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Seismic - Stratigraphic framework of the Statfjord Group on the Utsira High

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Geology
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I Abstract

Sandstones of the Statfjord Group are important reservoir sandstones in the Northern North Sea. However, in the rest of the North Sea the Statfjord Group is underexplored. Sub-regional seismic interpretation on the Utsira High show available accommodation space during the deposition of the Statfjord Group, with increased accommodation space towards the end of deposition of the Group. A variation in the thickness of the Statfjord Group can be observed in the study area, with a thinning of the succession eastwards in the area. This suggests the variations of the Statfjord Group thickness is controlled by available accommodation space, hence the change in base level through time. Seismic horizons and faults show a post-rift Permo-Triassic depositional trend, affected by a later episode of Middle-Late Jurassic rifting and a reactivation of the Permo-Triassic faults. The varying thickness of the group, show the Permo-Triassic faulting generated the structural setting present during the deposition of the Statfjord Group. Regional well correlations and sub-regional seismic interpretations show the Utsira High was a paleotopographic high during deposition of the Statfjord Group. Well data shows continental environment dominated by large floodplains and rivers prevailed during the deposition of the group, with a thin layer of marginal marine deposits overlying the continental strata. High net-to-gross values of the Statfjord Group on the Utsira High indicate a proximity to the source area, but the high is situated a significant distance away from known provenance areas, implying a local source of sediments, possibly remnant rift topography on the high itself from the Permo-Triassic rift event. This suggests the high could divide two different fluvial drainage provinces in Late Triassic-Early Jurassic in the North Sea. Well correlations show differences in thickness and net-to-gross of the Statfjord Group in wells on the Utsira High, in the Viking Graben and Stord Basin, suggesting that available accommodation space during deposition was a controlling factor of sandstone connectivity.

II Sammendrag

Sandsteiner i Statfjord Gruppen er viktige reservoarbergarter i Nordlige Nordsjø, men i resten av Nordsjøen derimot, er Statfjord Gruppen lite utforsket. Sub-regional seismisk tolking på Utsirahøyden viser tilgjengelig akkomodasjonsrom under avsetning av Statfjord Gruppen med en økning av akkomodasjonsrommet mot slutten av avsetningen av gruppen. Variasjoner i tykkelsen på Statfjord Gruppen kan observers i studieområdet, og gruppen blir tynnere mot øst i området. Dette indikerer at variasjoner i tykkelse på Statfjord Gruppen er kontrollert av tilgjengelig akkomodasjonsrom og med dette også endringer i erosjonsnivå gjennom tid. Seismiske horisonter og forkastninger viser en post-rift permo-triassisk avsetnings trend som senere er påvirket av midtre-sen jura rifting og en reaktivering av permo-triassiske forkastninger. Den varierende tykkelsen av Statfjord Gruppen viser at de permo-triassiske forkastningene dannet den strukturelle settingen som var tilstede da Statfjord Gruppen ble avsatt. Regionale brønnkorrelasjoner og sub-regional seismiske tolkning viser at Utsirahøyden var en paleotopografisk høyde under avsetningen av Statfjord Gruppen. Brønndata viser at et kontinentalt miljø med store elvesletter dominerte under avsetning, med et tynt lag av marginal marine avsetninger i toppen av gruppen. Høye "net-to-gross" verdier for sandstein i Statfjord Gruppen på Utsirahøyden indikerer en nærhet til kildeområdet, men høyden er plassert en betydelig avstand unna kjente kilde områder. Dette indikerer en lokal kilde av sedimenter under avsetning, mulig rester av rift topografi på Utsirahøyden etter den permo-triassiske riftingen. Utsirahøyden kan ha delt to fluviale drenerings provinser i sen trias-tidlig jura i Nordsjøen. Brønn korreleringer viser ulik tykkelse og "net-to-gross" verdier av Statfjord Gruppen i brønnene på Utsirahøyden, Tampen utstikkeren og Stord bassenget. Dette tyder på at tilgjengelig akkomodasjonsrom under avsetning var en kontrollerende faktor for kontakt mellom sandstein avsetninger.

III Acknowledgements

I want to thank my supervisor at the Norwegian University of Science and Technology, Professor Stephen John Lippard for constructive feedback and help with literature during this project. I also want to thank Det norske oljeselskap ASA for providing me with data and software to make this work possible. A special thank my co-supervisor Dr. Evy Glørstad-Clark for defining this project, guidance, and good feedback on my work throughout the year.

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Karoline Ertesvåg

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Masteroppgave Karoline Ertesvåg

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1 Introduction

This master thesis was written by Karoline Ertesvåg during the fall of 2014 and spring of 2015 at the Department of Geology and Mineral Resources Engineering at the Norwegian University of Science and Technology (NTNU), Trondheim, and in cooperation with Det norske oljeselskap ASA.

The Utsira High area represents an area of great interest in petroleum exploration in the North Sea, but the Statfjord Group (Late Triassic-Early Jurassic) on the Utsira High is poorly understood. A number of wells exist on the high and the surrounding areas, but not all wells penetrate Triassic strata. This limits information about the group in the area. Multiple publications on the Statfjord Group exist, but most of the studies are focused around the Tampen Spur and Horda Platform areas. This leaves the group underexplored in the Utsira High area.

1.1 Aim of the study

The aim of this study has been to provide a semi-regional, stratigraphic framework of the Statfjord Group on the northern part of the Utsira High, and to understand the stacking patterns within the group and the distribution of depositional facies.

Seismic interpretation is used to establish a stratigraphic framework and to understand the thickness distribution of the group. Detailed well correlations provide a basis for interpreting facies associations and vertical stacking patterns. The lateral distribution of the different facies is interpreted based on seismic mapping and well correlations, whereas biostratigraphic data provide the basis for understanding the Statfjord Group in time and space.

The seismic quality of the Early Jurassic succession in the northern Utsira High area makes interpretation difficult, due to little variance in acoustic impedance and a limiting vertical resolution. The Statfjord Group generally has few major changes in facies associations, consequently few lateral continuous events, both due to the nature of the depositional system. Due the lack of lateral continuity of Statfjord deposits and the limited seismic resolution relative to well data, there are geological events not detected in the seismic.

2 Database

The study area is covered by 3D seismic data of varying vintages and quality. The seismic database for this study is shown in Fig. 2.1. The main survey used for the evaluation of the study area is the PGS 3D survey, MC3D NVG11M. The survey was acquired in 2011, the quality of the data is good but could be better with a targeted processing flow, and not just a general multi-client processing. Full stack data is available for the seismic cube. The seismic survey used during this work was provided by Det Norske Oljeselskap, together with well data, biostratigraphic data and software. The rest of the data is from public sources, mostly "fact pages" from the Norwegian Petroleum Directorate (www.npd.no).

The study area is in block 25, close to several fields and discoveries such as the Frøy Field and the Lille Frøy and Skirne discoveries. The Jotun, Jette, Ringhornet, Balder and Ivar Aasen fields are south of the study area (see Fig. 2.2). There are a number of wells on the Utsira High, but not all penetrate the Jurassic and Triassic successions. Several wells were used to understand the regional distribution of the Statfjord Group, key wells are listed in Table 2.1 and shown in Fig. 2.3. For general wellbore information, NPD was used.

Table 2.1 Depth of Top and Base Statfjord from NPD.

Well	Top Statfjord (m)	Base Statfjord (m)	Thickness (m)
25/2-13	3696	3887	191
25/2-5	3652	3847	195
25/2-6	3504	3705	201
25/5-1	3232	3374	142
25/5-4	3052	not drilled	x

The well database consists of all available data, i.e. mud logs, check-shot data, sonic data, core data, composite logs; gamma ray, density, neutron and interpreted biostratigraphic data and petrophysical logs. All the wells are important to understand the facies associations, stacking patterns and lateral variations within the Statfjord Group on a sub-regional to local scale. Most wells are drilled vertically, implying they are drilled normal to the layers in the sedimentary succession. Key wells are listed in Table 2.2, and all the wells located on the Utsira High are shown in Fig. 2.3.

Table 2.2 Well database.

Well	Status	Year	TD (mMD)	Biostratigraphy	Photos of cores
25/2-13	oil/gas	1989	3909		yes
25/2-5	oil/gas	1976	4000	yes	
25/2-6	oil shows	1977	3750	yes	yes
25/5-1	oil/gas	1987	3429	yes	yes
25/5-4	gas/condensate	1990	3185		

The wells drilled through the Statfjord Group in the Utsira High area were used throughout this thesis work, and the key wells were used to tie the stratigraphy to the seismic. The wells that contained cores at Statfjord levels were used to study the vertical lithology transitions within the group and to develop a depositional model for the area.

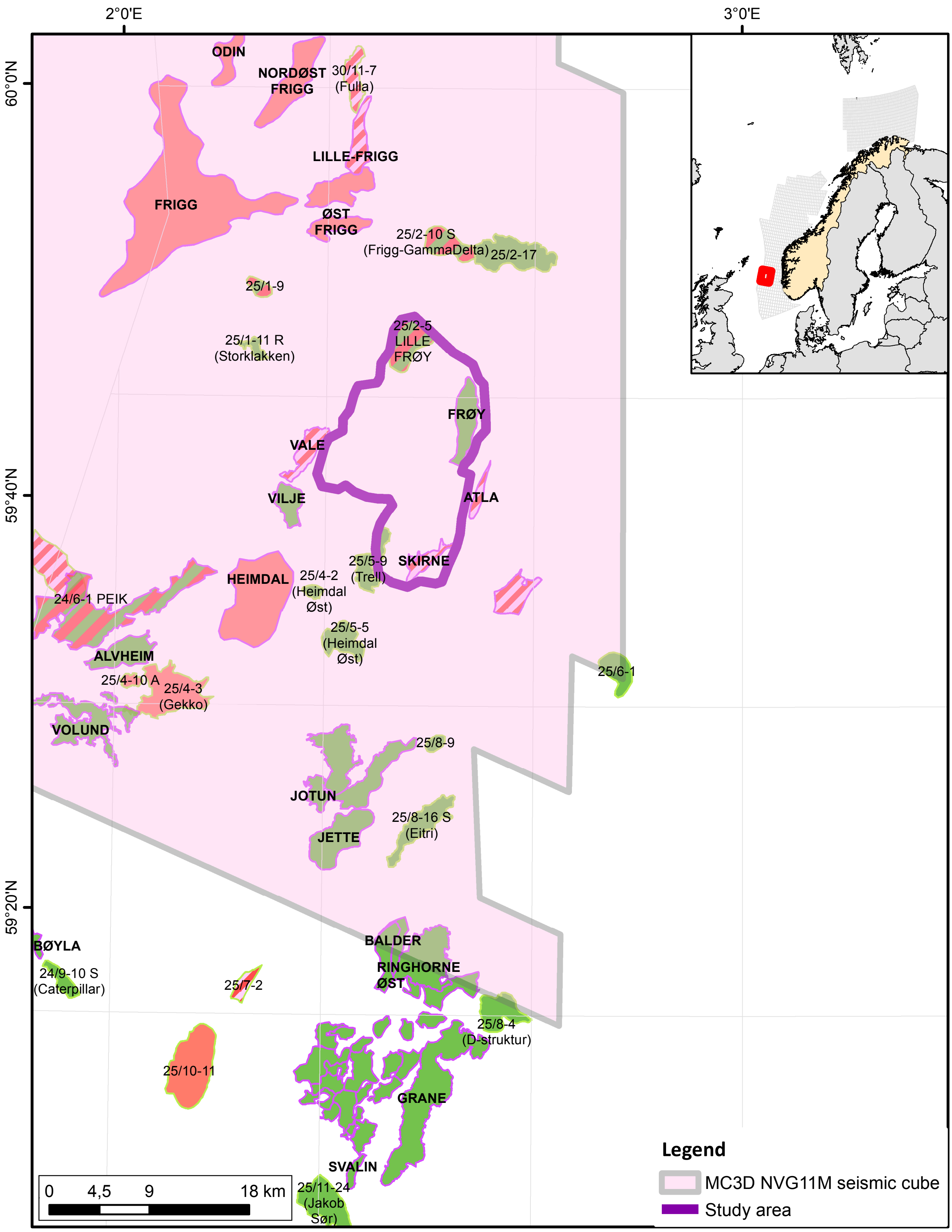


Fig. 2.1 Seismic coverage, MC3D NVG11M cube.

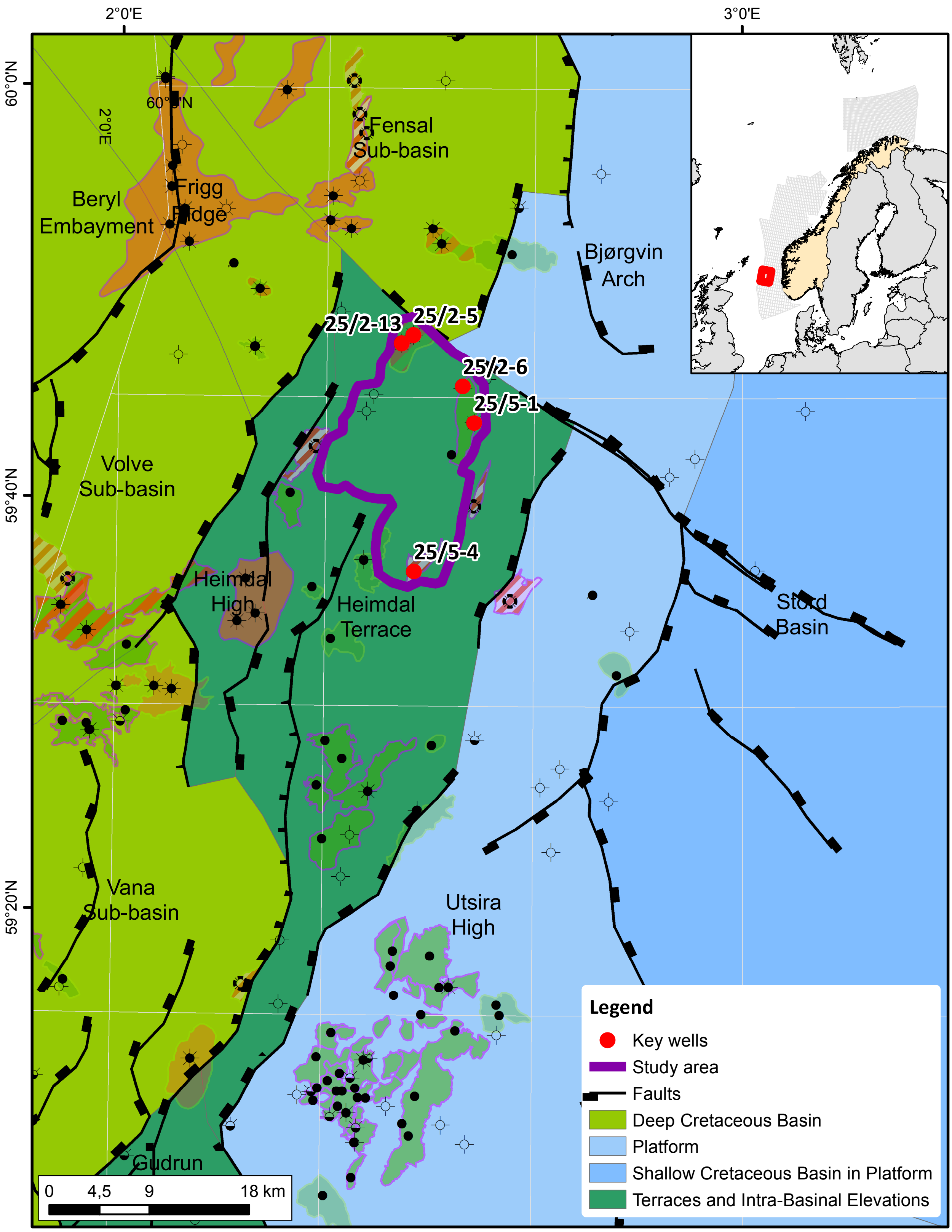


Fig. 2.2 Study area, structural elements and key wells.

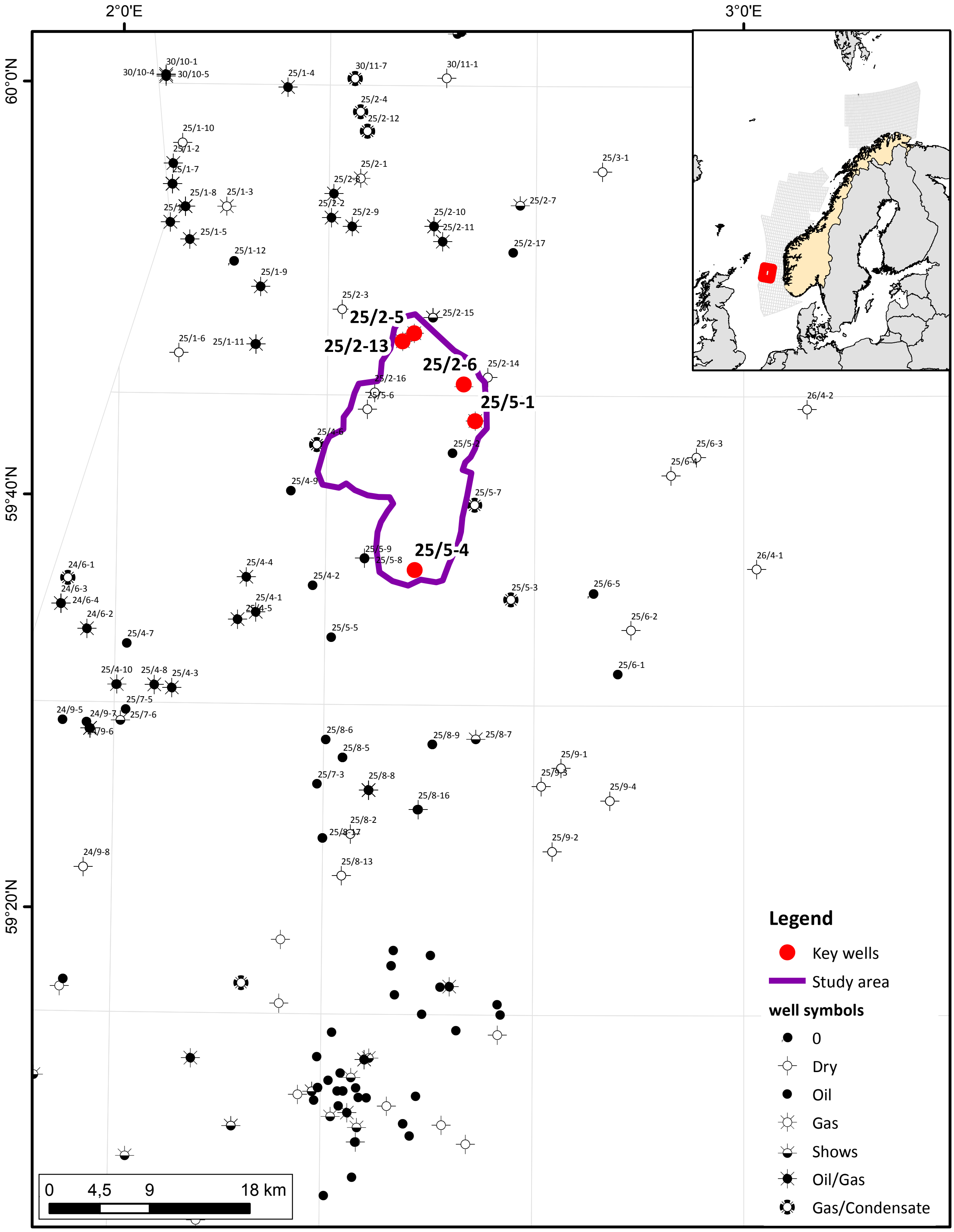


Fig. 2.3 Well coverage in the Utsira High area.

3 Geological Setting

The study area is located in the northwestern flank of the Utsira High, on the Heimdal Terrace in the Central North Sea, between 59,30°N and 59,45°N , and 2,20°E and 3°E. The Southern Viking Graben is located west of the study area, on the downthrown side of the major fault bounded segment, and the Horda Platform is located northeast of the study area (see Fig. 2.2).

3.1 Structural framework

The North Sea has a complex structural history due to multiple periods of stretching and subsidence, with related syn-and post-rift sediments distributed in a complex pattern in the North Sea (Færseth, 1996). The rift basin is a result of the original crustal structural framework and subsequent rift episodes which have reworked the framework of the basin into the structures present today. Major events involved in the development of the basin include the pre-Mesozoic, Mesozoic and Cenozoic episodes.

The North Sea underwent two major rifting events, in the Permo-Triassic and Middle-Late Jurassic, with corresponding thermal cooling, subsidence and related syn- and post-rift sedimentation phases, which contribute the complexity of the structure (Færseth, 1996).

Post-orogenic Caledonian extension in Devonian time developed large crustal lineaments in the North Sea. Rifting commenced with the extension of thickened Caledonian crust during Devonian time, where the Nordfjord-Sogn Detachment and the Hardangerfjord shear zone represents large basement structures (see Fig. 3.1). These shear zones are oriented SW/NE across the North Sea basin and the Utsira High is situated between these (Færseth, 1996). These events were followed by Carboniferous strike-slip faulting. The Sorgenfrei-Tornquist zone represents a NW/SE oriented strike-slip zone extending from the Southern North Sea and southeastwards into the former Proto-Tethys ocean (Larsen et al., 2006; Zanella and Coward, 2003).

According to Færseth (1996), Permo-Triassic extension affected the whole width of the North Sea basin as far as the East Shetland Basin. The extension occurred in an E-W direction, and the graben segments developed orthogonal to this, generating northward trending grabens. The Triassic sedimentary basin is represented by a 170-180 km wide north trending depression with the Øygarden fault complex making up the eastern margin of the basin, while the western limit was located east of the present eastern boundary of the Shetland Platform. See Fig. 3.1 for the main graben generated by the rift phase. The faults generated in this extension phase are both easterly and westerly dipping (Færseth, 1996).

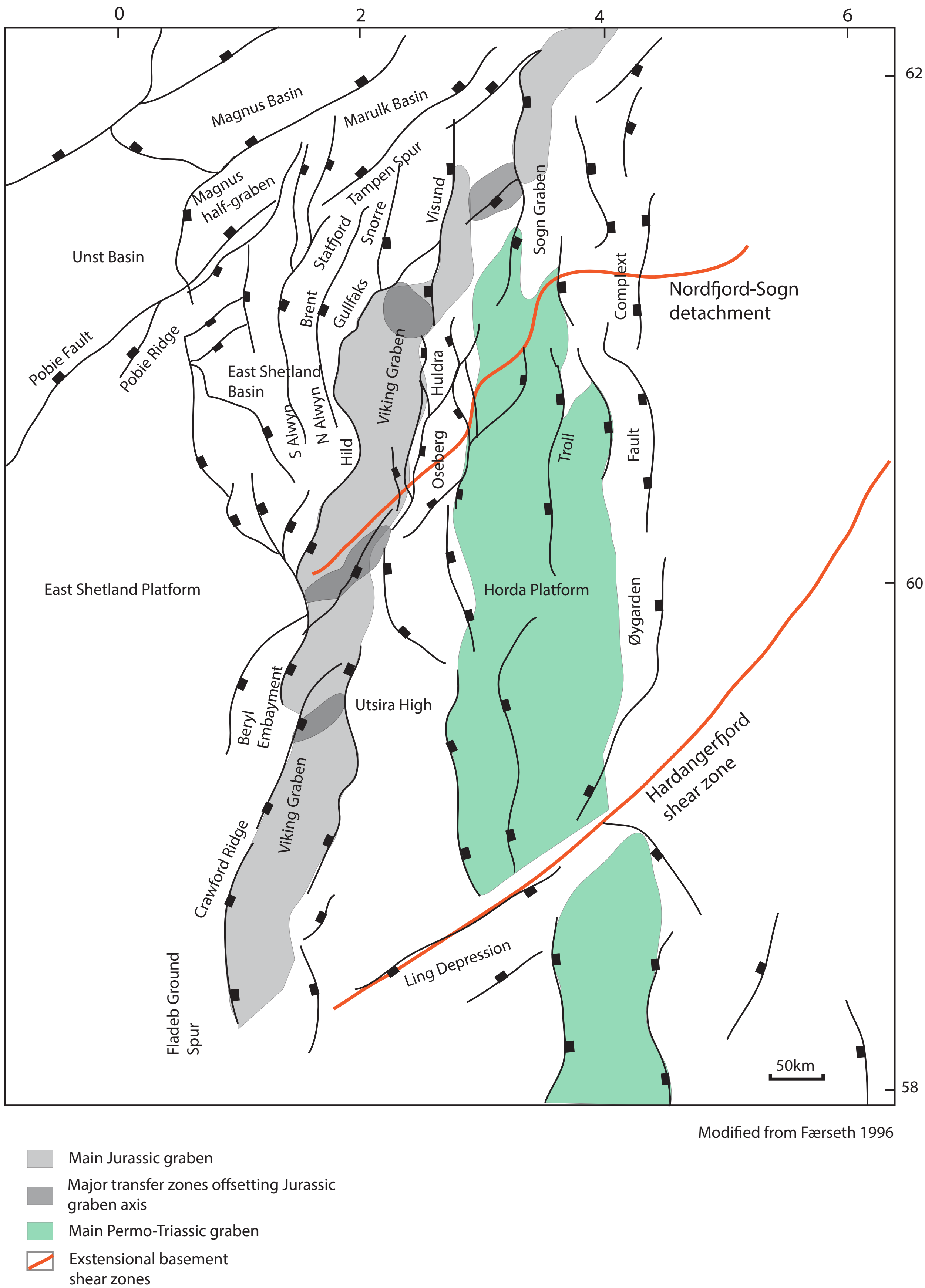


Fig. 3.1 Main Structural elements in the North Sea.

After the Permo-Triassic rift phase, the Utsira High was situated on a westerly dipping fault block. The crestal area towards the east shows thin successions or absence of Trassic strata in the area where pre-Permian rocks are situated at depth of 2-2,5 km. This reflects the overall reduced thickness of Triassic strata in the southwestern part of the basin. The thinning of the strata and erosion points to the Utsira High being at a topographic level near sea level during this period (see Fig. 3.2) (Steel and Ryseth, 1990; Færseth, 1996; Lervik, 2006).

During the Middle Triassic to Lower-Middle Jurassic, sediments related to the post-rift stage of the first rift phase were deposited. According to Steel and Ryseth (1990) the strata from this period was deposited during thermal subsidence following the rift stage. In the Early Jurassic, uplift of the Mid-North Sea Dome caused erosion in the Southern Viking Graben. This episode is associated with thermal uplift and volcanism and it created the Mid-Cimmerian Unconformity, separating the Triassic from the overlying Middle Jurassic strata (Underhill and Partington, 1993; Jackson et al., 2010).

The Middle-Late Jurassic extension was more localized than the Permo-Triassic, and mainly concentrated along the axis of the Sogn and Viking graben. The East Shetland platform represents the western boundary for the Jurassic basin. The faults are mainly easterly dipping and the extension had a NW/SE direction, which is shown by the NE/SW trend of the graben segments. The basin geometry varies from a symmetric graben in the north to an asymmetric graben in the south. Many of the Permo-Triassic faults were reactivated during this second rift phase, and only a few large faults were generated in the Middle-Late Jurassic rifting (Færseth, 1996). See Fig. 3.1 for a structural overview of the North Sea rift basin after the two rifting events.

The study area is located on the northwestern part in the greater Utsira High area, on the down faulted Heimdal Terrace. The general trend in this area is the NE/SW trending faults that terminate against the NW/SE bounding fault to the north. On the eastern side of the Utsira High lies the Stord Basin, separated from the high by one main NW/SE trending fault. To the west of the greater Utsira High area lies the South Viking Graben. The NW/SE trending normal fault in the north separates the High from the Bjørgvin Arch. The overall trend from the Utsira High to the Viking Graben are large westerly dipping fault blocks. The North Sea basin shows both easterly and westerly dipping fault blocks of different magnitude as a result of the two rifting phases. During the first rifting event, the Utsira High was positioned on the western side of the main graben, while it was positioned on the eastern side of the main Jurassic graben (see Fig. 3.1 and Fig. 3.2).

The Middle-Late Jurassic rifting caused a change in rift direction and created the triple-rift system, consisting of the Viking Graben, Central Graben and the Moray Firth, which developed in the Late Jurassic. The rifting generated faults down to the west on the Utsira High, and the area shows the character of a structural high, with the Viking Graben downfaulted to the west and the Horda Platform to the east (see Fig. 3.2) (Færseth, 1996).

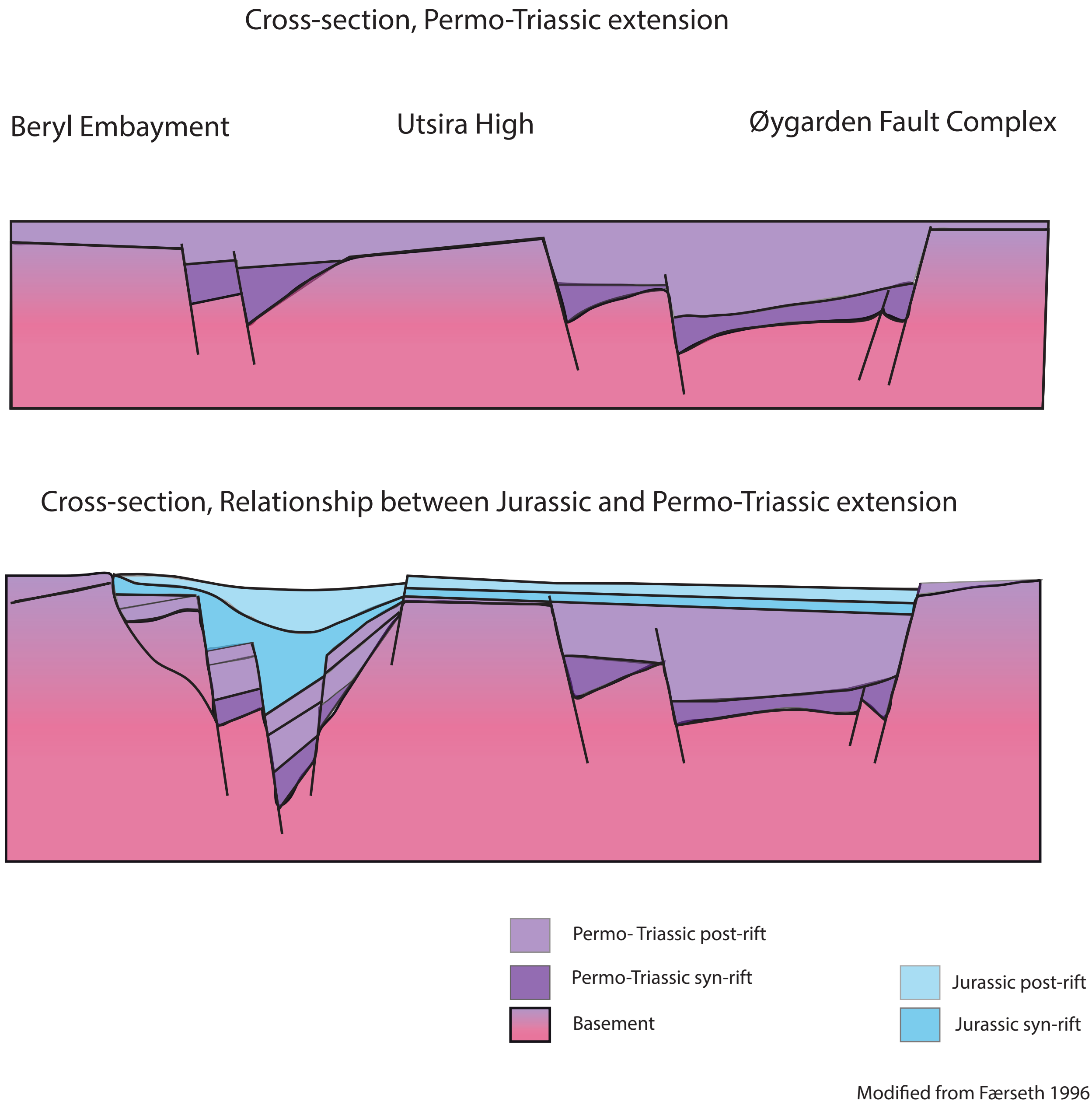


Fig. 3.2 Cross-section Utsira High. *Relationship between the two rift phases*

The Permo-Triassic and Middle-Late Jurassic rift phases are believed to have had approximately the same magnitude, reaching β values of 1.4-1.5. Both rift phases have created associated syn and post-rift sediments (Færseth 1996; Steel and Ryseth, 1996). See Fig. 3.3 for timing of the rifting and following syn- and post- rift deposits.

During the Cretaceous there was a relative tectonic quiescence, but during the Late Cretaceous and Early Paleocene, structural inversion affected the North Sea. The inverted structures were perhapes generated as a result of complicated stress field interactions related to the Alpine collision (Biddle and Rudolph, 1988). Following this event the basin margins were subjected to major uplift in the Cenozoic due to the regional compressive stress created by the North Atlantic rift zone and the Alpine collision in southern Europe. Following these events, the North Sea basin underwent regional subsidence creating the present day structural basin shape (Zanella and Coward, 2003).

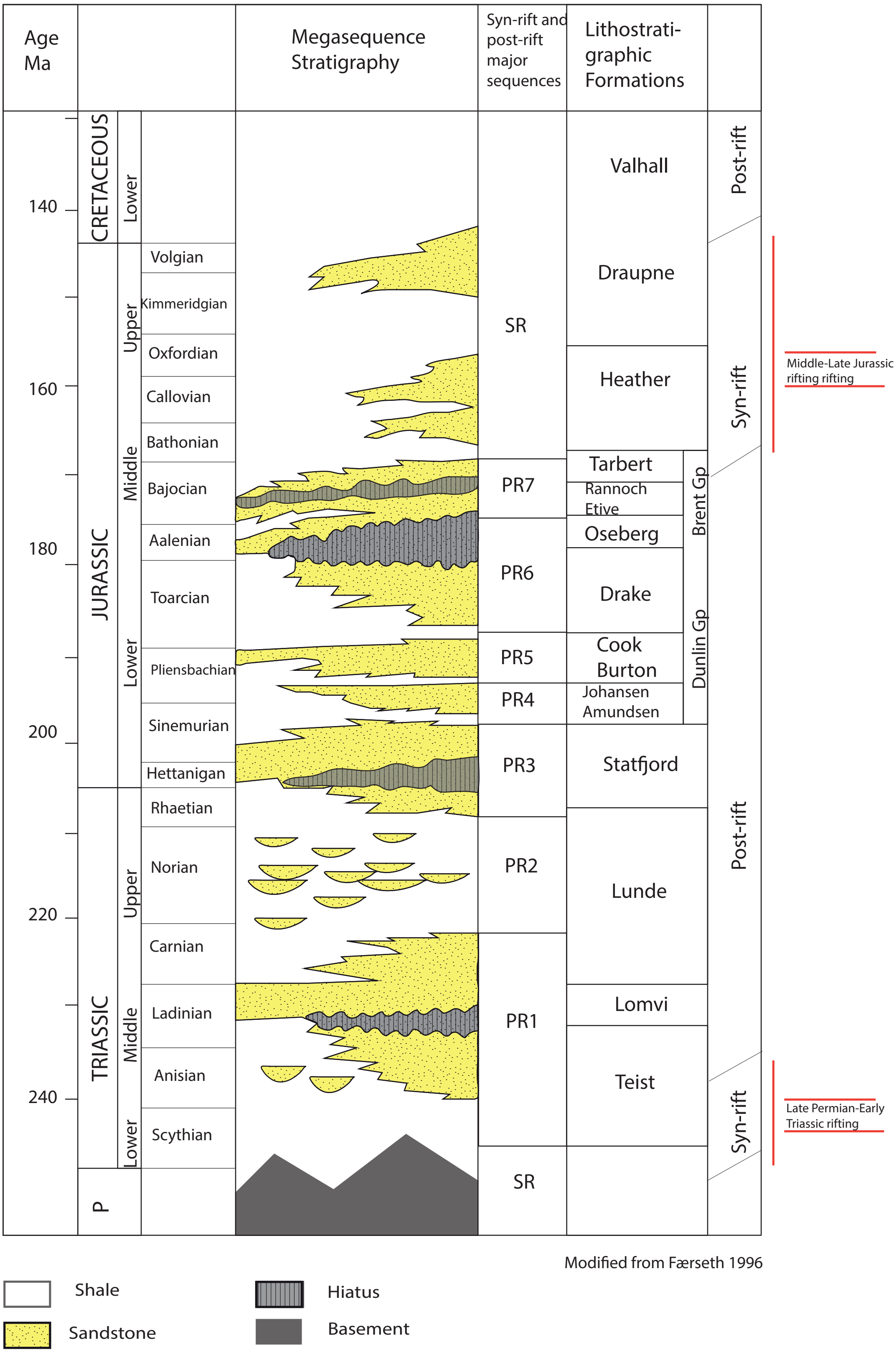


Fig. 3.3 Late Permian-Early Cretaceous tectonic development. *with associated syn- and post-rift sediments*

3.2 Stratigraphic framework

The Smith Bank Formation of the Hegre Group was deposited during the Early Triassic and it represents the Lower Triassic strata in the study area (Lervik, 2006). Continental deposits of the formation range in size from silty claystone to conglomerates and are of a monotonous red colour (Vollset and Doré, 1984; NPD).

During the Late Permian-Early Jurassic the European continental plate moved from 20-30°N to 40-50°N. The continental drift resulted in a general cooler climate and an increasing humidity. The sediments deposited during this period were deposited in an arid to semi arid climate that transitioned into a more humid climate (Goldsmith et al., 2003; Doré, 1992; Van Der Zwan and Spaak 1992). According to Doré (1992) there was a general sea level rise during Late Triassic and Early Jurassic, and by the end of Early Jurassic there was a continuous seaway through the Atlantic rift system which connected the Boreal and Tethyan oceanic realms.

The Late Triassic-Middle Jurassic Statfjord Group is subdivided into three lithostratigraphic units, the Raude, Eiriksson and Nansen Formations (Deegan and Scull, 1977). See fig Fig. 3.4 for a lithostratigraphic overview of the Statfjord Group. The group consists of sandstones and conglomorates alternating with siltstones and shales of varying colors (Goldsmith et al., 2003). The succession from Triassic and Early Jurassic on the Utsira High area was deposited in intracontinental basins in an alluvial setting (Ryseth 2001; Goldsmith et al., 2003). The Statfjord Group with the Raude, Eiriksson and Nansen Formations, is widely distributed in the North Sea, and recognized in the area between the East Shetland Platform in the west to the bounding fault zone of the Fennoscandian Shield in the east. Fig. 3.5 and Fig. 3.6 shows the distribution of the Statfjord Group and the formations within the group, respectively.

Due to the northward migration of the European continent, the basal part of the Statfjord succession was deposited in an arid-semi arid climate. Upwards in the sequence the sediments change color from red to olivegreen to grey. The presence of soil and carbonate nodules in the Raude Formation and coal in the Nansen Formation supports the model of northward migration of the plate (Goldsmith et al., 2003). According to Nystuen et al. (2014), the change in climate also had a significant influence on the sediments in terms of variations in weathering, sediment production and sediment discharge. This can be observed in paleosol development and sandstone and mudstone mineralogy, from mudrocks dominated by smectite in the Raude Formation to green-grey mudstones dominated by kaolinite in the Eiriksson Formation.

Deegan and Scull (1977), were the first to define the Statfjord Formation and its three members Raude, Eiriksson and Nansen when creating a lithostratigraphic nomenclature for the central and Northern North Sea. Vollset and Doré (1984) tried to unify the British and Norwegian lithostratigraphic nomenclature for the Triassic and Jurassic. They agreed with Deegan and Scull's definition of the Statfjord Formation and, in addition, they defined the underlying Hegre Group, with the Teist, Lomvi and Lunde Members. Lervik (2006) established a gross nomenclature that covered the entire Northern North Sea, and proposed to upgrade the Statfjord Formation and its respective members to the Statfjord Group with the Raude, Eiriksson and Nansen Formations. (For this thesis the term Statfjord Group will be used when describing the Rhaetian-Sinemurian succession, even when the literature was published previous to 2006.)

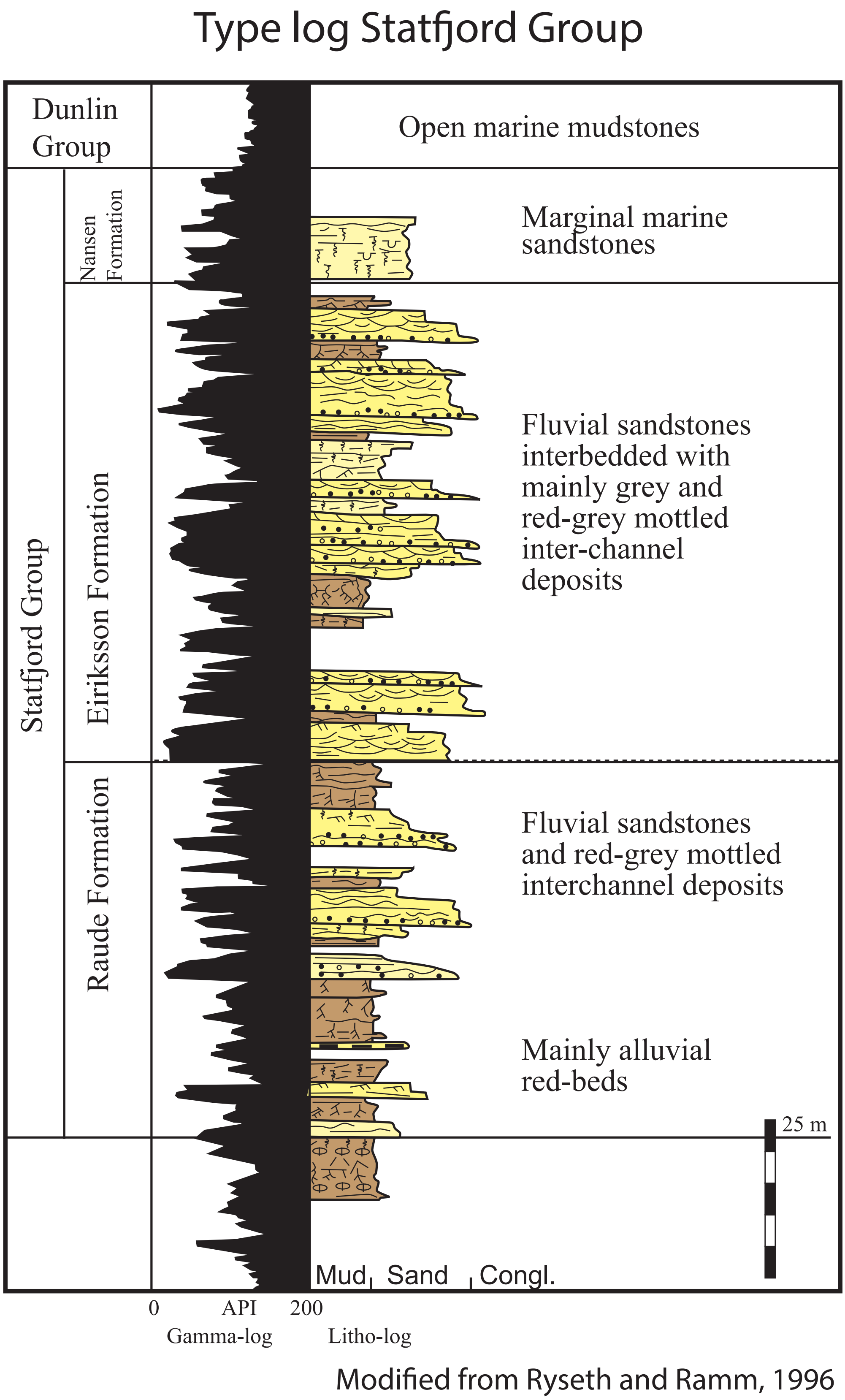


Fig. 3.4 Late Triassic-Early Jurassic lithostratigraphy. *Northern North Sea*

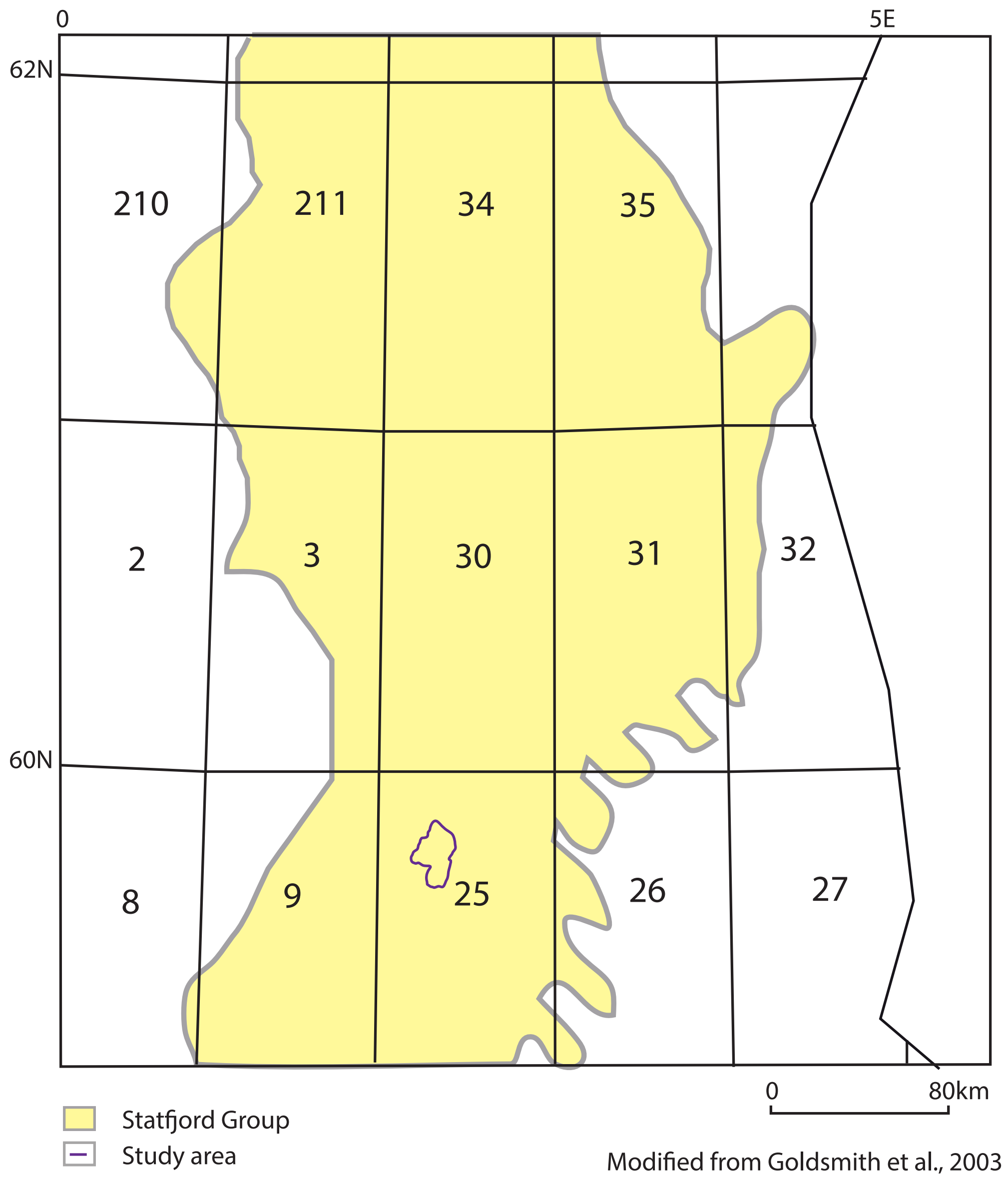


Fig. 3.5 Distribution of the Statfjord Group, Northern North Sea.

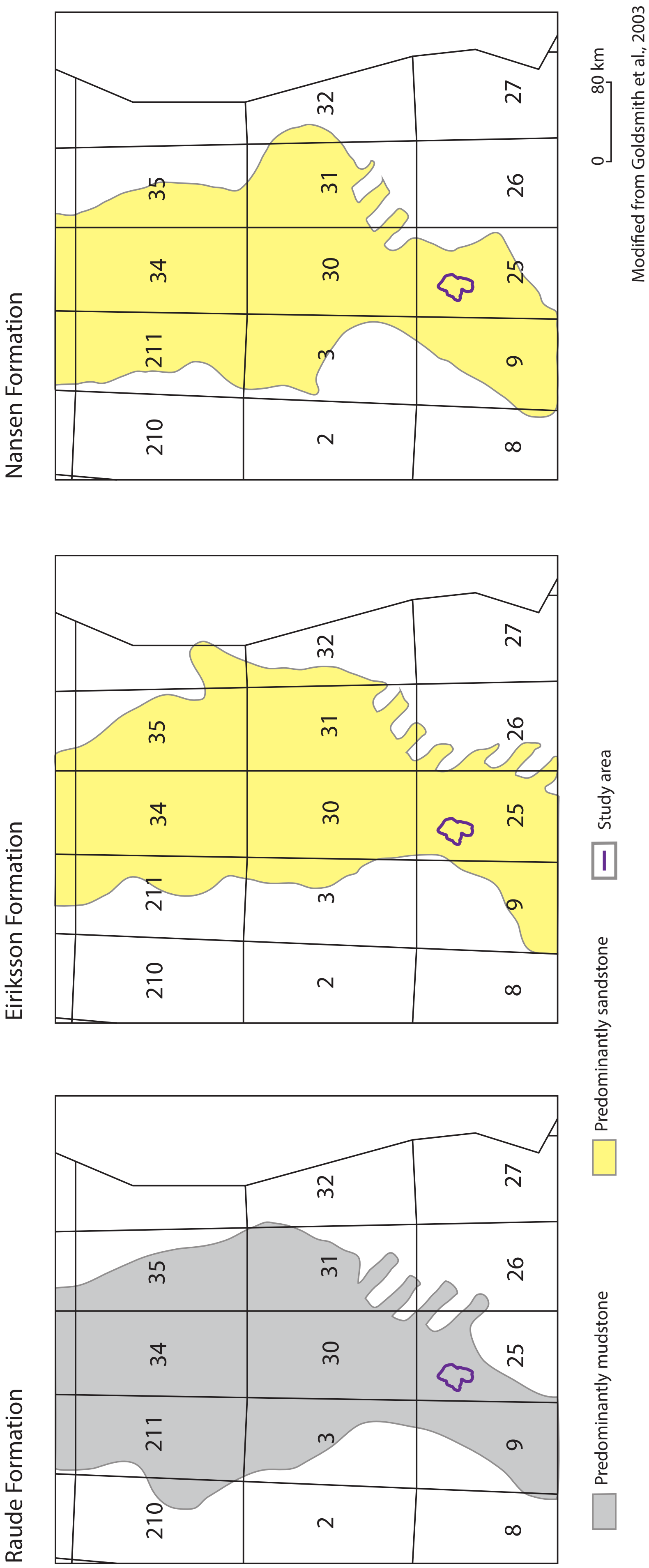
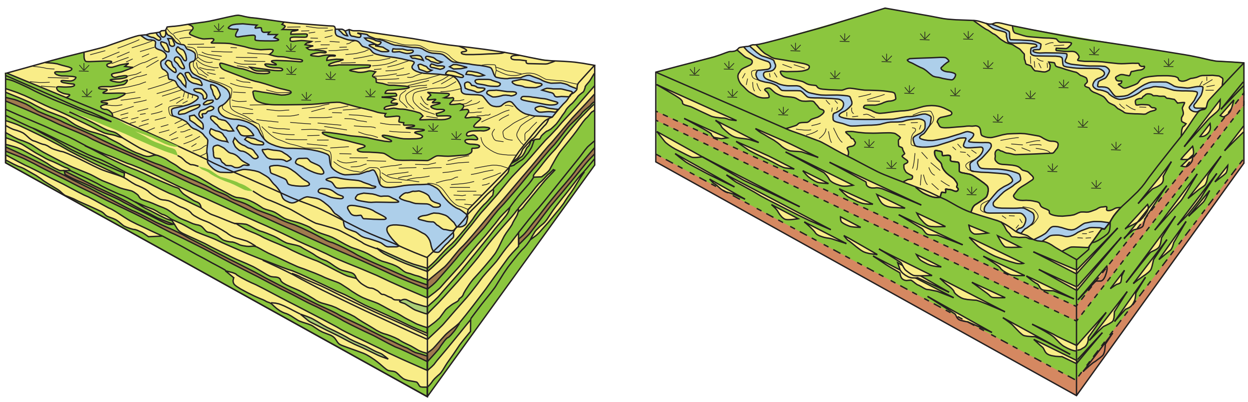


Fig. 3.6 Distribution of the formations in the Statfjord Group. *Northern North Sea*

The Raude Formation is named after the Viking discoverer Eirik Raude, and mainly consists of continental mudstones, siltstones, claystones and sandstones (NPD). The succession comprises alternating red claystones and sandstones with an overall coarsening upward trend from dominantly mudstones in the base to sandstones in the top. The sequence also contains carbonate nodules and soils. At the base of the Formation; grey and arkosic sandstones, and white and grey-brown dolomitic limestones can be found together with red-brown, green and grey silty claystones (Goldsmith et al., 2003; NPD). Deegan and Scull (1977) suggested a braided stream environment for the Raude Formation, while Røe and Steel (1985) proposed a distal alluvial fan dispersing into a flood basin. Nystuen and Fält (1995) implied that the redbrown claystones, paleosols, carbonate nodules and root structures pointed to floodplain deposits in a semi arid environment. Ryseth (2001) used comparative facies analysis on the Tampen Spur, Horda Platform and Utsira High areas to understand the difference in depositional facies in the respective areas. He related the decreasing grain size from Tampen Spur in the north to the Utsira High in the south as a response to decreasing slope gradient. Further implying braided rivers in the areas with higher depositional gradients, and meandering rivers in areas with lower depositional gradients (see Fig. 3.7).

The Eiriksson Formation is named after the discoverer of North America, Leiv Eiriksson and the succession is made up of massive sandstones, shales and coals. The basal part of the massive cross bedded sandstone unit contains conglomerates, very coarse grained sandstones and pebbles, and white to light grey sandstones interbedded with shales and thin horizons with pebbles and granules. Glauconite and marine fossils are observed near the top of the formation in some wells (Goldsmith et al., 2003; NPD). Røe and Steel (1985) argued for a proximal braided stream deposit in an alluvial fan body in a coastal floodbasin environment, while Deegan and Scull (1977) suggested a coastal environment with barriers, mouth bars and backswamps. Nystuen and Fält (1995) emphasized a coastal alluvial basin with rivers of variying morphology. Ryseth (2001) suggested the same depositional environment as for the Raude Formation (see Fig. 3.7).



Modified from Nystuen et al., 2006

Fig. 3.7 Braided and meandering river systems

The Nansen Formation is named after the Norwegian polar scientist and explorer, Fridtjof Nansen, and it contains calcareous sandstones with thin layers of shale and occasional layers with pebbles and granules. There is also calcrete, coal and root traces present in this unit and marine fossils near the top. The formation has cleaner sandstone units than the underlying ones, and has an overall coarsening upwards sequence (Deegan and Scull, 1977; NPD). Several authors (Deegan and Scull, 1977; Røe and Steel, 1985; Nystuen and Fält, 1995) have interpreted the

Nansen Formation as a massive fluvial sandstone with evidence of a marine transgression only near the top of the Statfjord Group. Deegan and Scull (1977) proposed a shallow marine environment with mouth bars and backswamps, while Røe and Steel (1995) suggested a subaerial environment for the lower part of the formation, with a gradual transition into standing water near the top, with both lenticular bedding, flaser bedding and abundant bioturbation. Ryseth (2001), agreed with the previous authors of a marine environment, and implied a transgression from the south.

Due to the marine transgression in the Early Jurassic, the sediments overlying the Statfjord Group are shallow marine shales and siltstones of the Dunlin Group. This group is subdivided into the Amundsen, Johansen, Burton, Cook and Drake Formations, and has a more widespread distribution than the underlying Statfjord Group. In the central part of the basin, the upper part of the calcareous sands in the Statfjord Group pass laterally into the lower part of the Amundsen Formation (Vollset and Doré, 1984; Jackson et al., 2010).

After the collapse of the Mid North Sea Dome, derived sediments from the erosion of the dome prograded northwards along the Viking Graben making a large delta. During the second rift phase in the North Sea the delta retreated and the Viking Graben was flooded (Johannessen and Nøttvedt, 2006). The Brent Group, with the Broom, Rannoch, Etive, Ness and Tarbert Formations was deposited in the Northern North Sea. This group consists of grey-brown sandstones, siltstones and shales with coal beds and conglomerates, and is overall sandy. The Sleipner Formation is the equivalent to the Ness Formation in the Central North Sea, while the Hugin Formation is the equivalent to the Tarbert Formation. Both formations represent non-marine strata and the Sleipner Formation, which was deposited on the lower deltaic plain, contains coal.

In Late Jurassic and Early Cretaceous, deposition occurred in isolated sedimentary basins under anaerobic conditions (Rawson and Riley, 1982). Sedimentation was continuous throughout this period and the Upper Jurassic Viking Group was deposited following a marine transgression from the south. The Upper Jurassic Heather and Draupne Formations consist mainly of grey silty claystones and dark grey to black claystones respectively (Vollset and Doré, 1984).

During the Cretaceous, the North Sea was subjected to fluctuating sea level, and it was a period of transgression with minor regression (Rawson and Riley, 1982). Relatively quiet conditions prevailed in Early Cretaceous, with the deposition of shales and marls, the Åsgård and Mime Formations respectively. A regional regression followed, and the claystones changed from calcareous rich to more organic rich, resulting in the deposition of the Sola Formation. At the same time, sandstones of the Agat Formation was deposited as submarine fans as a response to erosion along flanks of structural highs (Isaksen and Tonstad, 1989).

A regional transgression followed the regression, the sea flooded onto structural highs and the organic rich shales passed into fine grained calcareous units of the Rødby Formation. The Upper Cretaceous deposits in the North Sea were deposited in an open marine environment, and there was a continuous rise in sea level throughout this period, resulting in more pure chalk deposits in the Hod, Tor and Ekofisk Formations (Isaksen and Tonstad, 1989; Brekke and Olaussen, 2006).

3.3 Provenance

Different authors have worked on the understanding of the provenance of the Lunde Formation and the Statfjord Group in the Northern North Sea (Mearns et al., 1989; Dalland et al., 1995; Morton et al., 1996; Knudsen, 2001) using different methods: Sm-Nd isotopes, zircon dating and variations in heavy minerals. There is a common agreement of different provenance areas for the lower and upper parts of the Statfjord Group in the Northern North Sea.

According to Knudsen (2001), the samples from the Raude and Eiriksson Formations show derivation characteristics from the East Shetland Platform, indicating a provenance area in the northwest. The samples gave Devonian and post-Devonian ages. Samples from the Lunde and Nansen Formations show signs of sediment re-deposition, and the Nansen Formation indicates a provenance of recycled Devonian sediments from SW Norway and some sediments from other sources. Dalland et al. (1995) suggested two different provenance ages for the deposits, one with ages greater than 1800Ma and one with ages less than 1800Ma. The samples showing higher provenance ages, were transported towards the south and are suggested of having a possible source area north of the Gullfaks field where exposed Lewisian gneisses could have formed a clastic sediment source terrain. The group showing lower provenance age shows indications of paleocurrents flowing towards NNE possibly from a source area derived from Triassic and Devonian sediments on the East Shetland Platform. Morton et al. (1996), suggested Protorozoic hinterland reworked by the Caledonian orogeny represented a provenance area for the Statfjord Group, based on detrital zircon ages and heavy mineral assamblages. He implied the sediments were supplied from the east, from the Norwegian Caledonides.

4 Method

Conventional 3D seismic mapping was performed in Petrel 2013 and 2014. Basic seismic interpretation implies picking and tracking laterally consistent seismic reflectors, aiming to delineate geological structures, stratigraphy and where possible, reservoir architecture. Seismic mapping of reflectors results in time structure maps with a geometrical expression in time. A seismic well tie will give further integration and understanding of the stratigraphy. Additionally, the seismic interpretation was used to further understand depositional geometries.

4.1 Seismic interpretation

The interpretation was performed in the 3D cube MC3D-NVG11M which covers the whole study area (see Fig. 2.1). The study area covers 214.39 km². The seismic data used in this thesis represent zero phase data and the polarity is of "European" convention, where an increase in acoustic impedance (AI) is represented by a trough (see Fig. 4.1) (Brown, 2010). Three seismic reflectors were mapped in the study area, representing Top Statfjord, Intra Statfjord and Near Base Statfjord. The events represent both hard (increase in AI) and soft (decrease in AI) events (see Table 4.1). The three interpreted horizons are not interpreted from the subdivision of formations within the Statfjord Group, but as a response in the seismic.

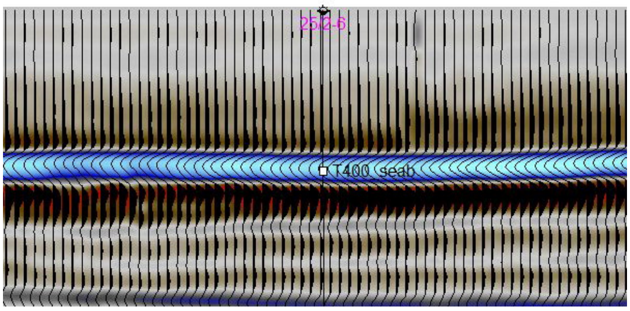


Fig. 4.1 Polarity of seismic cube MC3D NVG11M

Table 4.1 Horizons and seismic pick.

Horizon	Seismic pick	Event
Top Statfjord	peak	soft
Intra Statfjord	trough	hard
Near Base Statfjord	peak	soft

The horizons have approximately the same extension, and every 25th xline and inline was interpreted. In areas where the structural setting was complex a lower increment was used. The interpreted horizons are situated at depths varying from 3000-3700 m. Only the large and continuous faults were interpreted in the study area. Small, very local faults, that do not extend over more than three xlines or inlines were not interpreted, but taken into account during the process. When interpreting the fault sticks, an increment of 50 was used in both the xline and inline (see Fig. 4.2). During the interpretation, the chosen reflectors were interpreted taking into consideration the dip of the Base Cretaceous Unconformity (BCU) and the deep crustal structures. In addition they were interpreted relative to each other when the amplitudes were weak.

Due to the depth at which the Statfjord Group is situated, the vertical resolution of the seismic is approximately 30 meters which is 1/4 λ, indicating there are lithology changes that will not be detected by the seismic. Due to the nature of the depositional system, there are lateral changes in lithology and therefore also in the seismic reflectors.

To improve the quality of the data, volume attributes were used on the seismic cube to enhance the signals and improve the interpretability. Structural smoothing to increase the continuity of the reflectors and Trace AGC to boost weak events.

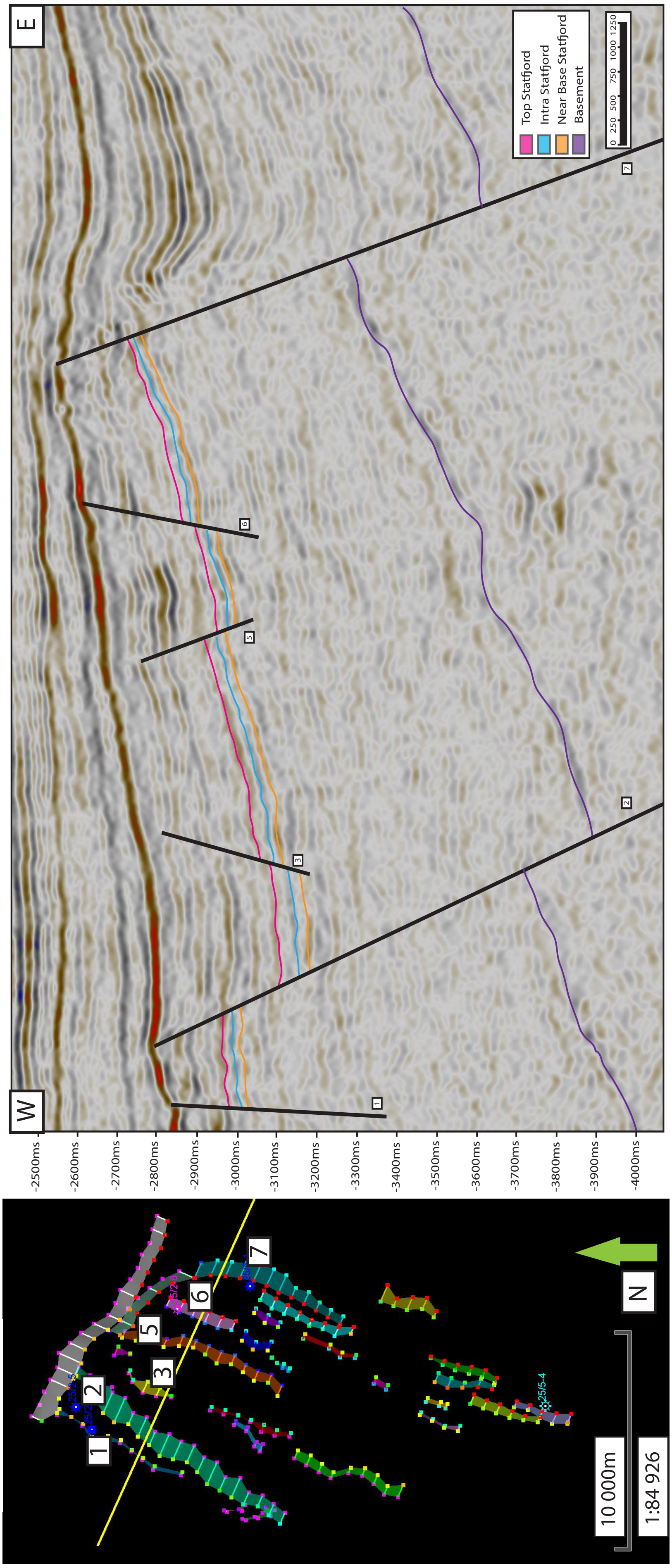


Fig. 4.2 Fault sticks in plan view and cross section. *Cross section = inline 25550*

4.2 Well tie

All the key wells within the study area are tied to the seismic data, and the well ties are of sufficient quality. All the key wells penetrate Lower Jurassic or Upper Triassic strata, and thus provide good control on the Mesozoic succession. The well ties were constructed to more accurately tie the well tops to the seismic data, and using a seismic well tie is better than just using checkshot data. The seismic well tie was made in Petrel, where the density and sonic curve from the respective wells were calibrated and used to make a reflectivity curve, further being convolved with a theoretical wavelet. The synthetic seismogram was generated by using a theoretical wavelet of 20 Hz with the same polarity as the seismic data. The "best fit" for the well was chosen, and the seismic tie for well 25/2-5 is showed in Fig. 4.3. Due to the theoretical wavelet and the poor vertical resolution, the synthetic seismic display more amplitudes than the original one, causing some misalignments in the tie. Fig. 4.4 shows the synthetic trace and the seismic in wells 25/2-6 and 25/5-1.

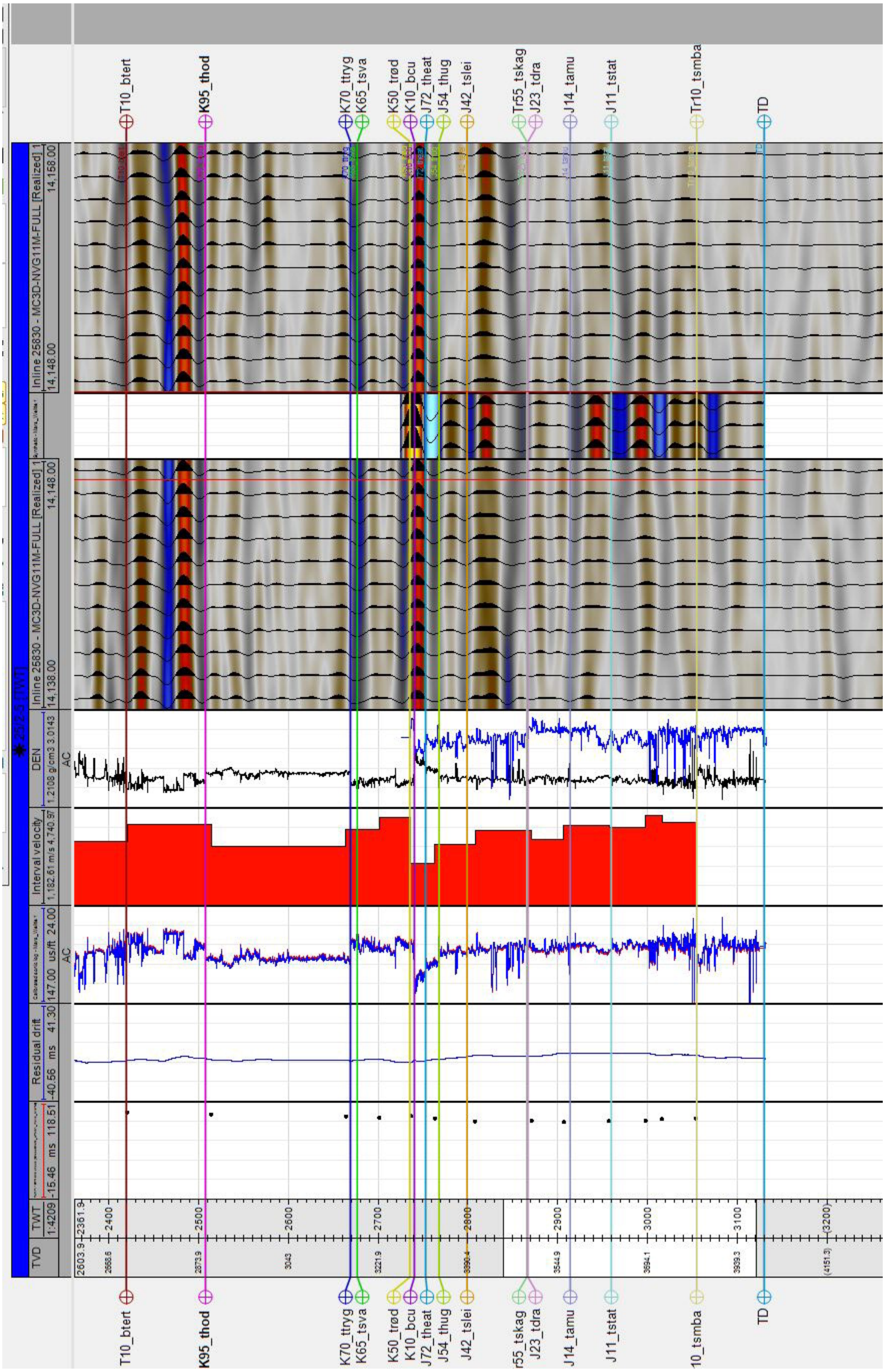


Fig. 4.3 Well tie, well 25/2-5. *Tie to MC3D NVG11M*

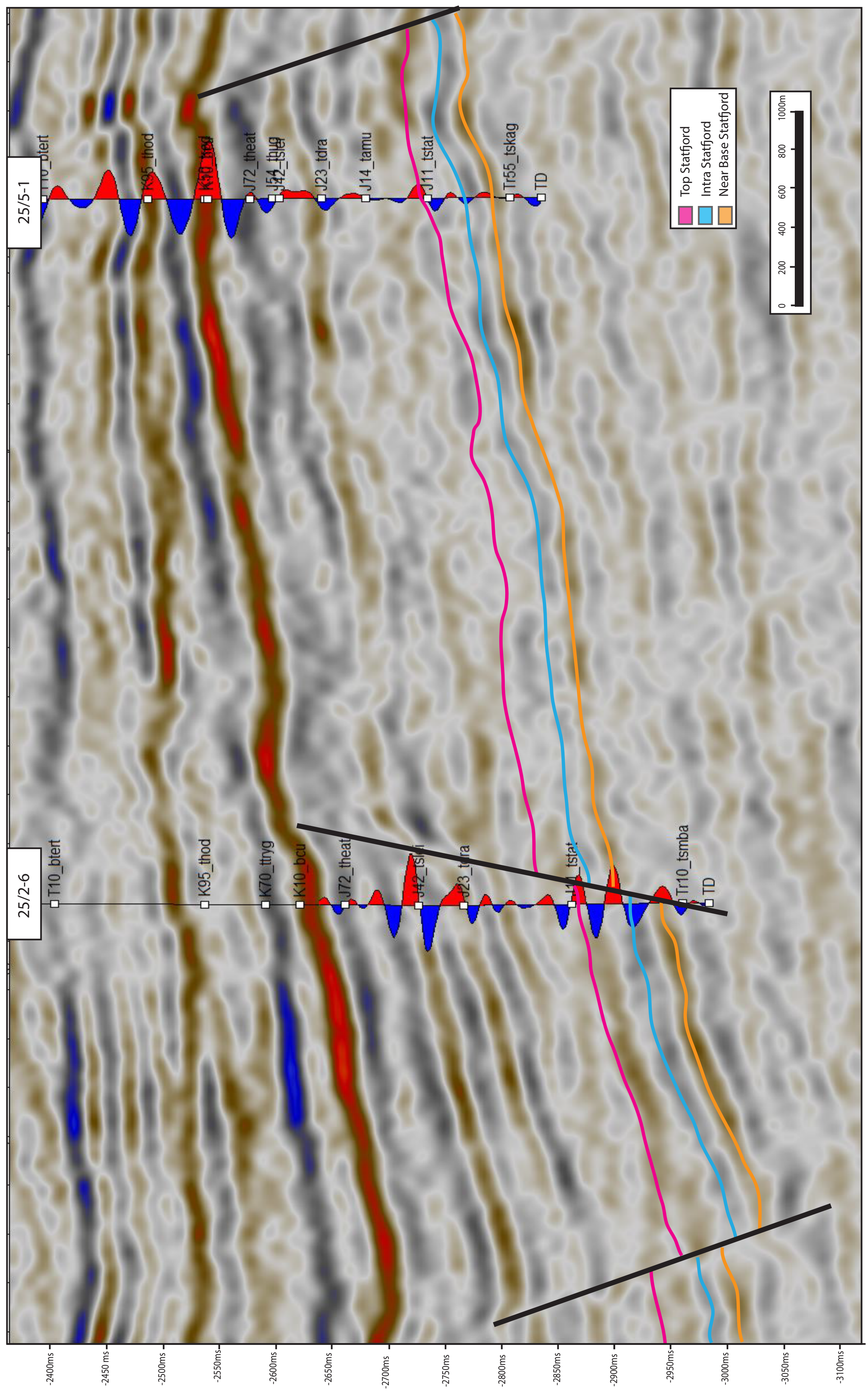


Fig. 4.4 Seismic well tie, wells 25/2-6 and 25/5-1. *Tie to MC3D NVG11M*

5 Results

5.1 Seismic interpretation

The seismic interpretation was performed to get an overview of the structural and depositional setting, and to provide an understanding of variation in sediment thickness and accomodation space. The key wells were used to constrain the interpretations and provide an understanding of the lithology.

The interpreted horizons and faults were used to generate time structure maps, thickness maps, attribute maps and fault polygons. They were used to understand the structural setting and the amount of accommodation space available during deposition. They contributed to gain the best possible understanding of the area, and together with regional structural data and well data they were used to understand the structural setting during deposition of the Statfjord Group.

5.1.1 Faults

The faults interpreted in the study area mainly show a NE/SW trend, which is the general trend in the area. The northern bounding fault in the study area show a very distinctive NW/SE trend, and it differs from the majority of faults interpreted. Fig. 5.1 show the position of seismic cross sections, and Fig. 5.2, Fig. 5.3, Fig. 5.4 and Fig. 5.5 shows the respective seismic sections.

The interpreted faults show one large westerly dipping fault block with local horst and graben systems. The faults have different magnitudes and can be divided into three groups;

1. Faults terminating in the BCU and cutting through basement.
2. Faults that terminate in the BCU, but do not cut through basement.
3. Faults terminating in Middle-Upper Jurassic Sleipner and Hugin Formations.

The faults in fault group 1 show the largest displacement of Statfjord horizons across the fault planes. Fault 2 on the western horst segment has a length of approximately 12 km in plan view and a maximum displacement of 160 ms of the Statfjord Group, and a basement displacement of 170 ms. Fault 7 displaces basement for approximately 350 ms, indicating it is the largest fault in the study area. From the seismic sections, it is not possible to determine whether fault 1 displaces basement or not, but based on the displacement of the Jurassic succession, it is interpreted to belong to fault group 1. See Fig. 5.4 for the displacement of basement of the respective faults.

The faults in fault group 2 shows a significantly smaller displacement of the Statfjord Group within the study area than the faults in fault group 1. Fault 6, which separates the eastern crest of the large fault block from the local horst and graben structures, show a 40 ms displacement of the Statfjord Group. Faults 11 and 12 in the southeastern part of the study area, show an approximately equal displacement of the Statfjord Group of 60 ms while fault 10 shows a displacement of 25 ms (see Fig. 5.2, Fig. 5.3 and Fig. 5.4). The faults extend for an average distance of 3 km.

Fault group 3 contains faults 3, 4, 5, 8 and 9. They extend for about 2-3 km and show a 20-30 ms displacement of the Statfjord Group in the study area. The exception in the group is fault 5, which extends for approximately 7,5 km, but it shows a similar displacement of 20 ms (see Fig. 5.2, Fig. 5.3 and Fig. 5.4).

The faults in fault group 1 make up the large westerly tilted fault block, a half graben, and the tilted trend generates a change in depth of 340 ms for the interpreted Statfjord Group from east to west. The faults in fault group 2 and 3 make up the local horst and graben system in the half graben. The northern bounding fault, fault 13, with the NW/SE trending style differs from the rest of the faults (see Fig. 5.1 and Fig. 5.5). This fault separates the Utsira High from the downthrown Bjørgvin Arch. It terminates in the BCU and cut the deep basement stratigraphy.

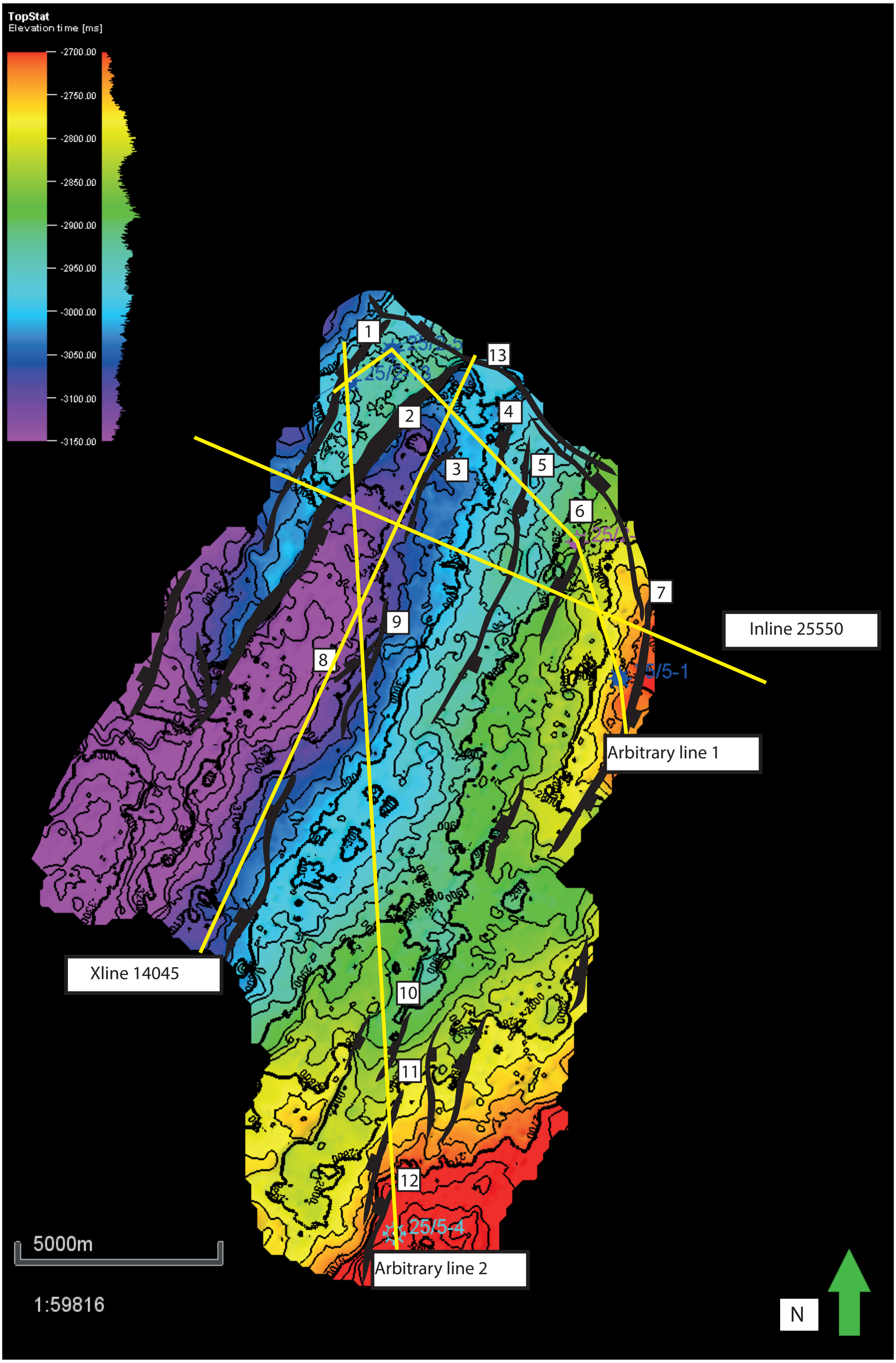


Fig. 5.1 Time structure map Top Statfjord. *Wells, faults and seismic sections*

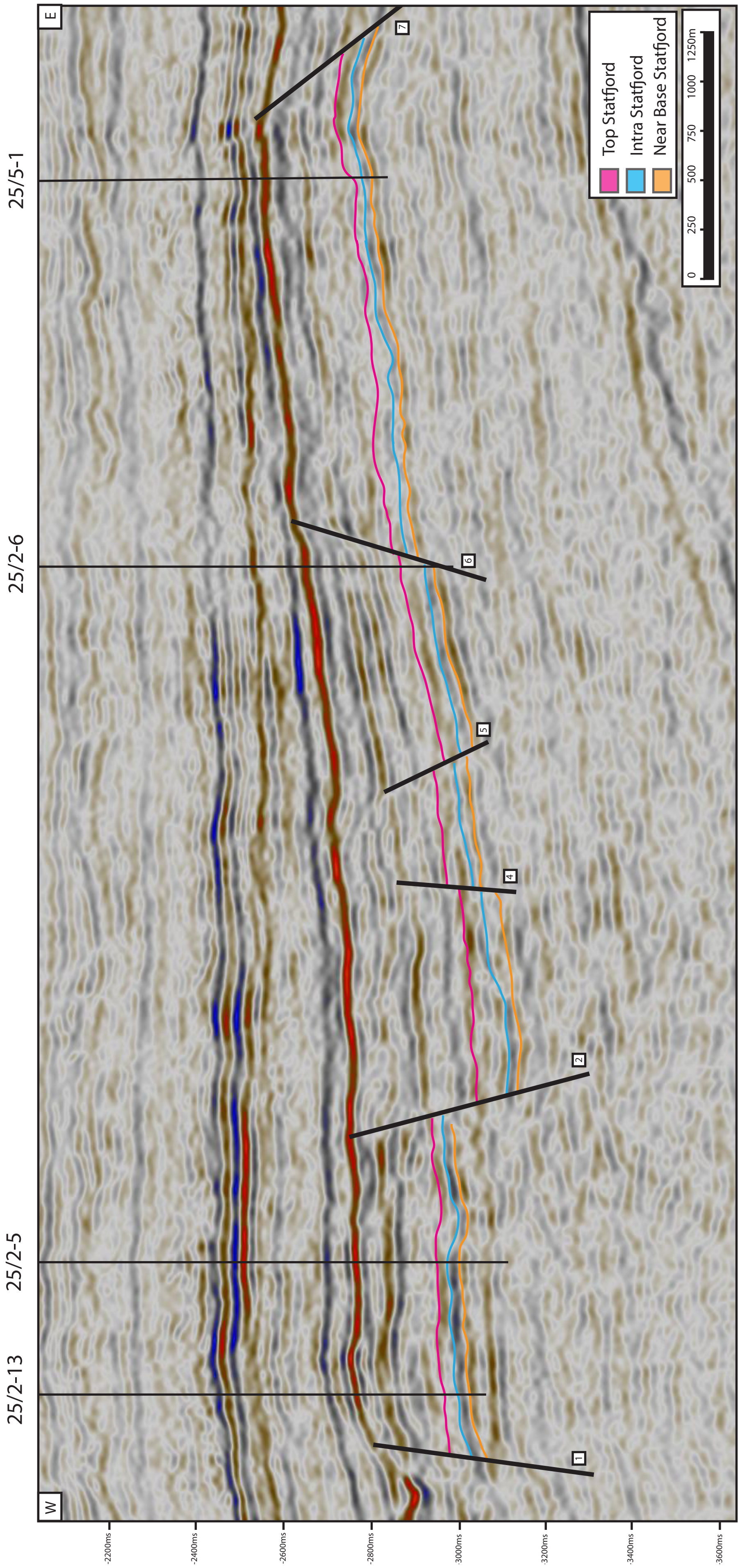


Fig. 5.2 Arbitrary line 1.

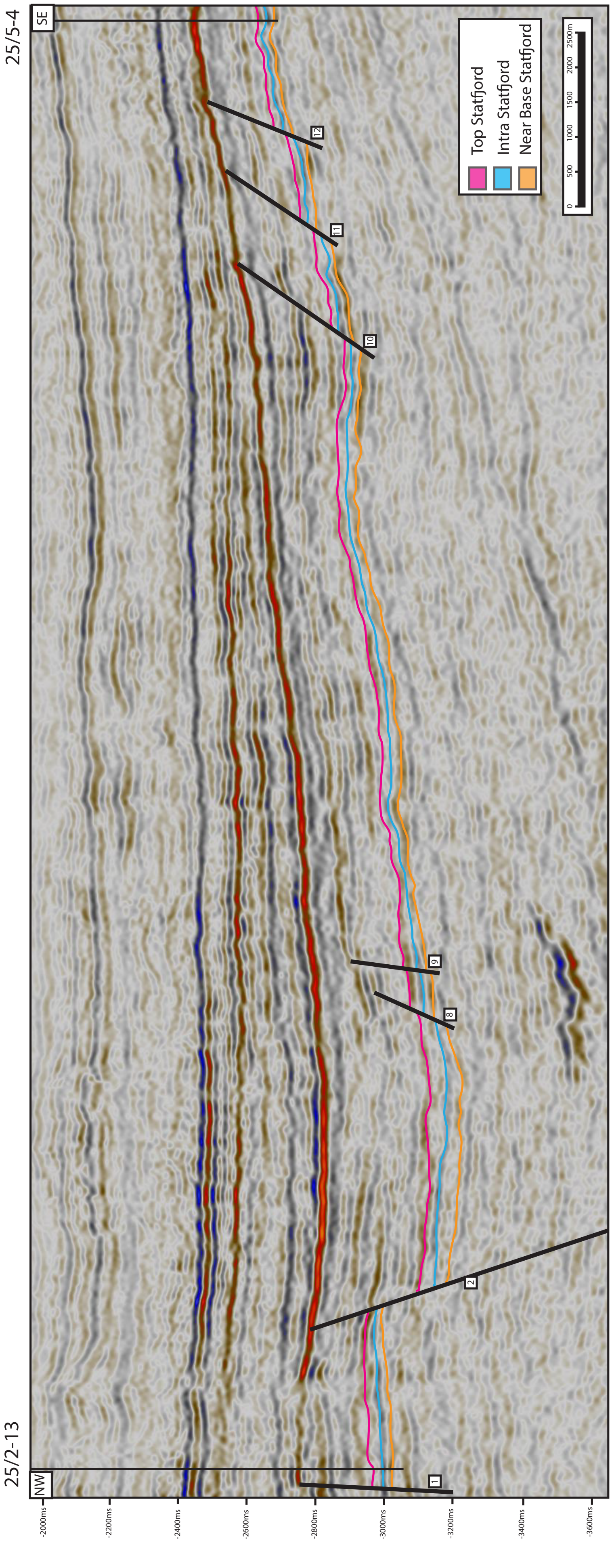


Fig. 5.3 Arbitrary line 2.

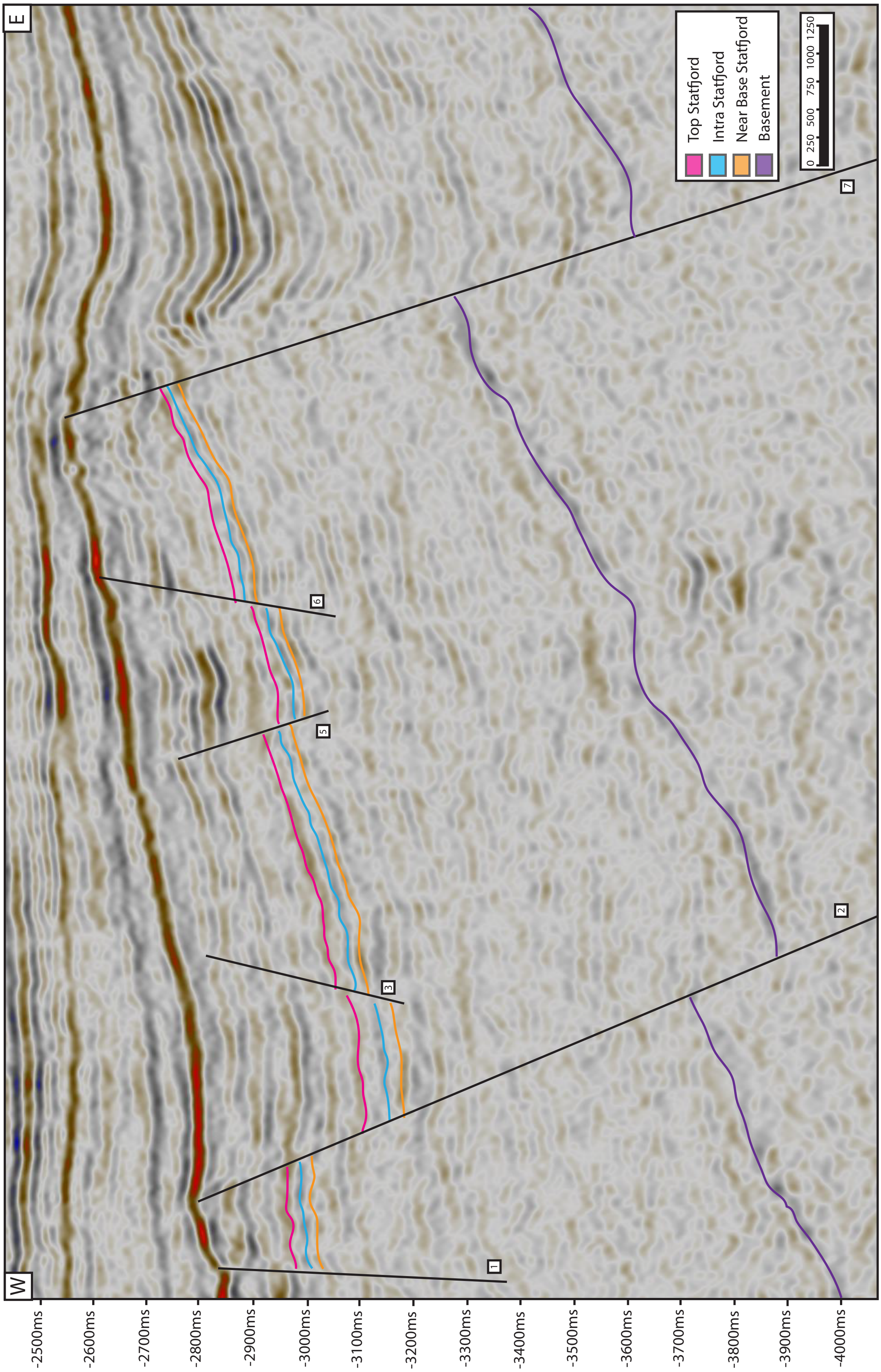


Fig. 5.4 Inline 22550.

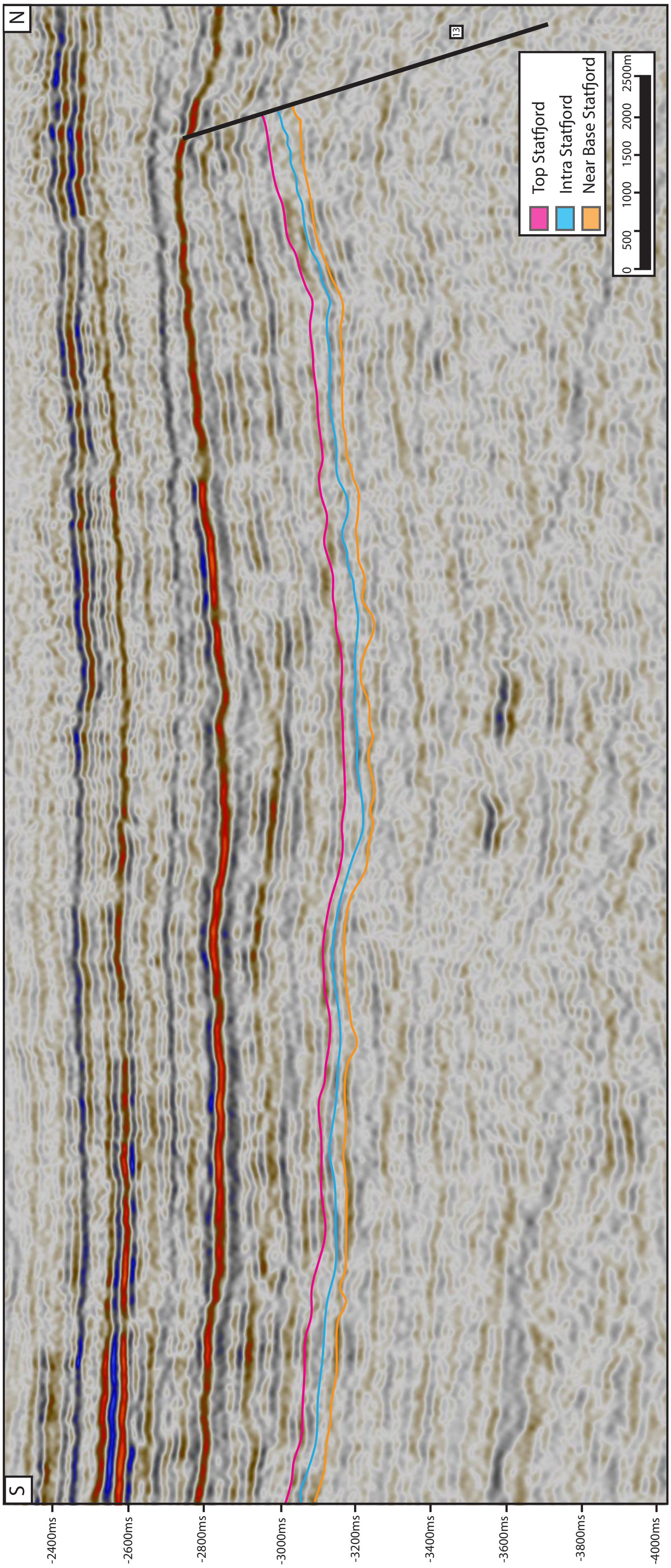


Fig. 5.5 Xline 14045.

5.1.2 Horizons

The Statfjord Group is defined between the Top Statfjord and the Near Base Statfjord horizons. Fig. 5.2, Fig. 5.3, Fig. 5.4 and Fig. 5.5 are used in the description of the interpreted horizons in addition to the time structure maps.

Overall the Statfjord Group shows a westerly dipping trend with a gradual thickening of the succession from the crest of the hangingwall block in the east towards the horst structure in the west. There are local variations within the succession, due to the large tilted fault block and the local horst and graben systems. The horizons show little displacement across the faults, except fault 2, which separates the half graben from the horst structure, with a 170 ms displacement of the Statfjord Group (see Fig. 5.4). From the time structure maps, the changes in depth is visible. The shallowest parts of the study area is in the southeast and the deepest areas are along the hangingwall of fault 2 (see Fig. 5.6, Fig. 5.7 and Fig. 5.8).

Near Base Statfjord

Near Base Statfjord was interpreted on a peak and represents a decrease in acoustic impedance. The base of the Statfjord Group is defined by the transition from a red brown shale into a sandstone unit. However, these layers are discontinuous in the basin and the boundary can not be recognized in the whole North Sea basin (NPD).

The Near Base Statfjord horizon shows an overall westerly dipping trend with local variations in depth due to the horst and graben system. The reflector the horizon was interpreted on was discontinuous and both separated into a doublet and thinned in different areas. In some areas it was only possible to map it because of the overlying reflector. It shows strong amplitudes and a continuous trend in the eastern areas, while following it westwards the amplitudes become weaker (see Fig. 5.2 and Fig. 5.3).

The time structure map of the Near Base Statfjord horizon can be seen in Fig. 5.6, it shows the variation in depth, in ms, with the areas in the south and east representing the highest elevations. The northeastern area lies on the crest of the tilted fault block, while in the south the horizon is in an area of down to the west normal faulting from the Utsira High.

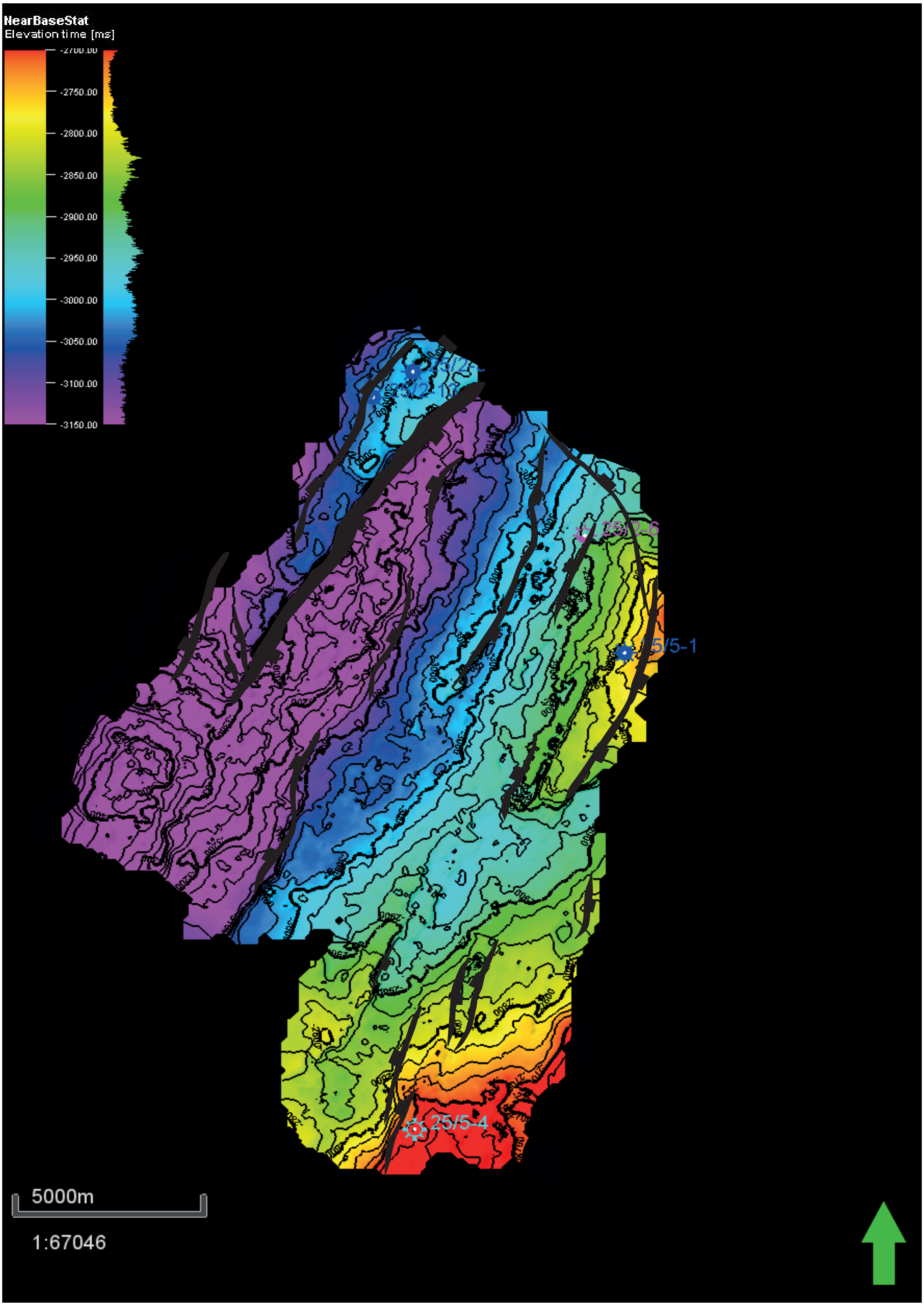


Fig. 5.6 Near Base Statfjord time structure map.

Intra Statfjord

The Intra Statfjord horizon was interpreted on a trough and it represents an increase in acoustic impedance from the overlying layer. The reflector used to interpret the horizon show stronger amplitudes than the overlying and underlying reflectors. Therefore it was often used as a reference horizon when interpreting the other horizons.

The overall trend for this horizon was also westerly dipping with local variations across the horst and grabens. Fig. 5.7 show the variation in depth for this surface. It shows the same trend as the Near Base Statfjord time structure map does, higher elevations in the east and southeast, and the deeper areas along the horst segment in the west. The Intra Statfjord reflector did not separate into a doublet, but became very weak in the central part of the study area. It shows little displacement across faults and throughout the study area it lies consequently closer to the Base Statfjord reflector than the Top Statfjord reflector (see Fig. 5.2 and Fig. 5.3).

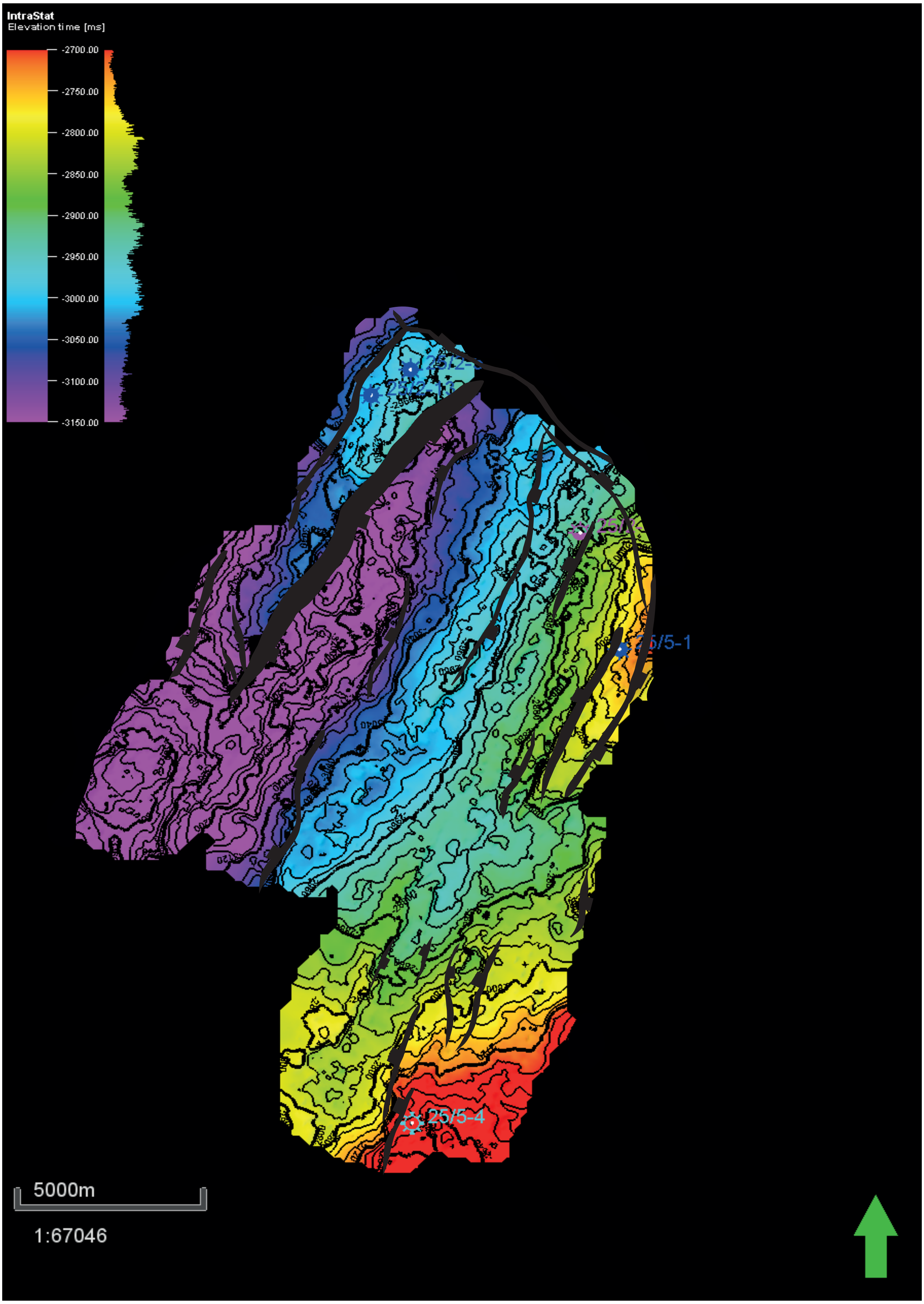


Fig. 5.7 Intra Statfjord time structure map.

Top Statfjord

The Top Statfjord horizon was interpreted on a seismic peak and represents a decrease in acoustic impedance. The reflector is a response to the transition from calcareous sandstones and siltstones into dark shale and siltstone.

The reflector used for the interpretation of Top Statfjord horizon was discontinuous throughout the study area, showing a trend of one single reflector, to splitting into a doublet. When following the Top Statfjord horizon westwards, it thickens and show a doublet trend frequently. Like the other horizons it show an overall westerly tilted trend with a local variation depth due to the horst and graben systems, with the shallowest areas in the east and southeast (see Fig. 5.2, Fig. 5.3 and Fig. 5.4). However, this is the uppermost Statfjord horizon, so it shows a higher elevation and extension of elevated areas than the others (see Fig. 5.8).

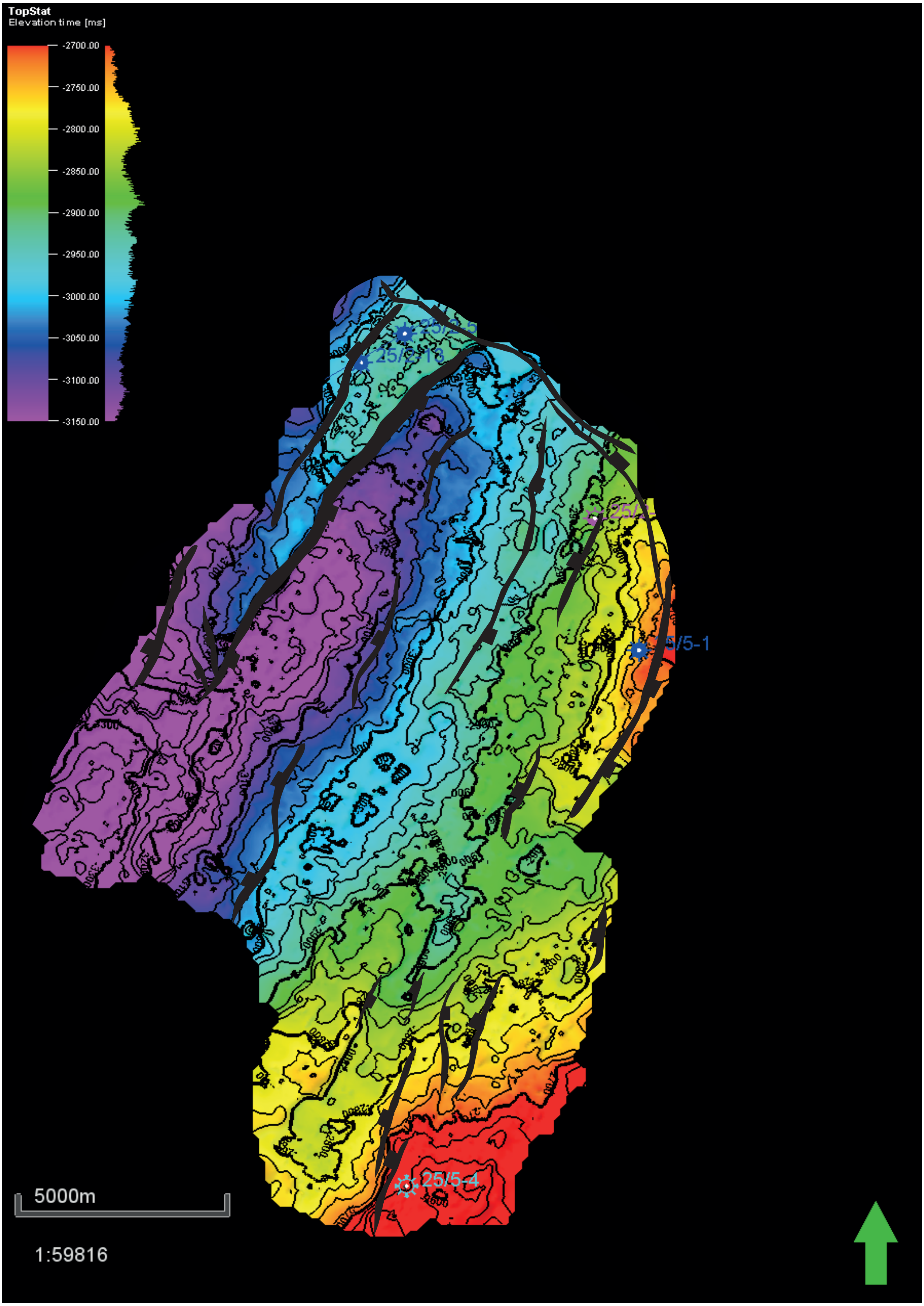


Fig. 5.8 Top Statfjord time structure map.

5.1.3 Thickness Statfjord Group

A time thickness map for the Statfjord Group shows the thickness between Top Statfjord and Near Base Statfjord (see Fig. 5.9). An increase in thickness along the hangingwall side of the western north trending horst can be observed. Additionally local areas in the north eastern part of the area also show an increase in thickness, this area represents a graben segment (see Fig. 5.2, Fig. 5.4 and Fig. 5.9).

The half graben area that shows a significant thickening of the Statfjord package, towards the fault plane, coincides with the deeper areas from the time structure maps. From the time structure maps generated of the three surfaces, it can be observed that the areas positioned at lower elevation are the same areas displaying a thicker Statfjord Group in the thickness map (see Fig. 5.6, Fig. 5.7, Fig. 5.8 and Fig. 5.9).

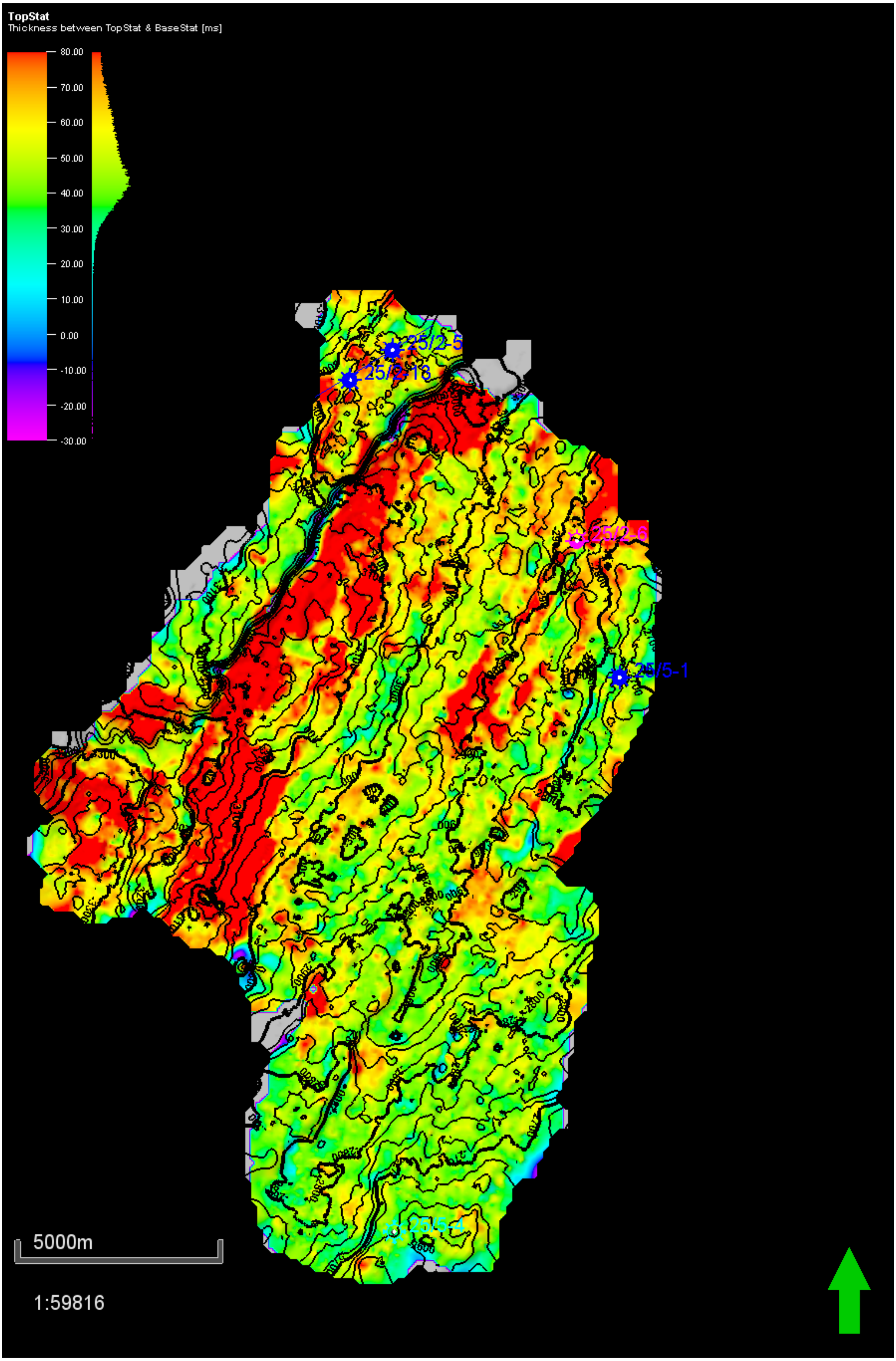


Fig. 5.9 Twt thickness map of Top Statfjord and Near Base Statfjord.

5.2 Wells

The five key wells used in the seismic interpretation were correlated based on the interpreted horizons from Petrel and lithology variations. A well correlation panel in the following well correlation chapter indicates lateral variations in stacking pattern within a relative small area. Well 25/2-13 and 25/2-5 are part of the Lille Frøy discovery. Well 25/5-1 is a part of the Frøy field, and well 25/5-4 is in the Byggve discovery which is a part of the Skirne field (NPD).

5.2.1 Well correlation

Table 2.1 shows the depth of the Statfjord Group and the total thickness of the succession in the key wells, where the wells are drilled through the group. Table 5.1 shows the depth from the interpreted horizons from Petrel. These depths were put into oilfield data manager (ODM) to observe the lithological transition where the seismic horizons are positioned in the key wells.

Table 5.1 Depth of horizons from Petrel.

Well	Top Statfjord (mMD)	Intra Statfjord (mMD)	Near Base Statfjord (mMD)
25/2-13	3684	3810	3847
25/2-5	3649	3736	3778
25/2-6	3526	3613	3655
25/5-1	3229	3283	3340
25/5-4	3094	3124	3156

To correlate fluvial channels in wells is generally difficult due to the alluvial architecture. The geometry of fluvial deposits is complex, and the continuity of sand packages is limited due to the surrounding finer grained deposits. In addition, the sparse amount of biostratigraphic data in the Statfjord Group makes the correlation within the group more speculative. The Statfjord Group was correlated based on the interpreted horizons and successions with varying net-to-gross. The change in alluvial architecture can be observed in the key wells, with a clear change in lithology between more sandstone prone and shaly units, in addition to varying succession thickness.

The Statfjord Group is interpreted into 5 successions of varying thickness within the key wells (see Table 5.2 and Fig. 5.10).

1. A basal succession of medium-coarse grained sandstones is present only in wells 25/2-13 and 25/5-4. The succession shows an overall fining upward trend, and an average thickness of 14 m.
2. A lower unit of fine grained sandstones and shales can be correlated in all key wells. The unit shows an overall uniform thickness in wells 25/2-13, 25/2-5 and 25/2-6 of 25 m, then it thins locally in well 25/5-1 to 10 m and thickens southwards in well 25/5-4 to 30 m.
3. A succession of coarse sandstone shows a uniform thickness of 35-50 m in all the wells, and a local increase of thickness in well 25/2-6 to 65 m.
4. A succession of fine grained sandstones and shales show shale with stringers of sand. It shows a halvation of thickness in well 25/2-5 compared to the others, with an average thickness of approximately 73 m to 35 m respectively.
5. The upper succession consists of coarse sandstone, and shows clean sandstone units separated by finer grained shaly units, and packages consisting of sandstone interbedded with shale. This succession is thickest in the northwestern well 25/2-13 with 93 m, followed

by an abrupt decrease in succession thickness in neighbour well 25/2-5 to 44 m, a local thickening towards well 25/2-6 to 67 m followed by a gradual thinning towards southeast in wells 25/5-1 to 43 m and 25/5-4 16 m.

Table 5.2 Succession thickness.

Wells	Succession 1 (m)	Succession 2 (m)	Succession 3 (m)	Succession 4 (m)	Succession 5 (m)
25/2-13	13	25	35	32	93
25/2-5	x	28	50	73	44
25/2-6	x	21	65	45	67
25/5-1	x	10	47	45	43
25/5-4	16	30	35	26	16

The interpreted Statfjord horizons are situated at different depths in the key wells, and from the well correlation it can be observed that the horizons are positioned within the same successions in key wells 25/2-13, 25/2-5, 25/2-6 and 25/5-1, with key well being the 25/5-4 the exception. Fig. 5.10 shows the position of the horizons in the key wells.

The Near Base Statfjord horizon is situated within a succession mostly made up of coarse sandstone interbedded with shale. The sandstone package shows an overall fining upwards trend. The horizon is situated at a vertical transition between lithologies within the sand package, at a transition from sand to shale. The Intra Statfjord horizon is positioned within a package consisting of shale with some fine grained stringers of sand in it. The Top Statfjord horizon is clearly positioned slightly above the top of the Statfjord Group in wells 25/2-13, 25/2-5, 25/5-1 and too deep in well 25/2-6 (see Fig. 5.10). This mislocation of the top Statfjord is related to the quality of the well tie. Ideally the Top Statfjord horizon should be situated on the transition between the coarse sandstone and the overlying fine grained argillaceous sequence. Where the horizons are positioned, there are small local alterations in lithology in the key wells, but the vertical alteration in lithology is not continuous throughout the study area. See Table 5.3 for the vertical lithology transition of the Statfjord horizons in the key wells.

Table 5.3 Lithology transition key wells.

Well	Top Statfjord	Intra Statfjord	Near Base Statfjord
25/2-13	shale	shale - sand	sand - shale
25/2-5	shale	sand - shale	shale - sand
25/2-6	sandy shale - shale	sand - shale	shale - sand
25/5-1	shale	shale - sandy shale	shaly sand - sand
25/5-4	sandy shale - shale	sand - shale	shale

The position of the Statfjord horizons in key well 25/5-4 differs from the other wells in the correlation panel. The Near Base Statfjord horizon is situated within the package consisting of fine sandstones and shales, the Intra Statfjord horizon in the succession of coarse sandstone and the Top Statfjord horizon in the transition between the coarse sandstone and fine grained sandstone and shale unit.

Biostratigraphic data from wells 25/2-5, 25/2-6 and 25/5-1 indicate bioturbation and fossils in the upper part of the group. Below the fossils and bioturbation, coal, rootlets and pieces of wood can be observed. In the lower part of the Statfjord Group, some plant debris, microfauna and pollen is present, but overall there is a general lack of microfauna in the key wells. Fig. 5.11 shows all biostratigraphic data in the key wells at Statfjord level.

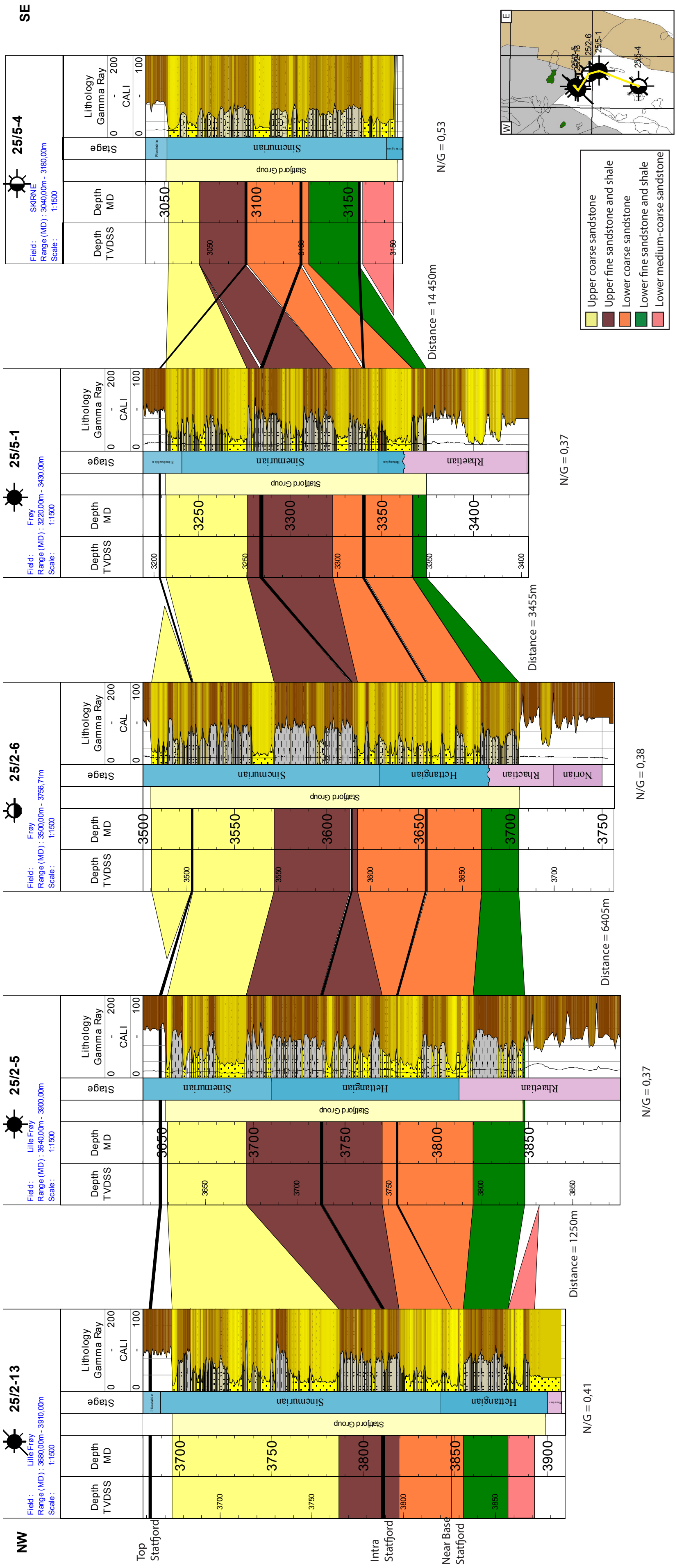


Fig. 5.10 Well correlation panel. *Key wells*

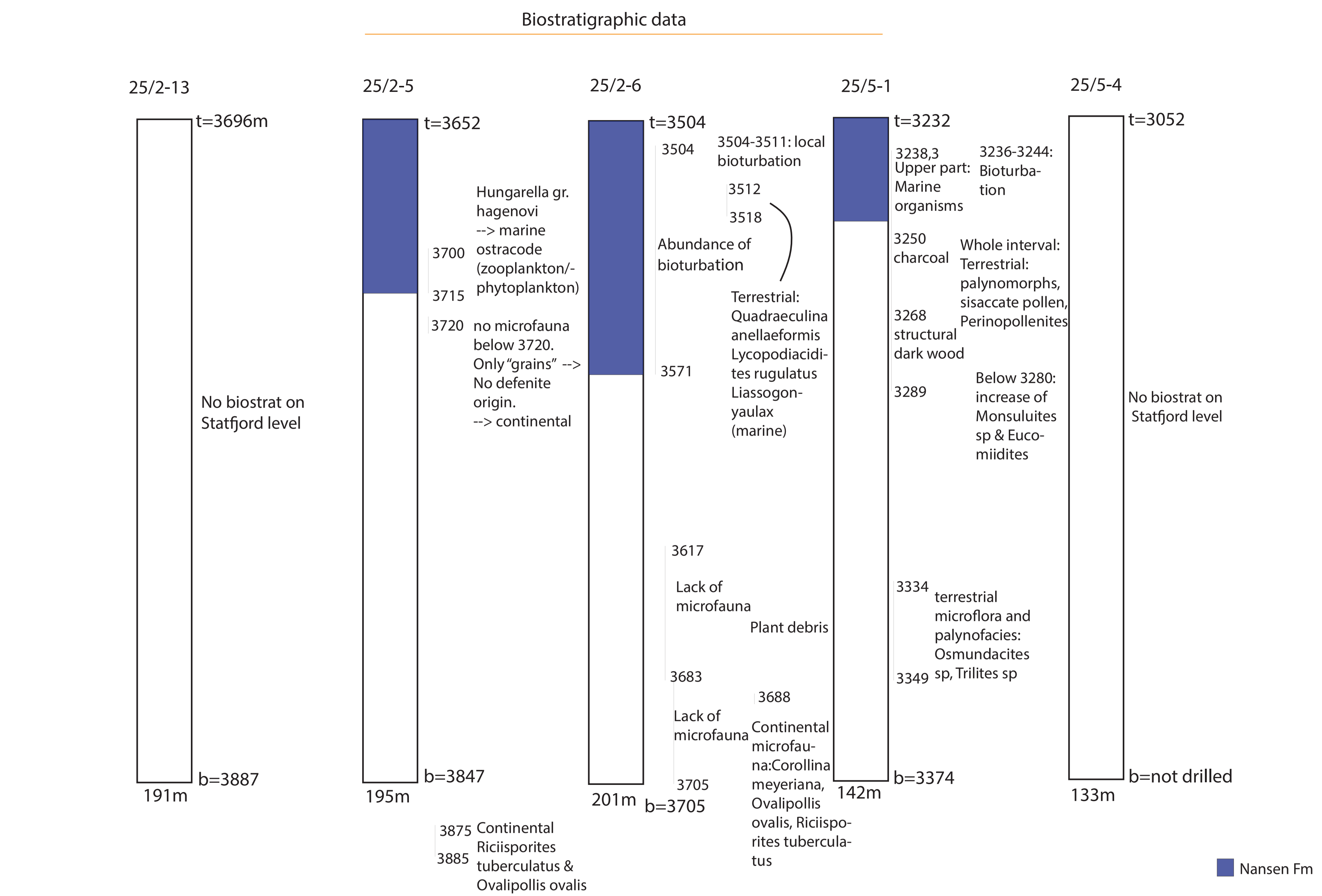


Fig. 5.11 Biostratigraphic data in key wells.

6 Discussion

In order to understand the Statfjord Group in the greater Utsira High area there has to be an integrated understanding of the structural setting and the depositional environment at the time of deposition. The depositional environment and the paleogeographic reconstructions interpreted in this thesis are based on seismic interpretation, well data and work of previous authors.

6.1 Data constrains

Due to a relatively limited vertical resolution of seismic data relative to well data, there are geological events not detected in the seismic both vertically and laterally. This leaves more room for interpretation, based on well data and correlations of facies and facies associations. The Statfjord Group is mostly comprised of a continental succession with local stacked fluvial channels combined with floodplain deposits. This results in a complex depositional system with significant lateral variations, comprising discontinuous channels and finer grained upper floodplain deposits. These lateral changes in depositional facies are normally not detectable on available seismic data in the area, hence limiting interpretations away from well bores. However, accommodation space for the Statfjord Group is mappable and general discussions, implications and interpretations based on these trends are made in this thesis.

The general quality of the seismic is adequate, but due to the depth the Statfjord Group, the vertical resolution is approximately 30 m. In addition to this, the lateral variations within the continental succession results in a lack of continuity of the reflectors. Strong continuous reflectors are interpreted to represent significant variation in lithology on a more sub-regional scale, often correlated to flooding surfaces. The amplitudes are variable, mostly due to the depositional environment. Fig. 6.1 and Fig. 6.2 illustrate amplitude maps at Near Base Statfjord and Intra Statfjord levels, which correlate respectively to channel and floodplain deposits in key wells 25/2-13, 25/2-5, 25/2-6 and 25/5-1. The Top Statfjord horizon was at times difficult to interpret when the amplitude became weaker and separated into a doublet. Fig. 6.3 shows the variation in amplitude for the succession that correlates to a transition from fluvial-marginal marine to marine deposits.

The amplitude maps does to some degree show the quality of the seismic interpretation, and the quality of the seismic data in general, where the Top Statfjord, Intra Statfjord and Near Base Statfjord maps theoretically should illustrate the phase it was interpreted on, hence the color of the reflector. The red colour indicate a horizon mapped as a peak, whereas the blue represent a trough. Stronger amplitides can be a result of a stronger contrast in AI or a tuning effect. Tuning effect is an effect of closely spaced reflectors with variations in the shape of reflection wavelets caused by interference of wavelets. The effect occurs when the thickness of the layer is less than 1/4 λ (Avseth, 2005; Brown, 2010). This may cause stronger amplitude events which do not reflect real geological events, but rather too closely spaced reflectors. Due to the lateral extent of the depositional system, tuning may occur. A seismic reflector may represent both vertically and laterally stacked fluvial channels, resulting in a visible change in acoustic impedance.

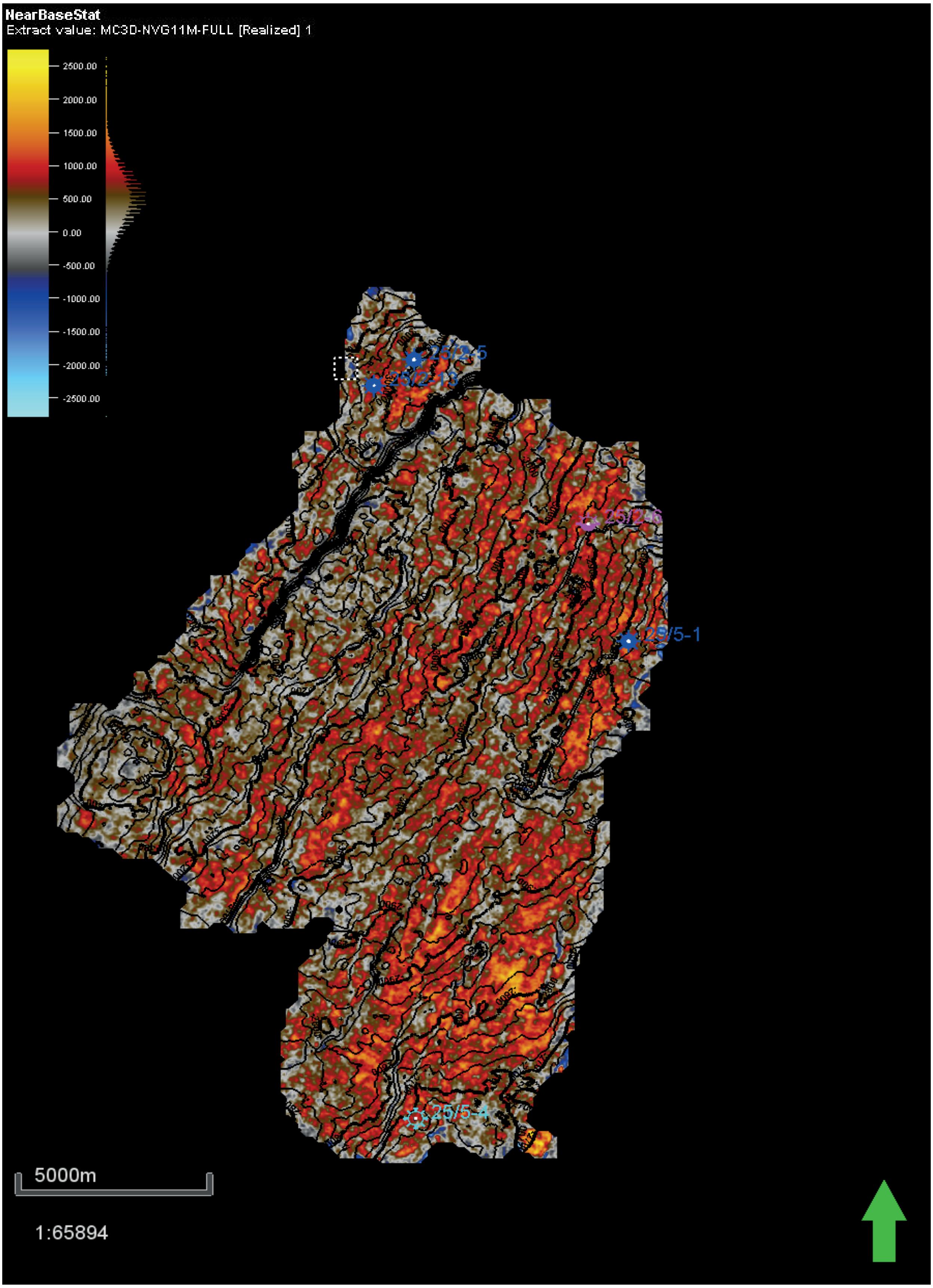


Fig. 6.1 Near Base Statfjord, extracted amplitude value.

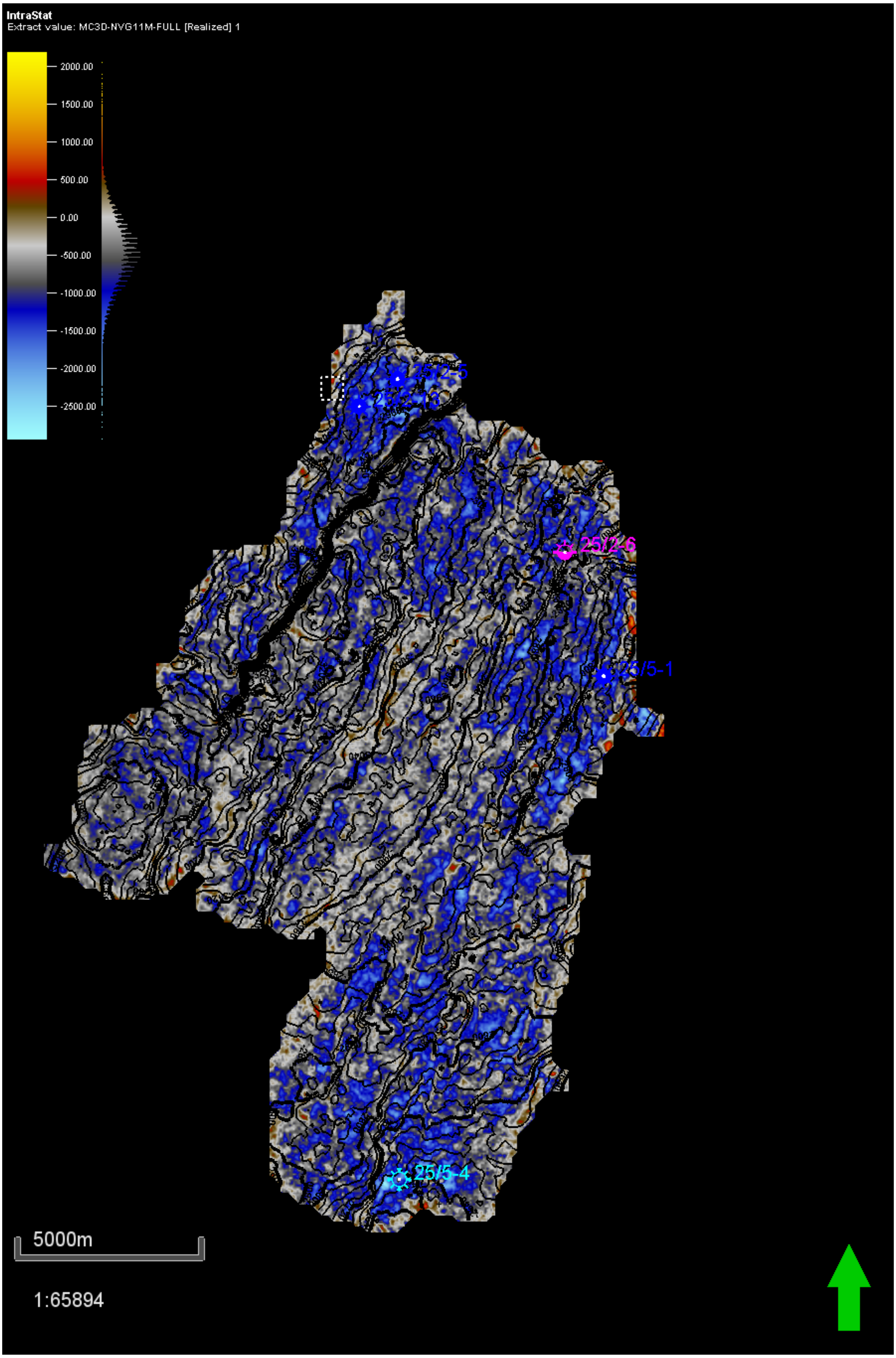


Fig. 6.2 Intra Statfjord, extracted amplitiude value.

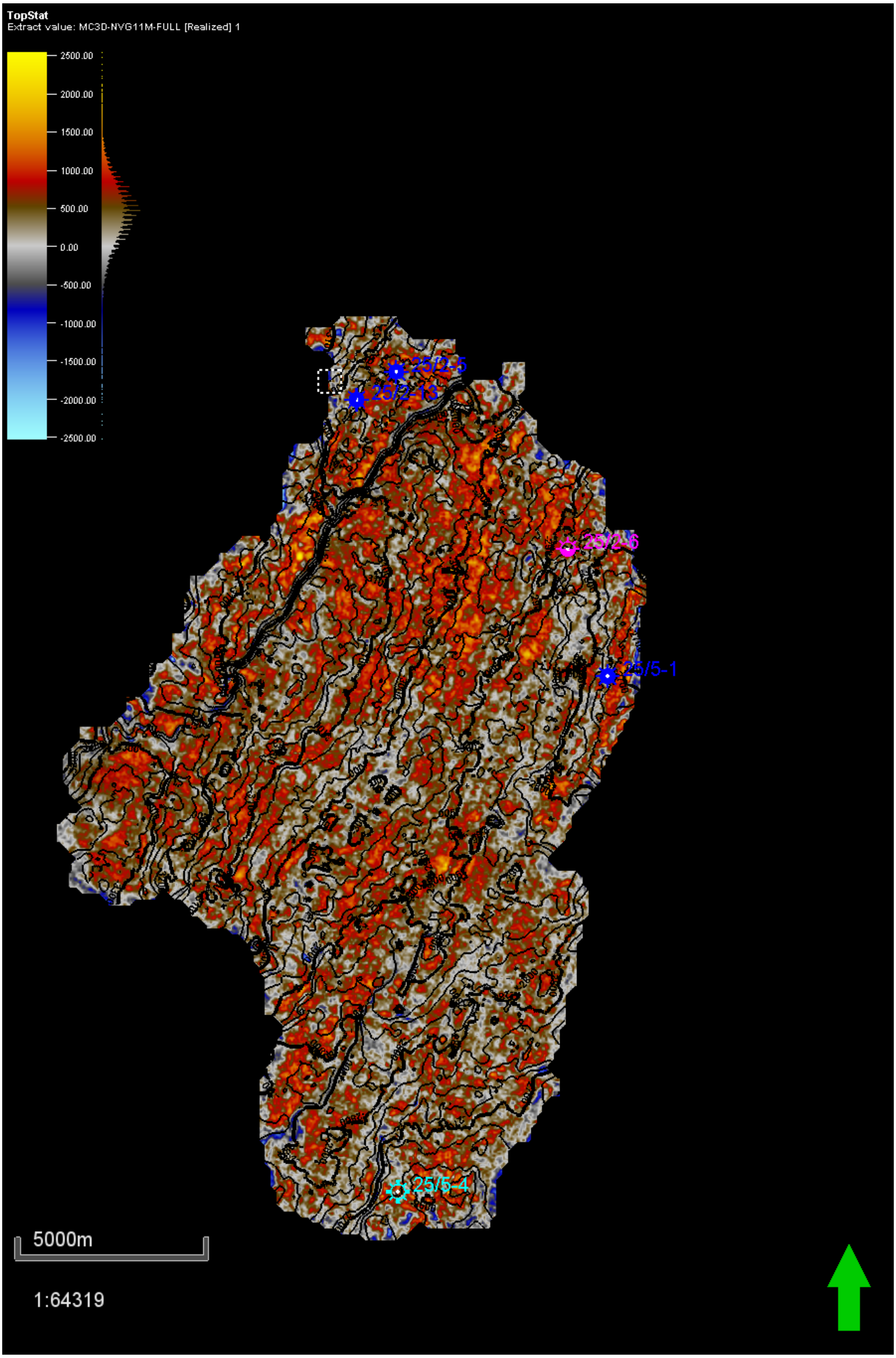


Fig. 6.3 Top Statfjord, extracted amplitide value.

Constructing the well ties was challenging due to lack of key data in the Statfjord succession, particularly the lack of sonic and density logs throughout the interval of interest in the key wells. Since a synthetic wavelet was used during the construction of the well tie, the seismogram display more signals than the seismic, causing a misalignment in the tie. The Statfjord Group is present at depths of 3050 m in the southeast to 3700 m in the northwest, and due to the vertical resolution of approximately 30 m, a small misalignment of well tops represent several meters. The position of the horizons is dependent on the quality of the well tie, since the well tops are shifted during the construction of a new time depth curve.

The well to seismic tie was difficult in key well 25/2-6, where the synthetic trace did not reach the BCU. This was due to a missing section of density data around the BCU interval. Ideally, the well tie should be adjusted down, but due to the lack of data, it was not possible. Top Statfjord is positioned 23 m above the actual top Statfjord in this well. The tie in well 25/2-13 could also be adjusted down somewhat, with Top Statfjord positioned 11 m too high, but at the depth the Statfjord Group is positioned at, this is ok. The ties in wells 25/2-5 and 25/5-1 were good, showing a misalignment of 3 m of the Top Satfjord in both wells. The well to seismic tie in 25/5-4 was difficult to make due to lack of data from the BCU and upwards. The section with missing data is caused by new casing in the well at that position during drilling of the well. Top Statfjord is positioned 44 m below the actual top of the group in this well. It is clear from the position of Top Statfjord that the well ties are of varying quality. It is likely the transition between the upper coarse sandstones of the Statfjord Group and the arcillaceous sequence of the Dunlin Group can result in an obvious seismic reflector, but due to the quality of the well ties, this is not shown in this work. See Fig. 5.10 for the position of the Statfjord horizons.

On the western horst, in well 25/2-13 and 25/2-5, a horizon positioned below the Near Base Statfjord horizon was interpreted to check its position, whether it could be a more accurate Base Statfjord than the one interpreted. In well 25/2-13 it positioned at a depth of 3899 m, which is below the Statfjord Group and within the Hegre Group. In well 25/2-5 however, it positioned at a depth of 3812 m, which locates it within the Statfjord Group. See Table 2.1 for the interval of the Statfjord Group and the respective succession thickness in the key wells. In the remaining key wells, the horizon was positioned below the Statfjord Group within the Hegre Group. Due to shallow TD of key well 25/5-4, the Base Statfjord could not be detected. This implies the Base Statfjord or the Top Hegre is difficult to map. Either the change in lithology between the groups does not give a strong contrast in AI, or the seismic resolution is not good enough to pick up transition, or both.

The Statfjord Group was not interpreted on the eastern side of fault 7, western side og fault 1 and north of the northern bounding fault, fault 13, due to lack of well data to constrain the interpretation and time.

The net-to-gross values for the Statfjord Group in the key wells were calculated based on a cut-off of medium grained sand and calculated from the Gamma Ray logs in ODM. The net-to-gross values could therefore be a few percentages off, around +/-2%.

6.2 Structural setting

During deposition of the Statfjord Group, the Utsira High was a large westerly dipping fault block (Færseth, 1996). From the seismic interpretation, a westerly dipping trend in the Statfjord succession is observed, and local horst and graben systems can be seen.

The interpreted faults in the study area show different magnitudes. The faults in fault group 1 terminate in the BCU and cut basement, whereas fault group 2 terminates in the BCU and do not cut basement and fault group 3 terminate in Middle Jurassic strata. Faults 2 and 7 likely represent reactivated Permo-Triassic faults, since evidence of offset of basement can be observed (see Fig. 5.4). Faults 6, 10, 11 and 12 terminate in the BCU, but these are likely of a Jurassic origin since they do not displace basement in the study area (see Fig. 5.2, Fig. 5.3 and Fig. 5.4). Faults 3, 4, 5, 8 and 9 terminate in the Middle Jurassic successions. There is no visible evidence these faults cut through Jurassic layers and terminate in the BCU (see Fig. 5.2, Fig. 5.3 and Fig. 5.4). Fault 13, which represents the northern bounding fault with the NW/SE trend, terminates in the BCU. There is no evidence of whether it cuts through basement or not, but based on the length of the fault, there is reason to believe this fault is old. It is present throughout the study area, and shows a continuation of approximately 11 km in plan view (see Fig. 5.5).

The faults in fault group 3 terminate in Upper Jurassic strata, however, a small bulge can be observed in the BCU, suggesting the fault terminates there (see Fig. 5.2 and Fig. 5.3). These faults typically show lengths of about 2 km, implying they are not large structures compared to the other faults in the study area. The lithology of the Middle-Upper Jurassic strata is composed of marine mudstones and shales, soft sediments, that can be deformed ductilely during a rifting event (NPD). This observation combined with the somewhat limited seismic resolution can be the reason the fault plane cannot be detected. Since there are no observations of the faults cutting basement or Upper Jurassic strata, they appear to terminate in the Sleipner and Hugin formations and are probably a result of the Middle-Late Jurassic rift phase. A bulge in the BCU is not enough evidence to say the faults cut through the Upper Jurassic strata, without supporting evidence of fault offset in the Upper Jurassic stratigraphy.

From Fig. 5.4 it can be observed that fault 2 shows a displacement of 160 ms of the Statfjord Group and a basement displacement of approximately 170 ms at depths around -3800 ms. Fault 7 shows a displacement of basement of 370 ms, this displacement is larger than the displacement of basement across fault 2. When comparing fault 2 and fault 7, it can be observed that both faults cut basement and show a westerly dipping trend. Fault 7 however shows a larger displacement of basement, indicating this fault was active during a longer period than fault 2. The displacement of basement, the significant displacement of the Statfjord Group and the fact that the faults terminate in the BCU, indicates that fault 2 and 7 are of Permo-Triassic age and were reactivated during the Middle-Late Jurassic rift phase.

According to Cowie (1998) and Gawthorpe and Leeder (2000), the development of faults is a process with several phases; from the initiation of fault movement where the crust is locally weak and the isolated faults nucleate at approximately the same time with similar growth rates, to the interaction and linkage of individual fault segments that are optimally located with respect to the other faults, and finally the generation of a through-going fault zone and suppressed growth of the faults that were not optimally located (see Fig. 6.4). This suggests that during a second rift phase, it is very likely that there will be a reactivation of older faults, causing them to continue to grow. The faults of fault group 1 represent faults that show such a development through time in the Utsira High area.

Fault 2 and 7 were likely of smaller magnitude during the first rift phase, and grew larger during the Middle-Late Jurassic rifting event. This implies the old Permo-Triassic faults represent locally weak crust, which was reactivated during a later stage of rifting. There is no evidence fault 1 displaces basement. Based on the increase in thickness of the Jurassic succession on the western side of the fault, the fault is interpreted to be a result of the Permo-Triassic rift event, and additionally represent a reactivated structure during the second rift phase (see Fig. 6.5). Faults 5, 9, 10 and 11 all terminate at the BCU, but none of them cut through basement (see Fig. 5.2 and Fig. 5.3). This gives reason to assume these faults are of Middle-Late Jurassic age. Faults 3, 4, 5, 7 and 8 all terminate in Middle-Jurassic strata, Heather and Hugin Formations, and none of them cuts through deep structures (see Fig. 5.2 and Fig. 5.3). They are all positioned between fault 2 and 7, which make up the large fault block. They comprise the horst and graben geometry within this tilted fault block (see Fig. 6.5). Based on these observations, a Middle-Late Jurassic age is suggested for the faults. The interpretation suggests most of the faults in the study area are of Jurassic age, with only a few Permo-Triassic faults which show evidence of reactivation.

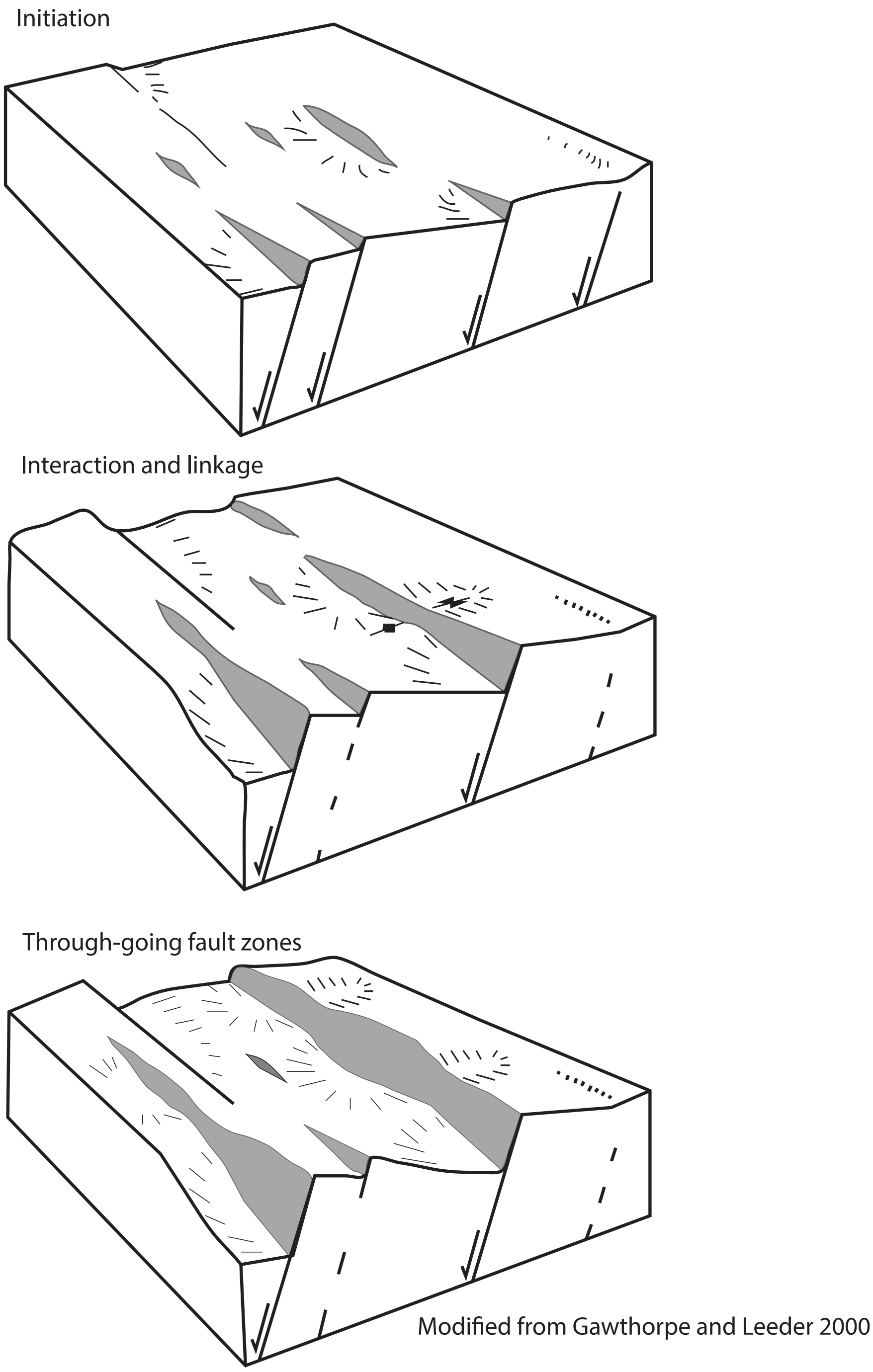


Fig. 6.4 3D evolution of normal faults.

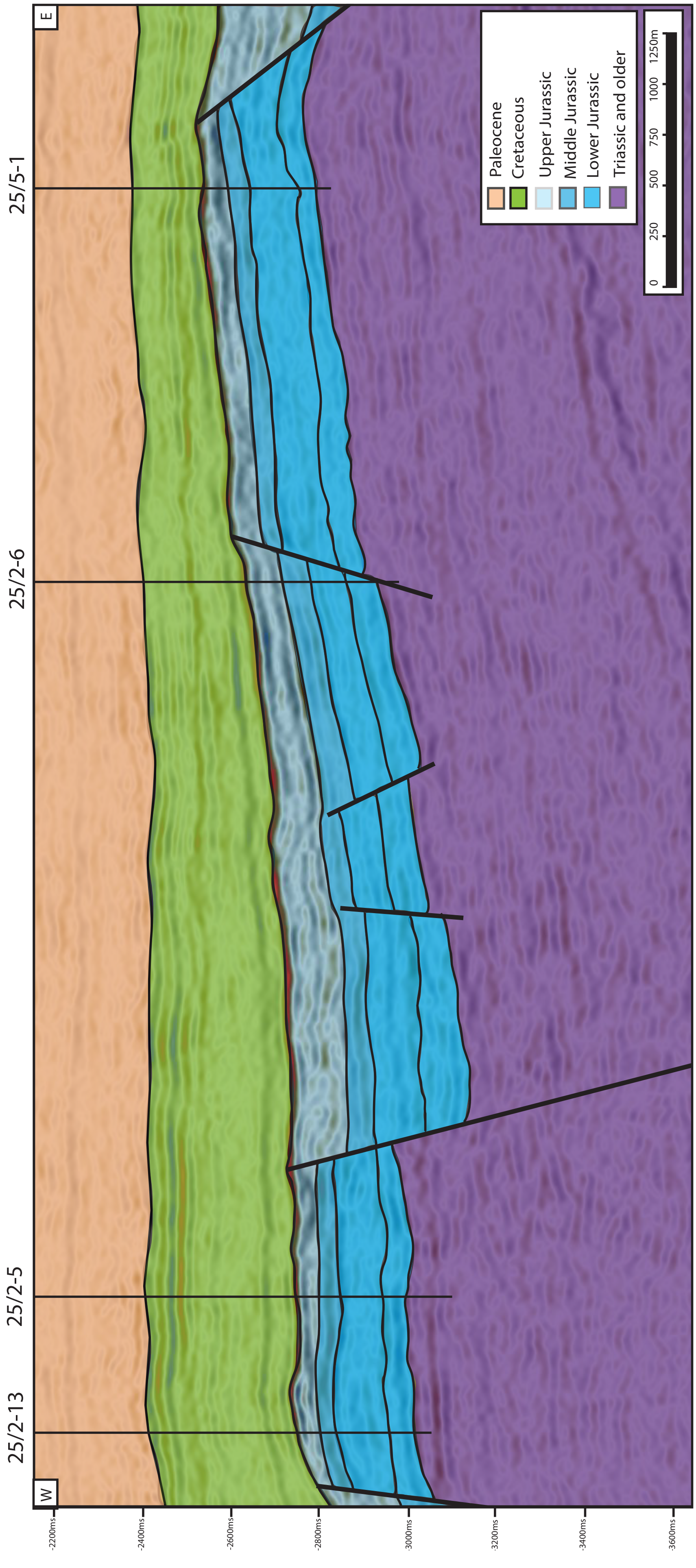


Fig. 6.5 Geoseismic section 1. *Based on Arbitrary line 1 (see Fig. 5.2). The lower sequence of the Lower Jurassic succession shows the interpreted Statfjord Group*

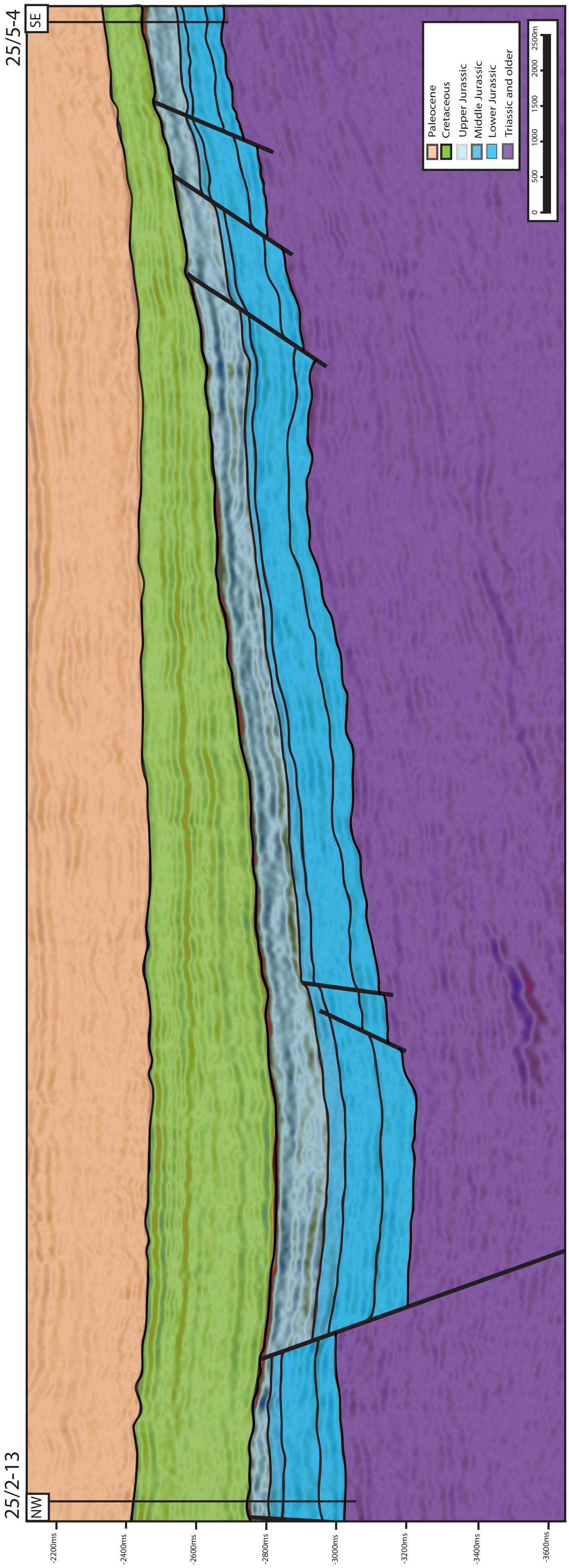


Fig. 6.6 Geoseismic section 2. *Based on Arbitrary line 2 (see Fig. 5.3). The lower sequence of the Lower Jurassic succession shows the interpreted Statfjord Group.*

During time of deposition of the Statfjord Group, the large faults of fault group 1 likely had smaller magnitudes of throw. The structural setting present during deposition of the Statfjord Group was less complex than today, and a setting of a horst and a westerly dipping half graben in the study area is suggested. The eastern block represents the half graben and is associated with an increase in accommodation space (see Fig. 5.9 and Fig. 6.5). This setting would show less displacement across the faults than observed in the seismic and the faults in fault group 2 and 3 would not be present, because they gain displacement in Middle-Late Jurassic, after the deposition of the Statfjord Group.

The northern bounding fault with the NW/SE trend is different from the rest. It is difficult to demonstrate the age of this fault without interpreting reflectors on both the hangingwall and the footwall side of the fault. With further investigation, syn-rift sequences can be mapped and it is possible to figure out how many rifting events this fault has undergone. It is likely that this fault represents an old basement structure that predates the formation of the Utsira High, based on the fact that is shows no clear association with either the Permo-Triassic or the Middle-Late Jurassic rifting events. It could also be a transfer fault, generated along an old weakness zone in the crust. Fig. 5.1 shows the length and trend of the fault and Fig. 5.5 shows the fault in a cross section.

The sediments deposited in Late Triassic Early Jurassic represent post-rift sediments deposited on top of clastic wedges and rotated fault blocks from the Permo-Triassic rift phase (Steel and Ryseth, 1990; Ryseth and Ramm, 1996). The deposited Statfjord Group was affected by this remnant rift topography, and the seismic data shows a typical post-rift trend with passiv infill characterized by a generally flat top and thickening of the succession in the center of the local basin (see Fig. 6.7) (Purser and Bosence, 1998). Fig. 6.5 and Fig. 6.6 show a thickening of the Statfjord Group in the graben along the western horst, this thickening is also supported by the thickness map (see Fig. 5.9). The horizons show an overall westerly tilted trend and increasing thickness between Top Statfjord and Near Base Statfjord towards west (see Fig. 5.9, Fig. 6.5 and Fig. 6.6). This increased succession thickness indicates increased accommodation space towards the west. Additionally this increase in thickness can be observed for the entire Jurassic succession (see Fig. 6.5 and Fig. 6.6).

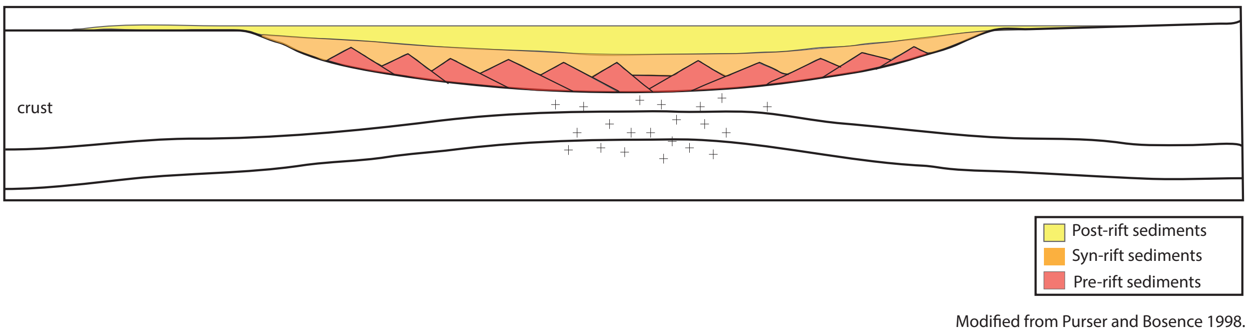


Fig. 6.7 Rift model. *Relation between pre- syn- and post-rift sediments.*

Fig. 6.5 and Fig. 6.6 illustrates the magnitude of the heave and throw across the faults. The small displacements of the Statfjord horizons across the faults are a result of faulting after deposition. The displacement across a fault will be filled in during syn-rift deposition, and only represent a minor effect on sediments deposited in post-rift time. The north trending horst in the west shows a more substantial displacement of the interpreted Statfjord Group across the fault. This, however, is believed to be a result of the reactivation of the NE/SW trending fault, fault 2, at a later stage.

Fig. 6.5 and Fig. 6.6 illustrates a lateral thickness variation across the area, with a thinner Statfjord Group in elevated areas, a thicker succession in the grabens and downfaulted areas, and an overall decrease in the succession thickness towards the east. In Fig. 6.6 the Statfjord Group shows a thinning towards southeast and a change in depth from approximately 2700 ms in the elevated areas to 3200 ms in the graben. Fig. 5.9, Fig. 6.5 and Fig. 6.6 show the lateral thickness variations, and based on this trend the areas with a thicker Statfjord succession represents depositional basins. The depositional basin is observed along the hangingwall of the western horst, where it is at its deepest (see Fig. 5.9). The half graben is of Permo-Triassic age, and the horst segment within the basin show the original position of the basin before faulting commenced in the Middle-Late Jurassic, generating the local horst and graben system (see Fig. 6.5).

6.3 Wells

From the well correlation panel the thickness variation of the Statfjord Group is observed (Fig. 5.10). The overall trend in the key wells is fining upward packages of sand interbedded with shale and finer grained deposits of shale between the sand packages. Well data indicates a clear thinning of the succession to the east. The Statfjord Group can be correlated based on flooding surfaces and further be divided into units with varying net-to-gross.

The following discussion of thickness variation of the different successions in the Statfjord Group can be seen in Fig. 5.10 and is summarized in Table 5.2.

A basal unit of medium-coarse grained sandstone is present in key wells 25/2-13 and 25/5-4. This unit could represent the transition of the coarsening upwards sandstone sequence and the underlying shaly unit present in the type well area (NPD). The unit of fine sandstones and shales is present in all key wells. The succession shows an equal thickness on the western horst and in well 25/2-6, a thinning towards 25/5-1 in the east, and a thickening towards southeast in well 25/5-4. The lithological alternation between clean shale and shale with stringers of sand, the presence of continental microfauna in the upper part of this succession and a general lack of microfauna in the lower part of this unit in well 25/2-6 suggests a floodplain environment.

The following coarse sandstone unit illustrates a thickening from the western horst eastwards towards 25/2-6. In key wells 25/2-6 this sequence show plant debris, and in 25/5-1 terrestrial microflora and palynofacies is present. Based on the biostratigraphic data and the general trend of coarse grained sandstone interbedded with shale, a fluvial depositional environment is suggested, where the succession of sandstone represents river channel deposits and the thin layers of shale represent flooding events (see Fig. 6.8).

The overlying unit of fine sandstones and shales comprises an uniform thickness, except in well 25/2-5, where the succession doubles in thickness. From biostratigraphic data, the upper part of this succession contains terrestrial palynomorphs and pollen in well 25/5-1. Based on the dominating shaly lithology and the biostratigraphic data, a floodplain environment is suggested for this unit (see Fig. 6.9). The cores show an overall shaly content and the presence of coarser grained sand.

The upper succession of coarse sandstones show a substantial thickness in well 25/2-13, a significant reduction of the thickness in well 25/2-5, then a local thickening in well 25/2-6 followed by further thinning in well 25/5-1. Southeastwards towards well 25/5-4 there is an abrupt thinning to one third of the thickness in the westernmost well, well 25/2-13. The upper part of the sandstone unit shows bioturbation and fossils, the presence of marine ostracodes in well 25/2-5 and bioturbation in wells 25/2-6 and 25/5-1, this indicates a marine environment. The lower half of the coarse sandstone sequence in well 25/5-1 also contains coal, structural dark wood, terrestrial palynomorphs and pollen indicating a continental environment. See Fig. 6.10 for coal at 3250 m, and the transition between the upper fine sandstones and shales and the upper coarse sandstone. Fig. 6.11 shows bioturbated sandstone in the upper part and an overall alternation between sandstones and shales. Fig. 6.12 shows the sandstones of the upper coarse sandstone succession.

3820-3825m

3825-3828m

3829-3834m

Fig. 6.8 Core photos well 25/2-13. *Lower coarse sandstone. Photos from NPD*

3277-3282m

3282-3287m

3287-3291m

Fig. 6.9 Core photos well 25/5-1. *Floodplain deposits. Photos from NPD*

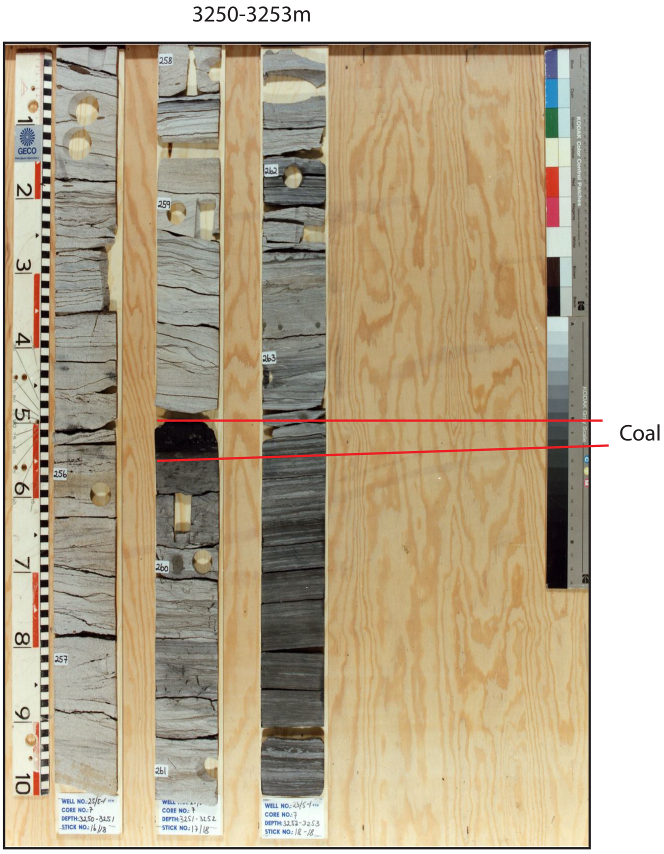


Fig. 6.10 Core photos well 25/5-1. *3250-3253m = coal at 3250. 3272-3276m, 3286-3287 = transition between upper fine sandstones and shales to upper coarse sandstone. Photos from NPD*

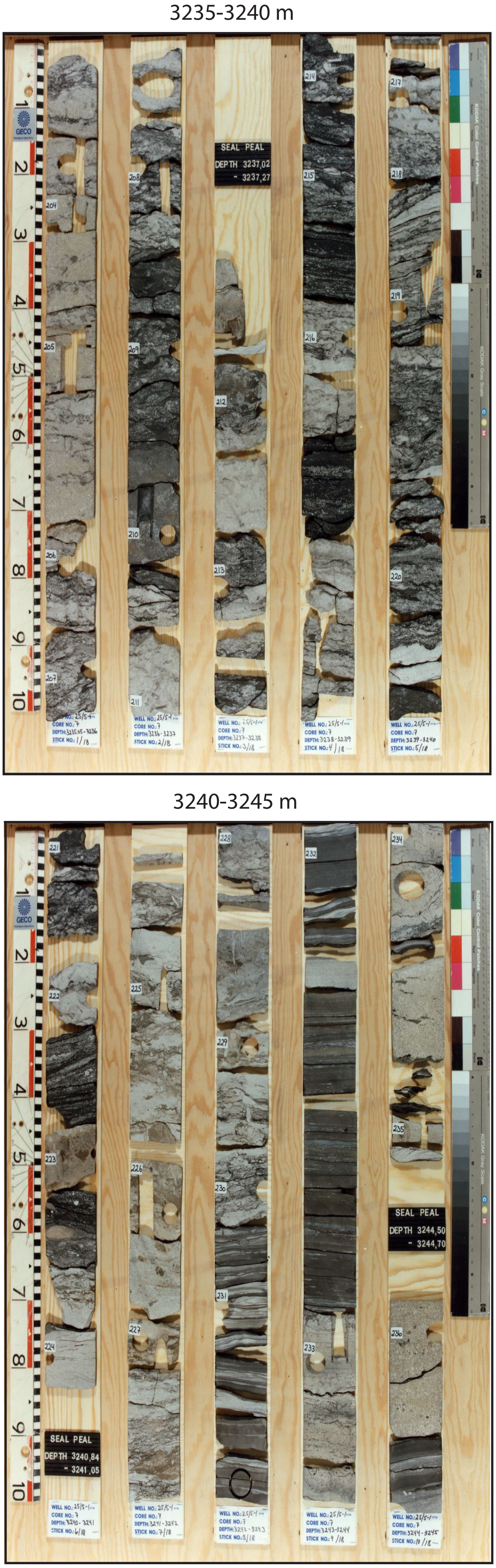


Fig. 6.11 Core photos well 25/5-1. *Bioturbation in the upper coarse sandstone. Photos from NPD*

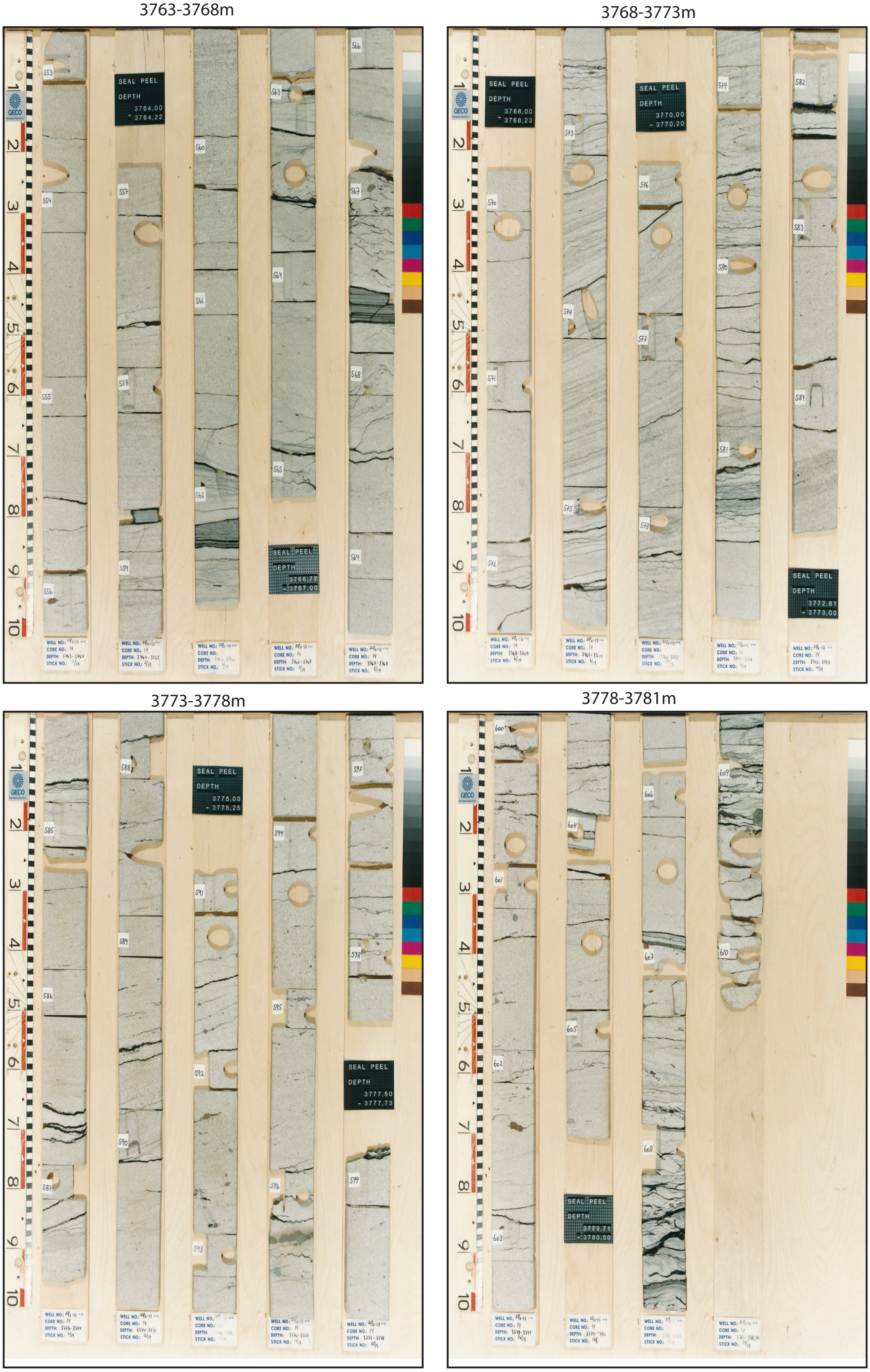


Fig. 6.12 Core photos well 25/2-13. *Upper coarse sandstone. Photos from NPD*

Based on the distribution of the upper coarse sandstone, presence of bioturbation and marine fossils, a fluvial system succeeded by shallow marine deposits is interpreted for this succession.

When rivers are too far inland from base level influence, fluvial accommodation may still be affected by climate or tectonism. Therefore inland fluvial settings use unconventional systems tracts for regional correlation of strata, high accommodation space and low accommodation space (Catuneanu, 2009). Accommodation space is the space available for potential sediment accumulation, or the space available to fill up the base-level. A rise in base level creates accommodation and a fall in base level destroys accommodation, base level is commonly associated with relative sea level (Jervey, 1988; Schumm, 1993). In fluvial systems, low-accommodation space and high-accommodation space is defined by the ratio between fluvial elements. The presence of amalgamated channel deposits indicates a low-accommodation setting, while floodplain dominated successions indicate a high-accommodation setting (Catuneanu, 2009). High rates of accommodation space gives a low net-to-gross of the succession, while lower rates of accommodation space give a high rate of net-to-gross of the succession. Sandy braided rivers are typically more sandstone prone than sandy meandering rivers, and meandering rivers show higher proportions of fine grained material (Miall, 1996). A decrease in accommodation space will typically result in braided rivers and lateral connectivity of sand, while an increase in accommodation space will result in a meandering system and a decrease in sand connectivity. Fig. 3.7 shows the difference in sand and floodplain deposits in the respective systems. According to Ryseth and Ramm (1996) lateral and vertical sand connectivity is likely to be higher when subsidence rates are lower, and the sand connectivity decreases with increasing rates of subsidence (see Fig. 6.13).

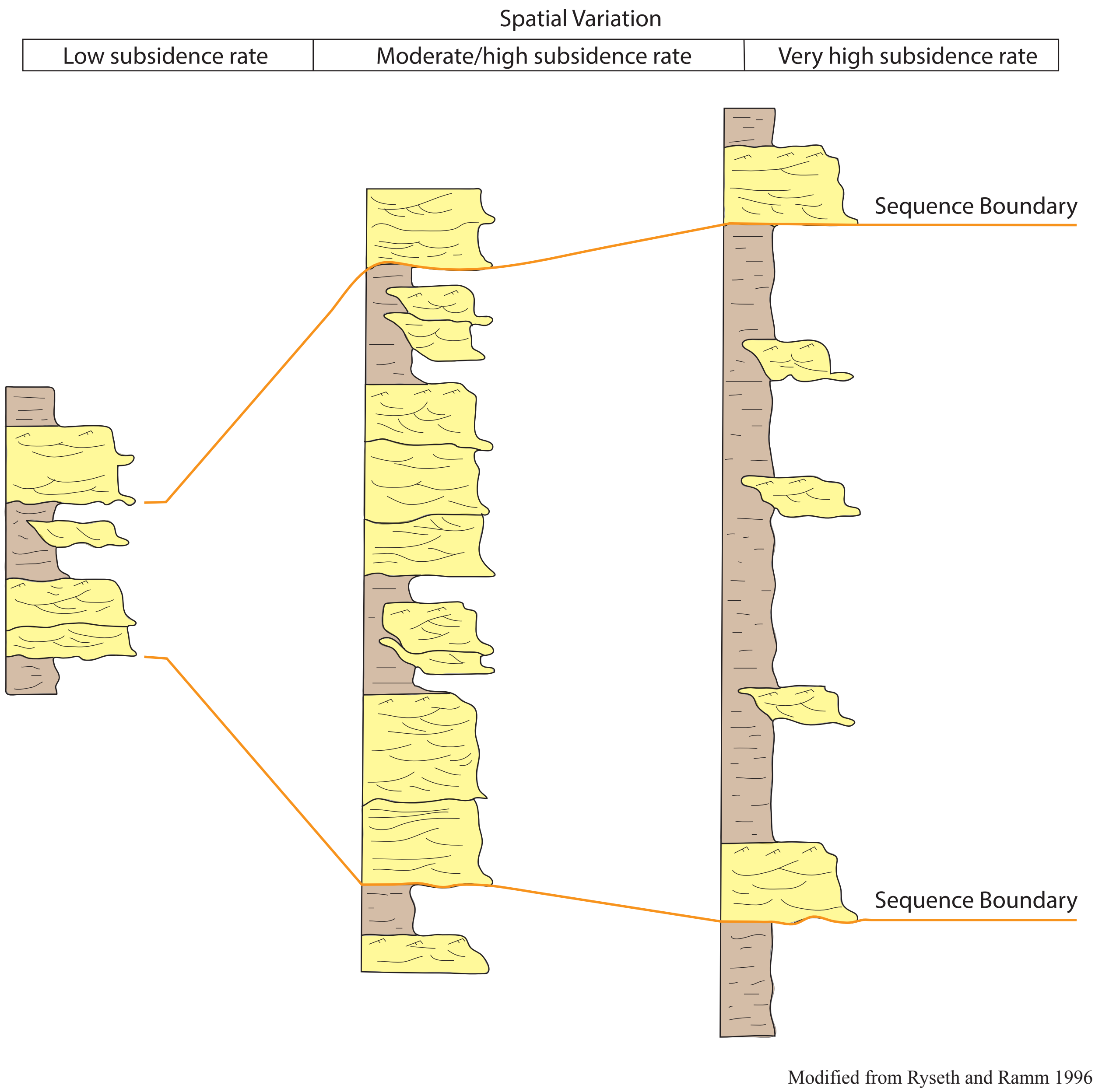


Fig. 6.13 Differential subsidence of the Statfjord Group.

There is no continuous lithology boundary throughout the key wells in the study area where the seismic surfaces are positioned, but rather a local transition in lithology. This discontinuity of lithology throughout the study area can be explained by the depositional system of the Statfjord Group. Table 5.3 shows an overview of the lithological transition where the seismic horizons are positioned in the key wells. A lithology transition from shale to sand indicates a lowering of base level, while a transition from sand to shale indicates a flooding surface and an increase in base level, and hence an increase in accommodation space.

The Near Base Statfjord horizon is positioned within a succession comprised of fluvial channels. This stacking pattern can be caused by either low accommodation space, high sediment input, or both. Periods with little accommodation space or high sediment input are likely to give high lateral and vertical connectivity of channels, displayed by a high net-to-gross for this succession. Lateral sand connectivity is therefore likely to be higher in this unit of sandstones. The Intra Statfjord horizon is positioned within a floodplain succession. During times of high accommodation space, rivers are often associated with meandering, and the succession has a lower net-to-gross. Lower lateral sand connectivity and meandering rivers can give rise to extensive floodplains and the development of coal, and this succession represents a period of higher base level. The Top Statfjord horizon is positioned within the upper part of the Statfjord Group, which is the thickest succession, and based on the biostratigraphic data, it represent a transition from a fluvial to a marginal marine environment. According to Coward et al. (2003), the Triassic-Early Jurassic basins were subjected to post-rift thermal subsidence with Late Triassic-Early Jurassic marine sediments filling the topography of the rift. The transition from an alluvial to a marginal marine environment caused an increase in accommodation space and "widespread deposition" of sand. This succession represents a unit of intermediate net-to-gross, with an overall higher net-to-gross than the floodplain succession, but a lower net-to-gross than the fluvial channel succession. This lower net-to-gross value is due to the fine grained sediments interbedded in the sand.

From the well correlation panel it looks like the fluvial sandstone unit is more sandstone prone than the marginal marine sandstone, however one well is not representative for an entire area and may hit a sandstone channel in a fluvial environment, hence give the impression of an extensive sandstone unit. The marginal marine environment of the Statfjord Group does show an overall lower net-to-gross in all the wells when compared to the fluvial channel deposits. The marginal marine deposits of the Nansen Formation shows indications of tidal dominated structures, lenticular bedding, flase bedding and mouth bars (Røe and Steel, 1985). A marginal marine environment affected by tide shows both presence of sand and finer grained sediments like clay and silt. The lateral connectivity of sand deposited in an environment like this will therefore show low net-to-gross values.

A regional well correlation panel from the Viking Graben across the study area and into the Stord Basin shows the difference in accommodation space and stacking pattern for the Statfjord Group on a regional scale in the North Sea (see Fig. 6.14). There is clearly an increase in accommodation space for the Statfjord Group from the Utsira High, both into the Stord Basin to the east and the Viking Graben to the west. Increased accommodation space may result in isolated channel sandstones encased in finer grained overbank successions. This setting is observed in wells 30/11-4 and 26/4-1, comprising a 600 m and 375 m Statfjord Group thickness respectively (NPD). The wells are characterized by an overall lower net-to-gross, observed as thin successions of sand separated by finer grained shale or sandy shale throughout the Statfjord Group. The wells on the Utsira High show a somewhat higher sandstone connectivity than the Statfjord deposits in the Viking Graben and Stord Basin. However, the net-to-gross is generally lower than described in the literature from the Horda Platform and Tampen Spur (Ryseth and Ramm, 1996; Ryseth, 2001). This is probarbly due to the distance from the source area. The Utsira High is located in the middle of the North Sea basin, and away from the main source area to the east and northwest (Dalland et al., 1995; Mearns et al., 1996; Knudsen, 2001). This results in lower net-to-gross of the deposits.

In Fig. 6.15 the change in Statfjord thickness can also be observed from the Utsira High and north into the Viking Graben, showing the difference in accommodation space present during deposition of the group. Moderate accomodation space gives stacked fluvial channel sandstones that are periodically surrounded by mud-rich intervals, and high accommodation space gives isolated channels and little lateral connectivity of sandstone.

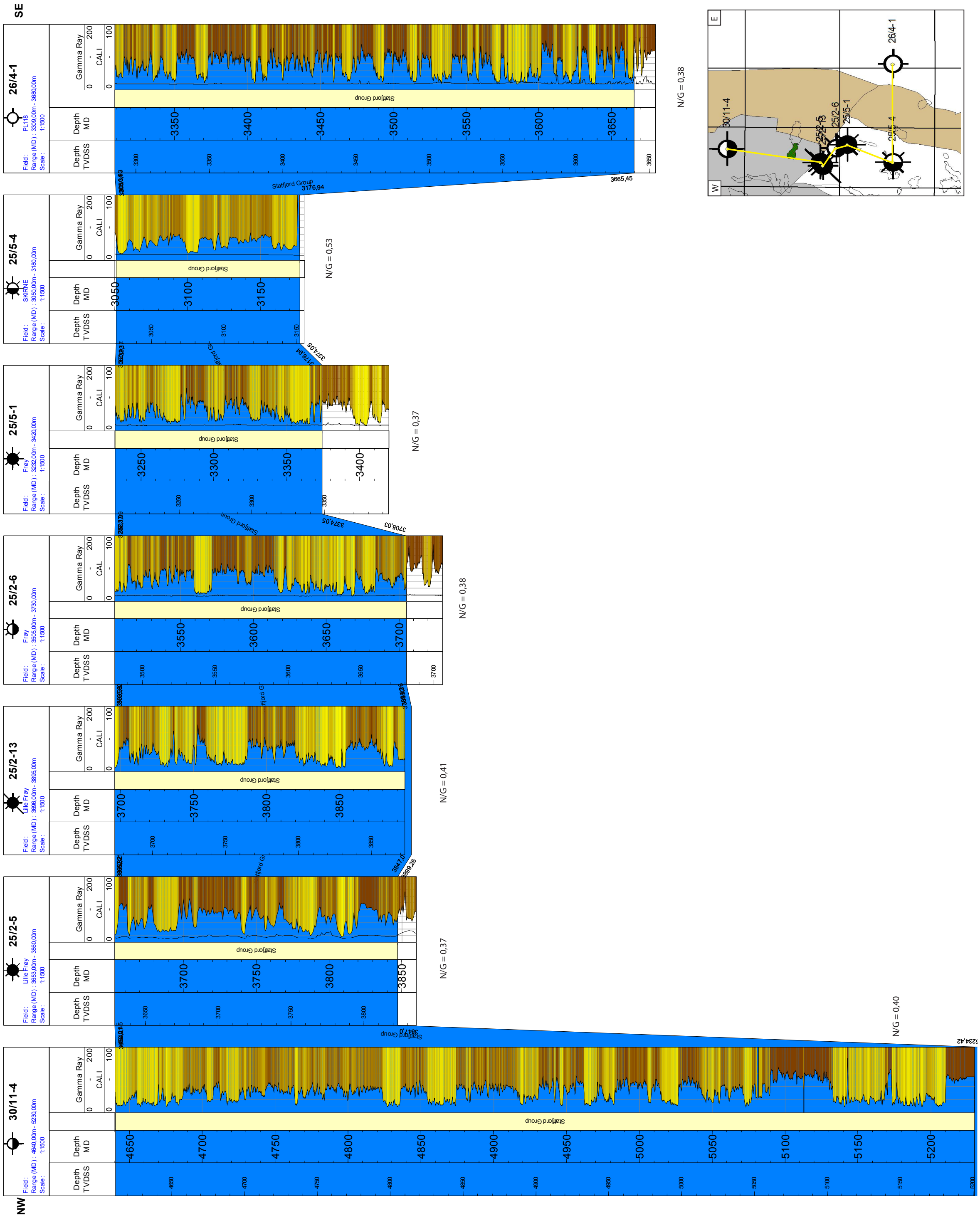


Fig. 6.14 Regional well correlation panel, North Sea.

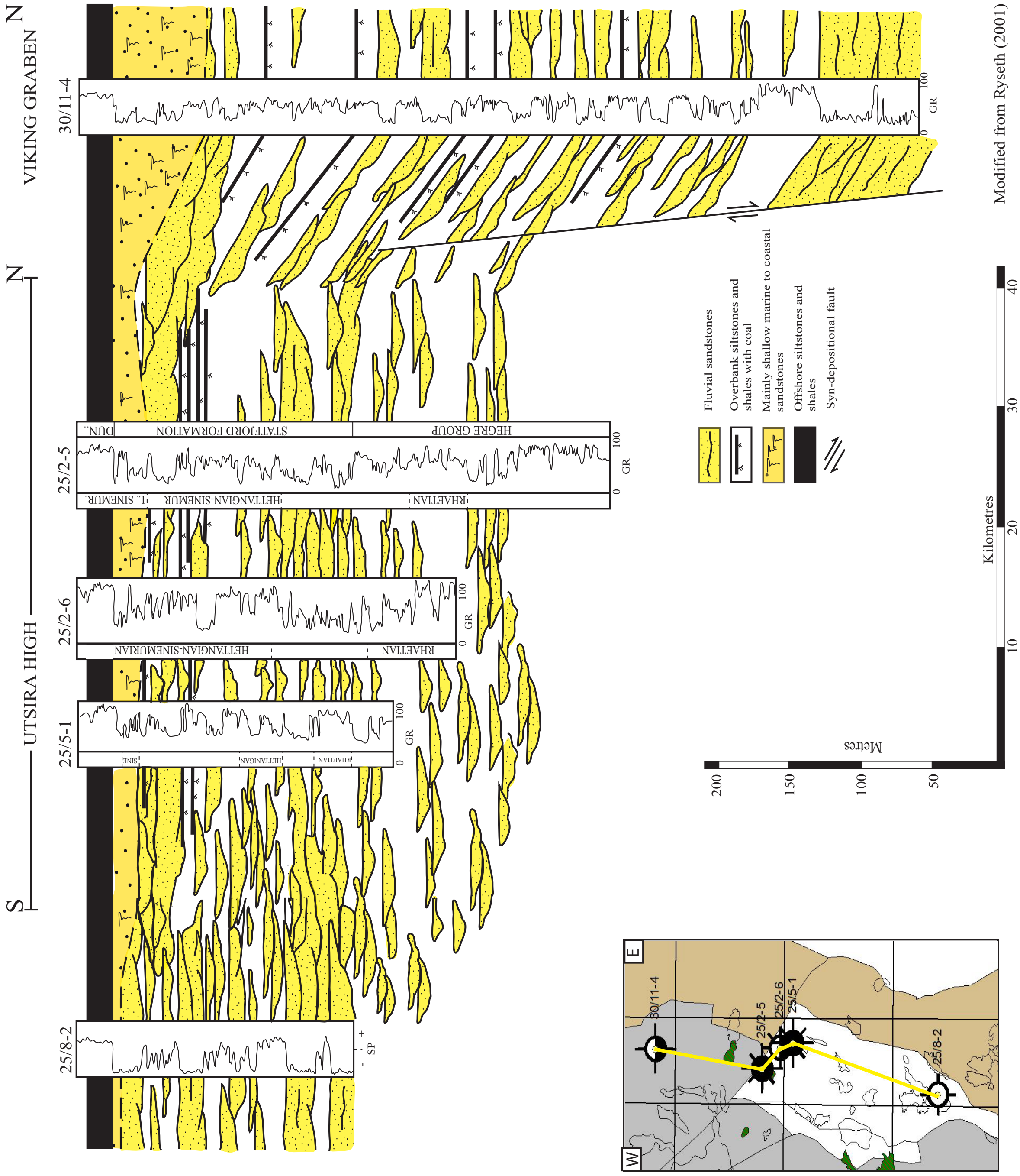


Fig. 6.15 Correlation panel Statfjord Group. *From the Utsira High to the Viking Graben*

Well 30/11-4 comprises one of the thickest Statfjord Group successions reported in the North Sea. The uppermost unit is interpreted as marine in origin, however, how much of the Statfjord Group in well 30/11-4 that is of marine origin is not certain, due to the lack of investigation of biostratigraphic data from the upper part of the group. The group shows a net-to-gross value of 0.40 in the northernmost well, and the succession shows isolated channels of sand separated by fine grained deposits in the lower part of the group, while sand units upwards are separated by fine grained deposits with sand in it. The succession becomes more sandstone prone towards the top, this could be a result of the marine transgression, sediment supply and high accommodation space. In well 26/4-1 there are only cores for the upper 8 m of the Statfjord Group, and due to the lack of cored data, it is difficult to determine how much of this succession is of marine origin. The net-to-gross value of 0.36 supports high accommodation space during deposition.

From the net-to-gross values it is clear that the Statfjord Group is more sandstone prone in well 30/11-4 than in 26/4-1, suggesting the area around well 30/11-4 had both a higher accommodation space and sediment input than the area around well 26/4-1. The net-to-gross values suggests well 30/11-4 was closer to the source area than well 26/4-1. This corresponds with Ryseth (2001), who suggested a southerly dipping paleoslope and rivers from the Tampen Sour and Horda Platform area towards the Utsira High.

The net-to-gross values in the wells on the Utsira High, should display lower values than the ones in the Viking Graben and Stord Basin, since the high is positioned further away from known source areas. However, they do not and the key wells shows an average net-to-gross value of 41.2. The structural interpretation and well data indicates the Utsira High was a topographic during deposition of the Statfjord Group, with moderate accommodation space, while the areas around well 30/11-4 and 26/4-1 were depositional basins. This paleotopography makes the large southerly dipping river systems difficult. The well data indicates the accommodation space is higher in wells 30/11-4 and 26/4-1 than the key wells, with an approximately 400 m and 175 m thicker Statfjord succession respectively, than in the key wells with the thickest Statfjord succession. This points to the Utsira High representing an area of intermediate accommodation space, while the others represent high accommodation space during the deposition of the Statfjord Group. The source area for the Statfjord Group on the Utsira High is somewhat speculative if the high was a paleototopographic high during deposition of the group. Sand cannot "climb" up on a high, and this scenario makes a northerly and easterly source area difficult. One explanation for the sand on the high can be local highs on the Utsira High itself, related to remnant topography from the Permo-Triassic rifting. Alternatively, the Utsira High did not represent a significant high during deposition throughout the Early-Jurassic. A combination of both is possible as well.

The fluvial system prevailed on the Utsira High throughout most of the deposition of the Statfjord Group in Late Triassic-Early Jurassic, but was followed by a marine transgression that capped the continental deposits. The fluvial system gradually migrated towards the east on the Utsira High as accommodation space was filled. The marine transgression flooded the Utsira High and the surrounding areas, depositing a thicker succession of the Statfjord Group where accommodation space was higher.

6.4 Facies and facies associations

The term facies has been described by numerous authors, and according to Walker (1992), facies is a body of rock characterized by a particular combination of lithology, physical and biological structures that show a different aspect from the bodies of rock above, below and laterally adjacent. Facies is used to understand sediments from different comparable depositional environments. The boundary between facies can be both sharp or gradual, and facies can change vertically and laterally within a stratigraphic unit. Facies associations is a set of related facies stacked on top of each other (Boggs, 2011).

In Fig. 6.16, a log from well 25/2-13 is shown. The section shows fining upwards successions of sand separated by finer grained sediments, silt and clay. The successions of sand all show the same trend, interpreted to represent stacked fluvial channels with coarser grained sand in the base and finer sand towards the top, comprising cross beds and ripples respectively. The stacked fluvial channels are separated by finer grained succession consisting mostly of mud and silt, representing floodplain deposits. The succession contains rootlets, paleosols and stringers of sand, indicating deposition from suspension, a lower flow regime, and periods of lower water level during times of lowering of base level on the floodplain. Periodically this succession was subjected to higher flow regimes, based on the presence of medium grained sand. The Nansen Formation is not described in this cored section, but based on a correlation with neighbour well 25/2-5 there is evidence of marine fossils down to depths of 3715 m, indicating the upper 19 m are of marine origin. The alternation between stacked fluvial channels and floodplain deposits indicates deposition during alternating flow regimes.

The Statfjord Group in well 25/2-13 shows the characteristics of depositions from a meandering river, where multiple episodes of meander migration causes vertical stacking of fining upwards successions (see Fig. 6.16). Meandering rivers make point bar deposits, with an erosive channel base and fining upward sequence. The decrease in grain size indicate a decrease in flow regime towards the top. Finer grained deposits, floodplain deposits, are present along braided and meandering rivers, but are particularly common along single channel rivers. During flooding or crevasse spills, fine grained sediments deposit out of suspension on floodplains, levees and oxbow lakes (Bridge, 2009; Boggs, 2011).

Due to the nature of meandering rivers, point bars usually show a full sequence from coarse sandstones in the base to fine grained floodplain deposits at the top. The channel deposits represent periods of lateral accretion while the floodplain deposits represent periods of vertical accretion in the fluvial deposits (Miall, 1996; Boggs, 2011). See Fig. 6.16 for the cored section through key well 25/2-13, showing both stacked fluvial channels and floodplain deposits.

The continental deposits of the Statfjord Formation was drowned by a marine transgression, and the Utsira High was covered by a shallow marine sandstone (Røe and Steel, 1985; Ryseth, 2001). This created vertical successions of sandstone, the upper one subjected to bioturbation, and an overall fining upwards sequence of sandstones and marine shales. The change from a continental to a marine environment can be observed by bioturbation in the upper parts of the Statfjord Group in key wells 25/2-5, 25/2-6 and 25/5-1 (see Fig. 6.11). A marginal marine environment represents the boundary between continental and marine depositional environments, and it is a narrow zone affected by river, wave and tidal processes, where estuaries and lagoons are characteristic during transgression (Boggs, 2011). Røe and Steel (1985), described lenticular bedding, flaser bedding and mouth bars in the Nansen Formation, pointing to deposition in a marine environment affected by both tide and rivers.

Based on biostratigraphic data and varying net-to-gross in the key wells, the different facies comprising the Statfjord Group was estimated. Approximately 43% of the Statfjord Group are channel deposits, 37% floodplain deposits and 20% is of marine origin. The presence of the Nansen Formation in key wells 25/2-13 and 25/5-4 was estimated based on the levels showing a marine origin in the other key wells, since they do not have biostratigraphic data on Statfjord levels. This data indicates that a continental fluvial environment dominated during the deposition of the Statfjord Group, with marine conditions dominating during the final stages. The marine part of the succession makes up approximately 20% of the Statfjord Group, indicating that a marine transgression from the north or the south flooded the high towards the end of the Early Jurassic. The marine part of the Statfjord Group is described by several authors (e.g., Deegan and Scull, 1977; Røe and Steel, 1985; Ryseth, 2001), and according to Ryseth (2001) the marine transgression came from the south.

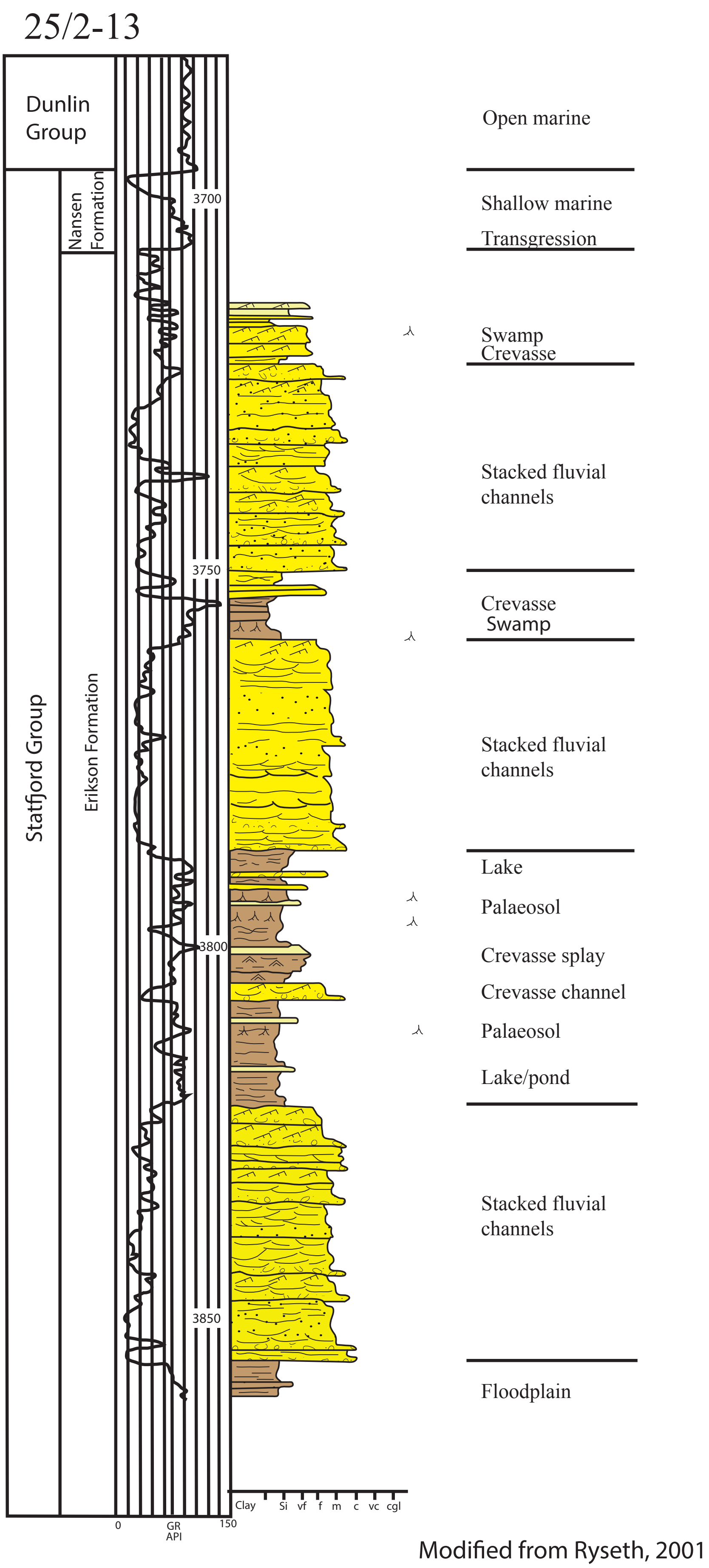


Fig. 6.16 Cored section from the Utsira High. *Well 25/2-13.*

6.5 Paleogeography

The reconstruction of the paleogeography is based on seismic interpretation and well logs. The structural setting and stacking pattern were used as a guide for the paleotopography and the evolution of the fluvial system in the Utsira High area at the time of deposition. According to Gawthorpe and Leeder (2000), basin architecture depends on the interaction between the evolution of basin linkage through fault development, drainage and the effect of changes in climate and base level. The deposition of the Statfjord Group on the Utsira High comprises the interaction between the structural setting, which generated the depositional space, and the nature of the depositional system through time.

The sedimentation rate during the Triassic and Early Jurassic was substantial, and the alluvial post-rift strata is approximately 2-5 km in vertical thickness (Steel and Ryseth, 1990; Steel, 1993; Ryseth, 2001). According to Steel (1993) the general duration of the Statfjord megasequence was 12 Myr, however the megasequence also comprise the Lunde and Amundsen Formations. During the deposition of the Statfjord Group, the structural setting in the study area was less complicated than the present day structural framework. According to Purser and Bosence (1998), rifting of a basin is a complex process and it is important to emphasize that during the evolution of a rift system, rifting may be episodic. Crustal shearing associated with old mountain processes predates the earliest rifting in the North Sea (Zanella and Coward, 2003). In Fig. 3.1 it can be observed that the Utsira High is positioned between basement structures, the Nordfjord Sogn detachment zone and the Hardangerfjord shear zone. The Permo-Triassic rifting created the structural framework for the deposition of the Statfjord Group. This was followed by the Early-Middle Jurassic rise of the North Sea Dome, that likely elevated the southern part of the Utsira high, subjecting it to erosion. (The Statfjord Group is not present further south than 25/11 on the Utsira High (NPD)). The Middle-Late Jurassic rifting reworked the structural setting in the North Sea, determining what was preserved and what would be subjected to erosion.

From rift models, it is concluded that the post rift succession thickens towards the centre of a rift and thins towards the flanks of a basin (Purser and Bosence, 1998). In Fig. 6.7 this trend is illustrated. In the study area, this trend can be observed locally, with a thickening of the Statfjord Group in the grabens and a thinning on the highs (see Fig. 6.5 and Fig. 6.6).

A less complex structural setting during the deposition of the Statfjord Group can be observed in Fig. 6.17. The Utsira High fault block represents a large westerly tilted fault block with the crestal area elevated in the east. The crest of the large fault block was positioned at a topographic level near the flanks of the rift basin, and a base level is indicated. This implies that parts of the high was exposed to erosion and represented a local source of sediments. During deposition of the group, the structural setting was therefore less complex than showed in seismic, and the Utsira High was situated on the margin the Permo-Triassic main graben. During the first rift phase, the Utsira High was situated on the western side of the main graben, while during the second rift phase it was situated on the eastern side, with a shift of the rift axis to the west in the Middle-Upper Jurassic (see Fig. 3.2) (Færseth, 1996).

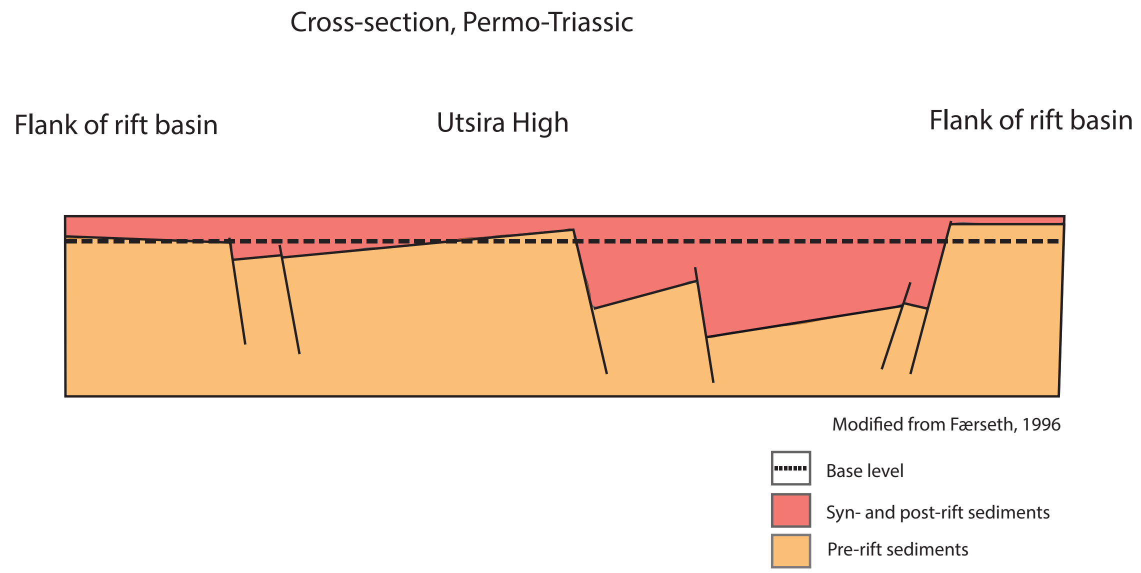


Fig. 6.17 Simplified structural setting after the Permo-Triassic rifting.

Based on the seismic interpretation, a structural model for the Utsira High block is suggested. By assuming the faults generated during the Permo-Triassic rift phase were of smaller magnitude, and grew during reactivation in the second rift phase, a structural setting is proposed. The faults of fault group 1 are reduced in length and displacement, and the faults in fault group 2 and 3 are removed to create the structural setting in the Utsira High area during the deposition of the Statfjord Group. This model does not take into account the effect of overlying layers and the water column. It shows a proposed structural setting after the Permo-Triassic rifting with associated syn- and post-rift sediments in the study area (see Fig. 6.18).

After the Permo-Triassic rifting the large westerly dipping faultblock showed a half-graben trend, generating a basin, with the deepest areas along the hangingwall of the western horst. Syn-rift sediments were deposited in this setting, creating syn-rift wedges. The Statfjord Group was deposited on top of these syn-rift wedges. In the western part of the study area, the syn-rift sediments did not fill in all the accommodation space, thus leaving some room when the post-rift deposition began. The post-rift sediments first filled in this available accommodation space, then filling the rest of the area. The basin gradually filled, with channels and floodplain deposits, from the hangingwall of the western horst and towards shallower areas as the river migrated (see Fig. 6.19). Fig. 6.18 and Fig. 6.19 do not show syn-rift sediments or the Statfjord Group on the western hangingwall of the horst or the hangingwall on the eastern fault, because no interpretations of the Statfjord Group were made in the respective areas.

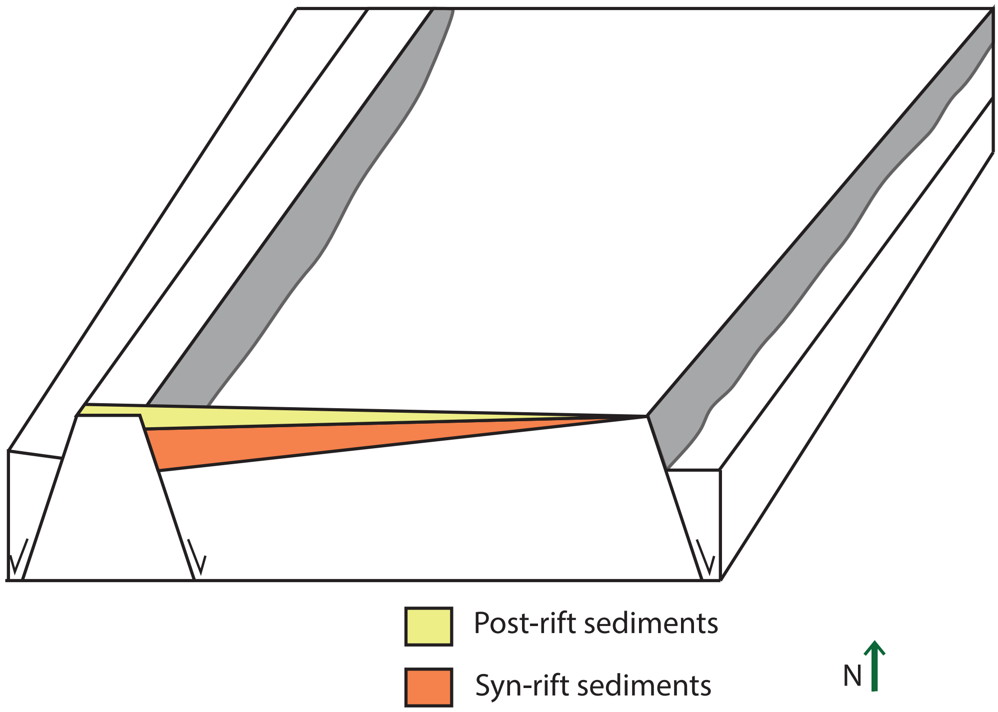


Fig. 6.18 Structural setting after Permo-Triassic rifting. *Simplified model of study area after the first rift phase.*

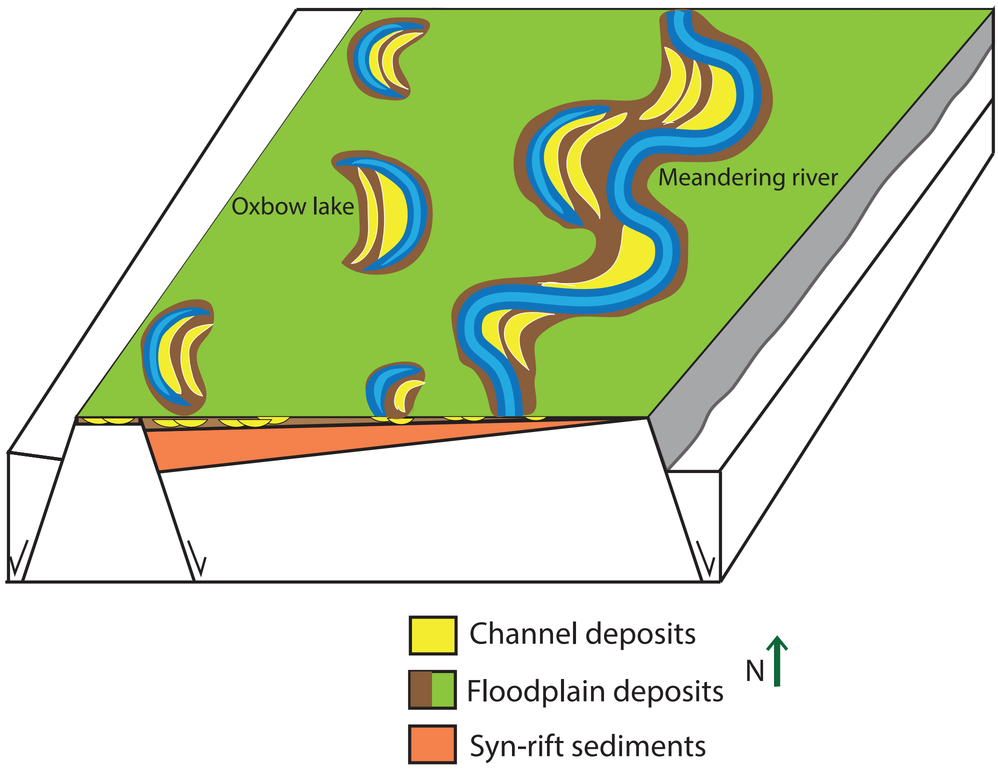


Fig. 6.19 Deposition of the Statfjord Group in post-rift time. *Simplified model of the depositional setting in Lower Jurassic in the study area.*

During Late Triassic-Early Jurassic, the North Sea land was dominated by large floodplains, water was evaporating or draining into shallow bays in the Tethys Ocean and the low land floodplain was dominated by large mud plains where the rivers dispersed, and the continental deposits were drowned by a marine transgression (Ryseth, 2001; Nystuen et al., 2006). Ryseth (2001) proposed a southerly dipping paleoslope, with the steepest depositional slope gradient on the Tampen Spur in the north and the lowest slope on the Utsira High. He further suggested the Horda Platform represented an area with medial slope gradient. The area north of the Tampen Spur and the Fennoscandian hinterland represent source areas for the river systems (Morton et al., 1996; Knudsen, 2001). A similarity in lithofacies composition and grain size distribution in the sandstone from the Tampen Spur and Horda Platform suggested similar discharge and competence, while the fluviale sandstones on the Utsira High were of a more fine grained composition (Ryseth, 2001). The structural interpretations from the study area and well data from the areas surrounding the Utsira High proves these large southerly draining river systems difficult. Well data from the Viking Graben and Stord Basin implies the respective areas were major depocenters during deposition of the Statfjord Group. Southerly draining river systems covering the whole North Sea land during the Late Triassic-Early Jurassic time proves difficult. According to Gawthorpe and Leeder (2000), fluvial channels usually migrate in areas with higher subsidence and avoid topographic highs. If the Utsira High was a paleotopographic high during deposition of the Statfjord Group, the rivers could not flow upwards on a high. However, a river system could come from the south and have a local source area.

A river system with a northerly dipping paleoslope and draining trend is suggested for the Utsira High, with rivers dispersing into basins on the northern part of the Utsira High, and river systems with a southerly dipping paleoslope for the Tampen Spur and Horda Platform systems. Different source areas for the fluvial part of the Statfjord Group explains the difference in lithofacies between the fluviale sandstones and the floodplain deposits on the Utsira High and the Tampen Spur and Horda Platform. Further suggesting the Utsira High separated a southerly and northerly drainage province.

A gross depositional environment map (GDE map) was made based on seismic interpretation, regional well data and the regional structural framework (see Fig. 6.20). The rivers show 2 different drainage trends, one towards the south and one towards the north. The northernmost part of the Utsira High separates these two different systems. The marine transgression enters the area from the southwest, filling up the lower lying areas first, and as the sea level gradually rises, it drownes the whole area. The development of the coastline through time is illustrated as a system stepping gradually towards northeast.

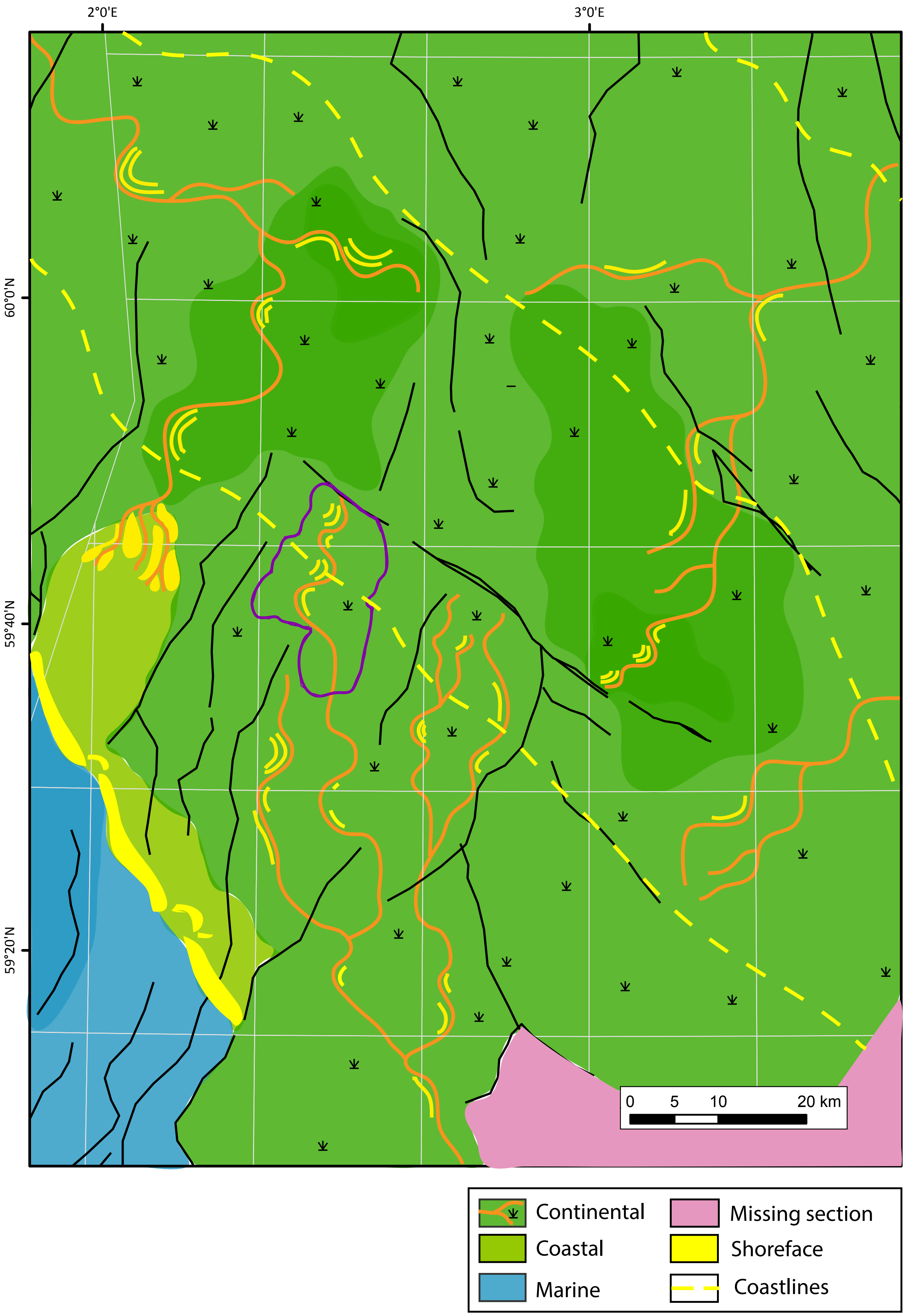


Fig. 6.20 GDE map. *The map shows the Utsira High, Stord Basin, Bjørgvin Arch and Viking Graben in Early Jurassic time.*

7 Conclusion

- The Statfjord Group, comprising the Raude, Eiriksson and Nansen Formations, was deposited during post-rift time in the Late Triassic-Early Jurassic, showing no signs of syn-depositional tectonic activity. Faults in the study area are both of Permo-Triassic and Middle-Late Jurassic age, all showing a NE/SW trend. Additionally the Permo-Triassic faults created the structural setting present during the deposition of the Statfjord Group, and there is evidence of reactivation during the Middle-Late Jurassic rift phase.

- Interpretation of 3D seismic indicates lateral variations in accommodation space of the Statfjord Group in the study area. Areas with a thicker Statfjord Group succession represents areas with higher accommodation space during deposition. Additionally the group displays higher available accommodation space towards the end of deposition of the Statfjord Group.

- The Utsira High was a paleotopographic high during the deposition of the Statfjord Group, separated by a NW/SE trending fault in the north. This fault show a different orientation than all the other faults in the study area.

- The Statfjord Group was deposited in a continental setting, dominated by large floodplains and rivers. The group was overlain by thin layers of marginal marine deposits affected by tidal processes, and the marginal marine Nansen Formation is present on the northern part of the Utsira High.

- High net-to-gross values show the river system on the Utsira High had a local source of sediments, since the high is positioned at significant distance from known source areas. The Utsira High may have separated two different drainage provinces in the Triassic-Early Jurassic, southerly draining systems from the north in the Tampen Spur area and east on the Horda Platform, and a northerly draining system on the Utsira High.

- The lateral and vertical continuity of the Statfjord sandstones is higher in areas with low accommodation space, and sand deposited on the Utsira High has a higher connectivity of sand than the sand deposited in the Viking Graben and Stord Basin.

- The base of the Statfjord Group is difficult to map in the study area. Lateral lithology variations within the base of the group and the vertical lithology transition between the Statfjord Group and the underlying Hegre Group may not give a significant contrast in AI, or the transition can not be identified by the seismic data due to the limited vertical resolution.

7.1 Further work

In order to develop a further understanding of the Statfjord Group on the Utsira High more data is needed. Seismic data shows large scale extension of the Statfjord Group, but the lateral changes in lithology is impossible to understand just with seismic. Wells are used to indicate and show lithology, and to constrain and quality assure the interpretation. However, the degree at which information from wells can be extracted into the seismic is limited due to the lateral variations in lithology within depositional systems.

- Continuation of the work on the Statfjord Group as new wells are drilled will provide more data of the succession, and subsequently develop the understanding of the stacking pattern and distribution of depositional facies in the area.

- A collection and comparison of biostratigraphic data on Statfjord level can help correlate the marine Nansen Formation on the Utsira High, further map the distribution of the unit and develop the understanding of the marine facies. Results from this work could indicate the direction of the marine transgression in the Early Jurassic.

- A provenance study of the Statfjord Group on the Utsira High will indicate the source area of the sediments. A comparison of provenance of the Statfjord Group on the Utsira High, Tampen Spur and the Horda Platform will decide the regional drainage trends for the fluvial systems in Late Triassic-Early Jurassic time in the North Sea.

- Seismic interpretation of syn-rift packages across the northern bounding fault on the Utsira High will help determine the age of the fault. This will reveal the number of rift phases the fault has undergone, show the displacement of the fault in the respective events and possibly indicate when the Utsira High became a structural high in the North Sea basin. With mapping of syn-rift packages across all the major faults separating the Utsira High from the surrounding areas, the development of the high through time cand be understood.

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