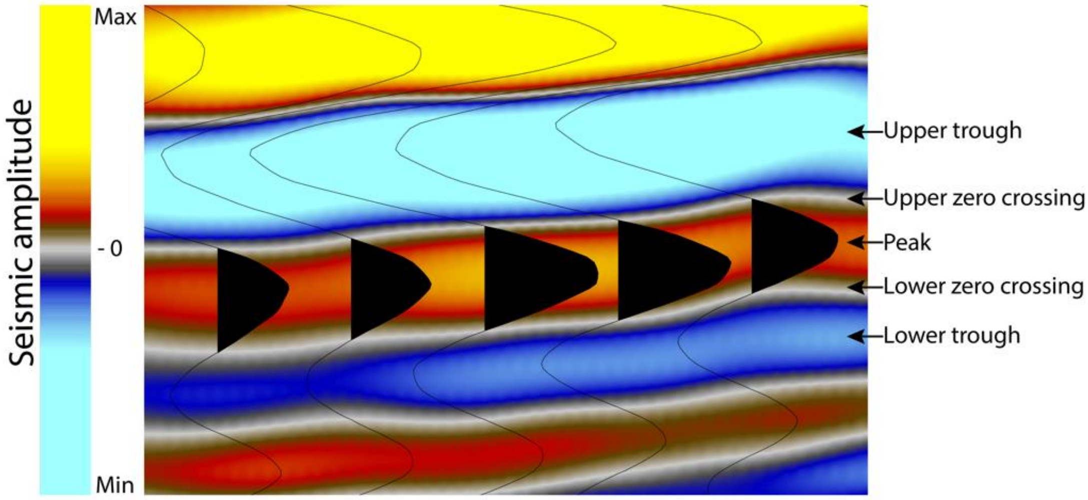


Fig. 3. 2. Close up image of the seismic data. Peaks are coloured red, troughs are coloured blue and zero crossings in grey to white. The phases are marked on the right hand side.

3.4.1 Horizons

Interpretations have mainly been done by manual interpretation combined with "shift" to snap the horizon on to similar signals as interpreted earlier. The horizons in this project are set to follow either peaks or troughs when auto-tracking. Using this combination of manual and auto-tracking gives the interpreter good control and speeds up the interpretations. Where it was possible, auto-tracking were used. In the datasets it still was necessary to go over the auto-tracked horizons and fill in the gaps, hence it was not very time-saving.

Well ties are crucial for picking the right reflection to follow. When interpreting without well ties, the continuity of the reflection and stratigraphic image becomes vital for choosing a reflection to interpret on. Stratigraphic features, i.e. onlap and toplap, are related to changes in the depositional environment and have been used to identify horizons of particular interest.

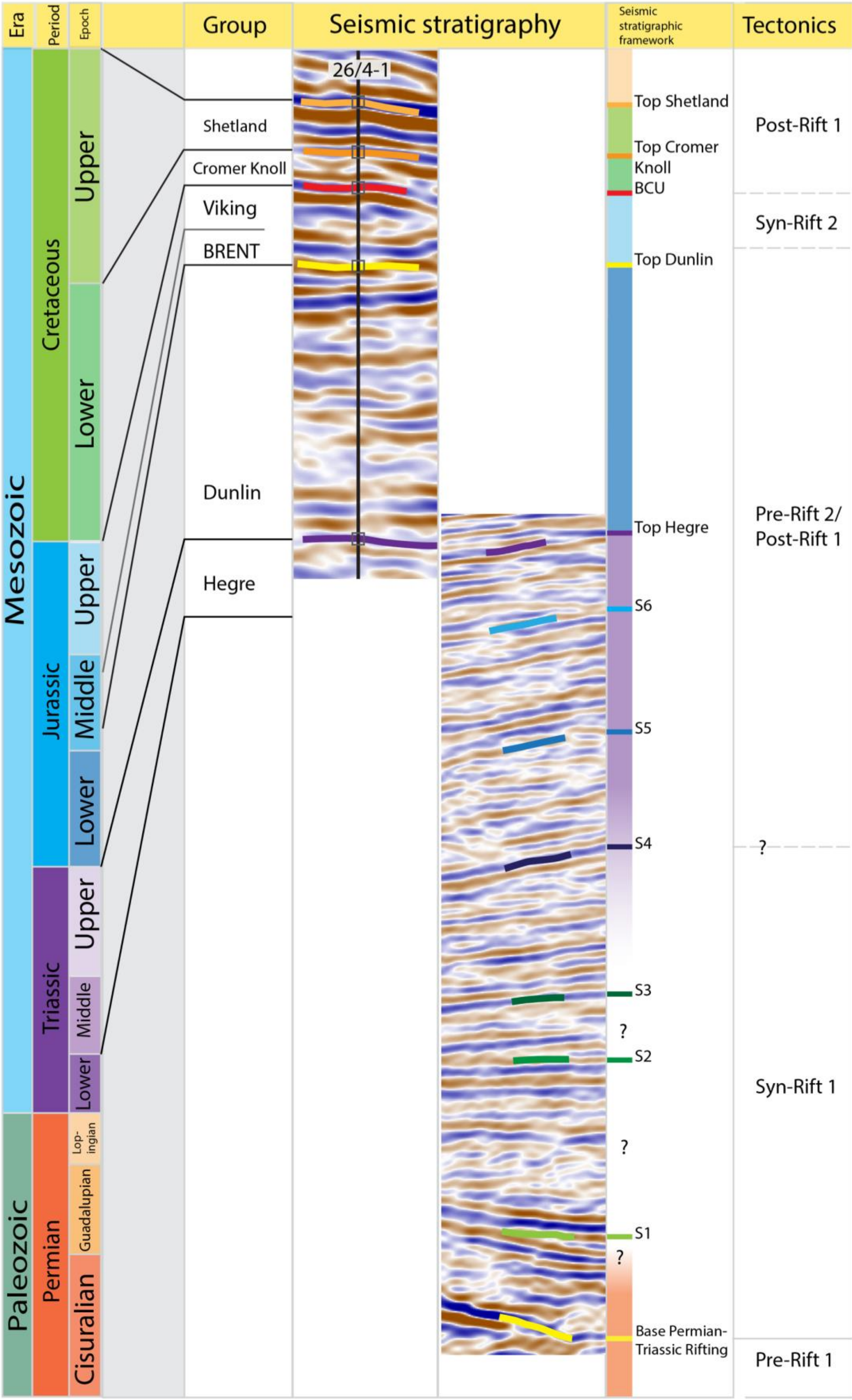


Fig. 3. 3. Stratigraphic column for the northern North Sea with interpreted horizons marked. Well ties from the intersecting well 26/4-1 are marked with black boxes. The horizon is linked with ages and the tectonics phases where possible and the tectonic settings are indicated on the right-hand side.

A number of marker horizons were seeded from well ties (Fig. 3.3) and interpreted in addition to the seabed, Nordland GP. These horizons are presented in chapter 4 with their seismic facies linked to interpretation (Fig. 4.2). The horizon from shallow to deep are as follows; Nordland GP, Shetland GP, Cromer Knoll GP, Base Cretaceous Unconformity (BCU), Hegre GP, Dunlin GP and Rotliegend GP. These horizons have been mapped in the northern North Sea with various extents. The reflections are of sufficient continuity to map the horizons over a large area. The horizons Base Permian-Triassic Rifting (Base PT) and Top Hegre have been imported from Dr. Hamed Fazli Khani's project. The continuation of reflections and the placement of the wells control the possible extent of the surfaces.

19 horizons have been mapped within the Permian-Triassic interval in the Stord basin. This area does not have wells penetrating these 19 horizons. Therefor the horizons do not have well tie information and their ages are not constrained very well. The reflections are chosen by looking at stratigraphic features seen in the seismic, as well as the strength and continuity of the reflections.

The extent of each horizon varies throughout the basin. Some horizons seeded at different fault blocks ends up overlapping. These horizons were merged into one horizon interpretation. Surfaces were made of the horizons, which were later used to make two-way-time thickness maps. The shallower surfaces of the post rift phase have larger extent. Horizons that do not cover the whole basin study area are not shown here, as the isolated horizons do not have an absolute age and the evolution of the fault block at that level cannot be compared to that of other fault blocks. The six Permian-Triassic horizons worked on further in this study are presented together with the Base Permian-Triassic Rifting map in a seismic facies figure in chapter 4 (Fig. 4.3).

3.4.2 Thickness maps

The two-way-time thickness maps, also known as time-thickness maps, are generated by using Petrel software 2013 and they show the spatial thickness variation in a time interval. These maps are used to analyse the stratigraphic patterns in the Stord Basin during RP1 and the following quiescence.

The thickness maps visualize the vertical thickness between two surfaces given in time, which is the same as stratigraphic thickness only if the layer is horizontal. As the maps calculate the vertical thickness, the maps are automatically limited to the overlapping extent of the two surfaces. Twelve time-thickness maps have been generated from the Base Permian-Triassic Rifting surface to the seabed.

Rift settings are characterized by normal faulting which creates accommodation space for sediments. Thickness maps depict the shape and patterns of sedimentary packages, which is highly influenced by the activity of nearby faults (Dawers and Underhill, 2000). For this reason, the thickness maps indicate fault movement through time. Constant or decreasing thickness with horizon age implies post-depositional faulting (Bell et al., 2014). Increasing thickness with horizon age implies syn-sedimentary faulting. Keep in mind that these relations depend on the accommodation space creation rate.

3.4.3 Faults

Fault interpretation in 2D seismic is difficult due to the average 5 km distance between the seismic lines. The low density of lines decreases the certainty of the lateral extent of the faults. These uncertainties are more prominent for smaller faults than the large faults. It is important to also keep in mind the restraints of seismic resolution.

The Base Permian-Triassic Rifting surface (Base PT) depicts all major basement cutting faults and proved more useful when dividing the area into fault blocks than the actual fault interpretation itself. For this reason, the major faults bounding each sub-basin have been drawn atop the Base PT map, which will be presented in the Result chapter.

Faults have been drawn atop the deepest surface, Base Permian-Triassic Rifting surface, controlled by looking through the seismic and fault interpretations for each fault. Only major faults are of interest in this study. This method provides smoother, continuous fault surfaces than the fault-stick interpretations. The fault interpretation has been validated during the dense fault analysis.

Faults grows either by propagation of fault tips through intact rock or by linkage with adjacent fault segments or structures (Cowie, 1998). Accommodation space is created by normal faulting, hence the fault block stratigraphy reflects the nearby fault activity (Dawers and Underhill, 2000).

3.5 Kinematics

This sub-chapter explains how generation of maps and measurements of faults are used to reveal the movement of the faults in question during the Permian-Triassic rifting phase (RP1). These analyses are vital to study the timing and the distribution of throw along a fault.

Footwall and hanging wall cut-offs were selected by fault stick points along fault on the seismic lines. Artificial lines chosen approximately perpendicular to the faults with the projections of the interpretations were used to make a denser plot. Each fault stick point has a x-, y, and z-values, which were exported and processed for the strain analysis. The throw is calculated by subtracting the depths of the hanging wall cut-off of a horizon with the footwall cut-offs' depth. Differential compaction on hanging wall and footwall may cause slight inaccuracy in the measurements (Dawers and Underhill, 2000).

3.5.1 Throw vs. length plots

Throw vs. length (T-x) plots are used to investigate the spatial evolution of faults (Peacock, 1991). The footwall and hanging wall cut-offs of a certain horizon was measured in TWT on seismic sections and plotted against the length of the fault.

Minima in the throw-curve in the T-x plots might indicate a segment boundary. The total displacement is lower in the area where the two fault tips meet and link up. A sudden high-gradient drop in the curve could indicate that the displacement is taken up a branching faults (Peacock, 1991). In general the maximum displacement is located in the centre of the fault and decreases towards the fault tips (Fossen, 2010b). Asymmetry of the throw-curve in the T-x plot combined with high displacement at a segment boundary, indicates *en echelon* evolution of the faults (Dawers and Underhill, 2000).

3.5.2 Equations

The following equations have been used on the measured cut-offs to calculate the distance (Eq. 3.1) and throw (Eq. 3.2) to set up the T-x plots. Equations 3.2 and 3.3 have been used to make the 2D throw and heave maps, respectively.

Eq. 3.1. $Distance\ along\ fault = \sqrt{FWx_2 - FWx_1)^2 + (FWy_2 - FWy_1)^2} + Dist$

Eq. 3.2. $Throw\ along\ fault = HWz - FWz$

Eq. 3.3. $Heave\ along\ fault = \sqrt{(FWx - HWx)^2 + (FWy - HWy)^2}$

Eq. 3.4. $Stretching = \frac{l_1}{l_0}$

Each footwall cut-off (FW) and hanging wall cut-off (HW) have x-, y- and z-values. The minor caps indicate which of the values is given. l_0 is the initial, pre-rifting length and l_1 is the length after a stage of stretching.

3.6 Restoration and stretching

A schematic image with interpreted horizons, based on a seismic cross-section, was used in Adobe Illustrator to do the restoration. The figure was sheared until the uppermost horizon was as close to horizontal as possible, as it would have been during deposition. This is the first step in the restoration. The top horizon was then removed and the process repeated with the next horizon. This was repeated until the basement (Base PT) was restored to pre-rift setting. Each step of the restoration was used to calculate the stretching in each interval by using Eq. 3.4. The restoration was conducted with regards to shear strain, while compaction, subsidence and isostasy was neglected.

4. Results

The results obtained through working with the seismic will be presented in the following sub-chapters to provide an overview of the data recovered about the Stord Basin.

4.1 Horizons

This section describes the interpreted horizons in the study by means of cross sections and time-structure maps. Fig. 4.1 shows a seismic line (NSR09-41153) transecting the Stord Basin with and without interpretations.The interpreted horizons are listed in stratigraphic order in Figures 4.2 and 4.3, together with their characteristics and examples of seismic expression. All horizon interpretations have been carefully correlated throughout the study area.

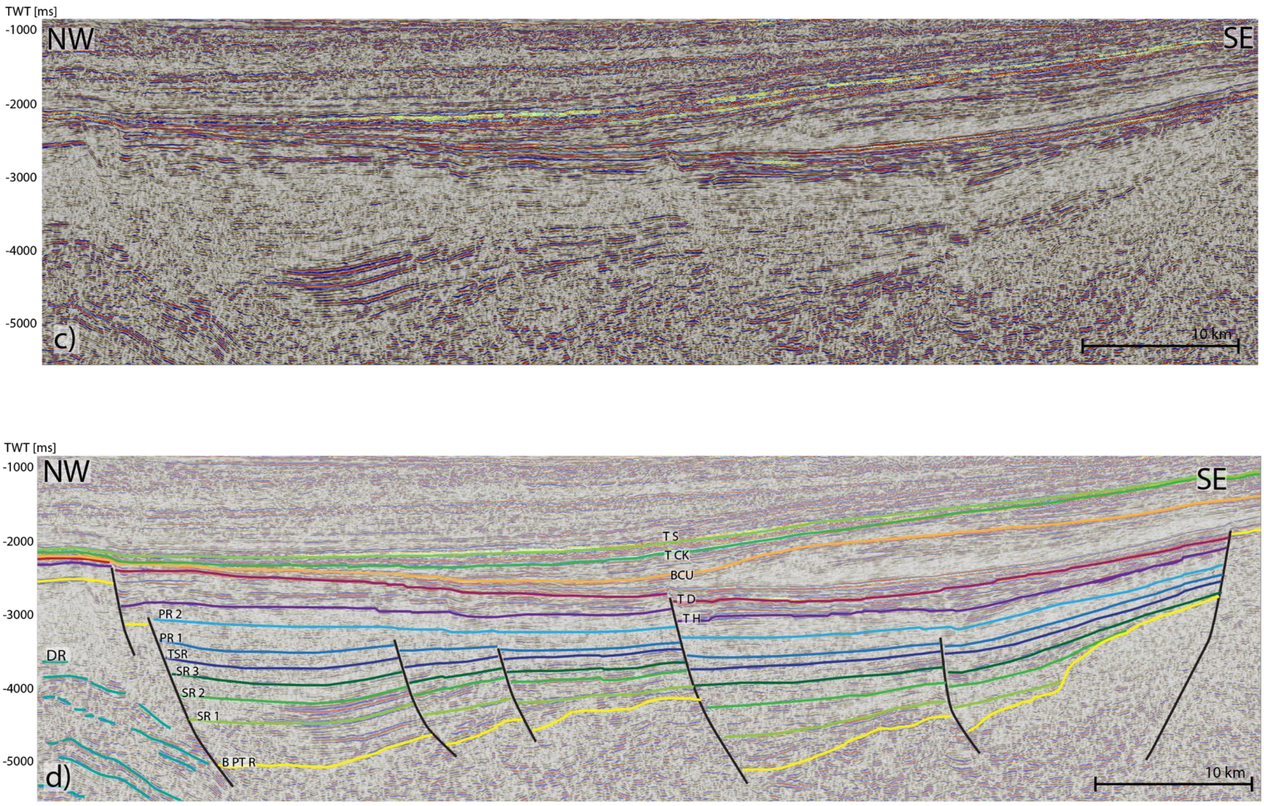


Fig. 4. 1. a) Uninterpreted and b) interpreted seismic line (NSR09-41153) traversing the Stord Basin in an NW-SE direction. a) shows a miniature of the study area, bottom right, with the seismic line marked with a red line. The interpreted horizons are marked with abbreviations: Base Permian-Triassic rifting surface (B PT R), Surface 1 through Surface 6 (S1-S6), Top Hegre Gr (TH), Top Dunlin Gr (TD), Base Cretaceous Unconformity (BCU), Top Cromer Knoll (TCK) and Top Shetland (TS). Utsira East Fault Complex 2 (UFC2), Fault 3 (F3), Fault 4 (F4) and Øygarden Fault Complex 2 (ØFC2) are also marked. High Amplitude Reflections (HAR) are lined out in the UFC2 footwall, representing the Utsira Shear Zone.

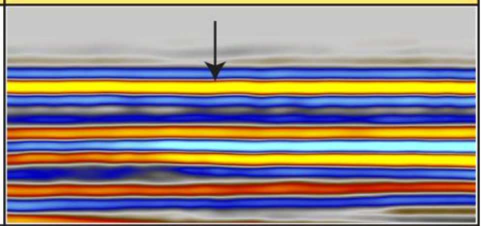
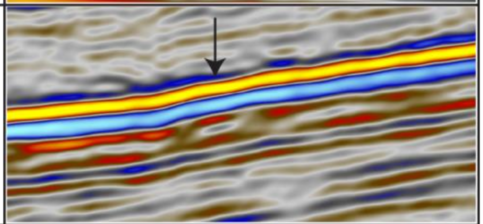
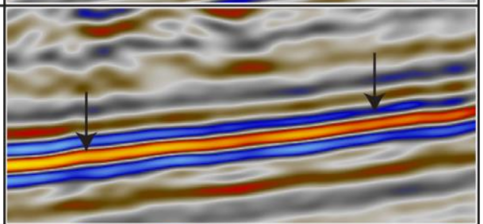
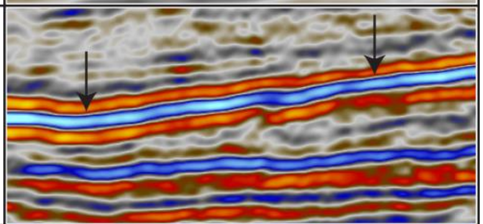
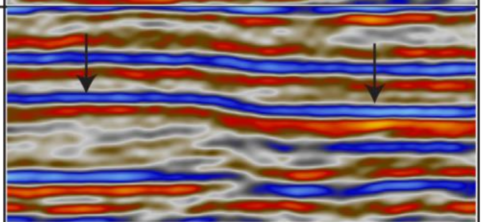
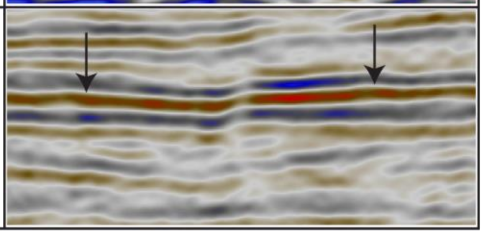
Era	Period	Reflector	Phase	Characteristics	Example
Cenozoic	Quater-nary / Neogene / Paleo-gene	Top Nordland Gr/Seabed	Positive amplitude (peak)	High amplitude, continuous, increase in acoustic impedence.	
Mesozoic	Cretaceous	Top Shetland Gr (Well tie)	Positive amplitude (peak)	High amplitude, continuous.	
		Top Cromer Knoll Gr (Well tie)	Positive amplitude (peak)	High amplitude, continuous, increase in acoustic impedence.	
	Jurassic	Bace Cretaceous Unconformity (Well Tie)	Negative amplitude (trough)	Medium to high amplitude, continuous.	
		Top Dunlin Gr (Well tie)	Negative amplitude (trough)	Medium to high amplitude, continuity.	
	Triassic	Top Hegre Gr (Well Tie)	Positive amplitude (peak)	Medium to high amplitude moderate, continuous.	

Fig. 4. 2. This figure shows the seismic facies of the horizons Top Nordland Gr, Top Shetland Gr, Top Cromer Knoll Gr, Base Cretaceous Unconformity, Top Dunlin Gr and Top Hegre Gr. The interpreted phase, characteristics and examples of the seismic facies is listed and shown in pictures. The chronological chart on the left hand side ties the ages of the interpreted horizons.

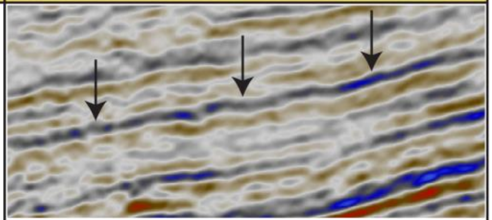
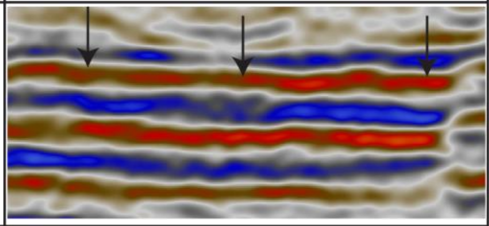
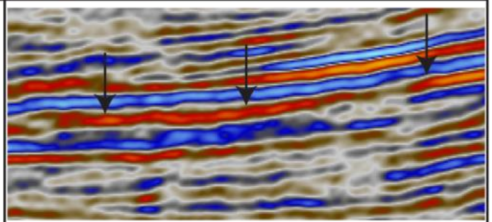
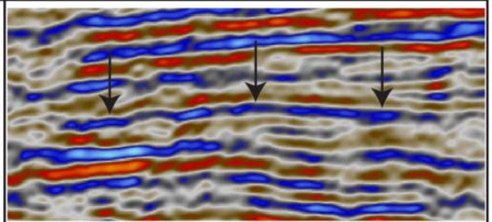
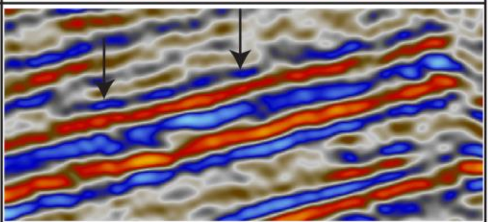
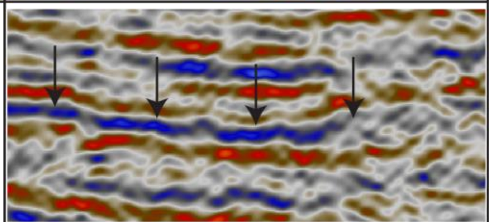
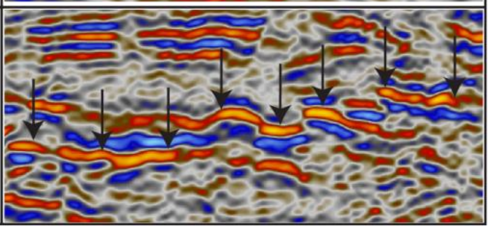
Period	Reflector/age	Phase	Characteristics	Example
Triassic	Surface 6	Negative amplitude (trough)	High amplitude, continuous.	
	Surface 5	Positive amplitude (peak)	Moderate to high amplitude, continuous.	
?	Surface 4	Positive amplitude (peak)	High amplitude, continuous.	
	Surface 3	Negative amplitude (trough)	Weak to high amplitude, various continuity.	
?	Surface 2	Negative amplitude (trough)	Medium amplitude, various continuity.	
?	Surface 1	Negative and positive amplitude (peak and trough)	Week to medium amplitude, moderate continuity, two merged surfaces.	
	Base Permian-Triassic Rifting	Positive amplitude (peak)	Medium to high amplitude, discontinuous.	

Fig. 4. 3. This figure shows the seismic facies of the Surface 1-6 and the Base Permian-Triassic rifting surface. The interpreted phase, characteristics and examples of the seismic facies is listed and shown in pictures. The chronological chart on the left hand side indicates the ages of the interpreted horizons.

4.1.1 Permian-Triassic succession

In this sub-chapter, the structural maps of the Permian-Triassic will be described as a part of depicting the tectono-stratigraphic evolution of the Stord Basin. The following structural maps have not been penetrated by wells, hence their absolute ages have not been determined, but as they lay beneath Top Hegre of the Upper Triassic there is a relative age constrain.

Base Permian-Triassic rifting surface

This surface represents the top of the acoustic basement and has been tested by several wells in the eastern margin of Horda Platform and Utsira High (Fazli Khani, In prep). Away from these wells, the interpretation of this surface is based on the seismic characteristic of basement rocks observed at the location of these wells. The surface separates pre-Permian crystalline rocks from the overlaying metasedimentary sequence tied to the Permian-Triassic rifting phase in the deeper parts of the Stord Basin. Along margins and structural highs, like the Utsira High, the Base Permian-Triassic rifting surface (Base PT) represents the top acoustic basement (Fig. 4.1). This study is focused on the Permian-Triassic rifting phase in the Stord Basin, i.e. the packages above the Base PT surface. Base PT marks the top of the Permian-Triassic pre-rift succession.

Major faults of interest are marked on the Base PT map and will be referred to while describing all the structural maps. The faults themselves will be more thoroughly described later, where length-throw plots also will be presented.

The Stord Basin (SB) is a 190 km long, N-S going rift basin between the Utsira High and the Stavanger Platform, offshore the west coast of Norway (Fig. 4.4). The basin is about 35 km wide in the Northern SB where the F1 bounds the basin to the west, forming a deep half graben. The Base PT shallows to the east where the Øygarden Fault Complex (ØFC) forms a smaller half graben before it shallows to the Stavanger Platform. In the Central SB the bounding faults are mainly trending NNE-SSW (Fig. 4.4). The width of the central basin from north to south goes from 65 km to 80 km, then narrows to 60 km. There are two west-dipping, intra-basin faults in the NE and one east-dipping, intra-basin fault in the central part, all displacing the Base PT to larger depths in their footwalls. The basin bounding faults in the Southern SB are at 60 km distance apart in the north and narrows to about 30 km before terminating against the Åsta Graben (Fig. 4.4). The Base PT shallows distinctly to the south in this area. The western boundary of the Stord Basin has a NW-SE trend and the eastern boundary goes perpendicular to this with a NE-SW trend and consists of bent fault segments. One east-dipping fault is located in the centre.

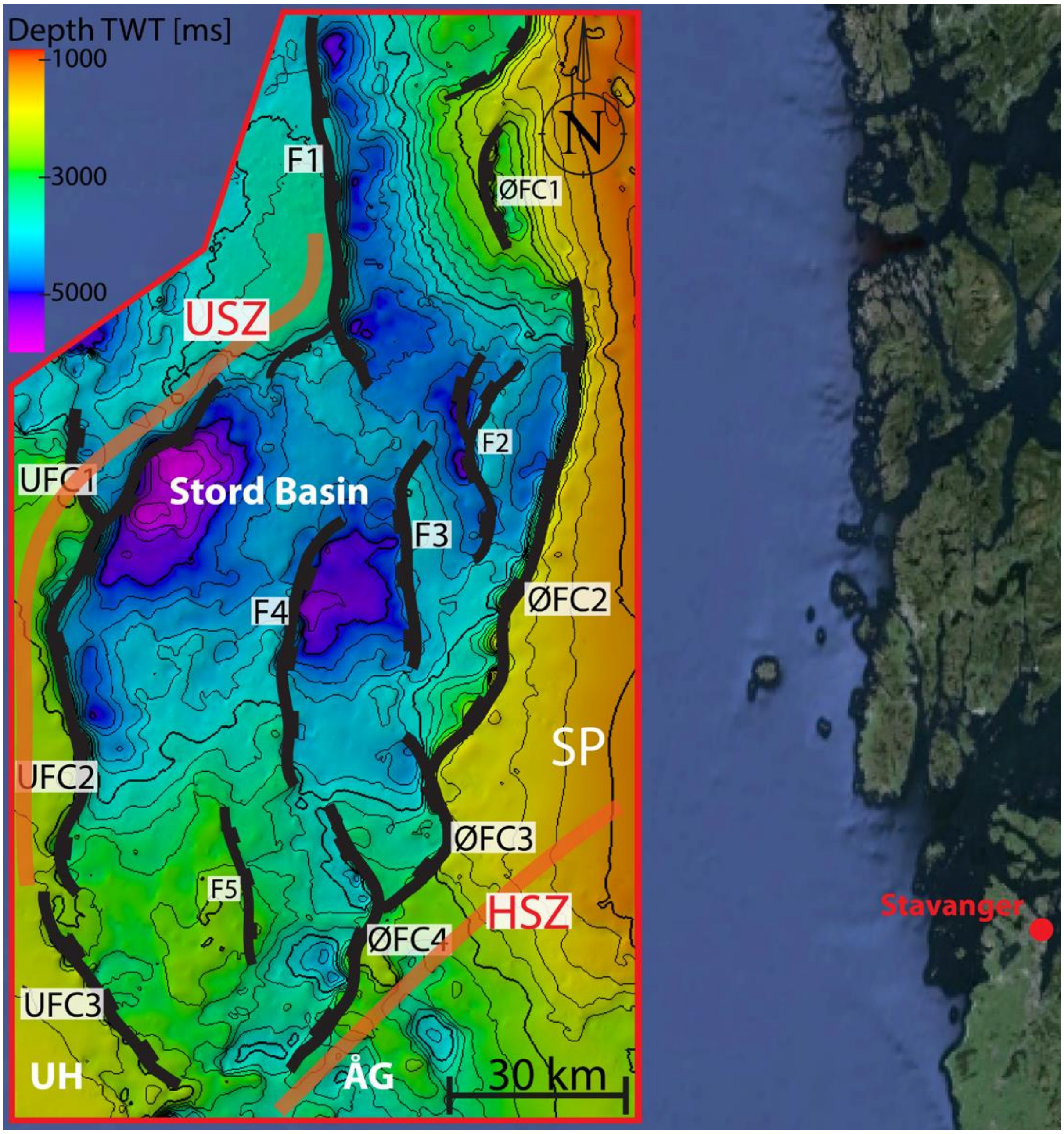


Fig. 4. 4. Structural map of the Base Permian-Triassic Rifting surface (Base PT) in the Stord Basin with major faults and structures labelled. Onshore Norway and Stavanger are displayed to show the location of the study area, which in turn are divided into the northern, central and southern Stord Basin (SB). The three faults of the Utsira Fault Complex are labelled UFC1-3, the four faults of the Øygarden Fault Complex are labelled ØFC 1-4 and the remaining faults are labelled F1-F5. The Utsira High (UH) is located west in the study area, the Åsta Graben (ÅG) in the south and the Stavanger Platform in the east. The Utsira Shear Zone (USZ) and Hardangerfjord Shear Zone (HSZ) are marked with thick, orange lines. The depths of the Base PT are colour coded in the legend at the top left.

Surface 1

Surface 1 covers the Stord Basin between the Utsira High and the Stavanger Platform. It was seeded in the Øygarden Fault Complex 2 (ØFC2) hanging wall (Fig. 4.5). Here, the interpretation was chosen at a strong signal covering a more transparent package, with increasing thickness towards the faults. The package below Surface 1 has a discontinuous and hummocky expression. The Surface 1 map has structural lows in the hanging walls of the faults (Fig. 4.6a). For F1-4 and UFC2 the Surface 1 reaches 5000 ms depths. All structural lows are restrained to fault proximities, i.e. they are located in the hanging walls in the areas closest to the faults. Comparing to Base PT, Surface 1 holds the general trend of the Base PT surface, but with lower reliefs and smoother appearances, a natural effect of the sediment infill. Surface 1 is interpreted to be a syn-tectonic deposit and is hence renamed Syn-rift horizon 1.

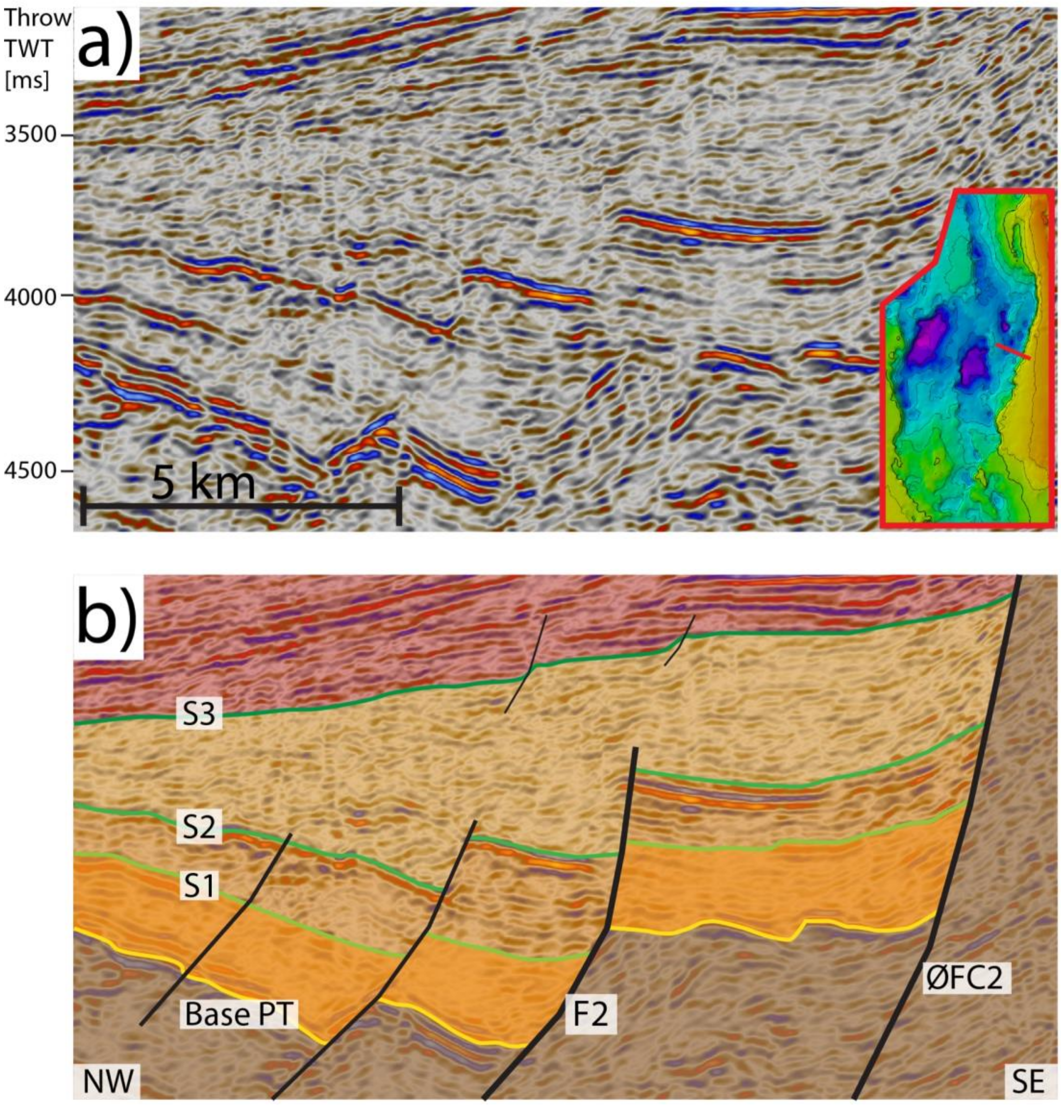


Fig. 4. 5. Close-up of a) uninterpreted and b) interpreted cross-section (NSR06-31158) of the Øygarden Fault Complex 2 (ØFC2) and intra-basin Fault 2 (F2). Surface 1 (S1), Surface 2 (S2) and Surface 3 (S3) are marked and the packages between them differentiated by colour. The location of the seismic line is indicated in the stamp in a), which shows the study area and a red line at the location of this close-up.

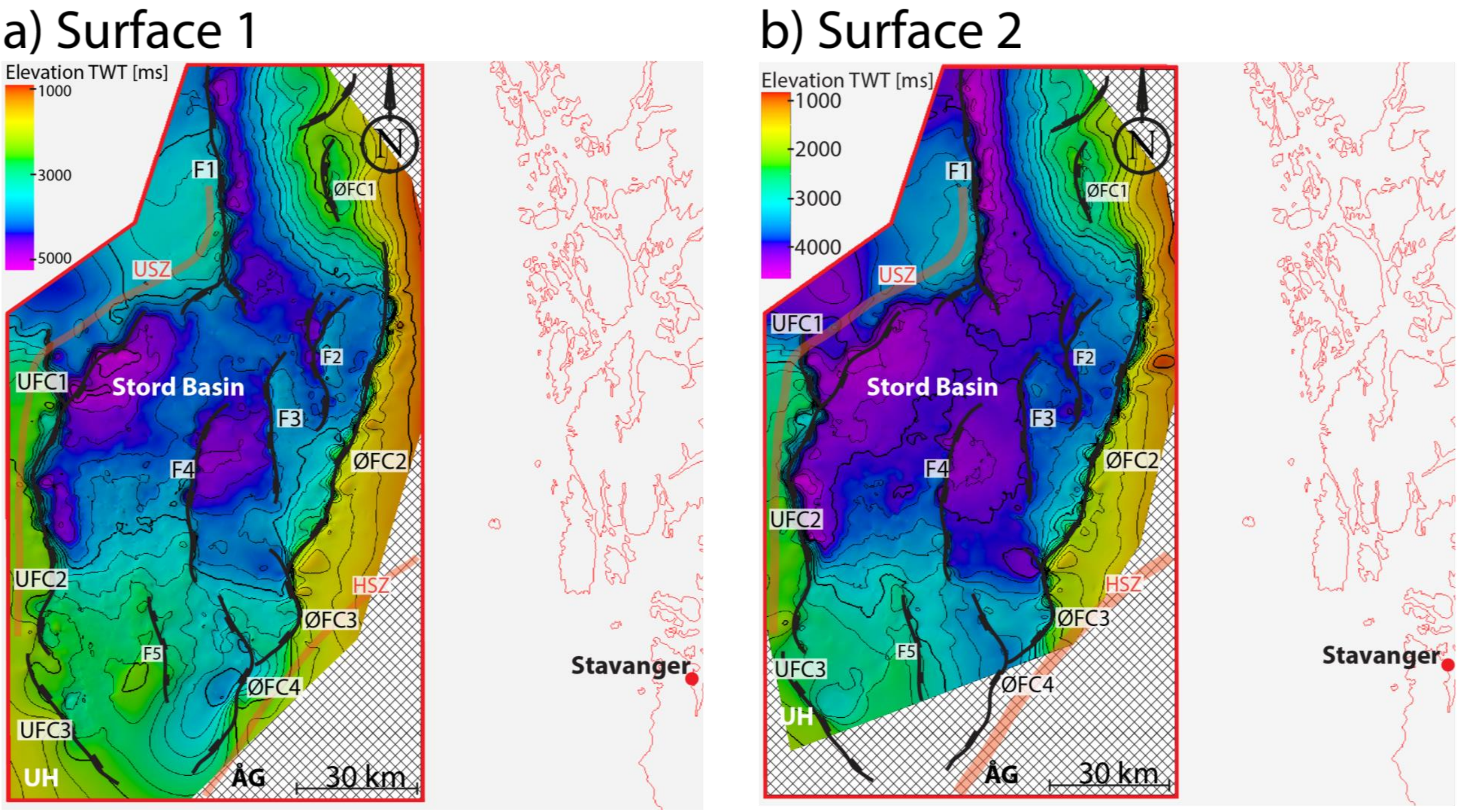


Fig. 4. 6. Structural Two Way Time (TWT) maps of the a) Surface 1 and b) Surface 2 in the study area. Utsira High (UH) lays to the east and Åsta Graben (ÅG) to the south. The three faults of the Utsira East Fault Complex are labelled UFC1-3, the four faults of the Øygarden Fault Complex are labelled ØFC 1-4 and the remaining faults are labelled F1-5 from north to south. The Utsira Shear Zone (USZ) and Hardangerfjord Shear Zone (HSZ) are marked in orange, transaprent lines. Colour scales are found in top left corners and the Norwegian coast line is shown in the east. a) Surface 1 and b) Surface 2 are not found in the box patterned area.

Surface 2

Surface 2 is interpreted on a medium amplitude trough with various continuity (Fig. 4.3). The surface was first interpreted in the ØFC2 hanging wall's middle section. The package below Surface 2 has week, discontinuous reflections in most areas and some areas of layered packaging (Fig. 4.5). Some of the seismic lines depict it with clearer, stronger layering, but still with discontinuous reflections and transparent areas. The package beneath Surface 2 has increasing thickness towards faults (Fig. 4.5). The depth of the surface reaches almost 5000 ms (Fig. 4.6b). Surface 2 holds resemblance to the S1 surface, but the structural lows in Surface 2 are extending further into the basin. Surface 2 is also interpreted to be a syn-rift deposit and is renamed Syn-rift horizon 2.

Surface 3

Surface 3 was interpreted on a weak to moderately strong signal (trough) with moderate to good continuity (Fig. 4.3). It separates two packages of different seismic appearance (Fig. 4.5). The underlying package is portrayed by a poorly structured seismic image while the overlaying package shows a series of parallel reflections. Surface 3 displays structural lows exceeding 4000 ms in connection with the F1-F4, UFC1-2 and the linkage area between ØFC2 and ØFC3 (Fig. 4.7a). Surface 3 follows the same trends as Surface 2 at a shallower level and is interpreted as Syn-rift horizon 3.

Surface 4

In the seismic image, Surface 4 shows the base of a layered package of more or less even thickness in the hanging wall of the ØFC2 (Fig. 4.5). The package above is layered and shows slight thickening towards the UFC2 (Fig. 4.8). The package below Surface 4 shows thickening against the faults in both areas (Fig. 4.2 and Fig 4.8). Surface 4 shallows towards the eastern boarders and to the south (Fig. 4.7b). It shows minor to no displacement along the intra-basin faults F2, F3, F4, F5 and ØFC1. The horizon has minor offsets on the basin bounding faults ØFC2, ØFC3, ØFC4, UFC1, UFC2 and UFC3, as well as the F1 fault. Surface 4 has a plane surface of 3500 ms depth in the middle of the Stord Basin reaching the UFC1 and UFC2 faults, as well as along F1. It shallows towards the southern end of the basin. It has been eroded on surrounding footwalls and has been interpreted on top of the Base PT on the footwalls. Surface 4 is interpreted to encompass the last clearly defined syn-rift package in the Stord Basin, which will be further explored in the discussion (Chapter 5). Surface 4 is renamed Top Syn Rift.

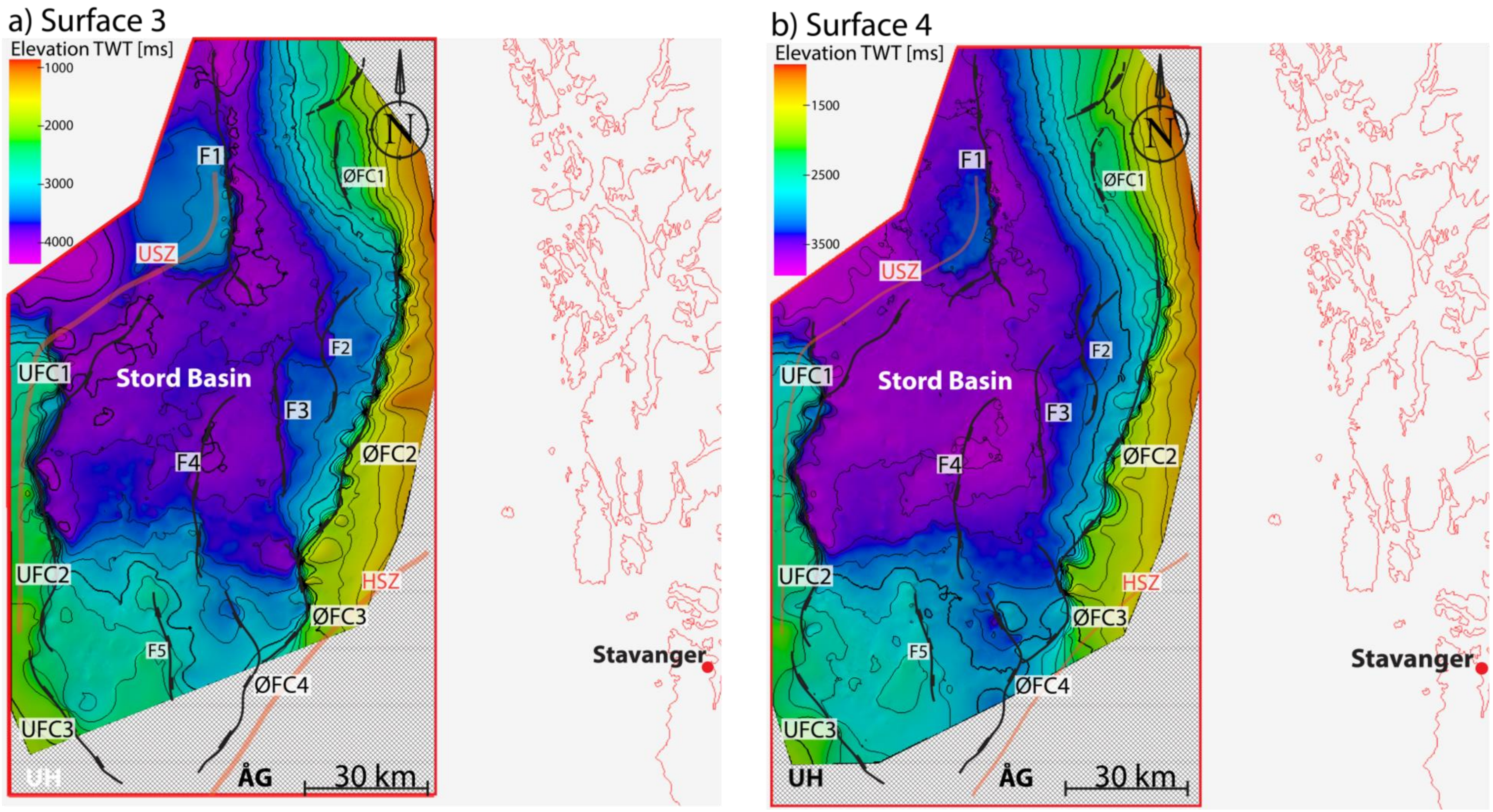


Fig. 4. 7. Structure TWT time maps of a) Surface 3 and b) Surface 4 with the Norwegian coastline displayed. Both maps have the Utsira High (UH) and Åsta Graben (ÅG) marked. The three faults of the Utsira East Fault Complex are labelled UFC 1-3, the four faults of the Øygarden Fault Complex is labelled ØFC 1-4 and the remaining faults are numbered F1-5 from north to south. The Utsira Shear Zone (USZ) and the Hardangerfjord Shear Zone (HSZ) are marked as transparent, orange lines.

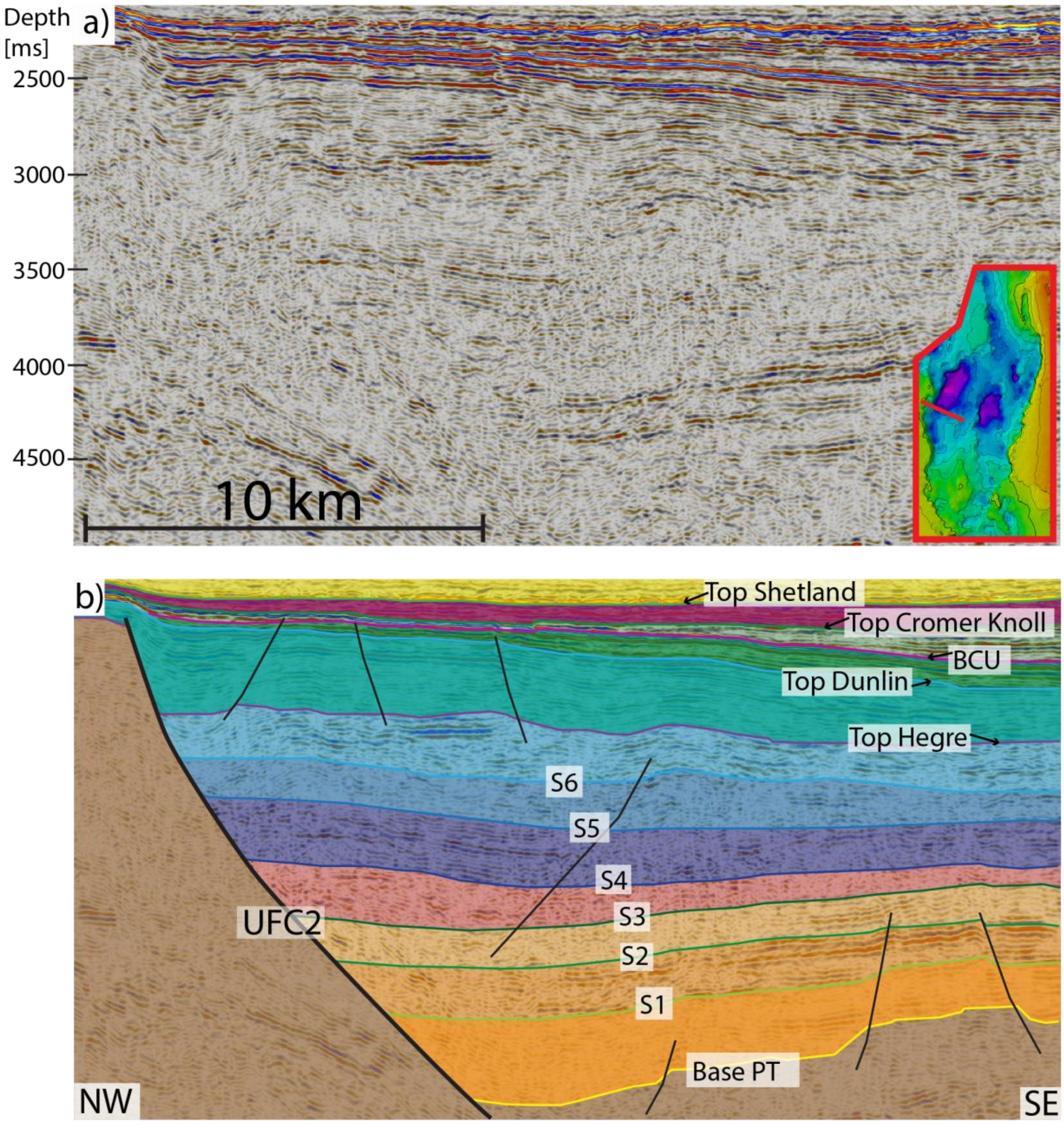


Fig. 4. 8. a) Uninterpreted and b) interpreted seismic section (NSR06-11152) transecting the Utsira East Fault Complex 2 (UFC2). Surface 1-6 are labelled 1-6. Deep reflections are seen in the footwall.

Surface 5

Surface 5 is interpreted on a moderate to high amplitude signal with moderate to high continuity (Fig. 4.3). The underlying package is clearly layered and has even thickness in the ØFC2 hanging wall (Fig. 4.8). The surface is gradually deeper from ØFC2 and ØFC3 into the basin (Fig. 4.9a). Surface 5 shallows rapidly towards the east and south, and more gradually towards the north and west. There are structural lows in front of UFC1, southern and central parts of UFC2, UFC3, ØFC4, the ØFC3 and ØFC2 linking point and in front of F1 (Fig. 4.9a). Surface 5 encompasses a fairly tabular package and is interpreted to be a post-rift deformation, hence the renaming to Post-rift horizon 1.

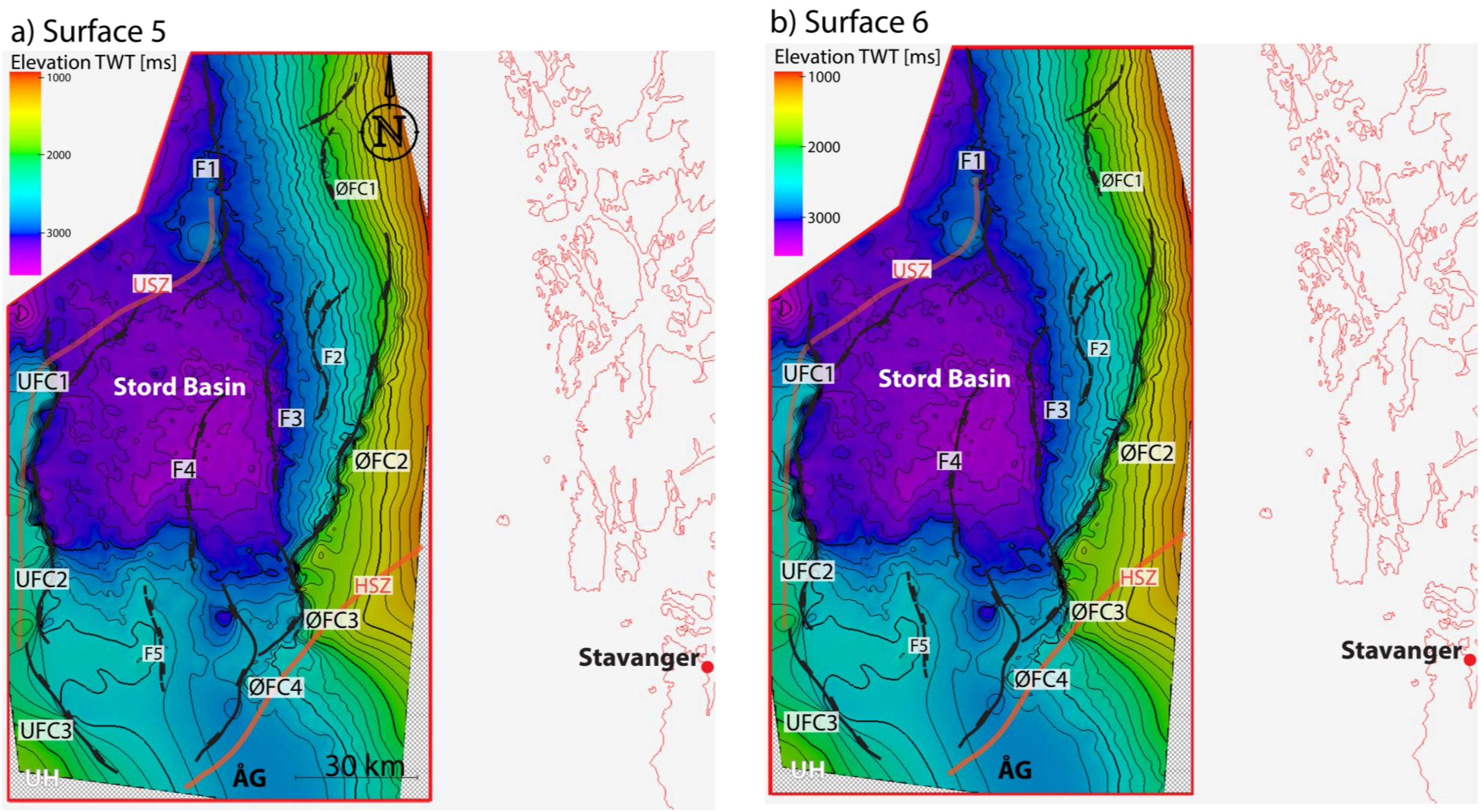


Fig. 4. 9. Structural TWT maps of a) Surface 5 and b) Surface 6 in relations to the Norwegian coastline. The structural elements Utsira High and Åsta Graben are labelled UH and ÅG, respectively. The three faults of the Utsira East Fault Complex are labelled UFC 1-3, the four faults of the Øygarden Fault complex are labelled ØFC 1-4 and the remaining intra-basin faults are labelled F1-5 from north to south. The Utsira Shear Zone (USZ) and the Hardangerfjord Shear Zone (HSZ) are marked in orange lines atop the map.

Surface 6

Surface 6 has been extended throughout the study area with high confidence, as a result of a strong and continuous reflections in most areas (Fig. 4.3). The surface is undulating in some areas, but encompasses a more or less tabular package (Fig. 4.5 and Fig. 4.8). The surface exceeds 3000 ms in the centre of the Stord Basin (Fig. 4.9b). From the central structural low, Surface 6 shallows towards the margins like the Surface 5 surface below, but with a slightly gentler gradient. The F1 footwall has increasing depths to the north. Structural lows can also be found in front of Utsira East Fault Complex, northern ØFC3, northern ØFC4 and ØFC2. This interpreted to be another post-rift deposit, so Surface 6 is renamed Post-rift horizon 2.

Summary of interpretations of Base PT through S6 surfaces

The Base PT surface represents the acoustic basement and is the surface of the Stord Basin area before rifting initiated in early-late Permian (Fig. 4.4). Syn-rift horizon 1 marks the top of a set of sedimentary wedges with increasing thicknesses towards the faults, covering the Stord Basin (Fig. 4.5 and Fig. 4.8). These wedges are interpreted as the results of syn-sedimentary deposition. The transparent appearance of this package combined with its restricted extent leads to the interpretation of it being an early rift deposit (Prosser, 1993). Syn-rift horizons 2 and 3 share the same morphology as Syn-rift horizon 1. The Top Syn Rift encompasses the uppermost syn-rift package, which displays increasing thicknesses towards the fault (Fig. 4.5 and Fig. 4.8). The package above Top Syn Rift has even thickness in the eastern Stord Basin, and is of post-rift tectonics. However, the overlying package has a slight thickening towards the western boundary of the Stord Basin (Fig. 4.8). Top Syn Rift and Post-rift horizons 5-6 are structurally lower in the F1 hanging wall than in the F1 footwall. Post-rift horizons 5 and 6 are dividing packages of (more or less) even thicknesses. This determination of the syn-rift and post-rift will be explored further in the discussion, chapter 5.

4.1.2 Triassic to present day succession

Well tied surfaces spanning from the Upper Triassic to the present day seabed are described in this sub-chapter. This younger succession, on top of the Permian-Triassic surfaces described in the previous sub-chapter, have been described in the literature. The seismic facies of the horizons were presented in Fig. 4.2.

Top Hegre Group

The top of the Hegre Group is dated to the Upper Triassic, Norian to early Rhaetian time. It is the top of the Lunde Formation, which consists of fluvial deposits prograding from Fennoscandia and possibly the Shetland Platform. The horizon was picked from multiple well ties, among them well 16/2-11 located on the Utsira High. The horizon is interpreted on a moderate- to high-amplitude peak with good continuation (Fig. 4.2). The interpretation was extended further south and north by extrapolation and well ties. The time structure map limited to the study area shows structural highs at the footwalls of Øygarden Fault Complex (ØFC) and Utsira East Fault Complex (UFC) (Fig. 4.10a). In the Stord Basin, the Top Hegre horizon deepens from the south to the middle and northern parts of the basin. The surface is cut by the Utsira East Fault Complex (ØFC) and the Øygarden Fault Complex (ØFC) 2-4. The cut-offs along these faults have been registered and plotted in the length-throw plots described later in chapter 4.4. No Triassic deposits are found on the ØFC footwalls.

Top Dunlin Group

The top of the Dunlin Group marks the end of Tarocian time, i.e. the top of the Lower Jurassic. The Top Dunlin Group interpretation is seeded from well ties at the Utsira High, for instance well 25/9-1. The seismic trace is a moderate to strong through with good continuation (Fig. 4.2). In the Study area, the surface shows structural highs at the footwalls of UFC and ØFC, similar to the Top Hegre surface (Fig. 4.10b). The Top Dunlin surface shallows to the south in the Stord Basin towards the Hardangerfjord Shear Zone (Fossen et al., 2016, Fazli Khani, In prep).

The Dunlin Group consists of variations of marine deposits and is sub-divided into five formations; Amundsen, Johansen, Burton, Cook and Drake Formations (Halland, 2011). The formations vary from silt and marine mudstone, and marine/marginal marine sandstones. The Top Dunlin surface marks a major marine transgression. In the Southern Viking Graben, Utsira and Stord Basin area, the surface represents the Mid Jurassic Unconformity.

Base Cretaceous Unconformity

The Base Cretaceous Unconformity (BCU) surface marks the beginning of the Cretaceous period and is an unconformity surface separating eroded layers of Jurassic age from Cretaceous layers. The interpretation is seeded in multiple wells, e.g. 25/6-1. The BCU surface has increasing depths going from the shore to the west, before having a minor decrease in depth at the southwest of the study areas (Fig. 4.10c). The early Cretaceous transgression caused the widespread deposition of shale, which is relatively easily identified in seismic and well data. It covers a large area of the northern North Sea, is a common cap rock for Upper Jurassic plays and it marks the end of Late Jurassic rifting phase.

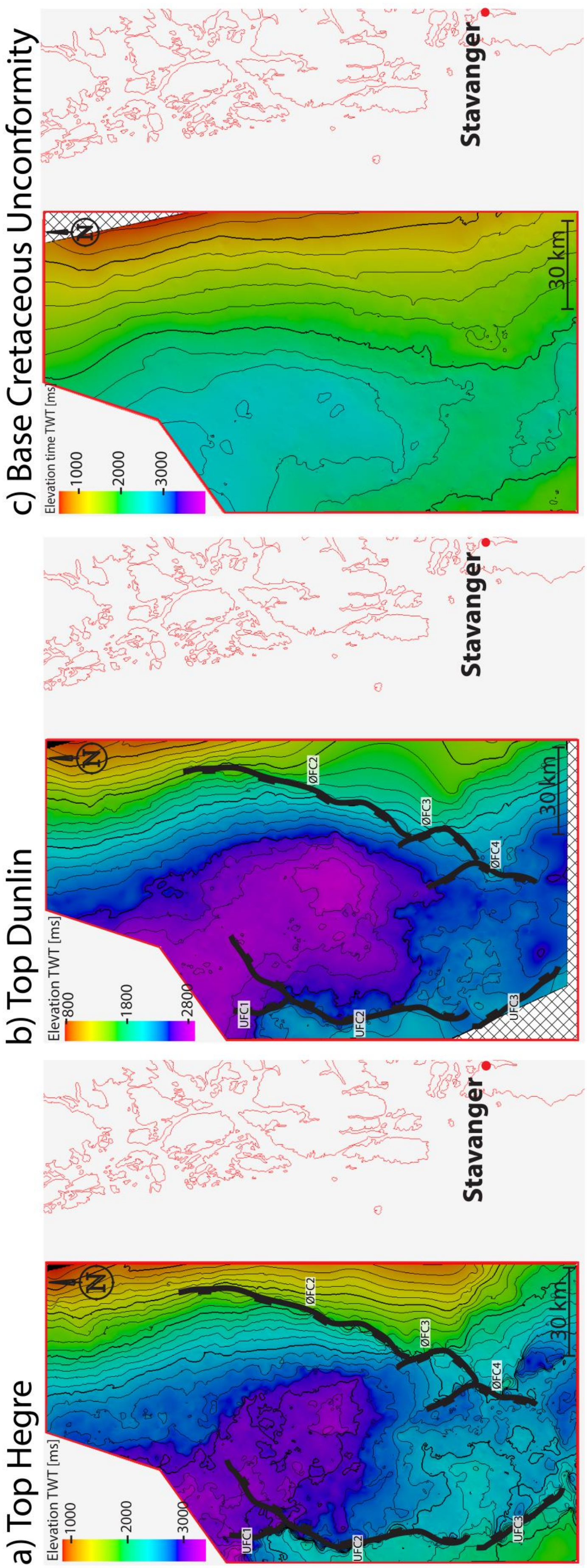


Fig. 4. 10. Structural TWT maps of a) top Hegre Gr, b) Top Dunlin Gr and c) Base Cretaceous Unconformity in relation to the Norwegian coast line. The gridded areas marks areas of erosion or limited extent. For a) and b) the transecting faults of the Utsira East Fault complex are labelled UFC1-3 and the southern three faults of the Øygarden Fault Complex are labelled ØFC 2-4.

Top Cromer Knoll Group

Top Cromer Knoll surface has multiple well ties and was interpreted on a strong peak beneath a strong trough and has good continuity. It has been interpreted from off the coast of Bømlo towards the western border of the Norwegian sector. In general, the Top Cromer Knoll surface has increasing depths moving away from the coast (Fig. 4.11a). The surface is deeper in the Stord Basin and to the northwest towards the Viking Graben. The Cromer Knoll Group ranges from Ryazan to Albian/Early Cenomanian age in the North Sea. It represents the top of the Lower Cretaceous deposits. The Cromer Knoll Group consists of marine sediments with several levels of calcareous material, deposited at low energy, open sea environment.

Top Shetland Group

The Top Shetland surface is interpreted on a strong peak chosen by well ties (Fig. 4.2). The total interpretation stretches from offshore Øygarden south towards the end of the Norwegian sector, but is displayed within the study area (Fig. 4.11b). The surface is shallower near the coast and goes deeper offshore with maximum depths to the northeast, following the trend of Top Cromer Knoll. The Top Shetland surface is structurally deeper in the west of Central Stord Basin. In the North Sea, the Shetland Group ranges from Cenomanian to Danian Age. It is deposited directly atop the Cromer Knoll Group and represents the Upper Cretaceous, and in some areas, the lowermost Paleocene. The Shetland Group was deposited at open sea environment during a transgression (Hancock and Kauffman, 1979).

Top Nordland Group

Top Nordland is the seabed surface. It has a positive, high amplitude, continuous reflection (Fig. 4.2). The structural map shows that the seabed is deeper in the eastern half of the study area (Fig. 4.11c). The surface has values around 400 ms depth in this area. The depth decreases rapidly when going over to the western side of the study area, where the seabed shallows to 150-200 ms.

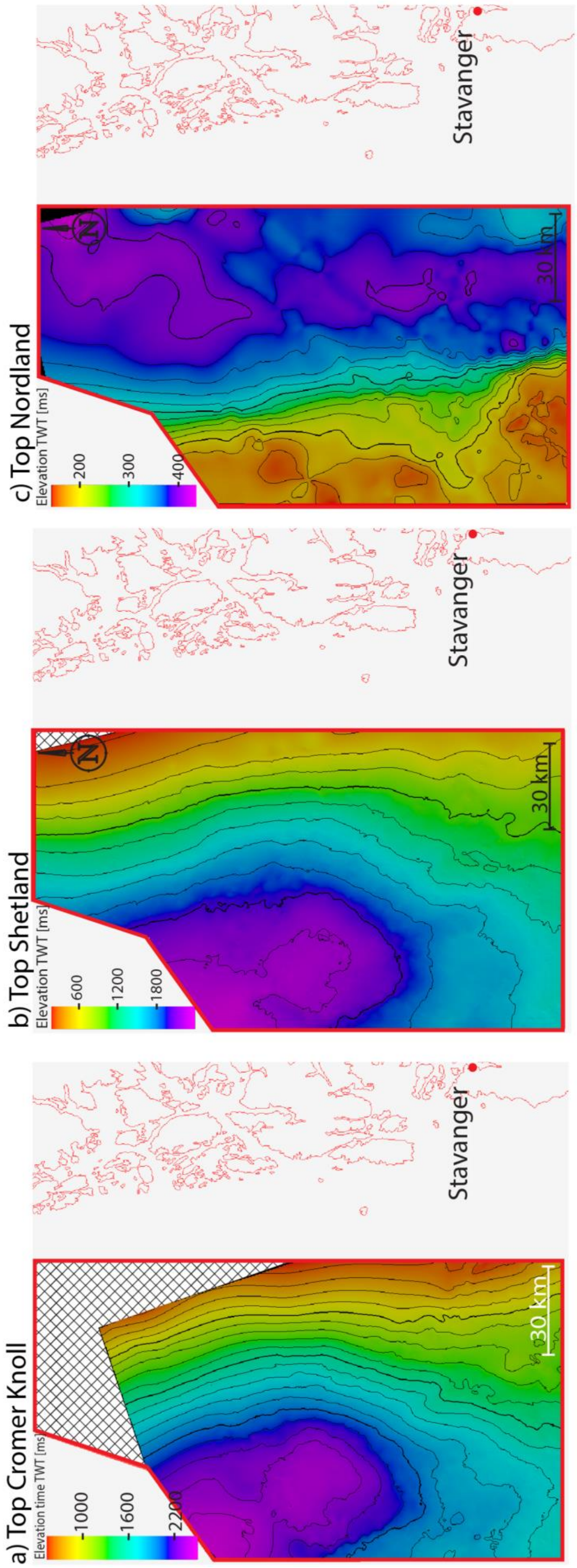


Fig. 4. 11. Structural TWT maps of a) Top Cromer Knoll, b) Top Shetland and c) Top Nordland in relation to the Norwegian coastline. The gridded area shows wehre the horizons are eroded.

4.2 Faults

The Øygarden Fault Complex (ØFC) bounds the Stord Basin to the East and the Utsira East Fault Complex (UFC) bounds it to the west. Both of the ØFC and UFC are curved along strike, but have a N-S main trend. Intra-basin faults divide the Stord basin into several fault blocks, a horst and a couple of grabens. The intra-basin faults have a main N-S trend as well. The northern fault tips of F2, F3 and F4 in the Central Stord Basin curve to the northeast and aligns with an area where the Base PT is elevated.

In the south, the Stord basin terminates towards the Hardangerfjord Shear Zone (HSZ). The Utsira Shear Zone (USZ) boarders the basin in the western and northern parts. Here are some of the key observations that emerged from the seismic interpretation. Faults of interest are displayed in map view (Fig. 4.12) and in profile view (Fig. 4.13). All of the faults presented here are cutting the deep Base Permian-Triassic Rifting surface (Base PT) and together they form the structural framework of the Stord Basin.

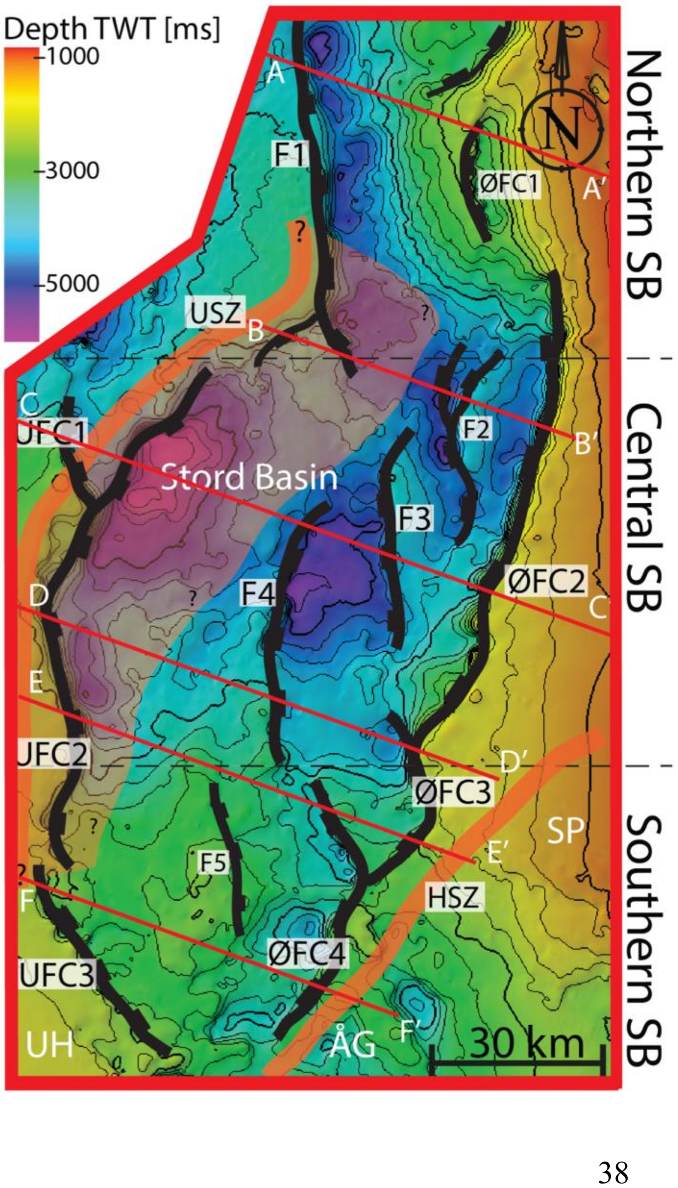


Fig. 4. 12. Base PT map of the study area with the traced Utsira Shear Zone (USZ) marked in transparent orange. The NW-SE red lines represent the location of the seismic sections shown in the next figure; Fig. 13 a-e. Remaining abbreviations are HSZ: Hardanger Shear Zone, UFC1-3: Utsira Fault Complex 1-3, intra-basin faults 1-5: F1-5, and ØFC 1-4: Øygarden Fault Complex 1-4.

A set of high amplitude reflections in an east-dipping tabular zone beneath the UFC, curving along-strike of the F1 south tip. This is interpreted to be a shear zone and has recently been named the Utsira Shear Zone by Fossen et al. (2016) (Fig. 4.13 b-f). The USZ is a long, narrow zone of highly deformed rocks with high densities. Shear zones are typically identified as high amplitude reflections, which are either long linear zones or short subparallel reflections (Brogi et al., 2003). The USZ extends deep in the basement as a low-angle lineament with a dip towards the east to southeast under the Stord Basin. The USZ terminates at depths along the Z-line marked orange in Fig. 4.12. It is interesting to note that the faults in Central Stord Basin, F2, F3 and F4, curve to parallel and terminate towards this Z-line. The study area north of the USZ is a narrow half-graben about 35 km wide, while south of the USZ the basin ranges from 60-80 km width.

The Hardangerfjord Shear Zone (HSZ) is a regional lineament of highly deformed rocks stretching NE-SW, south in the study area (Fig. 4.12). The shear zone has been mapped onshore and continues offshore through the study area and further through the Ling Depression (Fossen and Hurich, 2005). The northern parts of ØFC3 and ØFC4 have N-S trends, while the southern parts curves and aligns with the HSZ more or less. The southern ØFC2, although at a distance from HSZ, is parallel with the shear zone.

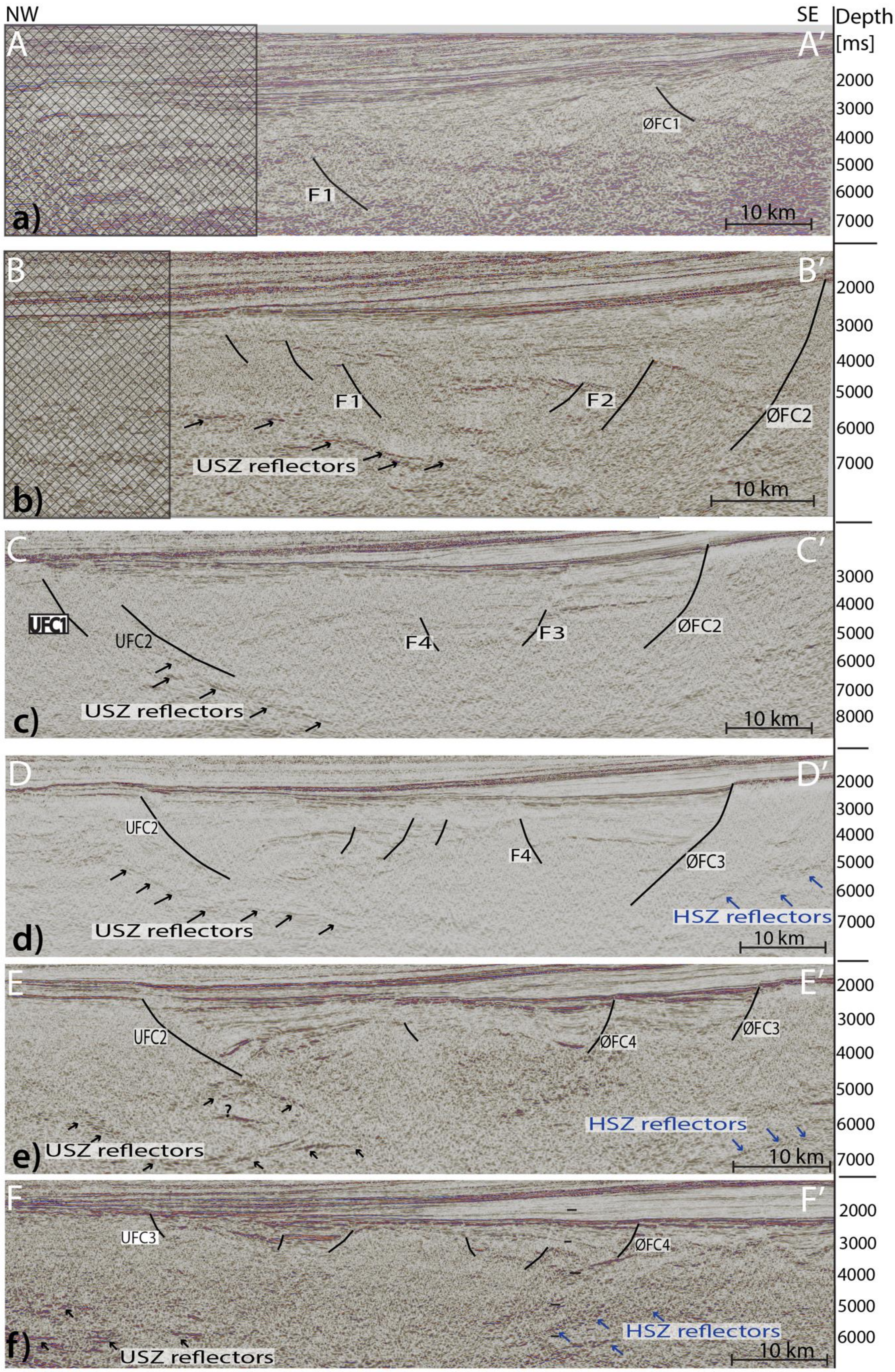


Fig. 4. 13. This figure illustrates NW-SE going seismic lines crossing the Stord Basin in the study area. Major faults and shear zones reflections are marked. The white letters atop each cross section are linked to the cross-sections placement shown in Fig. 4.12. The cross-sections are sorted from north to south from a) through f).

4.3 Fault analysis

Throw-length (T-x) plots are presented in this sub-chapter to investigate the spatial evolution of the faults. The T-x plots have been constructed by using Eq. 3.1 and Eq. 3.2. Footwall erosion on the structural highs surrounding the Stord Basin limits the possibilities of analysing each horizon in the plots. Base PT cut-offs have been plotted for the UFC 1-3, F1, F3, F4 and ØFC 2. For UFC 1-3 and ØFC 2-4 it has also been possible to plot the Top Hegre cut-offs. The 2D data available in this project has a maximum line spacing of 5 km and less in areas where the lines and surveys intersect. The throw measurements are projected along a South-to-North axis, which is the main fault strike direction in the Stord Basin. As the faults have bends in map view, this cause minor discrepancies in the plots.

4.3.1 Øygarden Fault Complex

The eastern boundary of the Stord Basin consists of four faults, which constitute the fault system traditionally called the Øygarden Fault Complex (Faerseth et al., 1995), but also the Øygarden Fault System (Fossen et al., 2016). The throw-length plot covers the ØFC2-4 as they are hard linked and more significant in the evolution of the Stord Basin than the ØFC1. The Øygarden Fault Complex marks the east and southeast boundary of the Stord Basin. Throw values measured along ØFC2-4 at Base PT and Top Hegre are displayed together in Fig. 4.14. The general trend of Base PT is increasing throw northwards until it reaches the ØFC2 maximum at 140 km. Further north the curve decreases and the fault terminates. The throw measurements of Top Hegre exhibit higher values in the south than in the north (Fig. 4.14).

The ØFC4 is divided into two fault segments at Base PT where the curve has a large minimum at about 24 km (Fig. 4.14). This segment boundary is located in the ØFC4's fault bend, where also the ØFC3 approaches the ØFC4. This fault branching corresponds with the sudden drop in the curve at around 24 km. The southern sub-segment of ØFC4 has a distinct peak at 18 km in the middle of the bell shaped curve. The northern ØFC4 sub-segment throw curve decreases gradually into the Stord Basin before it terminates. The Top Hegre throw curve does not extent as far south as the Base PT curve for ØFC4. The Top Hegre curve follows the main trend of the Base PT curve with a minimum at 24-26 km, representing a segment boundary. The southern sub-segment is bell shaped with a maximum at ca 17 km. The northern sub-segment at Top Hegre level differs from the Base PT level with a maximum throw located in the middle, which gradually decrease away from the centre.

The Base PT throw curve for ØFC3 is a low flat at 30-35 km in the south, close to the ØFC4 (Fig. 4.14). The curve has an abrupt increase to a local peak at 40 km. From here, the curve has local minima at 42 km and 48-50 km, separated by a peak. This part of the curve corresponds to the fault bend in ØFC3. The curve continues to increase northwards until it peaks at a flat plateau ca 60-63 km, where the ØFC3 links with ØFC2. The cyclical and similar amplitudes of the peaks and lows from 40-55 km can be artefacts from the data on top of the true trend, due to interpolations between the 2D lines.

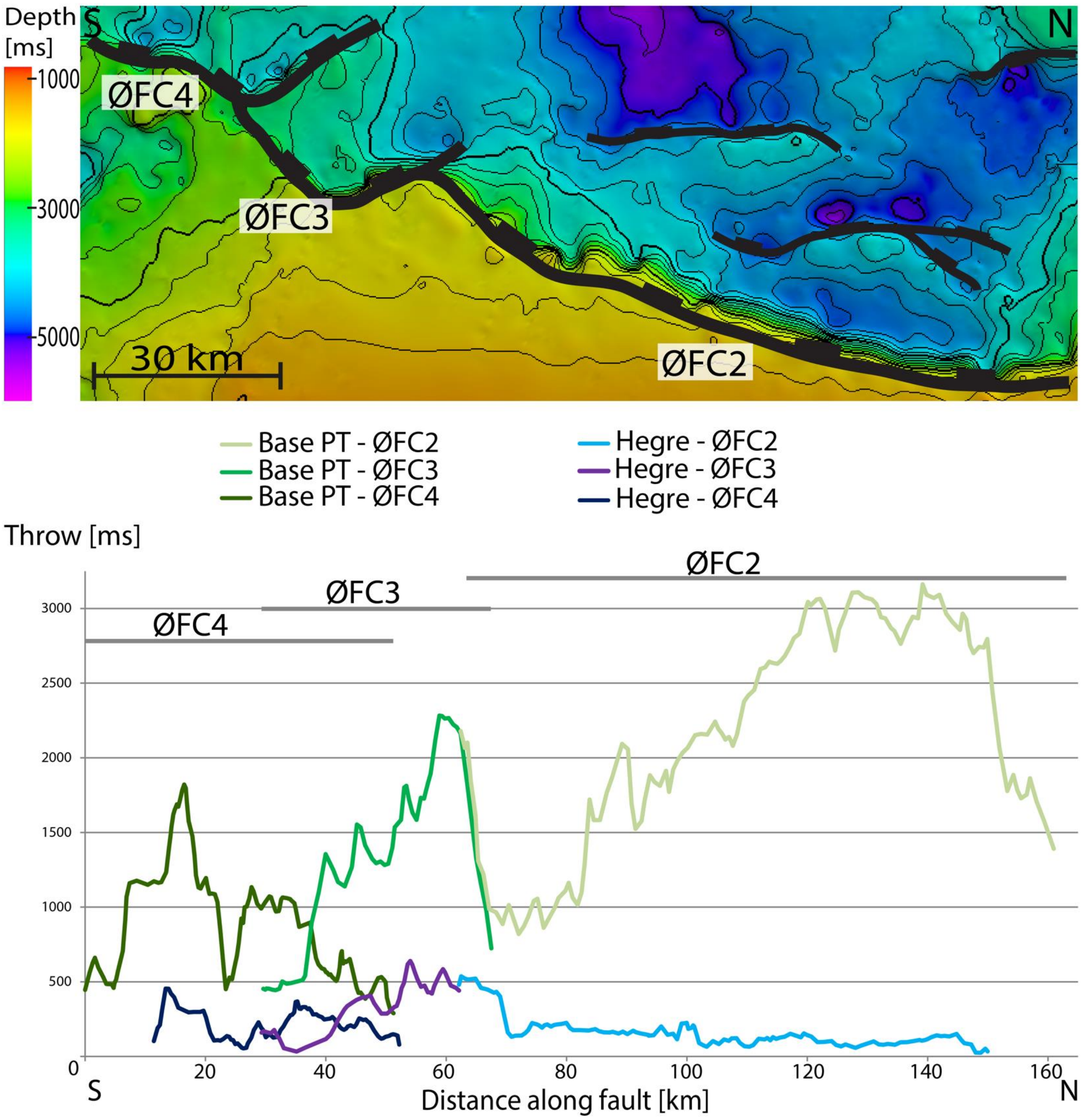


Fig. 4. 14. Length- throw plot showing Base PT and Hegre cut-offs for the three southernmost faults of the Øygarden Fault Complex; ØFC2, ØFC3 and ØFC4. The plotting direction goes from south to north, and the faults overlap in some areas, as shown in map view above the plot. Legend for the throw curves is listed atop the graph.

The ØFC3's splay into the Stord Basin have an abrupt decrease in throw values for the Base PT, which is a typical expression for fault branches in T-x plots. The Top Hegre throw curve reflects the trend of the Base PT along ØFC3. The fault splay into the Stord Basin has not been reactivated in the later inter-rift or Late Jurassic rift phase. The Top Hegre curve has a flat low at 32-40 km and slightly higher values at the south tip (Fig. 4.14). At Top Hegre level, the ØFC3 curve combined with the ØFC2 curve forms one bell shape between 40 km and ca 70 km, showing that they are hard linked and acting as one fault at this level.

As previously mentioned, the Base PT throw curve for ØFC2 is linked with the ØFC3 segment at a peak at ca 62 km (Fig. 4.14). The ØFC2 hits the ØFC3 at a 90º angle, creating a fault bend into the basin. The curve drops steeply from 63 km to 67 km. Further north, the curve has a minor increase in throw up to 83 km, which can be interpreted as a sub-segment of ØFC2. From here, the curve is bell shaped as it rapidly increases to a local maximum at 90 km followed by a local minimum at 92 km, which may be a second sub-segment. Further north, the curve gradually increases until it forms a plateau-shape in the interval 118-150 km with minor undulations before the curve decrease and terminates to the north. This section 92-160 km is interpreted to be the third sub-segment of ØFC2 at Base PT level. The throw maxima are located on the 118-150 km plateau where most of the displacement along the Øygarden Fault Complex is concentrated.

The Top Hegre throw curves have similar, but lower values compared to the Base PT curves for ØFC3 and ØFC4 (Fig. 4.14). This is not the case for ØFC2. The Top Hegre throw curve follows the same trend as the Base PT curve where the ØFC2 and ØFC3 makes up one fault (40-70 km). The ØFC2 throw curve from 70 km to its termination at 150 km has a flat, table shape, which is distinctly different from the nice bell shape seen in the Base PT curve. The long table shape in the Top Hegre curve tells that the ØFC2 accumulated an almost equal amount of throw along the fault by reactivation during either inter-rifting or the Late Jurassic rifting. Differential compaction in an inter-rift period can explain the table shaped curve. The sediment filled hanging wall sags in contrast to the crystalline footwall during inter-rifting. The Top Hegre throw curves for ØFC3 and ØFC4 have bell shapes, which indicate active faulting in the Late Jurassic.

4.3.2 Fault 1

The east-dipping fault F1 bounds the Stord Basin in the north in the study area. The fault forms a large N-S trending half graben. The Base PT cut-offs have been plotted to analyse F1 features (Fig 4.15).

The throw curve gradually increase from south to north until the curve drops at 42 km to a lower level where the curve undulates around 900 ms throw (Fig. 4.15). The F1 is interpreted to consist of two main fault segments. The southern fault segment goes from 0-45 km and the northern segment goes from 45 km to almost 70 km. The southern segment is furthermore subdivided into three minor segments. From 0 km to 13 km the curve increases with minor fluctuations in the curve, which is interpreted to represent the first sub-segment. Continuing north, the curve increase with a high gradient until the overall maximum level from 18-21 km. The large increase is interpreted to be a result of a fault branch to the west of the main F1 fault (Fig. 4.15). The curve has a local minimum at 25 km, which represents a segments boundary, i.e. the end of the second sub-segment, represented by a bell-shaped curve (Fig. 4.15). The third sub-segment has increasing throws from 25-42 km. North of this, the curve falls greatly in the 42-45 km interval, which implies another fault branch taking up parts of the total displacement. The northern main fault segment fluctuates between 700-1100 ms throw (Fig. 4.15). The three peaks and the associated lows between them could represent three sub-segments, but their cyclicality and placement of the 2D seismic lined opens the question of artefacts in this segment. Keeping this in mind, the northern segment is interpreted to be divided into two sub-segments where the segment boundary is located at 52 km.

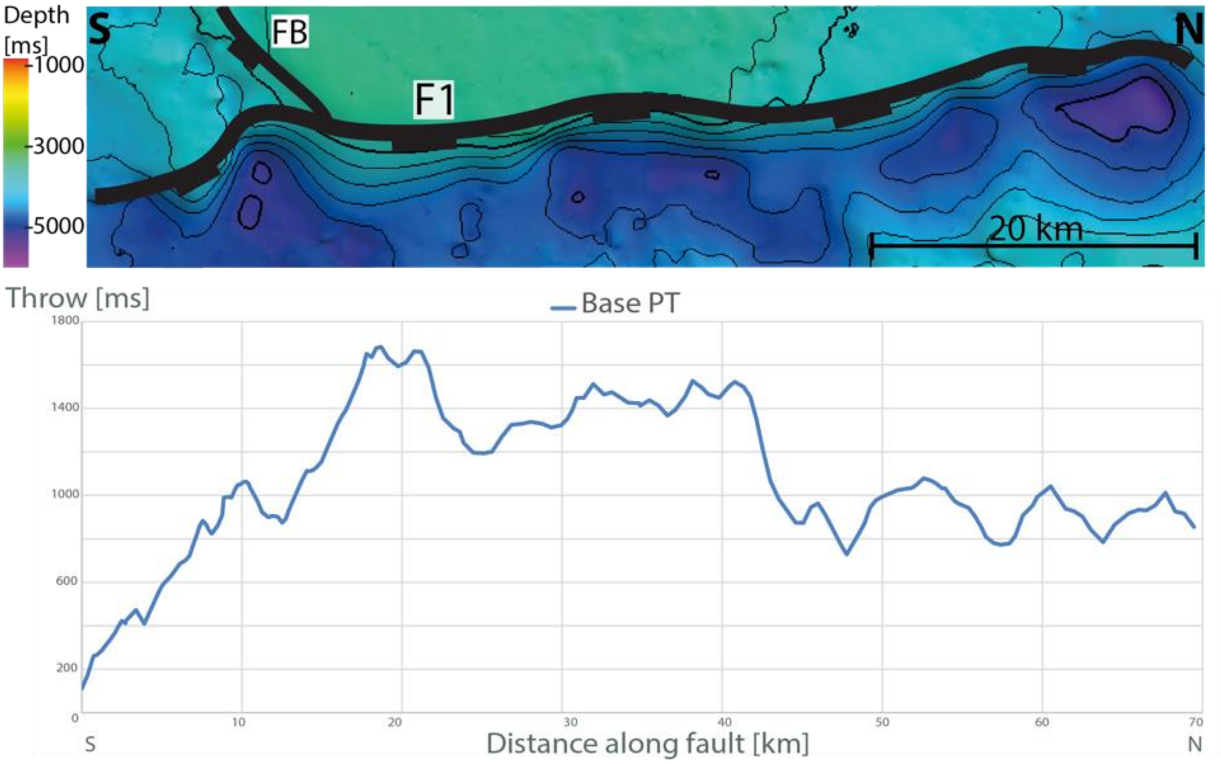


Fig. 4. 15. Length-throw plot along the east-dipping F1 in the Northern Stord Basin. Two main segments can be determined from the plot, with a segment boundary at 45 km. Above the plot, the Fault 1 (F1) and a fault branch (FB) are displayed in map view.

4.3.3 Fault 3

Fault 3 (F3) is located in the centre of the Stord Basin where it together with Fault 4 forms a N-S trending graben. F3 constitute the west-dipping fault of the graben.

The Base PT cut-offs along F3 have been plotted to show the throw accumulated along the fault (Fig. 4.16). The graph is convex up in the southern half before the throw values increase to the north. The northern half of the graph is bell shaped with two distinct peaks of maxima before the throw values decrease towards the fault tip.

The convex up southern half of the plot has minimum values at 0 km and 17 km, which is the localities of the southern fault tip and a probable segment boundary, respectively (Fig 4.16). Two minor peaks are located at 5 km and 12 km on the segments, which in total have throw values ranging from 400-700 ms. North of the 17 km minimum, the throw curve has a sharp gradient to the maximum of the bell shaped half, and the graph in total, at 21 km. The curve has a local minimum and maximum at 26 km and 28 km, respectively, before the throw values gradually decreases towards the northern fault tip. On a large scale, the curve shows that F3 is made up by two main fault segments (Fig. 4.16). The southern segment goes from 0 km to the throw minimum at 17 km and the minor peaks on the curve could be due to lower-order fault segments. The second segment starts at 17 km and extends to the northern fault tip at 37 km. The two large maxima separated by a minimum suggests that this segment is the product of two merged lower-order segments.

The F3 is interpreted to consist of two hard-linked fault segments. The southern segment stretches the first 17 km where the graph shows a convex trend (Fig. 4.16). The other segment goes from 17 km till it dies out at 37 km. The graph roughly resembles a bell, but with two peaks.

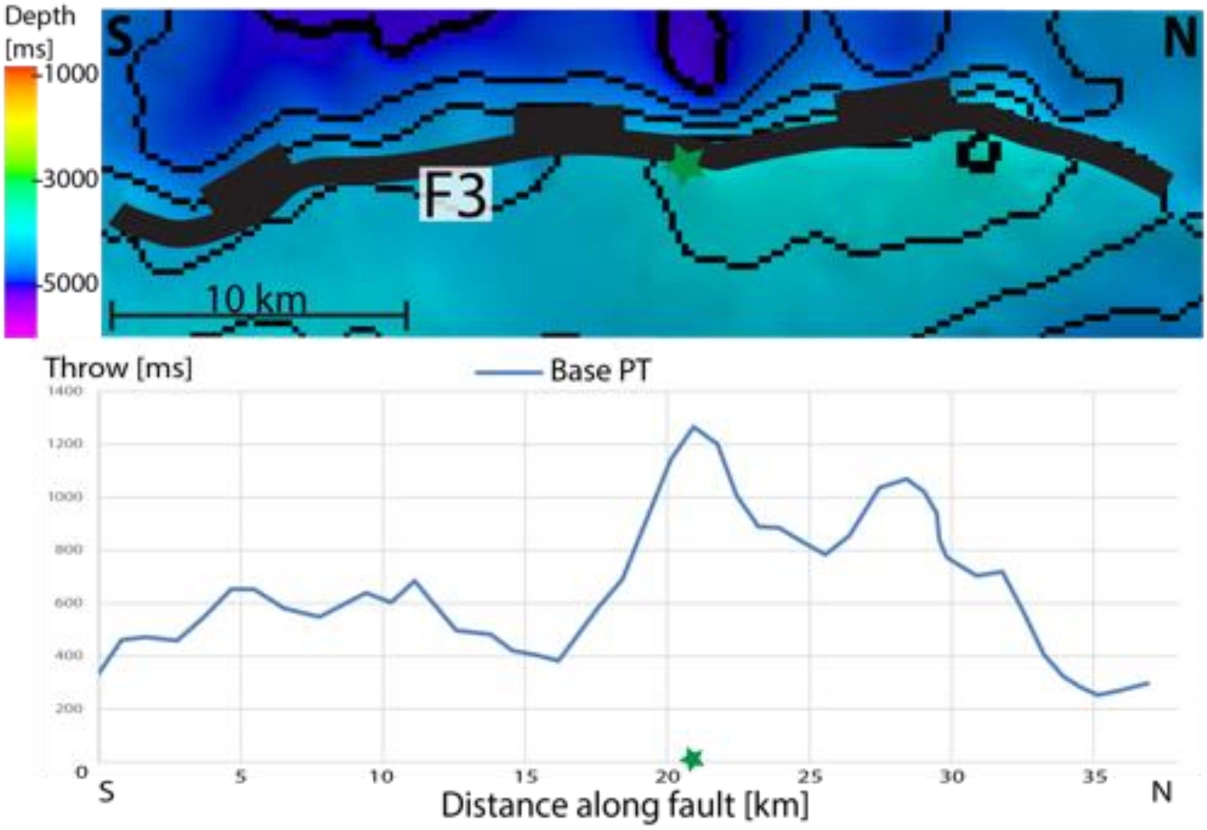


Fig. 4. 16. Length-throw plot along the west-dipping Fault 3 (F3) in the Central Stord Basin. The fault is displayed in map view above the plot. The green star correlates the map view with the graph.

4.3.4 Fault 4

The intra-basin faults F3 and F4 are both N-S trending, have opposite dipping directions and together they form a graben structure. F4 is east-dipping, while F3 dips to the west. Base PT cut-offs have been plotted to depict the segmentation of the F4.

The length-throw curve for F4 shows multiple variations, with three flat topped bell shapes separated by throw minima (Fig. 4.17). The curve has a rough trend of gradually increase from 700 to 1200 ms the first 40 km from the south, with the exception of the largest minimum at 19 km and a local minimum at 31 km. The fault segment stretching the first 19 km has a peak at 2 km, minimum at 5 km and two peaks at 9 and 11 km, before the throw curve decreases to its highest minima at 19 km at a segment boundary. The first 19 km is interpreted to represent one fault segment.

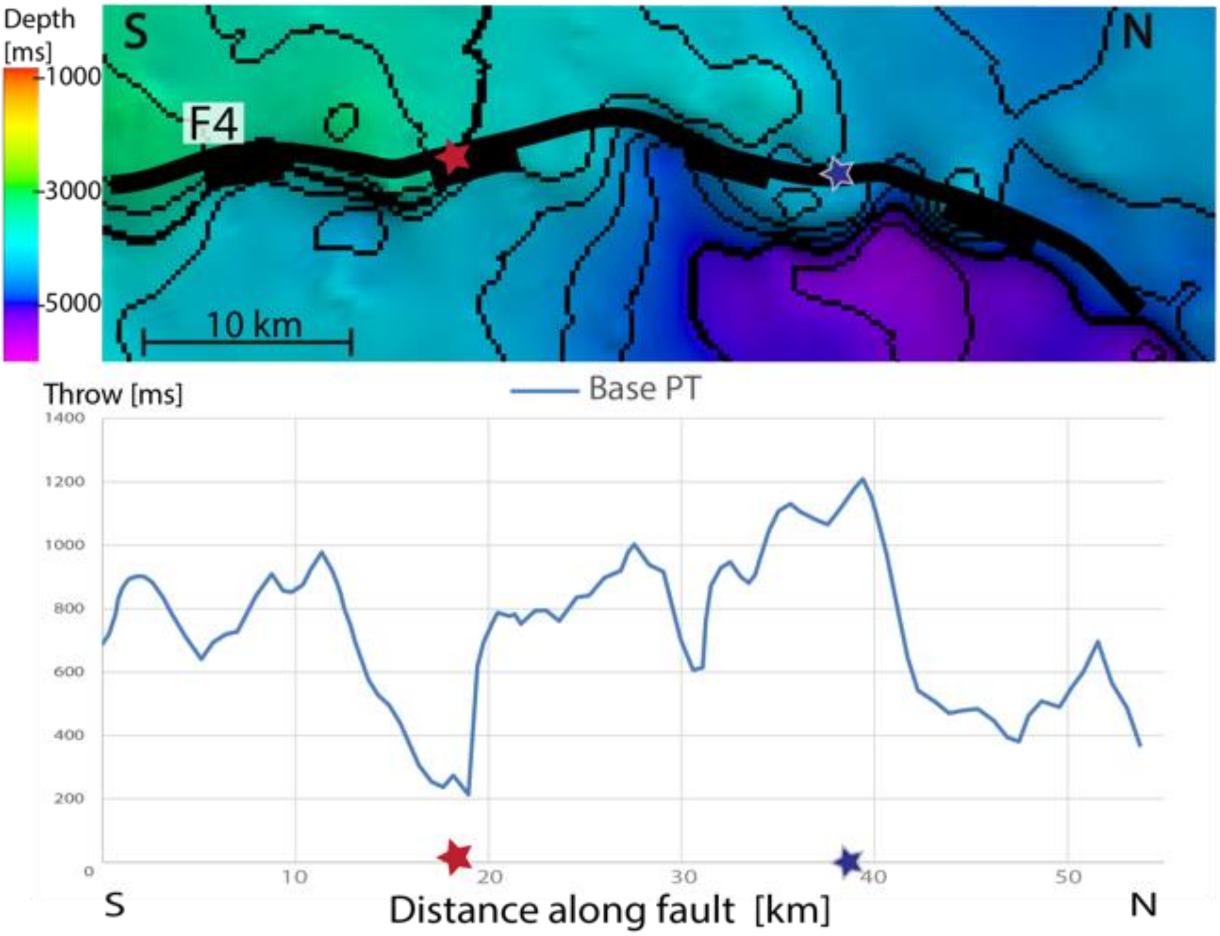


Fig. 4. 17. Length-throw plot for the Base PT along the intra-basin fault F4. Stars correlate the graph with the map. Multiple fault segments can be distinguished in the plot.

The throw variations within the fault segment is interpreted to represent a series of lower-order fault segments, which have merged to one larger fault segment. North of the segment boundary at 19 km, the curve increase with a very high gradient (Fig. 4.17). In this case it is speculated to be an effect of a change in fault geometry, as it corresponds with increased heave along the fault in this area (Fig. 4. 28a). Most likely it is a result of branching faults. The second fault segment, stretching from 19-40 km, has increasing values northwards and is divided in two minor segments at 31 km where there is a local minimum in the curve. From 40-41 km there is an abrupt decrease in the curve. In this case the high gradient can be the result of northwards branching of the fault, where the total displacement is taken up by a set of faults instead of being concentrated on one fault. The low at 41 km is the segment boundary between the second and the third, northernmost fault segment. The third main segment of the F4 has a minimum at 48 km and maximum at 52 km before the curve decreases and the F4 terminates.

4.3.5 Utsira East Fault Complex

The Utsira East Fault Complex (UFC) consists of three large fault segments named Utsira East Fault Complex 1-3 (UFC1-3). The UFC makes up the western boundary of the Stord Basin in the central and southern part of the study area. The general trend for both Base PT level and Top Hegre level are separate bell shapes for UFC3 in the south, and high, varying throw values in the large central part of the combined UFC1 and UFC2 before decreasing to the north (Fig. 4.18).

The Base PT throw curve for UFC3 is overall bell shaped, but with a throw minimum at 31-34 km from the south, which separates two maxima on each side (Fig. 4.18). This suggests that the UFC3 fault segment is the product of two hard linked sub-segments. The fault slightly bends out into the Stord Basin at the segment boundary. The Top Hegre throw curve reflects the Base PT curve and shows two sub-segments as well. The Top Hegre curve in the northern sub-segments has consistently low throw values north of the maximum at ca 38 km and thus differs from the Base PT level, where the throw values decrease gradually towards the northern fault tip. The UFC3 was formed in the Permian-Triassic rifting phase and likely reactivated during Late Jurassic rifting.

The UFC2 and UFC1 are one continuous fault at Top Hegre. For this reason, the trends in the T-x plot at Base PT will firstly be described for each of them. Thereafter the Top Hegre trends will be described for both faults combined.

The UFC2 Base PT curve is bell shaped from 51 km to 110 km, where the low at 100 km represents a segment boundary (Fig 4.18). This part of the curve is skewed to the north in the T-x plot and represents one sub-segment of UFC2. There are two flat topped maxima around 85km and 95 km, which are divided by a minimum at 90 km. Further north there is a maximum at 105 km. These maxima could be the central parts of three lower-order fault segments. Continuing north of the segment boundary at 110 km, the Base PT curve has a major peak at about 124 km, where the UFC1 links up with UFC2 (Fig. 4.18). Further north the curve decreases towards a throw minimum at 137 km. The combination of UFC2's footwall shallowing and its hanging wall structurally deeper causes the major peak in the throw curve. Going north, the UFC1 branches out from UFC2, which explains the sudden drop in the Base PT throw curve. The third sub-segment of UFC2 in the NE-going splay into the basin from 137 km to its fault tip. The Base PT curve for this is bell shaped, but with a minimum at 145 km in a fault bend into the footwall, which could be a segment boundary between lower-order segments.

The UFC1 Base PT throw curve is bell shaped and has lowest values at the northern fault tip and maximum in top of the bell shape in the interval 129-139 km before the throw decreases towards the UFC2 at 124 km (Fig. 4.18). The UFC1 is one continuous fault with increasing throw values immediately away from the linkage point with UFC2. The throw then decreases northwards, especially when the fault splays off the Utsira High.

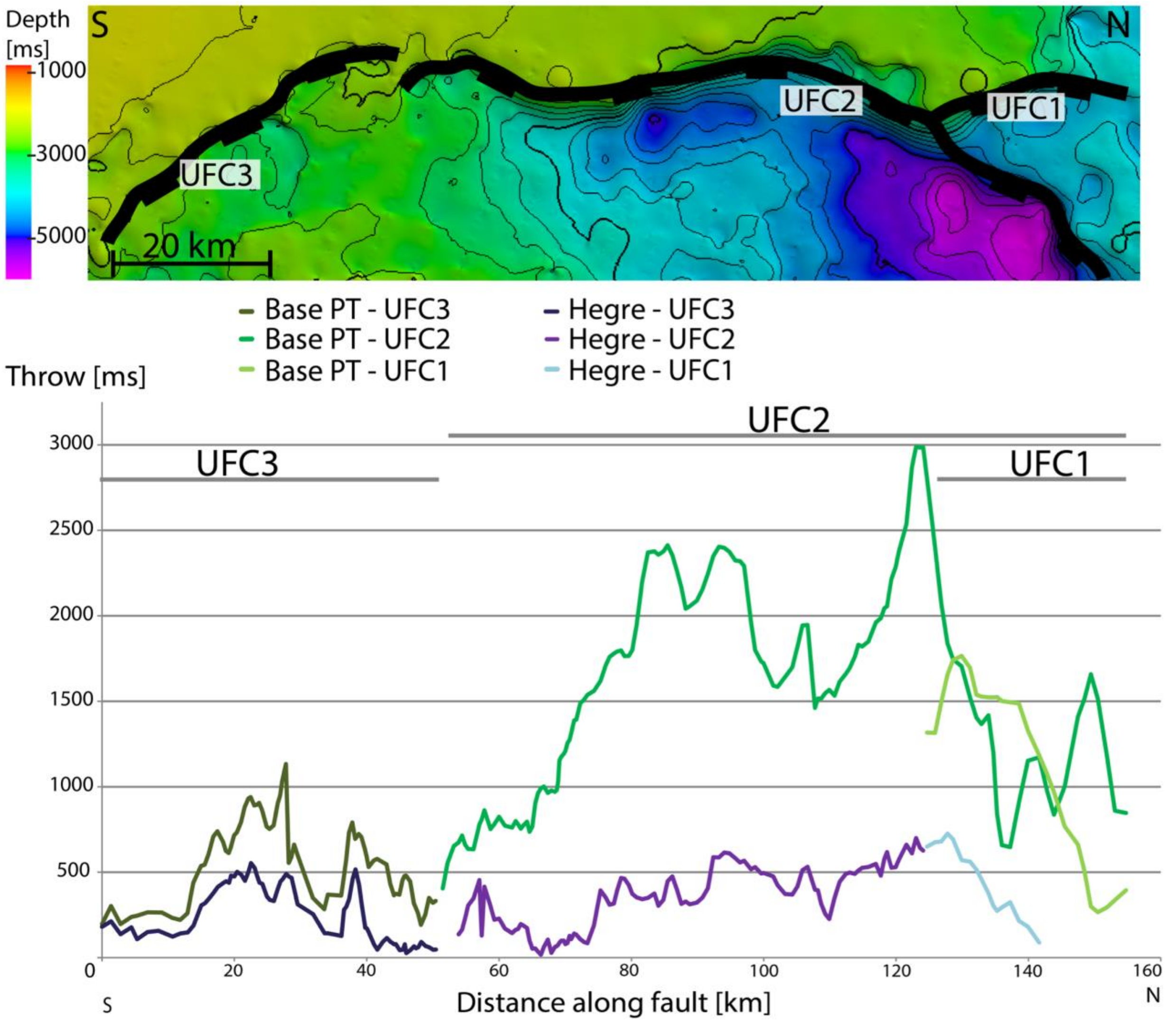


Fig. 4. 18. Throw displacement plot for the three faults of the Utsira East Fault Complex 1-3 (UFC 1-3) at Top Hegre and Base PT levels. Structural map of the Base PT is shown above the plot with the faults drawn on. The grey lines in top of the plot shows the extent of the different faults.

At Top Hegre level, the UFC1 and UFC2 are one continuous fault. The fault segment of UFC2 north of the linkage point with UFC1 is rendered inactive after the Permian-Triassic rifting. The combined Top Hegre throw curve for UFC1 and UFC2 reflects the shape of the Base PT very well (Fig. 4.18). A minimum at 66-74 km followed by a higher level from 77- 88 km are differing from the trend of the Base PT when it comes to the trend of the UFC2's southern sub-segment. This southern sub-segment is further divided into two lower-order sub-segments at the Top Hegre level at the 66-74 km segment boundary. The Top Hegre curve has a local minimum at 110 km, then gradually increases to its maximum at the linkage point before it decreases. This forms the curve into a nice bell shape. The linkage point and corresponding area of maximum throw values are located at a fault bend into the basin. The nice bell shape of the throw curve indicates that there are no fault branches at the Top Hegre level. The UFC1 and UFC2 merged fault was reactivated in the Late Jurassic rifting phase, when it resumed accumulating displacement.

Summary

Some general features are observed along the large, Permian-Triassic faults in the Stord Basin. The main strike direction is N-S. The largest deviations of this trend is found in the Southern SB, where the eastern and western boundary faults converge towards each other, and in UFC2 in the Central SB. All the analysed faults display curves and fault bends, which sometimes corresponds to segment boundaries. The faults consist of sub-segments that eventually linked laterally. This has earlier been suggested for the Øygarden Fault Complex (Odinsen et al., 2000). Each fault is made up by two or more sub-segments. With better resolution data, it will likely be possible to detect even more sub-segment of a lower order. The ØFC and UFC show vertical linkage in the Central Stord Basin and a straighter appearance than at depths.

4.3.6 Permian-Triassic rift phase analysis

The Top Hegre surface represents the Top Triassic, hence it was deposited after the Permian-Triassic rift phase. It has mainly been faulted by the Late Jurassic rift phase. The Base PT surface has in addition to the Late Jurassic rifting been displaced by Permian-Triassic rifting. By subtracting the throw accumulated on the Base PT with that accumulated on the Top Hegre, the throw accumulated during Permian-Triassic rifting (syn-rift and post-rift) is isolated. The isolated throw values have been plotted along the faults to analyse the Permian-Triassic rift phase (Fig. 4.19 and Fig. 4.20).

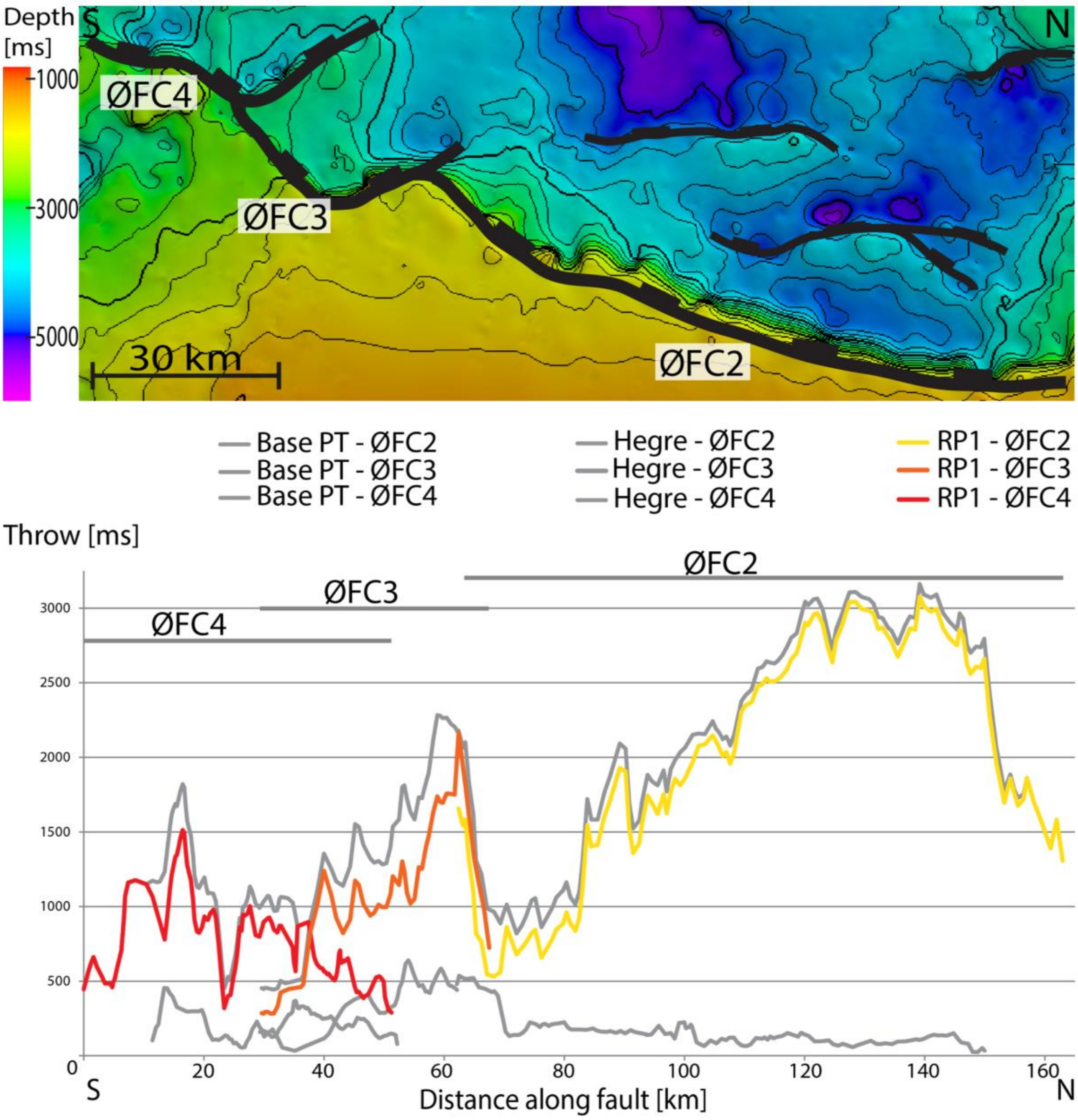


Fig. 4.19. This figure shows the amount of throw accumulated during Permian-Triassic rifting (RP1) along Øygarden Fault Complex 2-4 (ØFC2-4). The throw values at Top Hegre was substracted from the Base PT values. Since the Top Hegre was deposited after the Permian-Triassic rift phase, the subtraction leaves us with a set of throw values obtained purely during Permian-Triassic rifting. Modified from Fig. 4.14.

The Utsira East Fault Complex and Øygarden Fault Complex displaces both Base PT and Top Hegre surfaces. The throw accumulation along the fault complexes during the first, Permian-Triassic rifting has been isolated and plotted in throw-length plots (Fig. 4.19 and Fig. 4.20). This allows to compare the intensity of the Permian-Triassic rifting phase with the product of all later rifting, mainly the Late Jurassic rifting.

For the Øygarden fault system the throw accumulation during Permian-Triassic rifting is very similar to the Base PT throw, but with more influence of later fault movement in the south, especially along ØFC3 (Fig. 4.19). This implies that the Permian-Triassic rifting phase is the most prominent in the Stord Basin and intra-rifting and the Late Jurassic rifting did not cause intensive movement along the fault complex. Most of the fault displacement must have been obtained during the Permian-Triassic rifting.

The throw accumulation during Permian-Triassic rifting along the Utsira East fault system is plotted in Fig. 4.20. For the Utsira Fault Complex, the throw obtained in Permian-Triassic rifting reflects the Base PT throws. The throw curve for the Permian-Triassic rifting is located close to the Base PT curve for UFC1 and UFC2, which illustrates that the bulk displacement along these two faults occurred during the Permian-Triassic rifting. The exception is the linkage area between UFC1 and UFC2, where about half of the total throw accumulated during later fault movement, mainly the Late Jurassic. The Permian-Triassic rifting along UFC3 is less dominant in its southern sub-segment. This trend indicates higher strain in the south in the later stages, i.e. a southwards strain migration after the Permian-Triassic rifting phase. This trend is similar to the trends observed along ØFC2, ØFC3 and ØFC4.

The T-x plots with the calculated Permian-Triassic movement included, provides a good illustration of significance of Permian-Triassic rifting in the Stord Basin compared to later fault movements. This tells that not only is the basin of Permian-Triassic origin, but also that the bulk tectonic and stratigraphic evolution of the Stord Basin was developed during this Permian-Triassic rifting phase. A concluding observation is that all the basement-cutting faults (i.e. cuts Base PT surface) are of Permian-Triassic age. Basement extension in the Late Jurassic rifting phase was purely due to reactivation.

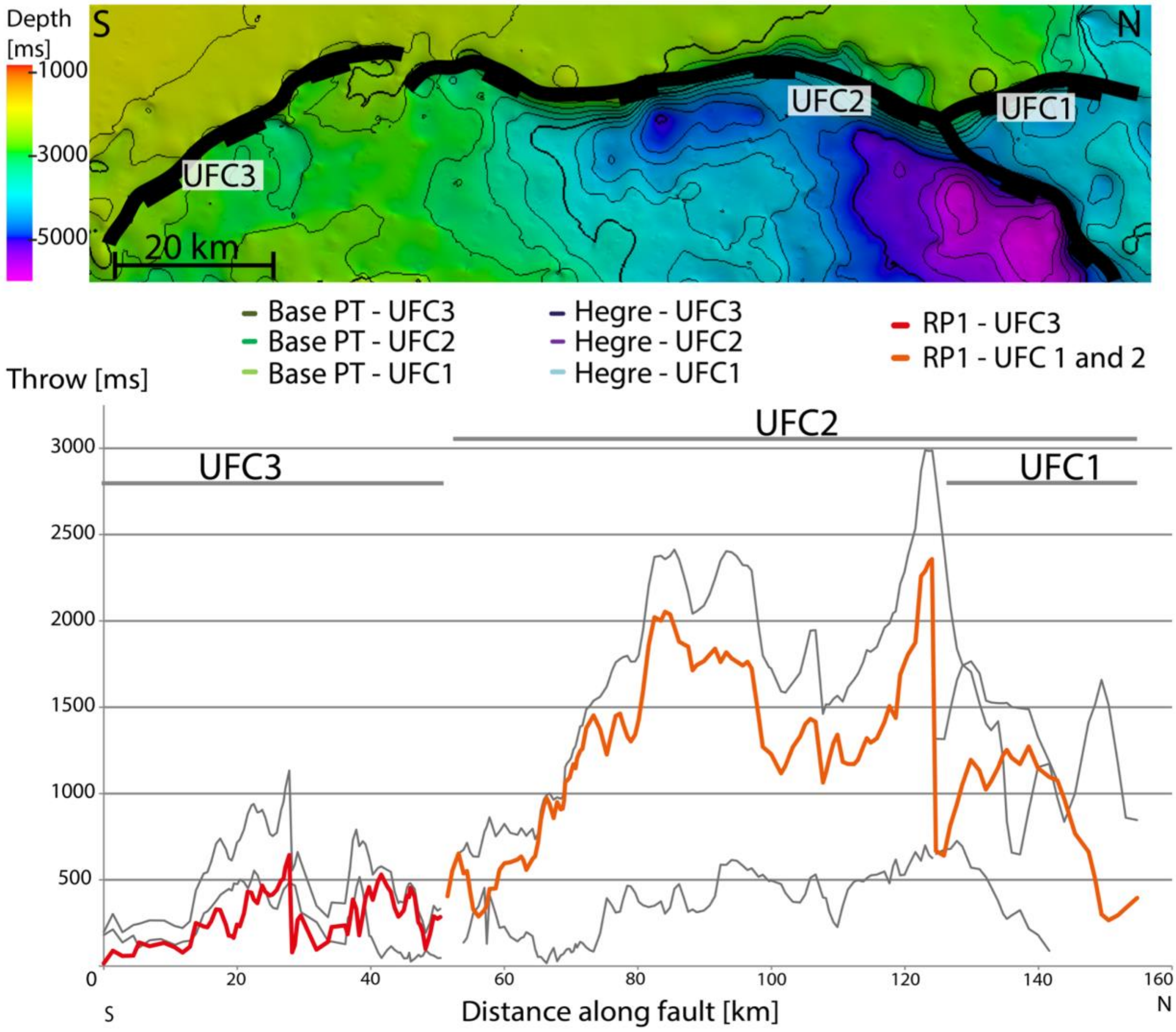


Fig. 4. 20. This figure shows the throw plots along Utsira East Fault Complex. It is a modification of Fig. 4.18 with the addition of the isolated throw accumulations from Permian-Triassic rifting displayed in red and orange. The previously shown throw values at Base PT and Top Hegre levels are displayed in grey to highlight the newly calculated values. The throw values at Top Hegre was substracted from the Base PT values. Since the Top Hegre was deposited after the Permian-Triassic rift phase, the subtraction leaves us with a set of throw values obtained purely during Permian-Triassic rifting. Permian-Triassic rifting is termed Rift Phase 1 in the figure with the abbreviation RP1.

4.4 Thickness maps

The two-way-time (TWT) thickness maps illustrate the vertical thickness variations between each sedimentary package bounded by the interpreted horizons. Multiple TWT thickness maps have been generated from the Base Permian-Triassic rifting surface (Base PT) to the seabed (Top Nordland), covering the complete stratigraphic column of the study area to further investigate the tectono-stratigraphic evolution.

4.4.1 Permian-Triassic succession

Within the Permian-Triassic rift succession there are four packages interpreted to be syn-rift sediments, enclosed by the Top Syn Rift surface. These packages were deposited in a syn-tectonic environment, i.e. during active faulting in the basin. Continued fault movement during deposition creates more accommodation space close to the faults. With high enough sediment supply, this leads to wedge shaped packages with highest thicknesses towards the fault. This is a key characteristic for the syn-tectonics. Above the syn-rift sediments there are two post-rift packages enclosed by Post-rift horizon 2. These are interpreted to have been deposited in a phase of fault quiescence as the packages are of a tabular geometry. Tabular packages are characteristic for post-tectonics. As the faults do not create additional accommodation space, the sediments fill the basin are more evenly than during syn-rift phase. Subsidence of the basin can cause thickening of the packages' central parts.

Seismic Unit 1

The Seismic Unit 1 TWT thickness map shows the thickness between Base PT and Syn-rift horizon 1. Thickening is seen towards the Øygarden Fault Complex 2 in cross section (ØFC2) (Fig. 4.21). The Utsira Fault Complex 1 and 2 (ØFC 1-2), intra-basin faults 1-5 (F 1-5) and the Øygarden Fault Complex 1-4 (ØFC 1-4) all have clear thickening in their hanging walls in Seismic Unit 1 (Fig. 4.22a). The main areas of thickening are found along the northern part of UFC2, in the F3 and F4 hanging walls, and in the ØFC2 and F2 hanging. ØFC3 have up to 200 ms thick packages in the northern and central areas of its hanging wall. The largest thickenings are found in the hanging wall of UFC2's northern part, in the graben between F3 and F3, and in the hanging wall of the northern part of ØFC2 and of F2.

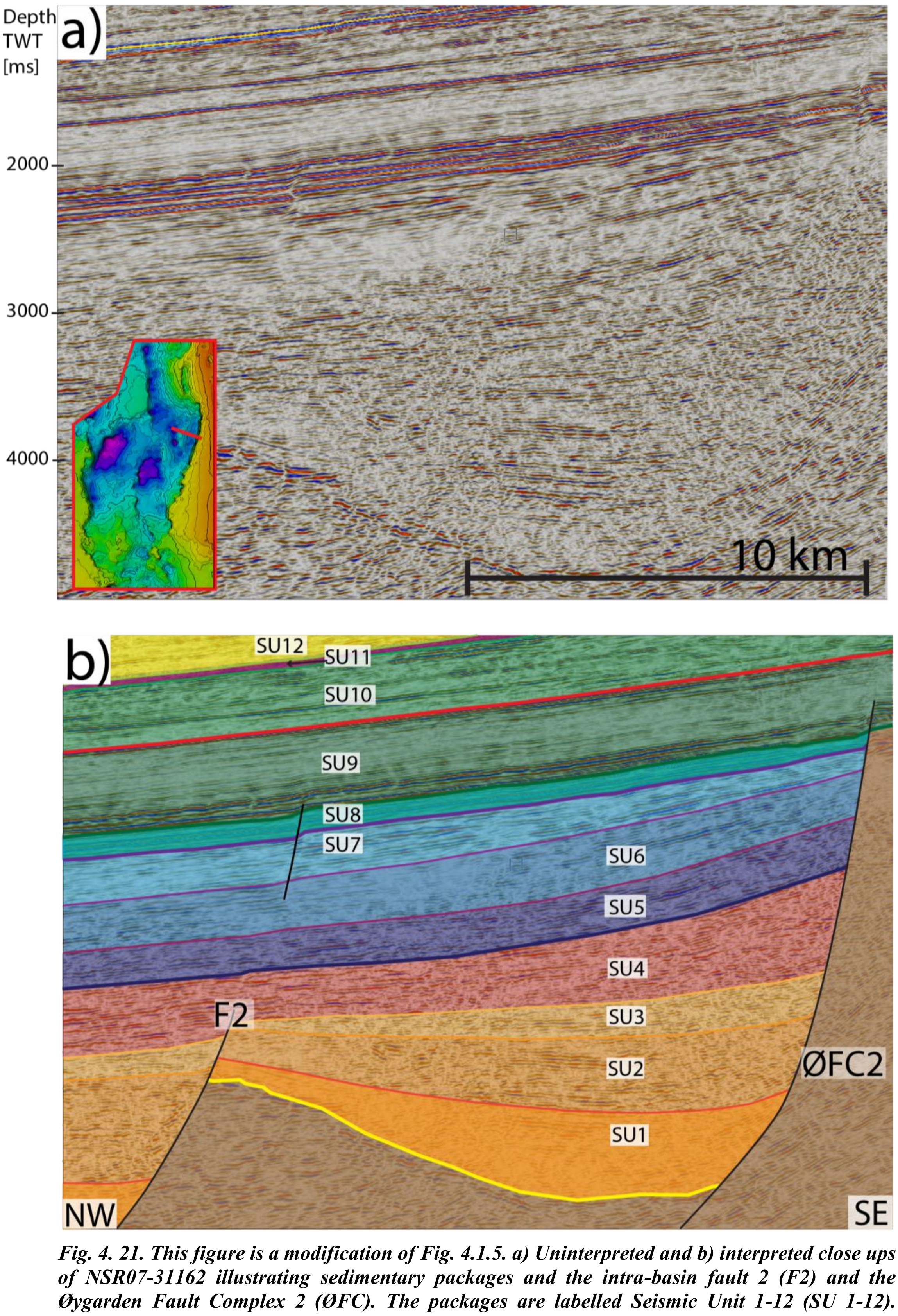


Fig. 4. 21. This figure is a modification of Fig. 4.1.5. a) Uninterpreted and b) interpreted close ups of NSR07-31162 illustrating sedimentary packages and the intra-basin fault 2 (F2) and the Øygarden Fault Complex 2 (ØFC). The packages are labelled Seismic Unit 1-12 (SU 1-12). Mininature of the study area in a) shows the location of this section

Along the UFC2 there are two major areas of thickening along the fault. Both areas of thickening are elongated in the strike direction and grading into the basin (Fig. 4.22a). In a fault bend between the two packages there is a small area of little to no deposition. The package in front of the southern part reaches about 300 ms at its largest point. The package in front of the northern part has a maximum of about 600 ms. This northern package has three centres of increased thickness. Both the thickness and areas of these centres increases to the north. There is a minor thickening in the UFC3 hanging wall, which more or less links up with the UFC2 hanging wall package.

The Seismic Unit 1 interval has thickening in the graben formed by F3 and F4 (Fig. 4.22a). The package is largest where the two faults are oppositely facing each other. In the hanging wall of F1 there are several lobes of thickening. In the southern part of the fault, the thickening continues into the adjacent basin towards F2.

ØFC2 has an along strike package of 100-175 ms thick in the hanging wall (Fig. 4.22a). Along ØFC2 the thickness is largest at the northern end and pinches out in front of the southern tip. Seismic Unit 1 shows over 400 ms thickness along F2 with a maximum of approximately 800 ms thickness in the central part. In the south, the package merges with the package in front of ØFC2. Seismic Unit 1 is very thin in front of ØFC3, but thickens at the northern tip. The N-S going segment of ØFC4 has one deposition centre in the southern part and on in the northern.

Thickening close to the faults continues into the basin. The faults UFC2, UFC3, F1, F2, F3, F4, F5, ØFC1, ØFC2, ØFC3 and ØFC4 were active during the deposition of Seismic Unit 1. UFC2 was possibly two large segments, northern and southern, which grew towards each other. Seismic Unit 1 shows clear thickening towards the faults, indicating syn-sedimentary depositions and will hence be referred to as Syn-Rift 1 from now on.

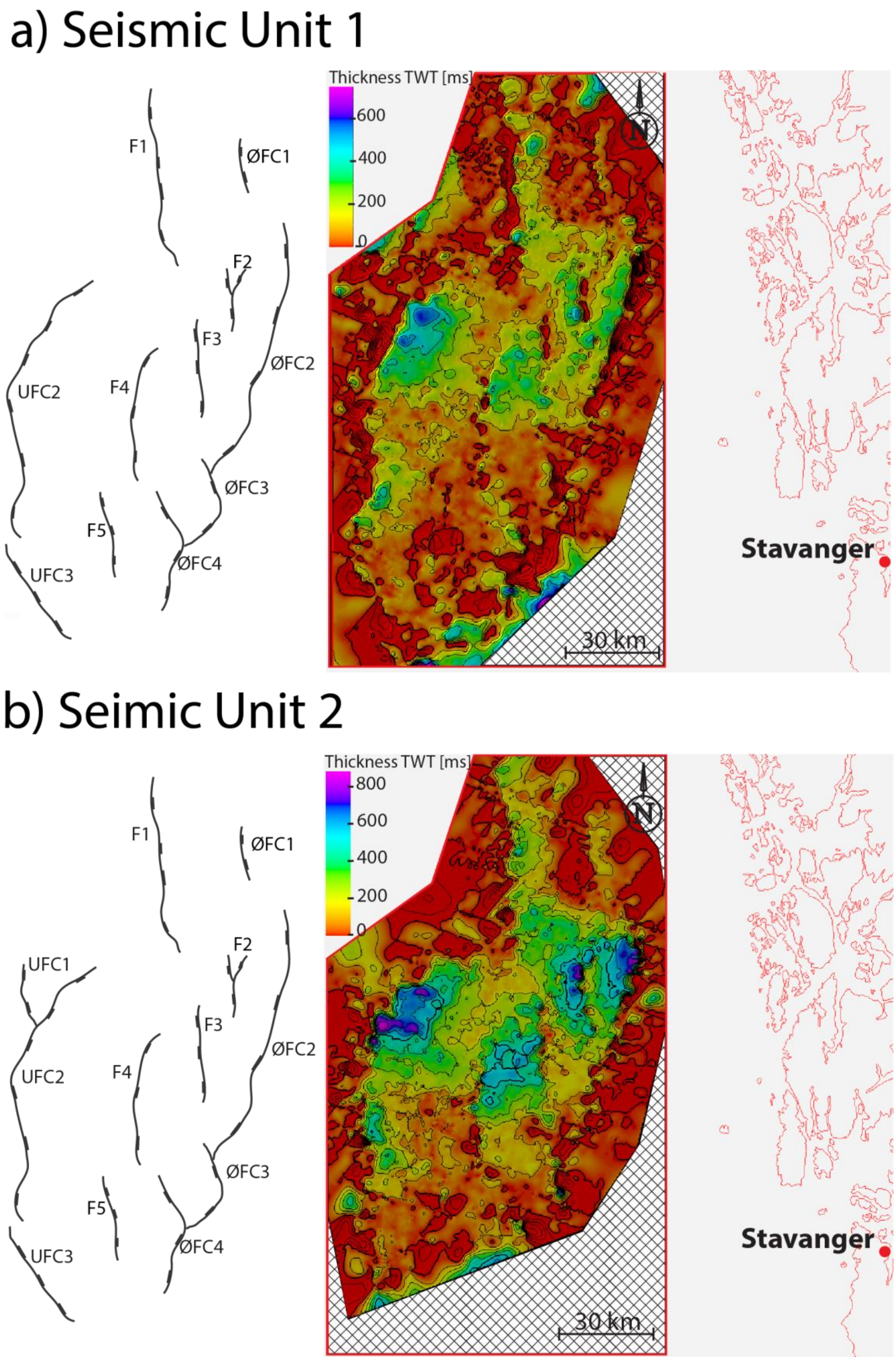


Fig. 4. 22. Thickness TWT maps of a) Seismic Unit 1 and b) Seismic Unit 2 in relation to the Norwegian coastline with Stavanger marked. The gridded areas represent where one or both of the surfaces used to generate the thickness map are eroded. Fault map on the left hand side displays the faults interpreted to be active in the respective interval. The three faults of the Utsira East Fault are abbreviated UFC 1-3, the four faults of Øygarden Fault Complex are ØFC 1-4 and the remaining faults have the numbering F 1-5.

Seismic Unit 2

Seismic Unit 2 TWT thickness map shows the thickness between Syn-rift horizons 1 and 2. The unit displays significant thickening towards the ØFC2 (Fig. 4.21). It has the largest thicknesses in the footwall of UFC2, in the graben formed by F3 and F4, and in the hanging walls of ØFC2 and F2 (Fig. 4.22b). The F1 fault has a substantial package, which links with the F2 package. Seismic Unit 2 has the same main trends as Seismic Unit 1, but the Seismic Unit 2's packages expand further into the sub-basins.

Both F2 and the northern part of ØFC2 have increased thicknesses in their hanging walls (Fig. 4.22b). In the deposition centre of northern ØFC2 the thickness reach 700 ms. The package gradually thins into the basin and southwards along strike. F2 have the same thicknesses as ØFC2 and shows the same trend of decreasing thickness into the basin. The Seismic Unit 2 thickness map shows localized thickening in northern, central and southern part of F1. The minimum thickness along F1 is about 200 ms. The deposition centre in the south is linked to the packages expanding from F2 and ØFC2. The ØFC1 has a clear thickening just shy of 200 ms along strike, tapering out towards the sub-basin to the south.

Seismic Unit 2 has a moderate thickness around 200 ms in the area between the ØFC3, ØFC4 northern fault tips (Fig. 4.22b). The F5, UFC3, ØFC3 and ØFC4 hanging walls have low thickness of 0-100 ms. The southern part of UFC2 has increased thickness in the hanging wall reaching about 500 ms at the depositional centre. The thickness decreases into the sub-basin and towards the southern tip. The northern part of UE2 has thicknesses exceeding 800 ms concentrated in two main depositional areas. The first deposition lays directly in front of where UFC1 links with UFC2. The other is placed further north close to UFC2 in its hanging wall. Seismic Unit 2 in the central parts in the F3-F4 graben have thicknesses reaching about 600 ms. Like with Seismic Unit 1, the Seismic Unit 2 is thickest in the area where the two faults directly oppose each other.

The Seismic Unit 2 shows the same main trends of Seismic Unit 1 with areas of thickness placed close to the faults. For Seismic Unit 2, however, the areas of thickness extend a larger distance from the faults. UFC1, UFC2, UFC3, F1, F2, F3, F4, F5, ØFC1, ØFC2, ØFC3 and ØFC4 are interpreted to have been active within the deposition of Seismic Unit 2.

The Seismic Unit 2 is interpreted to have been deposited during active rifting and will be referred to as Syn-Rift 2 from now on. In comparison to the Syn Rift 1 interval, sediments were deposited in a larger area of the Stord Basin during Syn Rift 2.

Seismic Unit 3

In the Seismic Unit 3 interval between Surface 2 and Surface 3 shows thickening towards the faults (Fig. 4.21) The deposited sediments cover more or less the whole Stord Basin (Fig 4.23a). Main areas of deposition are found in the hanging wall of the central and northern part of F1, the central part of ØFC2 and along UFC2. Compared to the previous intervals Seismic Unit 1 and Seismic Unit 2, some of the depositional centres have shifted.

The ØFC2 hanging wall has the largest thickness in the central part, reaching 700-800 ms thickness (Fig. 4.23a). The along-strike package north of this has an even thickness around 300 ms and decreases into the sub-basin. The package along ØFC2 to the south has a thickness of around 100 ms toward the ØFC3.

Seismic Unit 3 reaches a thickness about 600 ms in the central and northern hanging wall of F1 close to the fault (Fig. 4.23a). The package gradually thins further away from the fault and along the strike southwards. The area between the southern F1 and ØFC2 has even thickness around 100-200 ms. Increased thickness is found in the hanging-wall of UFC2 and, to some degree, UFC1's hanging wall. The package along UFC2 expands gradually further into the basin, going from south to north. Two main centres of maximum thickness of 400-500 ms are found. The first centre is located on the NE-trending part of UFC2. The other is located on the northern half of the N-trending part of UFC2. The southern tip of the UFC2 has little to no thickening in its hanging wall.

A wide package of about 200-300 ms is found in F4's hanging wall. The package's thickness decreases towards F3. In the hanging wall of central F3 there is a small increase in thickness. ØFC3 shows thickening in the northern part where it exceeds 200 ms and seems to connect with the package found in the F3-F4 graben. A thickening of about 150 ms is associated with ØFC1. Areas of low thicknesses are found off the south of F1, in the southern hanging wall of F2 to the northern footwall of F3, in the southern footwall of F4 and in general in the Southern Stord Basin.

The faults UFC 1-3, F1, F3, F4 and ØFC 1-4 are interpreted to have been active sometime during the deposition of Seismic Unit 3. The depositions of Seismic Unit 3 are in general less concentrated close to the faults and expands gradually further into the basin compared to the underlying thickness maps, but there is still wedging towards the fault, hence Seismic Unit 3 is renamed Syn-Rift 3.

Seismic Unit 4

Seismic Unit 4 was generated between Syn-rift horizons 3 and Top Syn Rift. Cross-section displays thickening towards the ØFC2 (Fig. 4.21). The map shows thickening in the whole basin between Utsira East Fault Complex (UFC) and the Øygarden Fault Complex (ØFC), and along F1 (Fig. 4.23b). In the southern hanging wall of F1, the thickness of Seismic Unit 4 is about 500 ms thick. It gradually thins towards the southeast before the package gets thicker again towards the F2 and ØFC2.

A thickening of 600-700 ms stretches along ØFC2's northern hanging wall half (Fig. 4.23b). The thickness decreases gradually towards the south. The southern half of UFC2's hanging wall has thicknesses around 300 ms. In the north of ØFC3's hanging wall there is a thickening close to the fault, which fans out and stretches to the southern F4. In the graben between F3 and F4, the thickness of Seismic Unit 4 decreases towards the north. Along the hanging wall of central and northernmost UFC2 there is a thickening of multiple depositional centres. UFC1 has a thickening of 300 ms in its hanging wall. From the UE2 fault towards the F4, the thickness decreases to 0-150 ms. Seismic Unit 4 has thicknesses of 50-150 ms in the UFC3, F5 and ØFC1 hanging walls.

All major faults are interpreted to have been active in some degree during the deposition of Seismic Unit 4, i.e. UFC 1-3, F1-5 and ØFC 1-4. Clear features of thickening towards the faults makes it reasonable to rename Seismic Unit 4 to Syn-Rift 4.

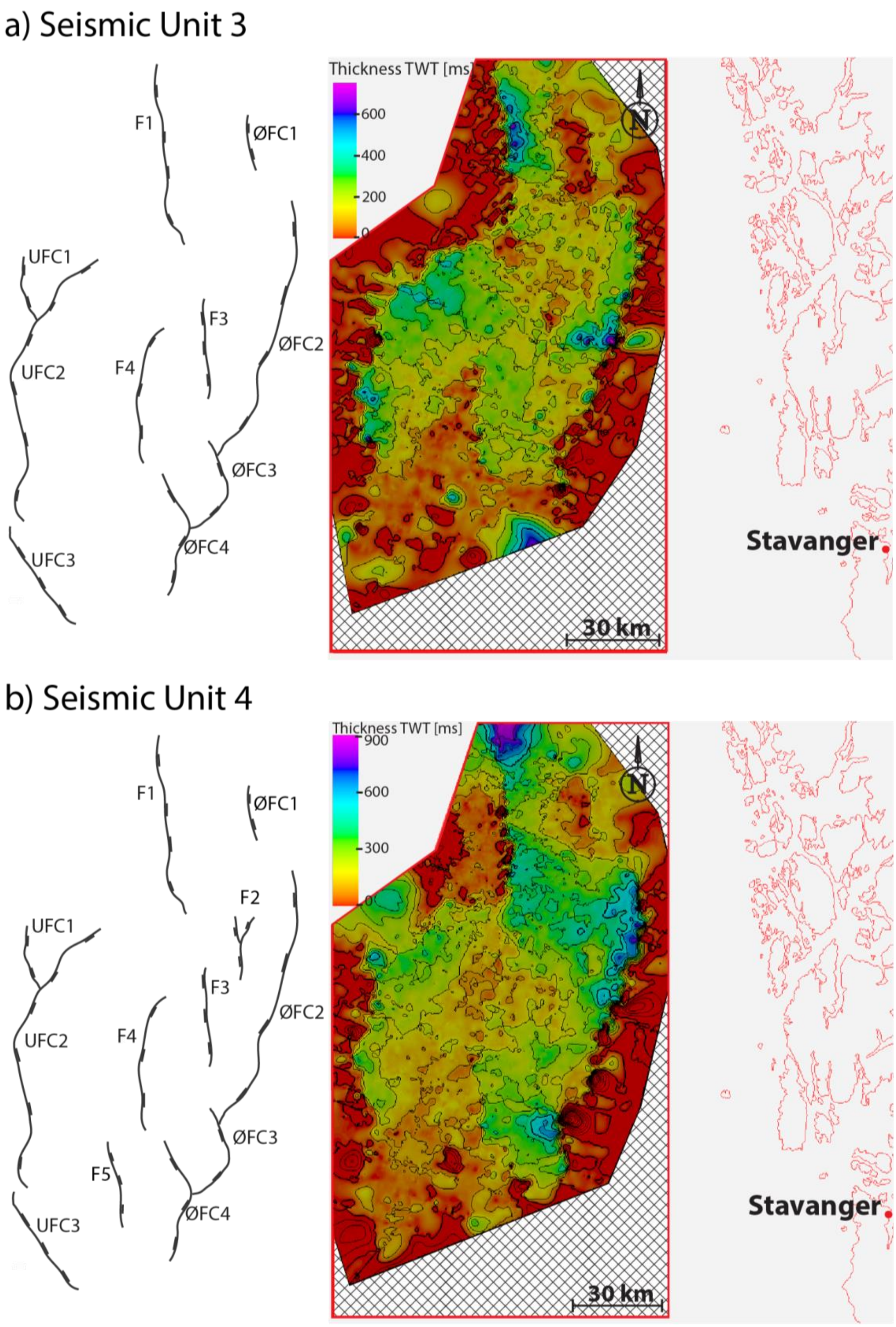


Fig. 4. 23. Thickness TWT maps of a) Seismic Unit 3 and b) Seismic Unit 4 in relation to the Norwegian coastline. Eroded areas have a gridded pattern. The fault maps on the left hand sides illustrates the active fault during each interval. The Utsira East Fault complex is abbreviated UFC 1-3, Øygarden Fault cComplex is abbreviated ØFC 1-4 and the remaining faults are numbered F 1-5.

Seismic Unit 5

In the Seismic Unit 5 interval between Top Syn Rift and Post-rift horizon 1, sediments have been deposited throughout the Stord Basin. The unit has a tabular shape (Fig. 4.21). Increased thicknesses of 400 ms are found in the UFC1 and UFC2 hanging walls. In the UFC1 hanging wall and south of UFC1 along UFC2 there are multiple deposition centres, which all gradually thins out into the basin and along strike (Fig. 4.24a). Along the whole of F1, the thicknesses are levelled around 300 ms. Minor thickening can be seen in the ØFC1 hanging wall. The northern part of ØFC2 holds thicknesses of 400 ms for Seismic Unit 5. This package decrease to 100-200 ms thickness along strike to the south. Seismic Unit 5 has thicknesses of 100-200 ms in the centre of the Stord Basin and in the Southern Stord Basin, including in the UFC3, ØFC3 and ØFC 4 hanging walls. UFC1-3, F1 and ØFC 1-4 are interpreted to have been active during the deposition of Seismic Unit 5. The fairly tabular shape of Seismic Unit 5 supports renaming this unit to Post-Rift 1.

Seismic Unit 6

The TWT thickness map of Seismic Unit 6, depicting the interval between Post-rift horizon 1 and 2, has a n overall tabular geometry (Fig. 4.21). The map shows thickening along F1 (Fig. 4.24b). It has a package of maximum thickness of 400 ms in the central part, which decrease to 200 ms to the north. Seismic Unit 6 has a thickness of 300-400 ms in F1's southern hanging wall, which extends into the basin and in front of ØFC2's northern half. The ØFC1 hanging wall displays thickening of 50-100 ms. The Seismic Unit 2 also show thickening in UFC2's hanging wall. Low thicknesses of 50 ms are found in the UFC3 hanging wall. At the central hanging wall of ØFC4 there is a maximum thickness of 400 ms and in the hanging wall of ØFC3 the thickness is around 100 ms. Faults that are interpreted to have been active during the deposition of Seismic Unit 6 are UFC 1-3, F1 and ØFC 1-4. Tabular shaped package is characteristic for post-tectonic, hence Seismic Unit 6 will be referred to as Post-Rift 2 from now on.

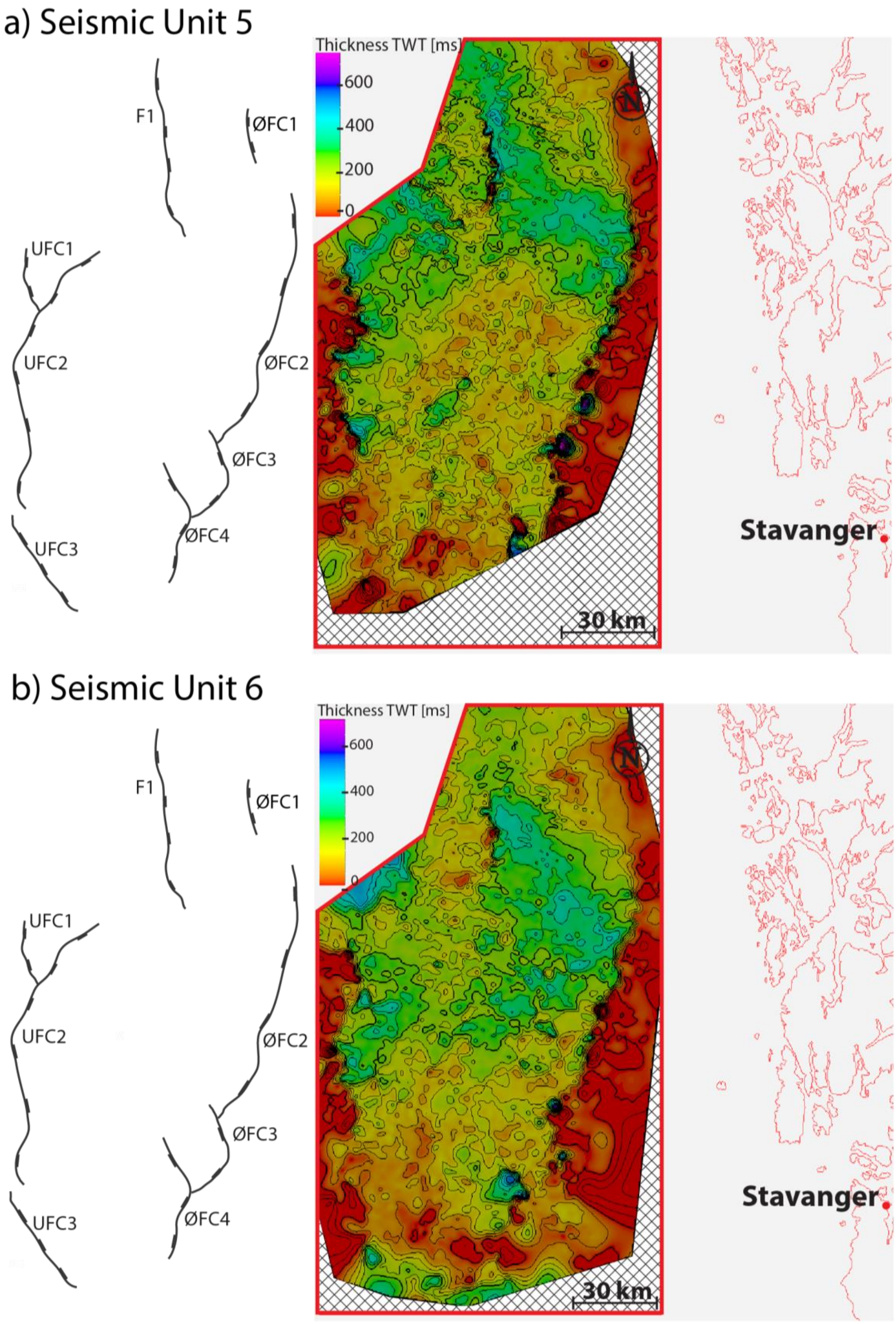


Fig. 4. 24. Thickness TWT maps of a) Seismic Unit 5 and b) Seismic Unit 6 in relation to the Norwegian coastline. Eroded areas are marked with a gridded pattern. The fault map to the left displays the faults that are interpreted to be active during the respective intervals. The fault abbreviations are intra-basin fault 1 is F1, the three faults of the Utsira East fault Complex are ØFC 1-3 and the four faults of the Øygarden Fault Complex are ØFC 1-4.

4.4.2 Triassic to present day succession

The marker horizons Hegre, Dunlin, Base Cretaceous Unconformity (BCU), Cromer Knoll and Shetland range from Upper Triassic to Upper Cretaceous age. These sedimentary packages have been labelled with their respective geological age. The TWT thickness maps allows the description of the geological history following the Permian-Triassic rifting phase.

Seismic Unit 7: Upper Triassic

The Seismic Unit 7 TWT thickness map was generated between Post-rift horizon 2, which is likely of Triassic age, and Top Hegre, which represents Upper Triassic age. Seismic Unit 7 is therefore termed as an Upper Triassic package. The cross-section shows a thickening towards the basin centre (Fig. 4.21). The general trend of the Upper Triassic thickness map is low thicknesses in the southern part of the study area between UFC3 and ØFC4, as well as in the UFC1 hanging wall (Fig. 4.25a). The central basin F1 hanging wall have increased thicknesses of 200-500 ms. These thicknesses are also seen in F1's northern footwall. The Upper Triassic thickness map shows thickening of about 200 ms in the northern UFC3's hanging wall, where it makes up a relay ramp towards UFC2. The area of the relay ramp has thicknesses of 200-300 ms. Along the strike of UFC3, the package pinches out and reaches zero thickness. The central part of UFC2 has a thickness maximum of 700 ms which decrease abruptly to the south. The thickness decreases gradually to about 200 ms where UFC2 links with UFC1 and continue to decrease along the northernmost section of UFC2. The ØFC3's hanging wall has an even thickness of about 300 ms which is seamlessly connected with the thicknesses in the southern and central ØFC2's hanging wall. The thickness decreases further north along the strike of ØFC2. The ØFC1 cannot be distinguished in the Upper Triassic thickness map. The faults interpreted to have been active during the deposition of Seismic Unit 7, the Upper Triassic succession, is UFC 1-3, F1 and ØFC 2-3.

Seismic Unit 8: Lower Jurassic

Seismic Unit 8 thickness map shows the vertical thickness between Top Hegre and Top Dunlin and hence represents the Lower Jurassic sediments. It is a tabular, layered succession, which covers the ØFC footwall (Fig. 4.21). Major trends are lower thicknesses in front of ØFC2 to the southern UE2 and southwards, and increased thicknesses in the northwest of the study area (Fig 4.25b). Thicknesses exceeding 600 ms is related to the UFC1 and UFC2 linkage area. The thickness decrease northwards and the northernmost segment of UFC2, which overlaps with

UFC1, cannot be distinguished in the Lower Jurassic thickness map. The thickness decrease along UFC2 southwards. The southern part of UFC2 has thicknesses falling below 200 ms. The relay ramp between UFC2 and UFC3 is now breached. UFC1, UFC2 and UFC3 are now hard-linked and constitute one continuous fault, defining the eastern limit of the Utsira High. The Northern Stord Basin has thicknesses ranging from 150-300 ms, which decrease to the south. ØFC4 have largest thicknesses in reaching 400 ms in the hanging wall where the fault bends. Along ØFC3 and ØFC2 the thickness range around 200 ms with the exception of the linkage area of these two faults. In this area the thickness of the package increases to 300 ms and expands in a lobe going northwest into the basin. The F1 cannot be unambiguously determined by the Lower Jurassic thickness map. Compared to the underlying Upper Triassic succession, the centre of maximum thickness of the Lower Jurassic package is now shifted towards the west, which implies a westwards strain migration.

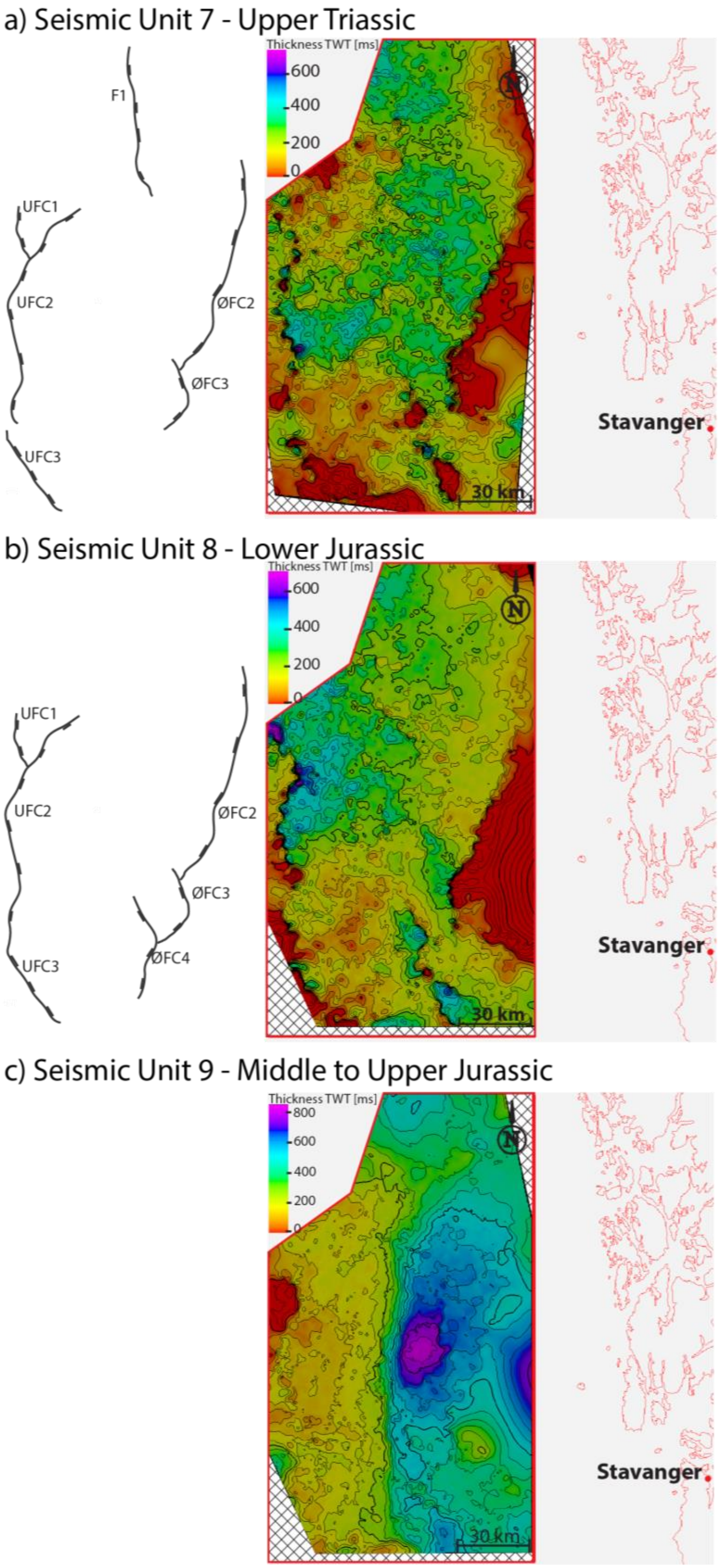


Fig. 4. 25. TWT thickness maps of a) Seismic unit 1 – Upper Triassic, b) Seismic Unit 8 – Lower Jurassic and c) Seismic Unit 9 – Middle to Upper Jurassic. The Norwegian coastline is displayed to show the location of the study area. Eroded areas are marked with gridded patterns. The fault maps on the left hand side in a) and b) display the active faults of the respective interval. The three faults of the Utsira East Fault Complex are labelled UFC 1-3, intra-basin fault 1 is labelled F1 and the four faults of the Øygarden Fault Complex are labelled ØFC 2-3. a) shows a relay ramp between UFC2 and UFC3, which is breached in b). A N-S trend line is observed in c) where it divides lower thicknesses to the west and higher thicknesses to the east.

Seismic Unit 9: Mid-Upper Jurassic

Seismic Unit 9 was generated between Top Dunlin and Base Cretaceous Unconformity surface. It contains sediments deposited from Middle and Upper Jurassic ages, hence this thickness map will be referred to as Mid-Upper Jurassic. A delta sequence prograding from the coast can be identified in cross section (Fig. 4.26). A N-S trending line divides thicknesses above 400 ms to the east from thicknesses below to the west (Fig. 4.25c). This suggests that the delta front in the Mid-Upper Jurassic was trending N-S. The north of the Utsira High do not have sediments from this interval. The rest of the western area is about 200 ms thick. The eastern side of the divide has a large, oval maximum thickness of 800 ms in the central area. The thickness decreases away from this centre. The northern part of the study area has thicknesses around 400 ms. None of the major faults of the Stord Basin transects the whole Mid-Upper Jurassic interval and its appearance is different from the previously described packages. However, cross section shows that the major faults F3, F4 and ØFC2 cut into the base of the package (Fig. 4.26).

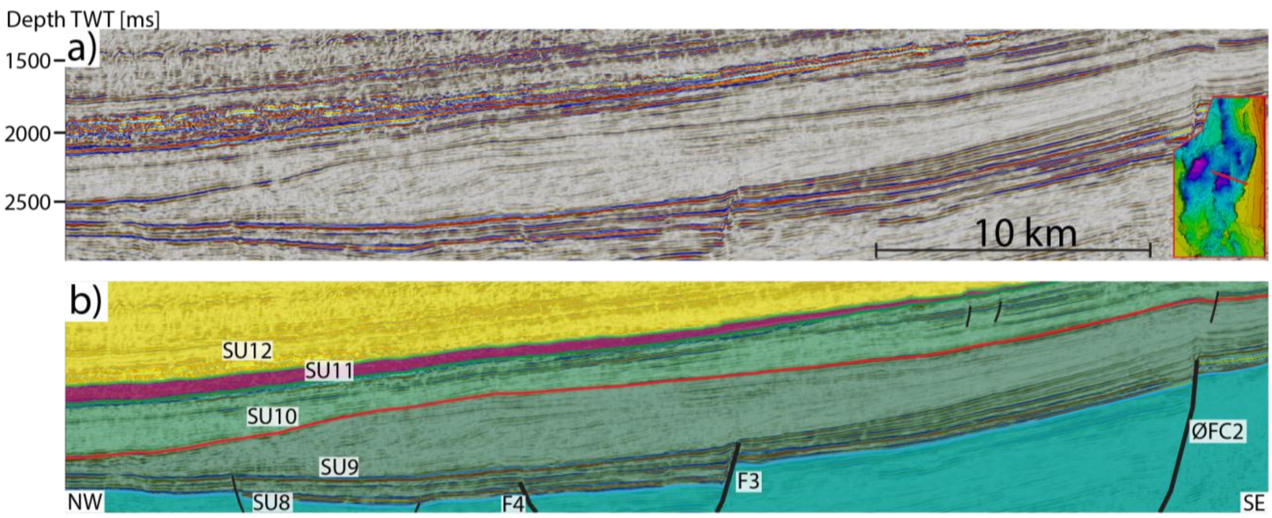


Fig. 4. 26. Close up of a) uninterpreted and b) interpreted section of NSR06-22156. a) A miniature of the study area in gives the location of the seismic section. b) The seismic units 8-12 (SU 8-12), intra-basin faults 3 and 4 (F3 and F4), as well as Øygarden Fault Complex 2 (ØFC2) are marked. The close up shows the clinoform of SU9.

Seismic Unit 10: Lower Cretaceous

Seismic Unit 10 was generated between the horizons Base Cretaceous Unconformity and Top Cromer Knoll surfaces and is therefore of Lower Cretaceous age. None of the thickness trends in this thickness map can be directly related to the Permian-Triassic faults discussed in this thesis. The northern and southern parts of the study area have increased thicknesses of over 600 ms, which grades to lower thicknesses in towards the central parts (Fig. 4.27a). Above the north-trending line dividing the previous succession, Mid-Upper Jurassic, there is a trend of lower thicknesses. Above and near the Utsira High west of this line, the thicknesses decrease. East from this North-trending line the thickness firstly decreases before it ranges around 300 ms. The faults described earlier in this chapter does not transect the Lower Cretaceous package.

Seismic Unit 11: Upper Cretaceous

Seismic Unit 11 thickness map was generated between Top Cromer Knoll and Top Shetland, hence it represents the Upper Cretaceous. It shows thickening from the ØFC2 into the basin (Fig. 4.26). The thickness trends in this unit differs from the previously presented maps. The largest thicknesses of over 200 ms can be found in the Southern Stord Basin (Fig. 4.27b). From the southwestern corner towards the northwest, the thickness of the Upper Cretaceous package rapidly decreases. Further east, there is a narrow area with the same northwest direction where the thickness is about 150 ms. East of this line, the larger thickness from the south has a shallower grading towards the northwest corner where it reaches 100 ms. The fourth area of northwest trend has 0-75 ms thicknesses which increase to 200 ms further east. The Upper Cretaceous package's setting differs from the underlying Lower Cretaceous package. None of the previously described faults transect this sedimentary package.

Seismic Unit 12: Cenozoic

The Seismic Unit 12 thickness map was generated between Top Shetland and Top Nordland, which represents the seabed. This package constitutes the Cenozoic sediments in the Stord Basin, which reaches over 2000 ms thickness. In general, the unit thins towards the Norwegian coast (Fig. 4.27c). From east to west, the thickness of the Cenozoic package decrease. The southwestern corner of the study area has a thickness of 1200 ms which increases to over 200 ms as one moves to the north. The Cenozoic has a different pattern than the previous Upper Cretaceous package and is not cut by the previously described faults.

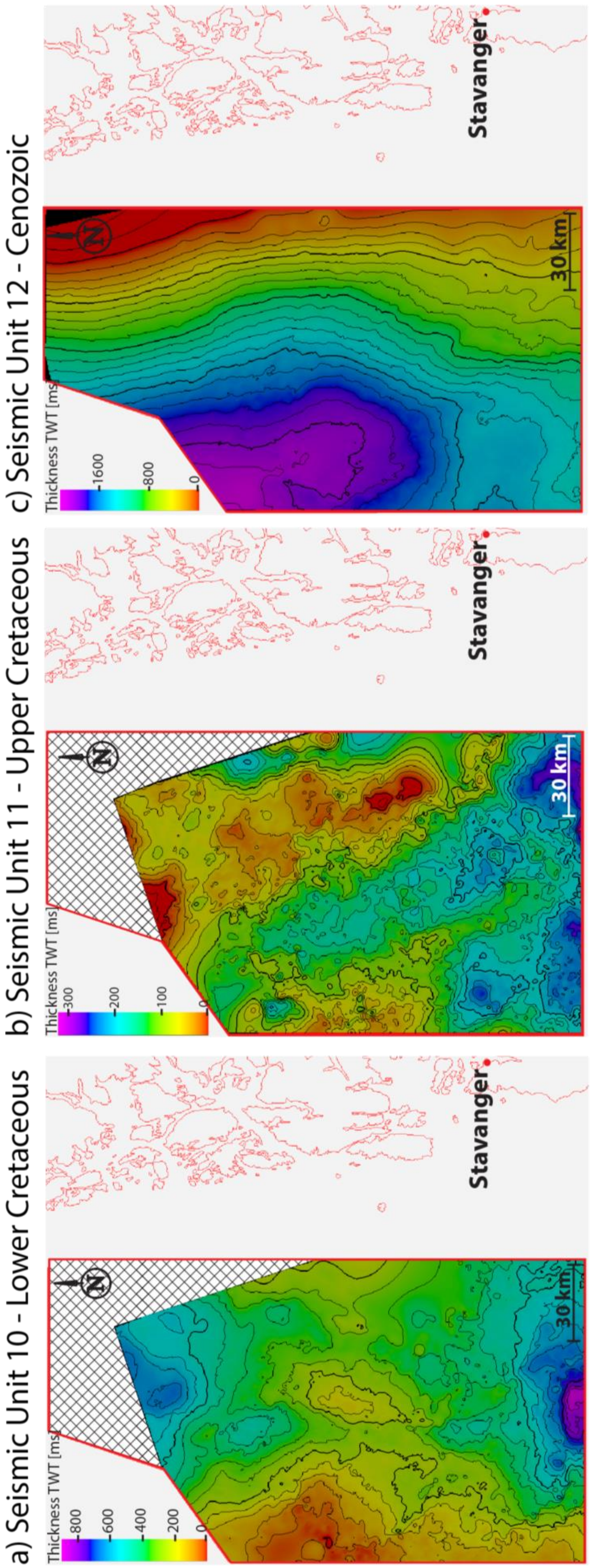


Fig. 4. 27. TWT thickness maps of a) Seismic Unit 10 of the Lower Cretaceous, b) Seismic Unit 11 of the Upper Cretaceous and c) Seismic Unit 12 of the Cenozoic. The major faults earlier discussed in this thesis cannot be distinguished in these three thickness maps. The Norwegian coastline is displayed to the right and gridded areas represents erosion.

4.4.3 Temporal fault activity

The thickness maps indicate the fault activity through time by looking for packages thickening towards the faults. The faults under evaluation at each interval is the UFC 1-3, ØFC 1-4 and F1-5. The activity of these faults through time is proposed in Fig. 4.28. At the Top Syn Rift level, the fault activity within the centre of the Stord Basin ceases. From this level up, only the basin bounding faults reflect activity in the thickness maps, although some movement can be seen along intra-basin faults locally.

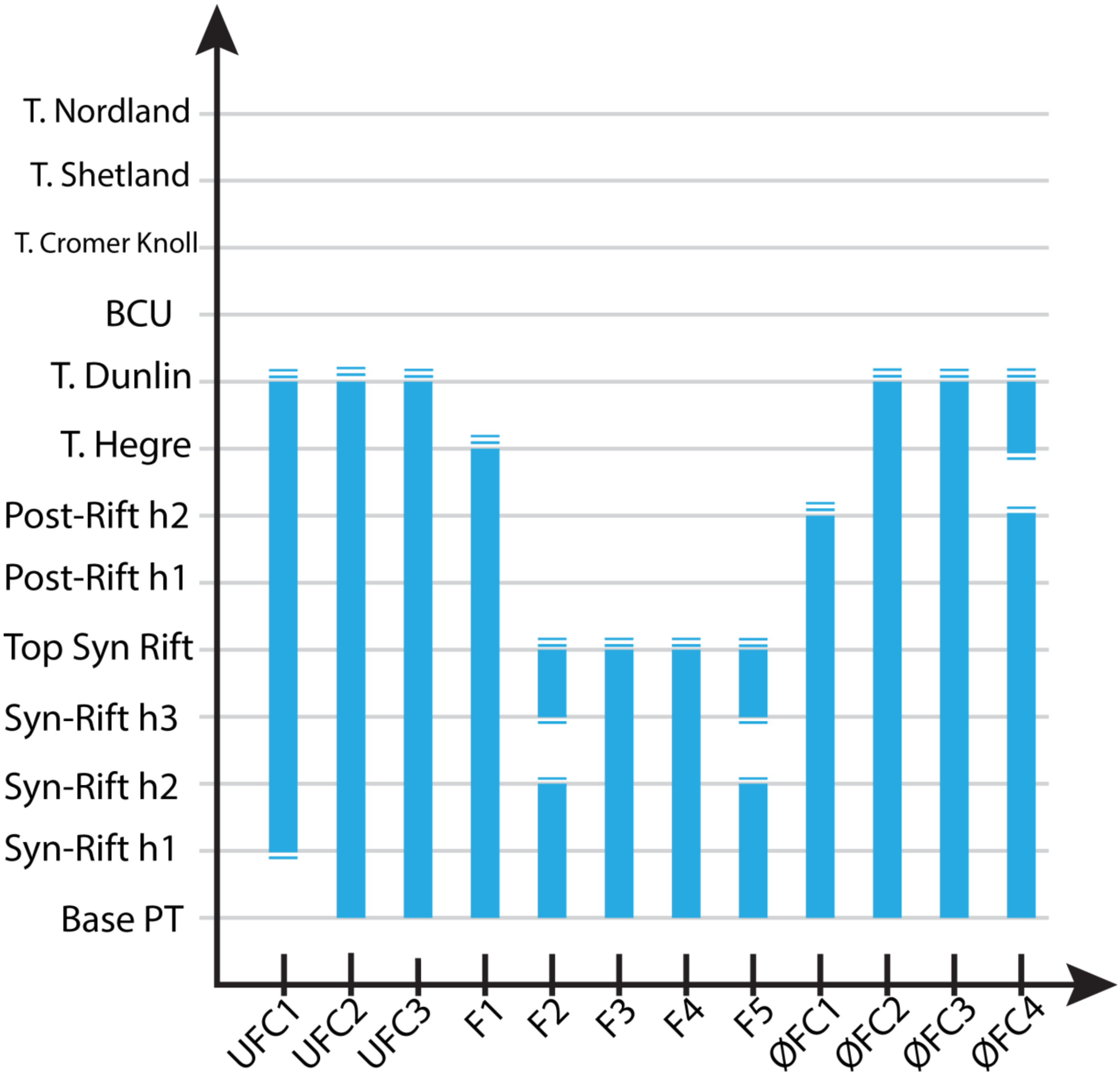


Fig. 4. 28. Diagram showing which faults (x-axis) were active at which level (y-axis). The fault abbreviations are as follows; Utsira Fault Complex 1-3: UFC 1-3, intra-basin faults 1-5: F 1-5 and Øygarden Fault Complex 1-4: ØFC 1-4. The horizons are Syn-Rift horizons 1-4 (Syn-Rift horizon 1-4) and Post-Rift horizon 1-2 (Post-Rift horizon 1-2), Top Hegre, Top Dunlin, Base Cretaceous Unconformity (BCU), Top Cromer Knoll, Top Shetland and Top Nordland.

The Seismic Units 1-4 (Base PT-Top Syn Rift) all show a clear trend of thickening toward the faults, with the exception of UFC1 for Syn-Rift 1. The early rifting Syn-Rift 1 package shows clearly thickening against the faults, especially in the Central Stord Basin, but the deposits does not extend far into the basin. The largest thickening towards the faults is found in the following Syn Rift 2, with the largest deposits in the Central Stord Basin. In this interval the packages extend further into the basin, covering a larger area. This indicates large creation of accommodation space and high sediment supply. The Syn-Rift 3 also show deposits covering most of the basin but no as distinct thickening against the faults, except from F1 in the north. The central and north have the largest thicknesses, but the deposition centre along ØFC2 has shifted southwards, and the F1 has significant thickening towards the fault. Syn Rift 4 covers the whole Stord Basin. The deposition centre along ØFC2 has now moved northwards again and thickening against the faults on the whole eastern boundary, in the north and in the central west is observed.

The ØFC2 and UFC2 are associated with the most expansion, indicating that they were highly displaced. The thickening is largest for UFC2 in Syn-Rift 1, pretty even for UFC2, the central intra-basin faults and ØFC2 in Syn-Rift 2-3, and largest for ØFC2 in Syn-Rift 4. This could be an indication of an eastward shift in where the maximum displacement was taken up, an eastwards shift in strain.

The Seismic Units 5-6 (Top Syn Rift-Post-rift horizon 2) does not show the clear thickening against the fault as the syn-rift successions and the intra-basin faults (F2-5) cannot be distinguished. Both packages have an area with the maximum thickness within the basin between F1 and UFC2, which for Post-Rift 2 extends further south. This could be an indication of subsidence. Thickening against the F1 can be distinguished in both intervals. Slight thickening against parts of the faults UFC1, UFC2 and ØFC2 in the Central Stord Basin can be observed, but it is not at prominent as in the syn-rift succession. A similarity between the syn-rift and post-rift is that the largest thicknesses are found along the bounding faults in the central and in the north.

The faults terminated in the Late Jurassic interval (Top Dunlin-BCU), which corresponds to the second rift phase. The faults cannot be distinguished in the Late Jurassic thickness map. The thickness map is dominated by post-rift deposits, but the Top Dunlin surface map is clearly faulted. This infers that there is Late Jurassic fault activity in the Stord Basin, which is followed by post-rift sediments, dominating the thickness map's appearance.

4.5 Strain analysis

Strain is the geometrically modification of something pre-existing by changing the length or shape of the object or mass in one, two or three dimensions (Fossen, 2010b). The deformation can be brittle or ductile. The rocks in the Stord Basin are strained through the process of faulting and creation of Devonian shear zones. Larger throw and heave means larger vertical and horizontal strain, respectively. The heave accumulation maps were created by using Eq. 3.1 and Eq. 3.3, while the throw accumulations were created by using the Eq. 3.1 and Eq. 3.2.

By importing the throw and heave values of the Stord Basin faults into Petrel together with the coordinates of the measuring point, one can compare the strain distribution along the faults at different levels in the Stord Basin in map view (Fig. 4. 29). This has been done for the major faults of the Øygarden Fault Complex (ØFC), the Utsira East Fault Complex (UFC), F1, F3 and F4, where possible. F1, F3 and F4 does not breach the Top Hegre surface.

For both the heave and throw of the Base PT, the highest values are found along ØFC2, ØFC3, F1, UFC1 and UFC2 (Fig. 4.29a, b). ØFC4 has an increase of heave in the central section, where it also has a minor increase in throw. The intra-basin faults F3 and F4 has the same range in values as ØFC4, while the UFC3 fault has very low heave and throw values. The largest horizontal strain is located in the Central Stord Basin and in the south of the Northern Stord Basin on the major bounding faults. Intra-basin fault F3-4 and the southern faults ØFC4 and UFC3 have the lowest values at Base PT level. The F1 in the north has moderately higher values. The ØFC2-3 and UFC1-2 have similar heave values, with some local maxima along UFC2's fault bends. The throw, however, is distinctly higher at the northern ØFC2.

The Utsira East fault Complex (UFC 1-3) and the Øygarden Fault Complex (ØFC 1-4) are the only major faults to transect the Top Hegre surface. The UFC1 and UFC2 are merged to form one single fault, where the fault activity has moved west by the abandonment of the northernmost segment of UFC2 to the UFC1 at Top Hegre level (Fig. 29c, d). The ØFC2 and ØFC3 on the east side of the Stord Basin have also hard-linked, with the northern ØFC3 segment abandoned too. The Utsira East Fault Complex has high heave values in the Central SB with a maximum towards the south. Its throw values are increasing northwards in the Central SB. Elevated heave and throw values are also found in the UFC3 in the Southern SB. The heave and throw values along the ØFC are increasing to the south, where they are at their maxima. The throw values peak in the ØFC2-3 linkage area. Both the heave and throw values for UFC exceeds the ØFC at the Top Hegre level.

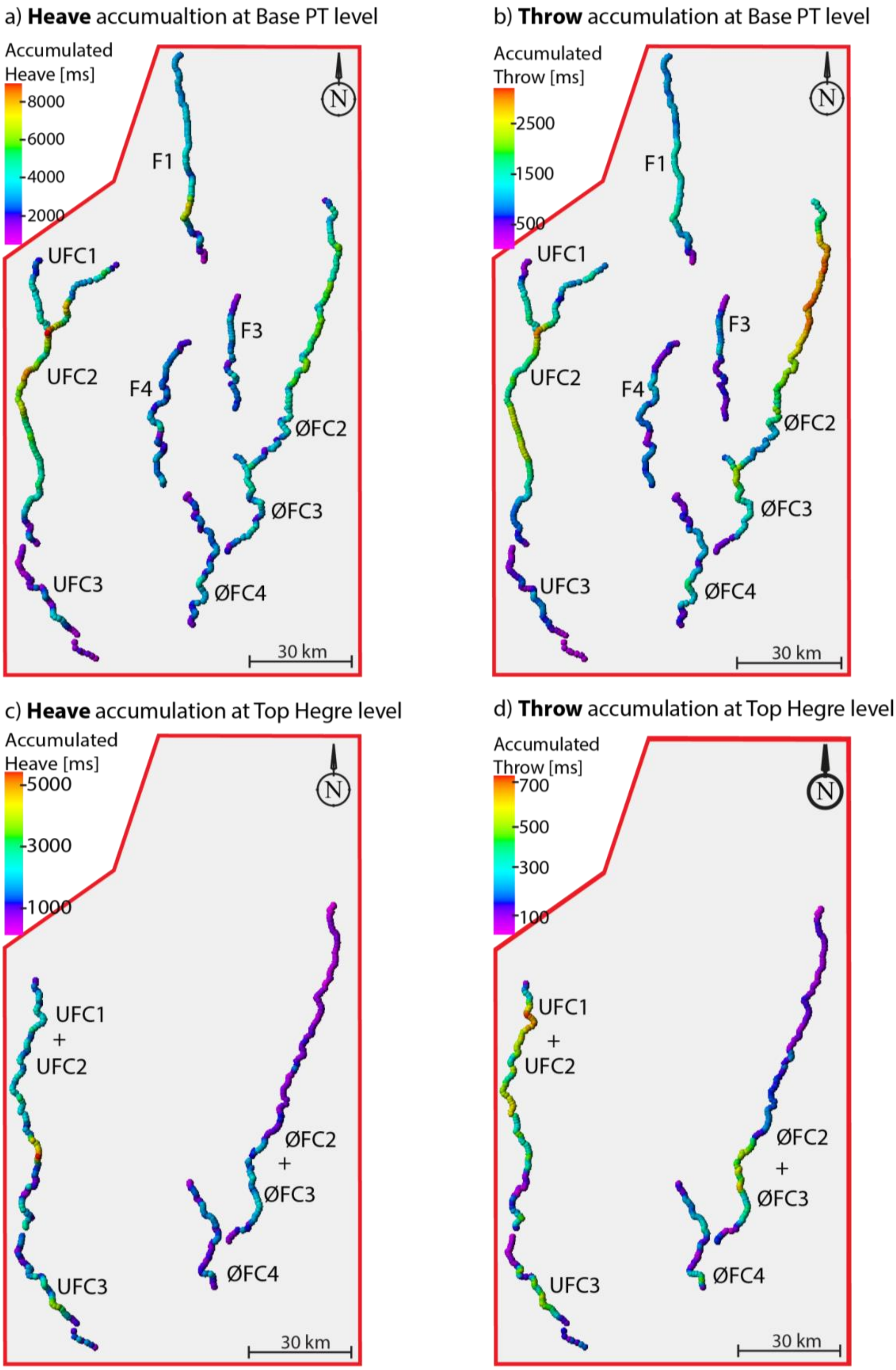


Fig. 4. 29. Map view of the heave and throw values placed directly on top of the fault in question. a) Heave accumulation at Base PT level. b) Throw accumulation at Base PT level. c) Heave accumulation at Top Hegre level. d) Throw accumulation at Top Hegre level. Note the different legends for the heave and throw values at each level.

The shift of strain concentration through time can be seen by comparing the changes in heave and throw maxima of the Base PT level with the Top Hegre level.

The Base PT has been through deformation in both the Permian-Triassic rifting phase and the Late Jurassic rifting phase. The maximum heave and throw values for the Øygarden Fault Complex are located on the central to north of ØFC2 at Base PT level, in the Central SB. The maximum values are located on the south tip of ØFC2 and along ØFC3 at Top Hegre level, in the Central to Southern SB. At Top Hegre level, UFC3 in the Southern SB has higher heave and throw values compared with surrounding values. This shift of vertical and horizontal strain maxima from the north towards the south along ØFC and higher movement along UFC3, implies that the strain migrated to the south from the Base PT to the Top Hegre faulting. The area of maximum heave and throw values along the UFC1 and UFC2 is approximately the same for both levels. Both heave and throw values have their maxima along the UFC in the western Stord Basins' central area. This implies a strain migration to the west. The general trend in the Stord Basin is strain migration towards the west and south after the Permian-Triassic rifting.

4.6 Restoration and extension factor

A cross section through the Stord Basin has been restored to better understand the Permian-Triassic rifting phase. This allows calculation of the stretching factor (ß) in the time interval from one of the interpreted horizons to the next. Adobe Illustrator has been used to restore each interpreted surface to its (more or less) horizontal appearance as it had during deposition. The restored section was constructed in collaboration with Haakon Fossen. Four steps from the present day setting to the pre rifting setting is presented (Fig. 4.30). Shear strain has been taken into account during the restoration, while compaction, subsidence and isostasy has been neglected. The complete succession of restored steps has been used to calculate the elongation and furthermore make a graph of the cumulative stretching through time. The seismic cross-section used, NSR09-41153, is oriented NW-SE. This deviates from the E-W stretching direction of the northern North Sea and will cause overestimation in the calculation of the stretching of the Stord Basin.

The restoration indicates the setting during the deposition of each of the restored horizons and provides insight in the evolution of the Stord Basin (Fig. 4. 30 a-d). The present day setting (Fig. 4. 30a) shows footwall collapse of UFC2 compared to earlier times (Fig. 4. 30b). The Upper Triassic displays more or less tabular packages on top a large sedimentary rift succession (Fig. 4. 30b). The section from intra Permian-Triassic shows substantial syn-tectonic packages (Fig. 4. 30c), while the pre-rifting surface displays variations in topography (Fig. 4.30d).

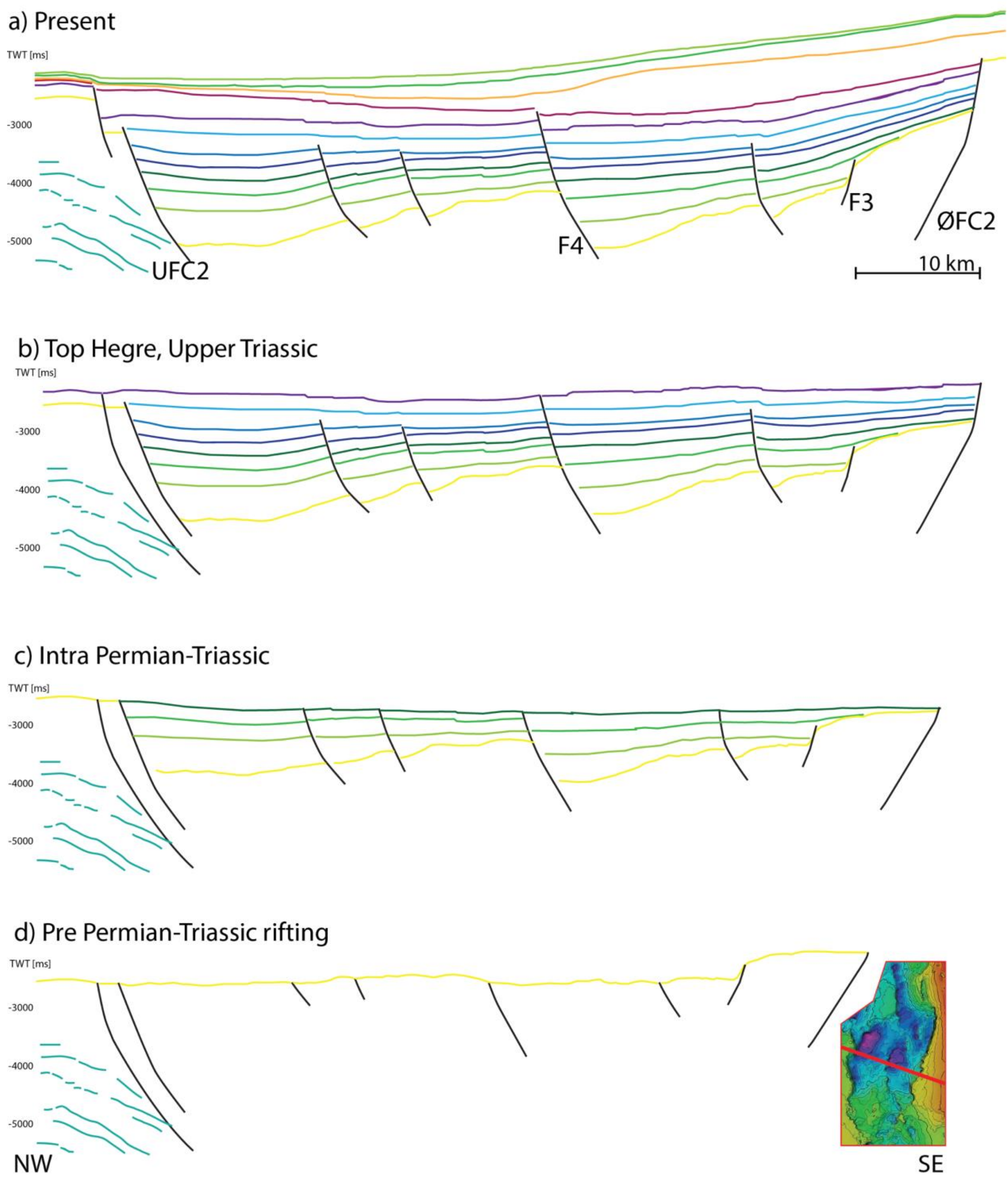


Fig. 4. 30. Four step restoration of a NW-SE transect across the Stord Basin illustrating the a) present day, b) Upper Triassic, c) intra Permian-Triassic and d) pre-rift settings. The small map in the bottom right specifies the location for the transect NSR09-41153. The major faults of interest have been labelled; Utsira East Fault Complex 2 (UFC2), intra-basin Faults 3 and 4 (F3 and F4) and the Øygarden Fault Complex 2 (ØFC2).

The elongation has been calculated for each interval and the stretching through time in the Stord Basin is presented in Fig. 4.31. The stretching is defined as 1 at pre-rift. The y-axis on the graph starts at 1.45 to better differentiate the stretching in each interval following SR1. The graph is cumulative giving the total amount of stretching during the Permian-Triassic to be 1.56, which is distinctly higher than the stretching of 1.3-1.4 found for the whole northern North Sea (Yielding et al., 1992, Faerseth, 1996). The stretching in this study is calculated along a transect deviating from the stretching direction, which causes overestimation. In addition, it could be possible with localized higher stretching for the roughly isolated Stord Basin.

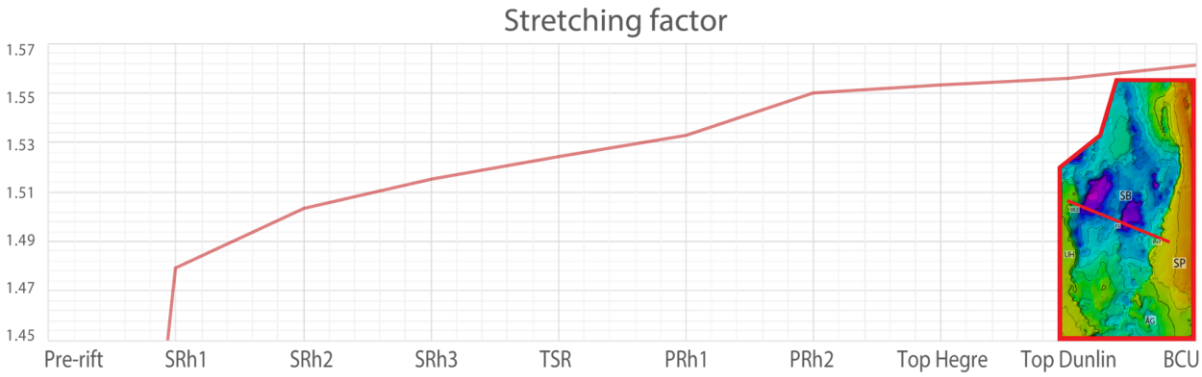


Fig. 4. 31. The graph is showing the cumulative stretching for each interval of interpreted horizons. The y-axis is adjusted to start at 1.45 to better see the details in the stretching. The stretching equals 1 at Pre-rift length. The seismic line in question is marked with a red lineon the stamp of the Stord Basin, lower right hand side.

The stretching from pre-rift to the deposition of syn-rift 1 is 1.48 (Fig. 4. 31). This constitutes 94.9% of the total Permian-Triassic stretching. Increased gradient to Syn-Rift 2 and Post-Rift 2 is also observed, but on a much smaller scale. (All though the intra PT surfaces are not age determined) one can conclude that the Stord Basin obtained a large amount of the Permian-Triassic stretching in the early stages of rifting. The stretching continued at a steady pace with a larger increase in the PR1-PR2 interval. The Permian-Triassic rifting phase and the Late Jurassic rifting phase is not clearly defined. The stretching is continuous from the first rift initiation to the Base Cretaceous Unconformity.

4.7 Evolutionary model

By analysing the presented data, an evolutionary model of the Stord Basin has been proposed (Fig. 4.32). The model is made up of four steps, ending at the present day setting. The first step is the Permian-Triassic rifting (Fig. 4.32a). In the model, the faults are thought to have established lengths early on, based on the previously described thickness maps, and sediments are deposited in the hanging walls and covering the basin. Step 2 is of intra-rift setting, where some inter-rift movement along parts of the major bounding faults are indicated by marking them with dashed lines (Fig. 4.32b). Step 3 displays Late Jurassic rifting with reactivation of some of the major faults (Fig. 4.32c). Step 4 of the model is the present structural setting of the Stord Basin (Fig. 4.32d). The top layer of the model in the Top Shetland representing the Top Cretaceous.

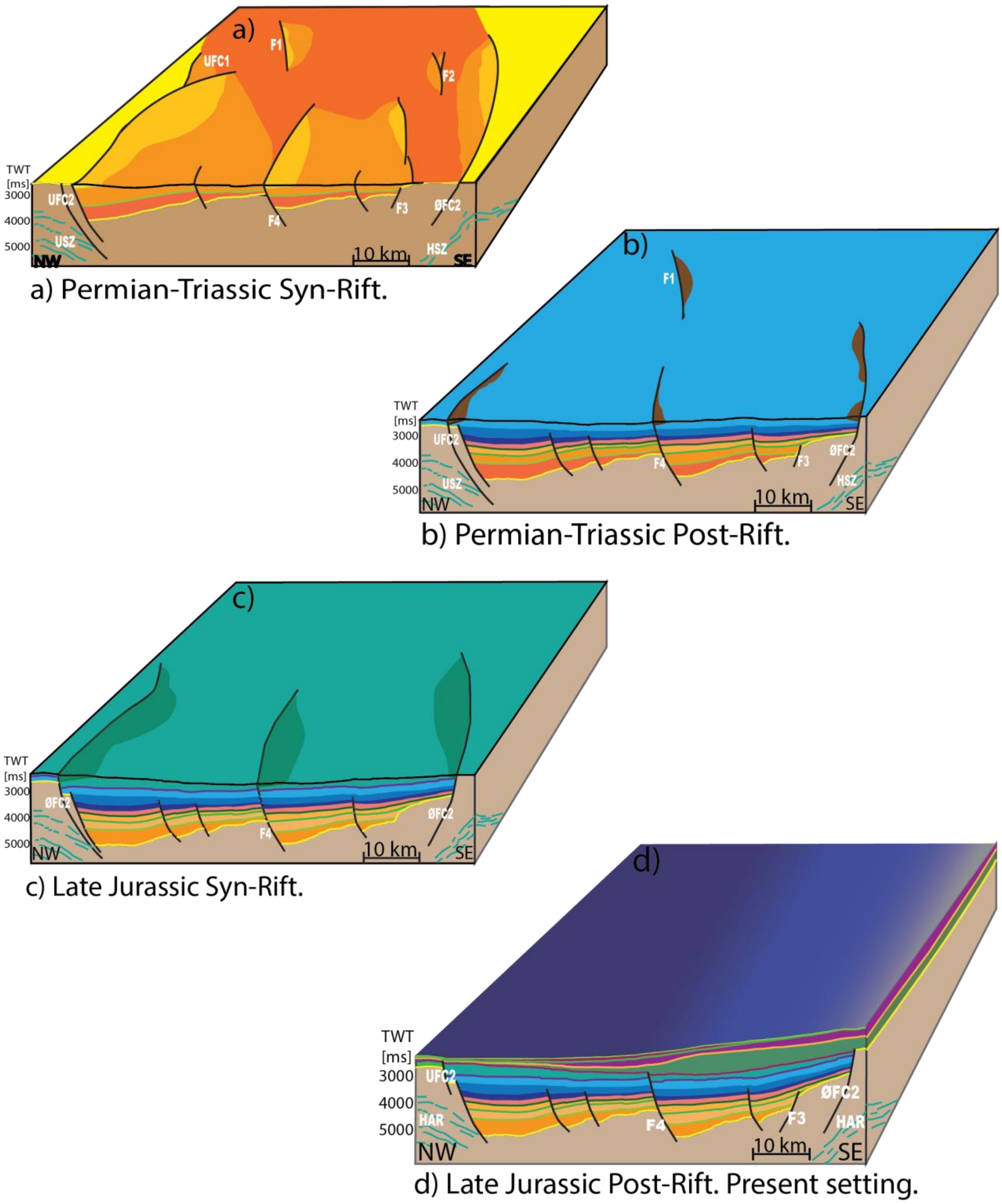


Fig. 4. 32. Proposed evolutionary model of the Stord Basin from the a) rift initiation and Permian-Triassic Syn-Rift and b) Permian-Triassic Post-Rift with contnuing movement along major boundary faults. c) Late Jurassic Syn-Rift with reactivation along major boundary faults and d) Late Jurassic Post-Rift and present day setting. Utsira East Fault Complex 1 and 2 (UFC1-2), Øygarden Fault Complex 2, Fault 1 (F1) intra-basin Faults 3 (F3) and 4 (F4) are marked in the d) present setting. Higth Amplitude Reflections (HAR) in the NW are of the Utsira Shear Zone and the reflection in the SE are of the Hardangerfjord Shear Zone.

5. Discussion

The Permian-Triassic stratigraphic evolution in the Stord Basin is directly linked to its structural evolution. This chapter will be initiated by a discussion of the syn-rift and post-rift labelling, which is important in determining the timing of rifting in the Stord Basin. It will continue with a look on the possible effect pre-existing structures, i.e. Devonian shear zones, had on the formation of faults in the Stord Basin. The discussion will be wrapped up by studying the Permian-Triassic rifting vs. the mainly Late Jurassic rifting and comparing the Stord Basin to other basins in the North Sea with Permian to Triassic origins. This is to see if the findings in the Stord Basin can be transferred to other basins or the other way around. By discussing these topics, I hope to shed light on the tectono-stratigraphic evolution of the Stord Basin.

5.1 Determination of Permian-Triassic syn-rift and post-rift

The lithospheric crust in the northern North Sea has been severely thinned through multiple rifting episodes (Faerseth, 1996). McKenzie (1978) proposed a two stage model to explain the rift-evolution in the northern North Sea, which led to the creation of multiple sedimentary basins, including the Stord Basin. The fault activity through time in the Stord Basin is indicated by the thickness maps previously presented.

The first stage of the model encompasses rapid thinning of the continental crust (McKenzie, 1978). The thinning of the crust causes a passive upwelling of the underlying asthenosphere, which heats up the crust. Block faulting and subsidence are characteristic in this stage, which causes syn-sedimentary, wedge shaped basin fills. This corresponds with the structures in the Stord Basin, where all the faults show syn-sedimentary features from Base PT to Top Syn Rift and is further supported by the calculated stretching (Fig. 4.31).

In the second stage of the model, heat conduction from the asthenosphere causes thickening of the lithosphere (McKenzie, 1978). Slow subsidence without any association of faulting is characteristic for this stage of the model, which means that tabular post-rift deposits would be expected. The Post-Rift 1 and 2 packages of intra Permian-Triassic shows thickening in the central Stord Basin, but also slight thickening against the basin bounding faults in some areas (Fig. 4.24). The F1 in the Northern Stord Basin shows clearly syn-sedimentary features in the interpreted post-rift succession. This indicates that the Stord Basin did not have a stage of complete fault quiescence between the Permian-Triassic rifting and the Late Jurassic rifting, as postulated by the McKenzie model. In addition, the restoration data tells that there was ongoing stretching from the rift initiation of the Permian-Triassic to the BCU, which marks the end of the Late Jurassic rifting. The stretching plots presented in the results shows large movement in the early syn-rift and continuous smaller-scale stretching from the initial rifting to the BCU. The two rift phases are not clearly separated by fault quiescence across the entire Stord Basin. This rises the discussion of the Top Syn Rift horizon labelling, namely if it is at the right level or if it is normal with some fault movement in the post-rift phase. Other works will be investigated to either validate or discard the determination of the top syn-rift level.

A factor which can explain the observed continued fault activity during the presumed post-rift phase is subsidence-induced fault movement, also called inter-rifting (Beach et al., 1987, Ravnås et al., 2000). Decay of the heat-flow anomaly created by rift-induced thinning of the crust caused subsidence in the Mid-Late Jurassic post-rift stage in the northern North Sea, and thereunder the Stord Basin (Biddle and Rudolph, 1988, Steel and Ryseth, 1990, Odinsen et al., 2000, Ravnås et al., 2000). In the Horda Platform and East Shetland Basin, the Permian-Triassic post-rift had multiple high subsidence rate periods (Steel, 1993). Increasing thicknesses in the Post-Rift 1 and Post-Rift 2 packages have been observed towards the central parts of the Stord Basin, which indicates subsidence (Badley et al., 1988). The T-x plot of ØFC2 earlier described, also indicates inter-rifting (Fig. 4.14). A study on 3D seismic covering a section of the Utsira East Fault Complex documented fault activity in the inter-rift period between Permian-Triassic and Late Jurassic rifting (Refvem, 2016). Activity along larger faults in the North Sea have been documented during the thermal cooling periods after the two rift phases (Odinsen et al., 2000). Subsidence-induced fault movement in the Stord Basin is therefore a possible explanation to the continued fault activity observed during Permian-Triassic post-rift phase.

Another factor which may explain the continued fault movement along some parts of the larger faults and the simultaneous cessation of fault movement on the intra-basin faults, is the possibility of a diachronous transition from syn-rift to post-rift within the Stord Basin. This is based on the assumption that the created accommodation space during rifting was filled by sediments before the post-rift, i.e. the sedimentation is mainly a product of active rifting. Looking at the whole northern North Sea, the transition from syn-rift in the mainly Late-Jurassic rifting to the post-rift phase was highly diachronous due to thermal variations in the crust (Gabrielsen et al., 2001). Papers regarding possible thermal variations within the Stord Basin have not been found, but the reactivation of Permian-Triassic faults have been found to be diachronous in the Horda Platform, Uer Terrace and Måløy Slope, which is located north of the Stord Basin (Bell et al., 2014). The thickness maps indicate continued minor fault movement in the Southern and Central Stord Basin from Top Syn Rift to the end of Late Jurassic rifting. F1 in the Northern Stord Basin shows fault activity from the Top Syn Rift which was deactivated at the onset of Late Jurassic rifting. The cessation of F1 in the Late Jurassic rifting could be explained by the fact that multiple westwards dipping faults took over the displacing at this time (Cowie et al., 2005). Large faults dipping towards the rifting axis are prone to large movement during reactivation, as well as reactivation of faults near the rifting axis. This resulted in strain migration towards the rifting axis beneath the Viking Graben.

Finding good examples of subsidence induced fault movement and diachronous syn- to post-rift transitions for the Permian-Triassic rifting is a difficult job due to the sparse literature on this interval of the geological history. Examples from the Late-Jurassic rifting phase is abundant and are found to be good analogues as the processes of the later rifting must follow the same physical principles as in the first. The McKenzie (1978) model does not completely fit the evolution depicted for the Stord Basin in this thesis. The northern North Sea has proven more complex than what the model implies, which is also the conclusion of Gabrielsen et al. (2001).

Considering the inter-rifting and diachronous cessation of rifting, the Top Syn Rift interpretation is deemed probable and the best representation of the tectonic divide. The thickness maps provide a good indication of the fault activity in the Stord Basin, which shows that the Top Syn Rift surface represents the divide between high and low activity. The Stord Basin goes from a setting with fault activity on all the major faults in the study area with relatively high displacements to a setting with low displacement along mostly the bounding faults. The underlying packages displays major wedging trends going towards the faults, while the overlying packages have a more tabular appearance with thickening towards the central Stord Basin. The Top Syn Rift horizon labelling is deemed good as it represents a significant drop in fault activity, separating the syn-rift from post-rift within the Permian-Triassic rifting phase. The top syn-rift level have been found to have maximum age of top Lower Triassic in the east and west flanks of Viking Graben (Nottvedt et al., 1995). The Top Syn Rift interpretation is an important part of the determination of the tectonic activity and timing of rifting in the Stord Basin, i.e. the determination of the tectono-stratigraphic evolution. The Stord Basin was initiated by Permian(-Triassic) rifting by the formation of major basement-cutting faults. This created rotated fault blocks filled with syn-tectonic sediments through continuous rifting up to Top Syn Rift. Above this level, in the post-rift, the intra-basin faults terminated, subsidence-induces faulting occurred along the basin bounding faults ØFC and UFC, and active faulting along F1.

5.2 Influence of pre-existing shear zones.

A shear zone is a tabular zone in the crust, which has been strained by ductile deformation, most often during simple shear (Fossen, 2010b). This sub-chapter will take a closer look at the possible links between pre-existing intra-basement shear zones and the orientation and geometry of the succeeding Permian-Triassic faults in the Stord Basin.

The Stord Basin is located between two NE-SW going domain boundaries, encompassing the structures of the basin in one domain (Fossen et al., 2016). The structural style of the Stord Basin is roughly divided from other domains by the shear zones. The Utsira Shear Zone (USZ) envelopes the basin to the NW and W, while the Hardangerfjord Shear Zone (HSZ) constrain the basin to the S and SE. A general trend can be detected by describing the map view geometry of the faults in relations to the shear zones. The intra-basin faults located away from the shear zones have a N-S orientation, as one would expect with the major stretching direction being E-W (Bartholomew et al., 1993, Faerseth, 1996, Cowie et al., 2005). Faults approaching the shear zones curves and aligns with them, in spite of the E-W stretching direction.

Permian-Triassic faults formed perpendicular to the current E-W stretching direction, but seems to bend off when encountering pre-existing basement structures. The intra-basin faults F2, F3, F4 and F5 are all oriented in a mainly N-S trend and are not located in close proximity of either of the two shear zones. The F2, F3 and F4 all curve northeast at their northern ends and align above the area where USZ is terminated at larger depths. The Base PT surface is structurally shallower in a NE-SW going trend, north of this alignment. Movement along USZ could have strained the basement rocks causing the creation of a minor high ground in the Base PT above the USZ termination. This area seems to act as a restriction for the fault propagation, as F2, F3 and F4 aligns with it before terminating, instead of transecting it. This implies that the intra-basin faults' termination northwards were controlled by the presence of a pre-existing shear zone. F1 also have a N-S orientation and aligns with the USZ in the southern footwall of the fault.

The pre-existing Devonian shear zones located in the study area makes the basement rock heterogeneous. All of the faults which deviates considerably from the expected N-S trend are invariably located in proximity to one of the shear zones. This implies that the pre-existing structure have influenced the orientation of later Permian-Triassic faults in the Stord Basin to some extent. Major N-S trending faults in the Oseberg South fault block have been found to have influenced secondary, smaller faults with orientations differing from the major faults' orientations (Maerten et al., 2002). The smaller faults formed in the later phase of the larger faults' development during E-W rifting, but elastic deformation around the larger faults caused the smaller faults to form with a different orientation. This setting is different from the setting in the Stord Basin where all the investigated faults, which initiated simultaneously according to the thickness maps, instead of at different stages. In spite of the difference between Stord Basin and Oseberg, the findings of Maerten et al. (2002) shows that pre-existing structures have a clear effect on the orientation and geometry of succeeding structures in their proximity. Pre-existing structures can cause later structures to form non-perpendicular to the dominating stretching direction. This fact supports the interpretation of the Devonian shear zones exerting control on the Permian-Triassic faults' orientation and geometry, although they are from two different tectonic events.

An interesting observation is that the USZ is located along the Stord Basin's western boundary and that the southeast boundary, made up by southern ØFC, is aligned with the HSZ. The shear zones seems to be a controlling factor for the extent of the Stord Basin and divide the Stord Basin into one structural domain, as documented by Fossen et al. (2016). The basin faults with the largest displacements are those which appears to be influenced by the shear zone, in addition to the major bounding fault ØFC2 further north of the HSZ. This could be due to higher strain accumulation in the shear zone areas, early fault initiation and hence longer period of fault activity near the shear zones, reactivation along these faults in Rift Phase 2 or any combination of these. A likely reason the Stord Basin was (likely) isolated during the Permian-Triassic rifting is the shear zones, which set the divisions of structural domains in the northern North Sea (Fossen et al., 2016).

The influence of pre-existing Devonian extensional structures, i.e. shear zones, on the later Permian-Triassic rifting is a fairly new focus area in the depiction of the northern North Sea's structural development. It has been proven that the HSZ, which cuts into the lower crust offshore (Fossen and Hurich, 2005), have affected the overlying rocks in respect to both folding and faulting (Fossen, 2010a). A the aforementioned trend of intra-basin faults F2-F5 in the Stord Basin, Fossen et al. (2016) have found that major N-S trending faults are bending or terminating against Devonian (Mode II) structures, i.e. shear zones. This supports the theory of the shear zones having a controlling factor on the extent of faults of newer age in the Stord Basin.

The location and orientation of younger faults are not necessarily influenced by the presence of older shear zones in all settings (Fazli Khani, In prep). In some cases, they form perpendicular to the stretching direction regardless of the shear zone, which they can transect and displace. The shear zones located in the study area have had a significant impact on the orientation and geometry of the Permian-Triassic faults. Hence, the shear zones are important features in the tectono-stratigraphic evolution of the Stord Basin.

5.3 Significance of the Permian-Triassic rifting

The seismic interpretations of the Stord Basin reveal a large sedimentary package from the Base PT surface to the Top Hegre surface. This succession was deposited during the Permian-Triassic rift phase and in the following post-rift phase. It therefore predates the mainly Late Jurassic rift phase. The package between Top Hegre and BCU, (more or less) represents the Late Jurassic rifting interval, which contains minor thickness in comparison. This shows that the Permian-Triassic rift succession is more prominent in the Stord Basin than the Late Jurassic rifting. The total extension of the Permian-Triassic rifting is higher than the Late Jurassic rifting in the Horda Platform, north of the study area (Bell et al., 2014).

The East Shetland Basin on the eastern Viking Graben flank is similar to the Stord Basin on the western Viking Graben flank in that it is a Permian-Triassic basin without salt deposits formed under E-W extension (Steel and Ryseth, 1990). The Late Jurassic overprint is about 15 % in the East Shetland Basin, about 5 % in the Horda Platform and even less in the Stord Basin (Tomasso et al., 2008). In general, the Late Jurassic rifting had higher influence in the northern Horda Platform than in the south. This tells that the East Shetland Basin is mainly a Permian-Triassic basin, like the Stord Basin, but the East Shetland Basin was probably more deformed during the Late Jurassic rifting. The East Shetland Basin had a period of erosion/non-deposition in Mid-Late Triassic (Steel and Ryseth, 1990). In the Stord Basin, the fault activity was continuous up to mid Jurassic and very limited after that, while in the East Shetland Basin the Late Jurassic activity is much more pronounced. Petroleum has been discovered in the East Shetland Basin in Upper Triassic-Lower Jurassic sediments in rotated, eroded fault blocks, covered by BCU (Tomasso et al., 2008). The same interval in the Stord Basin is sub-horizontal layered packages, hence the play of the East Shetland Basin cannot be transferred here.

The Egersund Basin is a half-graben, Permian basin located offshore the south coast of Norway, further south than the Stord Basin. The presence of salt in the basin caused the vertically decoupling of faults and strongly affected the fault evolution (Tvedt et al., 2013). The Stord Basin does not have vertical decoupling, but consist of continuous faults, transecting the basement and sediment infill. The presence of salt caused a very different structural evolution in the Egersund Basin than the Stord Basin.

Like the Stord Basin, the Viking Graben is also of Permian-Triassic origin, but their current geometries are quite different. The Viking Graben was later severely deformed during the mainly Late-Jurassic rifting phase, overprinting the Triassic structures. A large amount of sediments was deposited during this event, reaching up to 4 km thickness, which contrasts the thinner Late Jurassic sediments observed in the Stord Basin. The thickness of this Late Jurassic package decreases to the east and is significantly lower at the Horda Platform. The Late Jurassic rifting was concentrated along Viking Graben and tapered out towards the margins and Stord Basin. It is possible that the Viking Graben and Stord Basin were similar after the Permian-Triassic rifting, but the Viking Graben underwent severe rifting and reworking of the older deposits.

The Egersund Basin and Viking Graben are two rift basins of Permian-Triassic origin which are not suited as analogues for the Stord Basin. They both have distinct characteristics not found in the study area. The East Shetland Basin, on the other hand, is a better choice for analogue basin in the northern North Sea, concentrating on the Permian-Triassic succession. Comparing the Stord Basins features with the other more known basins of the northern North Sea provides insights on the likely tectono-stratigraphic evolution of the Stord Basin.

The heave and throw accumulation maps provides an illustration of the strain migration from the Permian-Triassic rift phase to the later rifting, mainly Late Jurassic (Fig. 4.29a-d). The maps show a trend of strain migrating westward and southward when comparing the values from Permian-Triassic rifting with the values of all the succeeding extensions. The westward migration of strain can be explained by the fact that more faults dipping towards the rift-axis and are located closer to the rift-axis tend to be prone to reactivation during later rifting and that the strain tend to migrate towards the rift-axis over time (Cowie et al., 2005). Late Jurassic rift-axis was located beneath the Viking Graben further west of the Stord Basin. The data clearly demonstrates that the Permian-Triassic rifting was the primary impact on the formation of the Stord Basin. From the Base PT to Top Hegre levels, there was an across rift strain migration towards the Late Jurassic rift-axis in the west, and an along rift strain migration towards the south.

The stretching factor of the Permian-Triassic syn-rift phase in the Stord Basin has been calculated to 1.53. This is higher than the stretching factor of 1.3-1.4 calculated across the Horda Platform, across the Viking Graben and to the East Shetland Basin (Yielding et al., 1992, Faerseth, 1996). A NW-SE seismic line was used to calculate the stretching factor in this study. The transect deviates from the E-W extension direction, causing the stretching factor to be overestimated. This discrepancy alone is unlikely to constitute the complete difference between the stretching factor in this study and the stretching factor found by Yielding et al. (1992). This could mean that the strain was higher in the Stord Basin to the south and decreased towards the Horda Platform to the north during the Permian-Triassic rift phase. The Horda Platform constitute of west-dipping faults, which have formed rotated fault blocks, while the Stord Basin is a bit different in that it is constrained by large, oppositely dipping faults. Deviation in the two calculated stretching factor is possibly an effect of the difference in rifting geometries in the two areas. It could also be an effect of the restrained length of the Stord Basin compared to the wide area from the Horda Platform over the East Shetland Basin.

6. Conclusions

The tectono-stratigraphic evolution of the Permian-Triassic rift event in the Stord Basin, northern North Sea has been presented in this master thesis. Results have been obtained by interpreting structural and thickness map, by doing fault and strain analysis and by restoration. Little data was previously available on the Stord Basin. The results from this research thesis have led to the following conclusions.

- The Permian-Triassic rifting phase have higher throw accumulation along Stord Basin's bounding faults than the throw accumulated in all the following extensions combined. Features from the Permian-Triassic rifting dominates the structural and stratigraphic setting of the Stord Basin and has not been overprinted by later events.
- The Stord Basin was isolated to the south during Permian-Triassic rifting.
- The Permian-Triassic and mainly Late Jurassic rifting phases are not clearly separated by a period of complete fault quiescence in the Stord Basin.
- Subsidence-induced fault movement is likely in the inter-rift period in the Stord Basin.
- Strain migrated across rift to the west and along rift to the south after the Permian-Triassic rifting phase in the Stord Basin.
- The estimated stretching factor for the Stord Basin from Permian-Triassic rift phase is higher than the stretching factor calculated further north in the Horda Platform.
- No basement cutting faults formed during deposition of the Late Jurassic rift interval. All major basement cutting faults show Permian-Triassic syn-rift activity in the Stord Basin.
- Fault analysis and thickness maps show that the major, mainly N-S trending Permian-Triassic faults consist of multiple linked sub-segments.
- The structural setting, i.e. location of the main bounding faults Øygarden Fault Complex and Utsira East Fault Complex in the Stord basin is restrained by the Utsira Shear Zone and the Hardangerfjord Shear Zone.
- Utsira Shear Zone is found to extend further north than presented in previous literature.

7. Implications and further work

This first model of the tectono-stratigraphic evolution of the Stord Basin proposed in this thesis can be utilized to continue the study of an evolutionary model. A suggestion for further work is to continue this study by an analysis of the expansion index at different latitudes in the Stord Basin. This can be combined by studying the heave accumulation across the Stord Basin in a north-south direction. Data collection of 3D-seismic and deep wells within the study area can facilitate higher resolution in the seismic interpretations and the dating of stratigraphy. This makes it possible to study the sedimentary depositions in detail from cores, to make a detailed study of the sedimentary succession and better constrain the tectonic environments. The increased amount of data can be used to possibly correlate the stratigraphy to other areas of the northern North Sea, e.g. Horda Platform and East Shetland Basin.

The results from this MSc thesis can be used as a basis for further work in the Stord Basin.

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