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Title page for Master's Thesis
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Paleozoic-Holocene tectonostratigraphic evolution of the Sørvestlandet High and the Åsta Graben, Southern Norwegian North Sea

by

Laila Doudouh

MSc Thesis

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University of Stavanger, June 2017

Laila Doudouh

Paleozoic-Holocene tectonostratigraphic evolution of the Sørvestlandet High and the Åsta Graben, Southern Norwegian North Sea

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Abstract

This study is presenting a three-dimensional seismic data set and published data from exploration wells which were used to reconstruct the tectonostratigraphic evolution of the Sørvestlandet High, Southern North Sea, Norway. The Sørvestlandet High is a southeast-northwest trending elongated Upper Jurassic horst. Four sub-salt fault families and four supra-salt families were recognized. The sub-salt fault families that are interpreted are: (1) a north-northwest-south-southwest striking fault family, (2) a northeast-southwest striking fault family, (3) an east-northeast-west-southwest striking fault family, (4) a north-northeast-south-southwest. The supra-salt faults that are interpreted are: (5) a northwest-southeast striking fault family, (6) a north-northwest-west-south-southeast striking fault family, (7) an east-west striking fault family, (8) north-northeast-south-southwest striking fault family.

Eight chronostratigraphic sequences defined by well and three-dimensional seismic data are interpreted and mapped: Devonian rifting in a sandy/lacustrine environment; Carboniferous late rifting to post-rifting lacustrine environment; Lower Permian pre-rift in a continental environment; Upper Permian rifting and deposition of the Zechstein salt; Triassic/Jurassic intracratonic setting and salt mobilization; Cretaceous flooding and chalk deposition; Lower Cenozoic and Upper Cenozoic progradation and basin margin uplift.

Similar to the Upper Jurassic Mandal High and Utsira High, where several hydrocarbon discoveries have been made, the Sørvestlandet High might consist of three petroleum plays, Devonian/Carboniferous sourced fractured and weathered crystalline basement, Devonian sands, and Lower Permian aeolian sands, with the Upper Permian salt sealing it. These three petroleum systems introduce a new possible future of hydrocarbon exploration in the Southern North Sea.

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Introduction

The heavily explored targets in the Central North Sea of the Mesozoic and Cenozoic have shown great success. The most successful intervals being the Jurassic sands, the Cretaceous chalk, and the Paleogene sandstones. The majority of Mesozoic accumulations occurring in the North Sea structural highs, follow a northwest-southeast structural trend controlled by the Central Graben rift and salt structures (Figure 1). Additionally, the successful Cenozoic discoveries follow a southwest-northeast Paleocene trend, primarily controlled by the major Lower Paleogene canyon incision (Rossland et al., 2013).

Nevertheless, the Mesozoic and Cenozoic intervals have not always proven to be successful, with the Utsira High and Mandal High representing success and failure cases respectively (Figure 2). They are both Upper Jurassic highs in the North Sea with initial drilling target being the Mesozoic sands. Utsira High is located 190 km west of Stavanger, in the North Sea (Rossland et al., 2013). The Jurassic sandstones in the Utsira High are mainly sourced locally by erosion of the crystalline high, host the second largest oil field in the Norwegian North Sea, the Johan Sverdrup field which has proven reserves of 1.7 to 3.3 billion barrels of gross recoverable oil. Unlike the Mandal High, which extends across the Norwegian-Danish border (Rossland et al., 2013) where the exploration does not appear to have commercial fields. The main reason for this is due to migration problems, proving that the Mesozoic is not always the source of a successful petroleum system (Rossland et al., 2013).

Despite showing a great success in the UK and Dutch sector, the Paleozoic intervals are still underexplored in the Central North Sea. Some of the biggest discoveries in the UK sector is within in the Devonian sandstones and lacustrine sediments (Figure 3), while for the Dutch and southern North Sea, the Carboniferous has shown great hydrocarbon success (Figure 4). According to Monaghan et al. (2015), the distribution of the mature source rock is the key controlling factor in the Paleozoic petroleum system. A variation of mainly gas-prone source rocks (coal, marine, and lacustrine shales) are proven, and a gas generative mature area has been described on the southern side of the Mid North Sea High in the Carboniferous sequence. The Paleozoic source rocks are believed to be preserved in the Northern Permian Basin. Oil staining and bitumen in Paleozoic rocks in southern parts of Norway firmly conclude that oil has been generated and expelled from the Lower Paleozoic marine shales in these areas (Dons, 1956; Eakin, 1989; Olaussen et al., 1994; Pedersen et al., 2006). Nonetheless, it is suggested that lacustrine Devonian (Figure 5)/ Carboniferous gas-prone mudstones and coals make up the source rocks, while the Lower Permian sandstones, the reservoir rock and the Upper Permian salt, the seal rock. The potential Upper Paleozoic source rocks most likely matured during rapid post-rift subsidence in Lower Triassic times (Pedersen et al., 2006).

Moreover, this Palaeozoic petroleum system has been proven to be a successful source in the southwestern Norwegian North Sea, in the Embla Field (Abay et al., 2014) (Figure 6). This field was the first development of a Paleozoic reservoir in the Norwegian sector of the Central Graben, in the Ekofisk area. The oil produced in this field showed to be of Devonian/Permian age, and it was suggested that it charged the Embla field at the end of the Triassic. The structure was uplifted and eroded during the Jurassic, and the Paleozoic oil accumulation experienced biodegradation at the oil-water contact. However, subsidence during the Cretaceous, a formation of a new seal and the Upper Jurassic source rock reaching the oil window resulted in a recharging of this structure (Ohm et al., 2012).

Hence the concept of preserved Paleozoic in the North Permian Basin and Central Graben is not entirely new to the hydrocarbon industry, but with today's newer and better seismic data acquisition and enhanced imaging of the subsurface using seismic can lead to better mapping and knowledge of the subsalt and the Paleozoic in the Central North Sea. Better imaging of the subsalt and Paleozoic combined with the limited published work on this topic will be the main motivation for this thesis. Also, a comparison of the exploration acquirements from the Upper Jurassic Utsira and Mandal High with the Sørvestlandet High will be done to understand the nature of these Highs, and their potential for a functioning petroleum system. Therefore, the main objectives will be to create a tectonostratigraphic framework of the Sørvestlandet High, an Upper Jurassic High close to the Danish border of the North Sea, to better understand the tectonic evolution of the Sørvestlandet High and Åsta Graben from the Paleozoic until Holocene. A two-dimensional restoration will also be conducted to better comprehend how the geometry of earlier stages of the geological evolution was in the Sørvestlandet High and Åsta Graben, as well as what implications it has on the petroleum system.

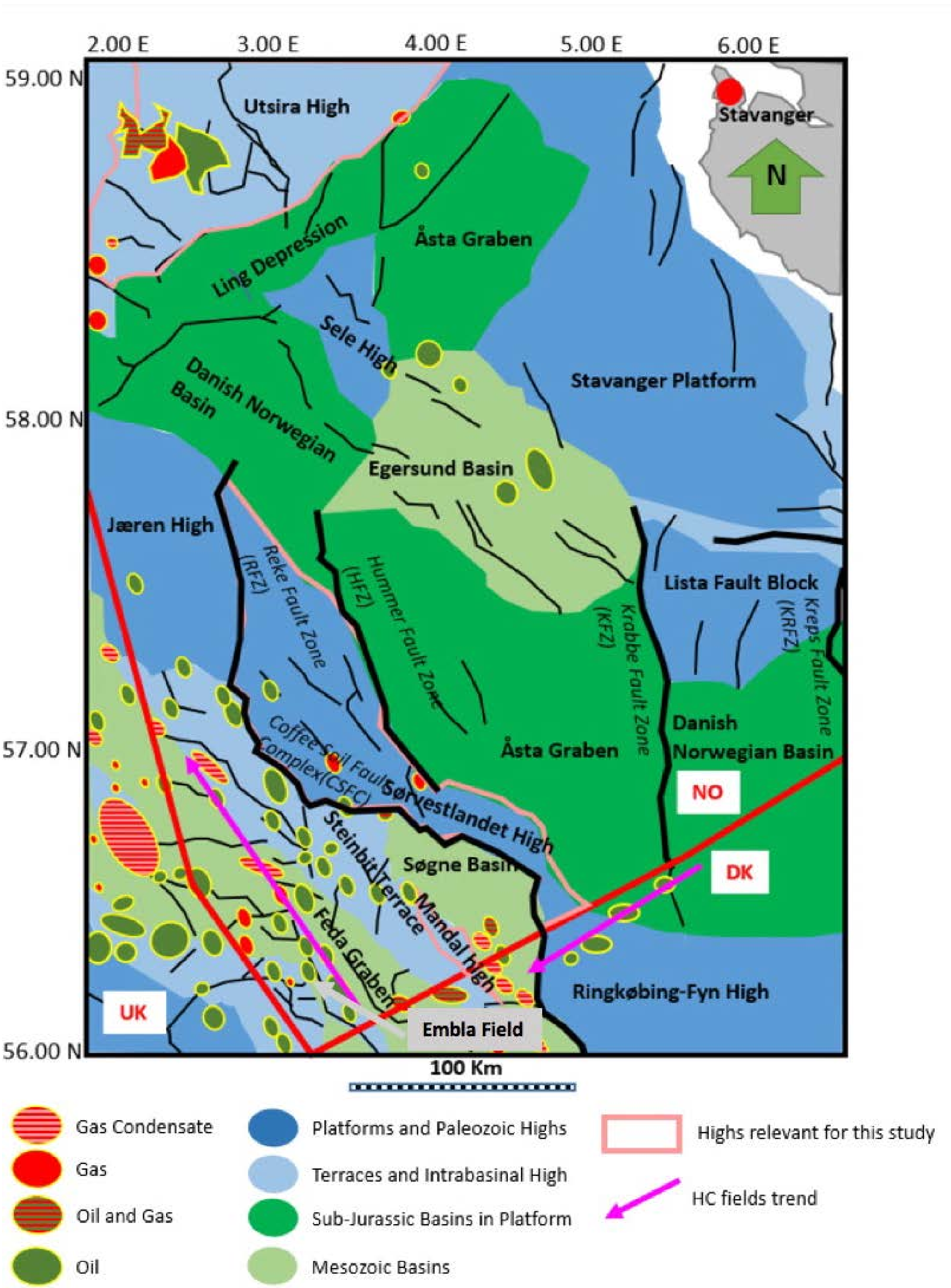


Figure 1: The main structural elements in the Central North Sea and the main HC fields and the different HC trends

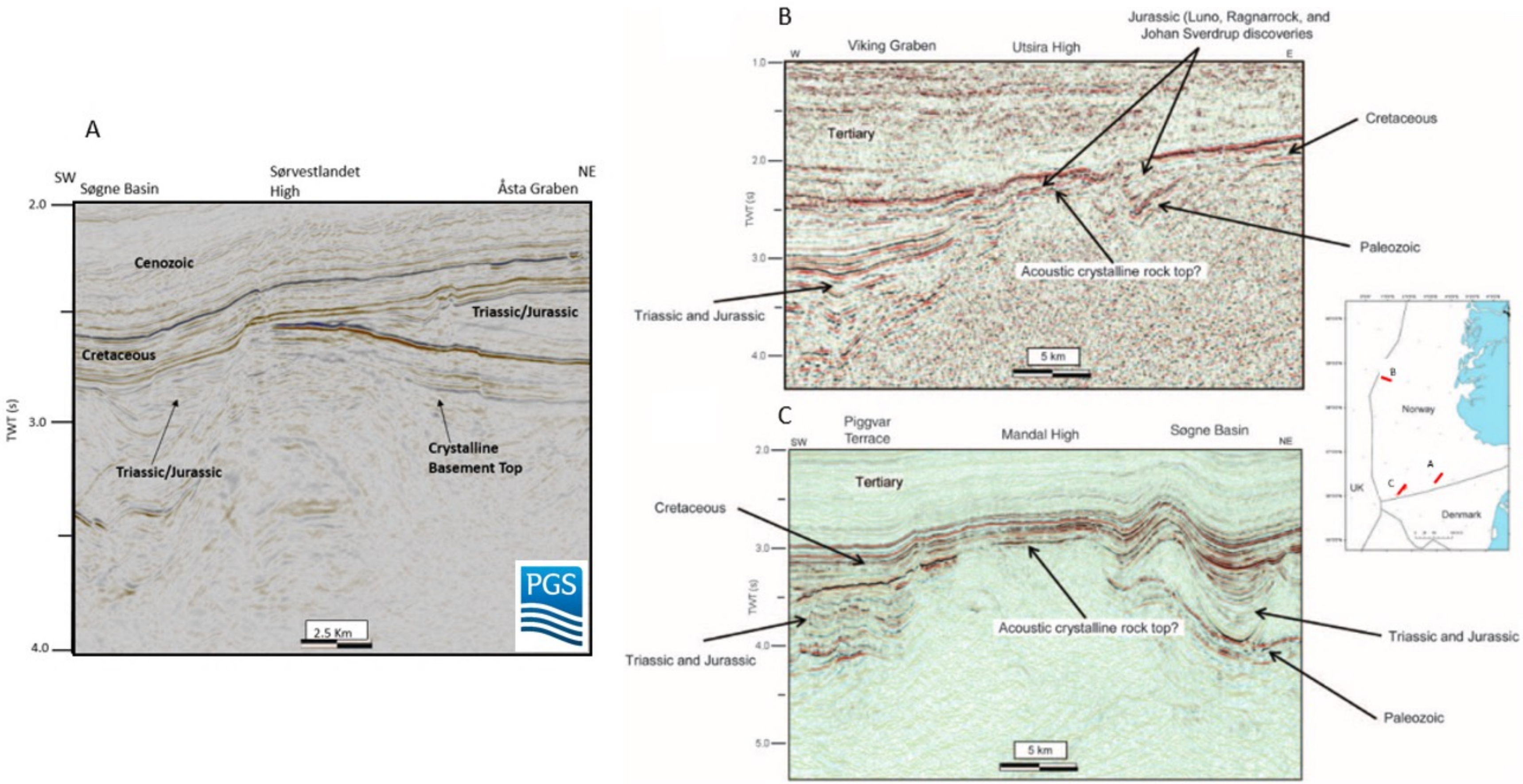


Figure 2: The three main highs that will be studied where a) is The Sørvestlandet High, b) The Utsira High that has produced commercial HC and c) The Mandal High that didn't produce commercial HC (from Rossland et al., 2013)

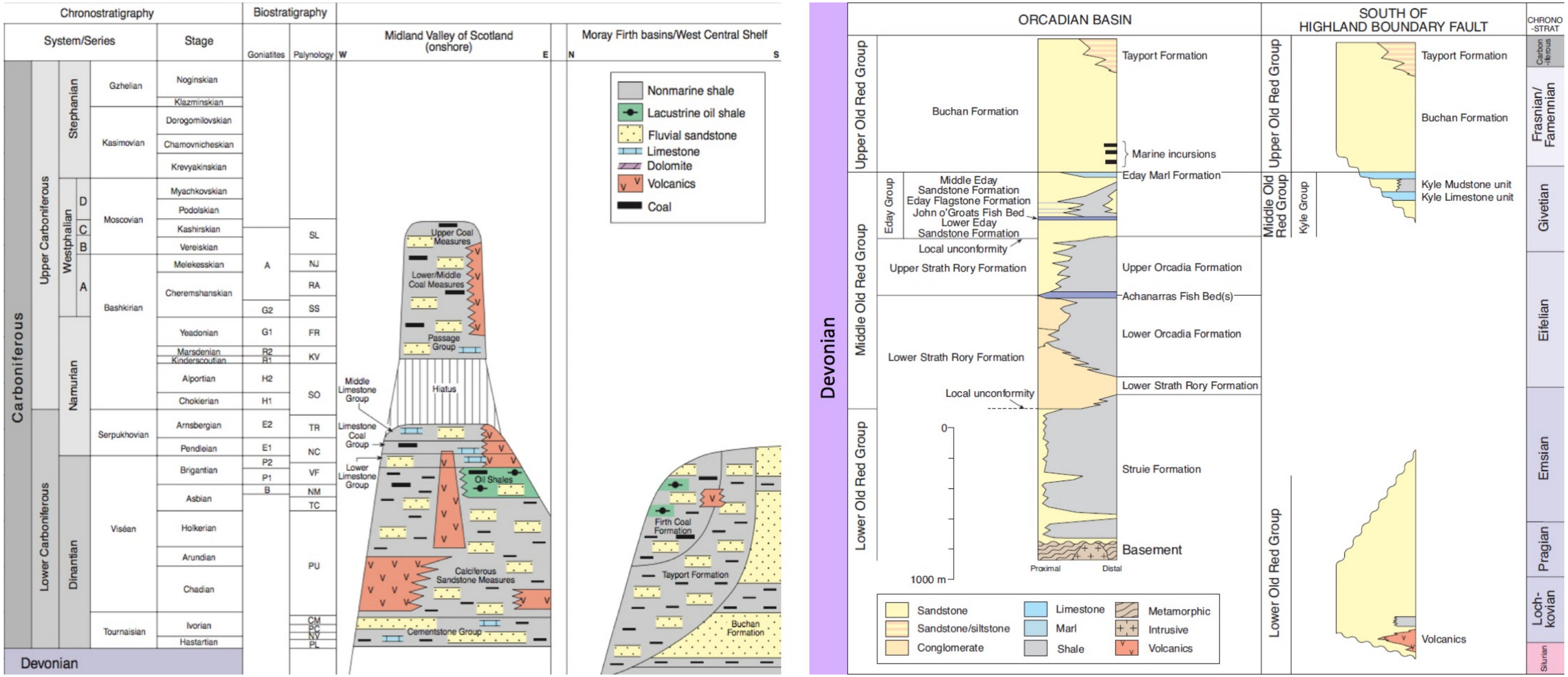


Figure 3: Carboniferous and Devonian stratigraphy in the UK sector of the North Sea (from Evans et al., 2003)

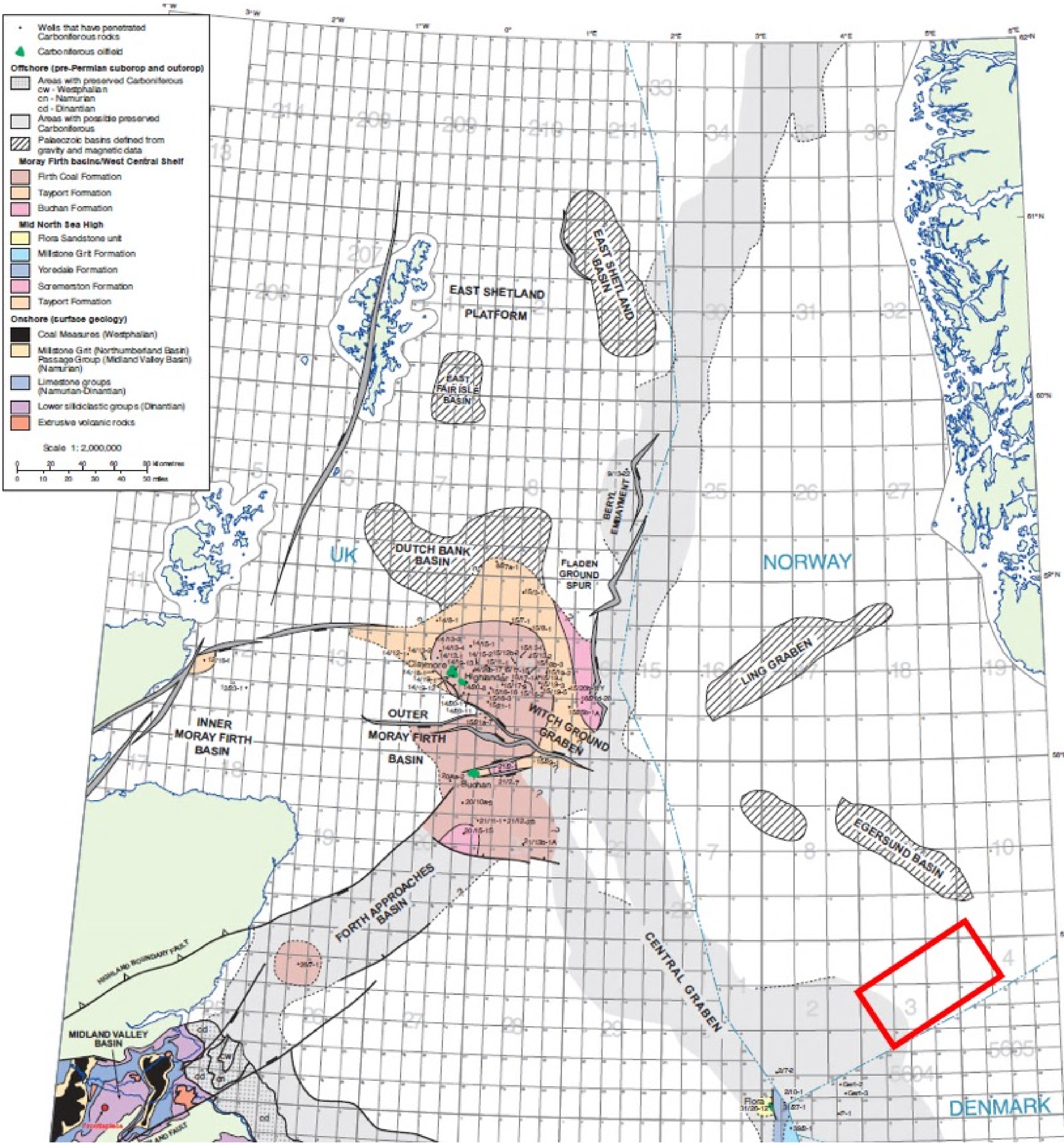


Figure 4: The lateral distribution of the Carboniferous, where the grey is the possible preserved Carboniferous in the North Sea, red square represents the study area (from Evans et al., 2003)

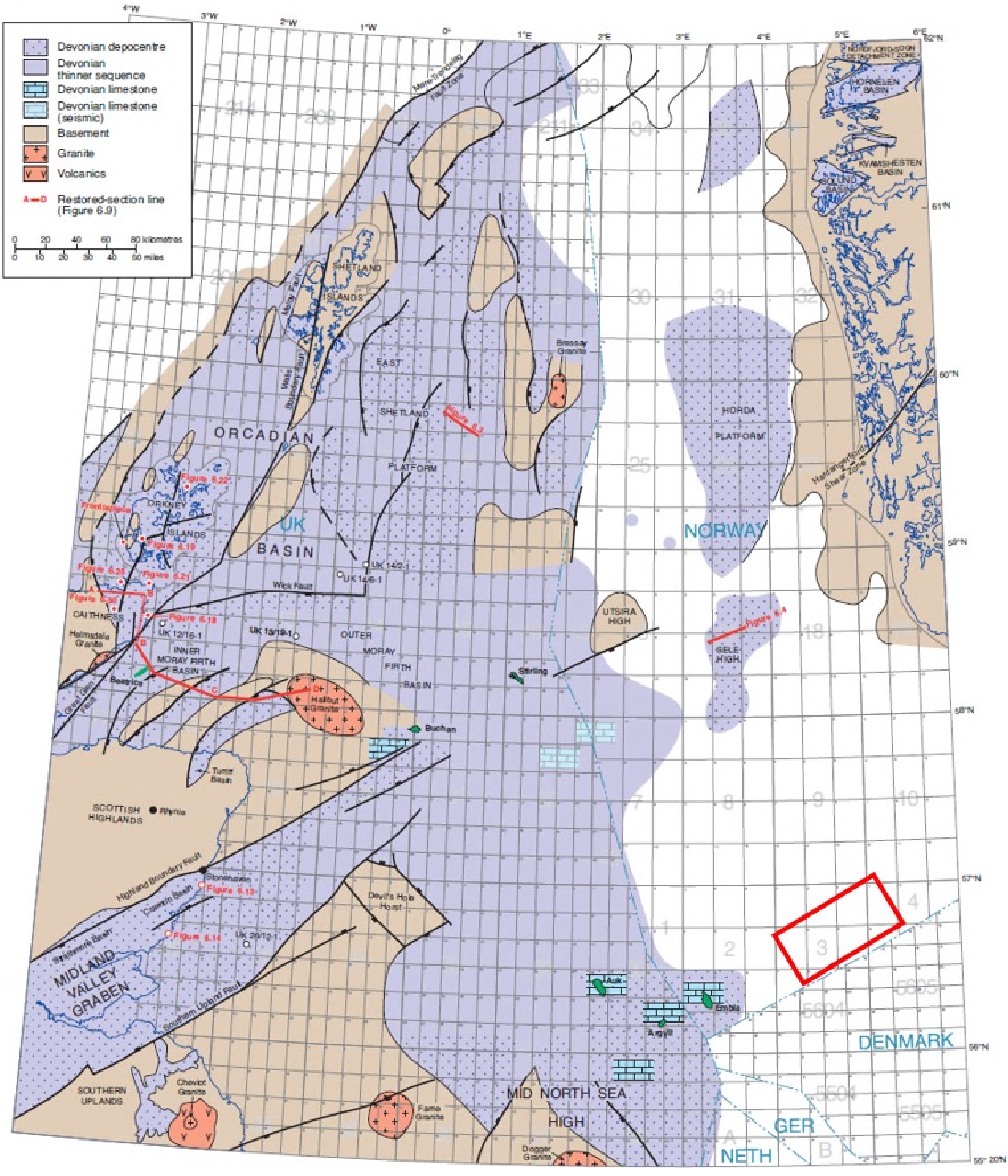


Figure 5: The lateral distribution of the Devonian, where the purple and blue represent the preserved Devonian in the North Sea, red square represents the study area (from Evans et al., 2003)

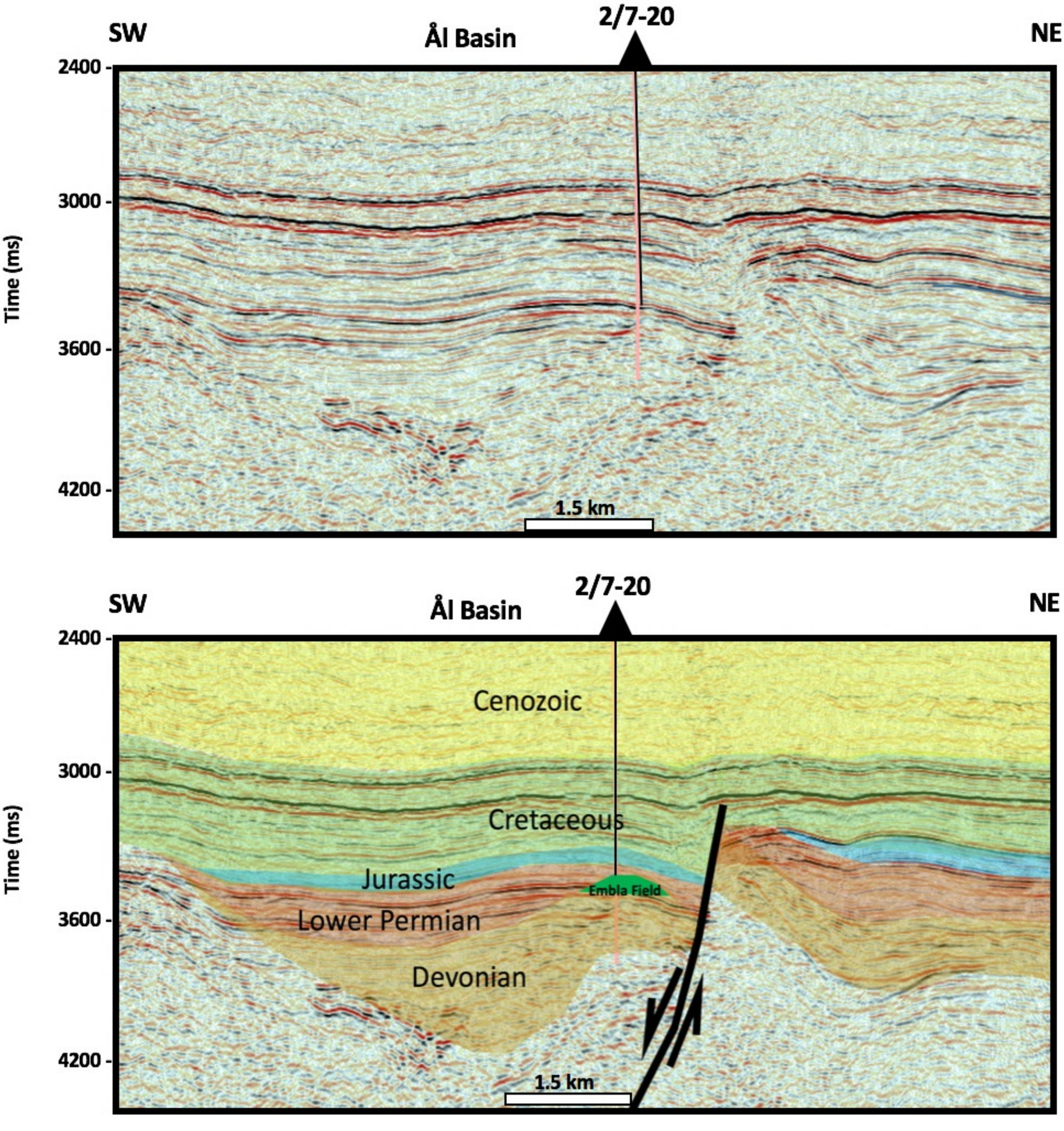


Figure 6: (Upper) uninterpreted (Lower) interpreted Two-dimensional seismic line showing the Embla Field has a Devonian anticline

Geological setting

Regional Evolution

From the aspect of basin development, following stages in the evolution of the North-Sea area were distinguished (Ziegler, 1975):

1) Variscan geosynclinals stage (Devonian-Carboniferous)
2) Permo-Triassic intracratonic stage
3) Taphrogenic rifting stage (Jurassic-Cretaceous)
4) Post rifting intracratonic stage (Cenozoic)

Devonian and Carboniferous Variscan geosynclinals stage

The Caledonian resulted in a fuse of the North American-Greenland and the North-West European continental plates with the Caledonian fold belt bisecting the northern North Sea. In Central Europe, the Caledonian orogeny led to an emphasizing of the Alemanic-Bohemian geanticline, and with this an obvious representation of the Variscan geosyncline came to place. Because of the Caledonian orogeny, the tectonic framework of the North Sea reached a new polarity; now the Variscan geosyncline dominated in the south while the Caledonian mountains to the north were swiftly diminished. Late to Post-orogenic uplift correlated with an incomplete collapse of the Caledonian mountains, resulting in the deposition of thick, in part lacustrine and bituminous series of the Devonian Old Red Sandstones in intramontane basins (Ziegler, 1975).

The Upper Devonian-Lower Carboniferous (Figure 7) Bretonic orogeny led to a consolidation of the Alemanic-Bohemian geanticline and the rise of the Armorica-Central German Highs. During the Lower Carboniferous, these highs formed the source of the thick, flysch-like culm series that were deposited in the Variscan foredeep. During the Visean, its distal northern parts were occupied by a wide carbonate shelf. Viscean coal-bearing sequences were locally deposited in the central North Sea and northern England. Thick, non-marine Oil Shale sequence was deposited in the Scottish Midland Valley. During the Upper Carboniferous, the Sudetic orogeny resulted in a further consolidation of the Variscan mountain system with deposition proceeding in intramontane successor basins. Paralic conditions predominated in much of the Variscan foredeep and in the northward adjacent shelf areas, leading to deposition of very thick coal-bearing sequences (Ziegler, 1975).

Permo-Triassic intracratonic stage

At the end of the Variscan orogeny a major change in the tectonic pattern in the northwest Europe occurred. An extensive period of compressive forces was replaced by an extensional stress regime. The Variscan fold belt was subjected to post-orogenic uplift resulting to its partial collapse and the establishment of continental intramontane basins. This process was followed by volcanic extrusion (Ziegler, 1975). The Variscan foreland was initially subjected to uplift, tilting, and erosion, followed by differential subsidence resulting in the formation of post-orogenic, intracratonic basins and set of narrow rifts and grabens (Deegan & Scull, 1977). Progressive subsidence led to the creation of the Middle/Upper Permian Roteliegend basins. (Ziegler, 1975).

The Southern and Central North Sea Basins (Permian Basins) were initiated at this point, separated by the Mid North Sea-Ringkøbing-Fyn High, and the formation of the Viking Graben may have occurred. The southern Permian basin Roteliegend sand dunes are the primary gas reservoirs in the southern North Sea, Netherland, and German onshore areas. The nature of the northern Permian Basin is less known.

Continued subsidence of the arid Roteliegend basins, possibly below sea-level, resulted in the ingression of the Zechstein seas. A great amount of evaporates in the southern and northern Permian Basins indicates that these basins had a narrow connection to the open seas. Diapirism of the Zechstein salts, both in the Southern and Northern Permian basins, heavily influenced the post- Triassic sedimentation (Ziegler, 1975).

During the Triassic, the North Sea area returned to a continental depositional regime (Ziegler, 1975). It was at that time that the Central and Northern North Sea formed part of an intracratonic basin in which dominantly continental sequences of clastic sediments were deposited together with minor amount anhydrite and carbonate beds. Distribution and thickness patterns, particularly of the coarser grained units, indicates that the main source areas were in the west and northwest of the northern North Sea and to the east, north-east and south of the Central North Sea. In general, tectonics and halokinesis had a significant influence on the patterns of deposition (Figure 8).

In the Central North Sea, Triassic sediments are commonly unconformably overlain by Jurassic to Lower Cretaceous rocks. (Deegan & Scull, 1977).

Jurassic and Cretaceous taphrogenic rift stage

The major control on the Jurassic sedimentation in the Central and Northern North Sea was the rift system which developed after a period of basin initiation in the Permo-Triassic (Ziegler, 1975). The main components of this rift system include the Central Graben, the Viking Graben, and the Moray Firth Basin, the North Sea triple junction (Figure 9). The limits of the rifts are marked by prominent structural high, mainly the East Shetland Platform, the Vestland Arch and the Mid North Sea High. Block faulting, tilting and erosion occurred throughout the Jurassic at varying times and varying rates, with climax occurring at proximately the end of the Lower Jurassic, the end of the Middle Jurassic and again at the end of the Upper Jurassic.

This tectonic control of sedimentation is reflected in a series of unconformities or transgressive and regressive cycles throughout the Jurassic, which is obvious in the margins of the rifts. Jurassic sediments within the rifts are normally related to a system of tilted fault blocks (Deegan & Scull, 1977). Erosion on the highs flanking the Central Graben cut down, e.g., in the Central North Sea, as deep as the Devonian.

By the close of the Jurassic period, Cimmerian tectonic activity had reached a climax, which led to a widespread regression that formed isolated sedimentary basins where deposition took place under dominantly anaerobic reducing bottom conditions. The sedimentation of these basinal areas were continuous from Upper Jurassic to Lower Cretaceous (Vollset & Dorè, 1984). The main expression of this tectonism is the Cimmerian unconformity or Base Cretaceous unconformity (BCU), which is a major tectonic and sedimentary break. Conditions where continuous deposition occurred, were more prominent in the deeper segments of the graben system. The Cimmerian earth movements continued into the Lower Cretaceous, but the graben system, which acted as the main control on Jurassic deposition, became progressively less important on the Cretaceous sedimentation (Deegan & Scull, 1977).

The Lower Cretaceous was a time of transgression with minor regression. During the transgression, the sea covered even higher areas. Under these Conditions condensed shallow-marine shales, marls and carbonates developed (Figure 10). The present distribution of these limestones, therefore, reflects the subsidence pattern of the topographically higher features. (Isaksen & Tonstad, 1989). The Upper Cretaceous was a quite tectonic period. In the Central and Southern North Sea, the supply of terrigenous material decreased from the transition to the Cenomanian onwards, and pure carbonates were deposited (Shetland Group chalk facies).

Cenozoic post rift intracratonic stage

The North Sea was an important basin of deposition throughout the Cenozoic, and a complete sequence of all the Cenozoic series from the Paleocene to the Pliocene is present in the center of the Cenozoic basin. There was a late Lower Paleocene (Figure 11) tectonic event accompanied by a global drop in sea level. This tectonic activity resulted in down warping of the North Sea Basin, mainly centered above the main Mesozoic rift system, followed by intrabasinal uplift (Ziegler, 1975).

The Cenozoic sediment covered the Mesozoic graben system and attained a thickness more than 3000 m at the depocenter, which coincides approximately with the center of the present North Sea. (Deegan & Scull, 1977). On the topographical highs, the Ekofisk Formation and sometimes the Tor Formation were eroded and redeposited in basinal areas by mass gravity flows. This reworking is commonly observed along graben margins and intrabasinal highs and close to rising salt diapirs. (Isaksen & Tonstad, 1989).

It is believed that intracontinental rifts such as the North Sea Graben are initiated because of regional extensional stresses resulting in “necking” of the crust, causing decompression of the mantle and the formation of a rift cushion through fractional distillation from the mantle. (Ziegler, 1975). During the Cenozoic, Central Europe was dominated by the Alpine Orogeny. In the North Sea, regional disconformities correlate roughly to these main orogenic phases that are reflected in the marginal troughs lesser inversion movements. There is no evidence of an Upper Cenozoic reactivation in the Central North Sea rifting system. (Ziegler, 1975).

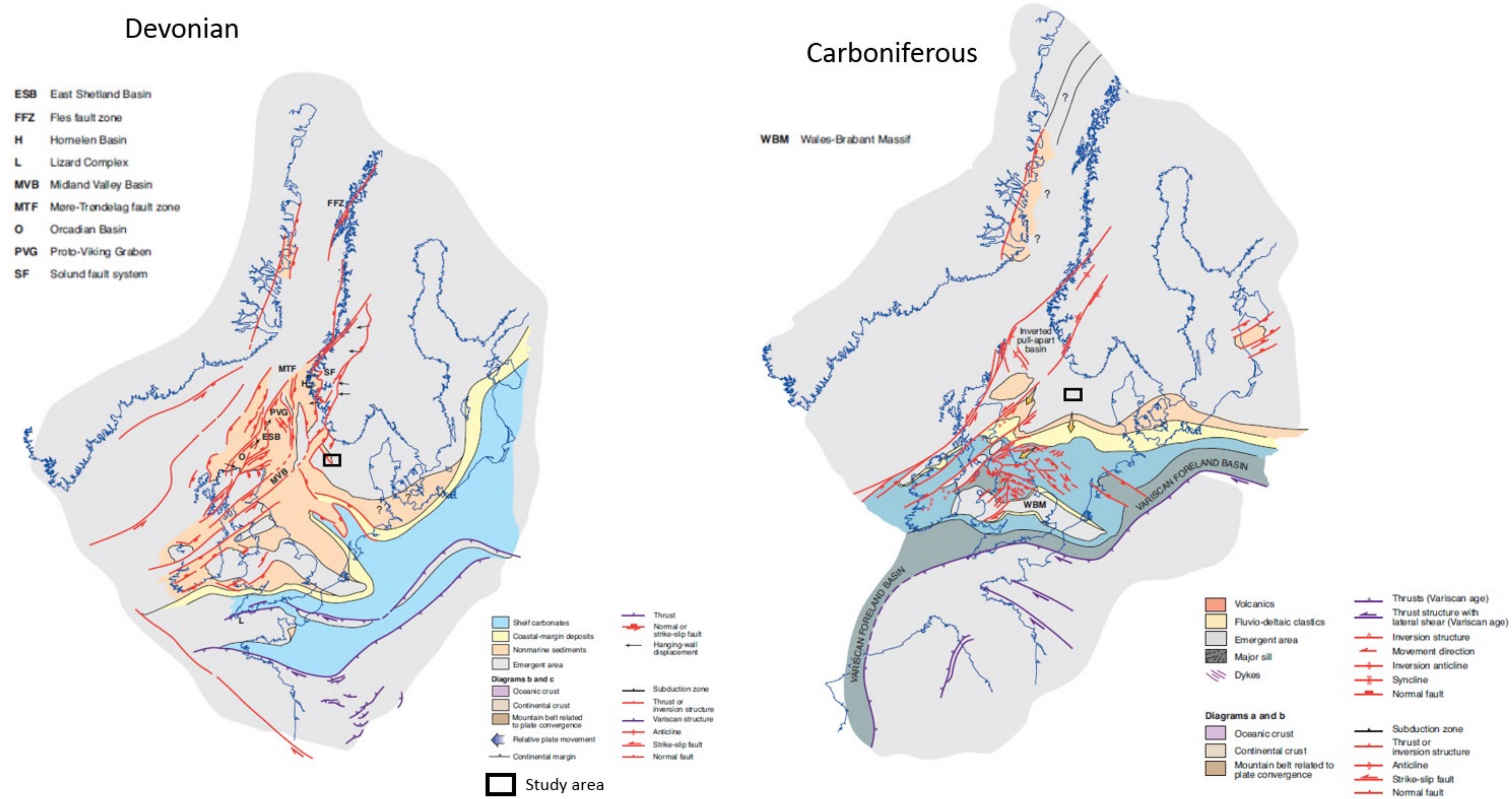


Figure 7: Paleogeographic maps showing the main structures and the lateral distribution of the different facies during Devonian and Carboniferous (from Evans et al., 2003)

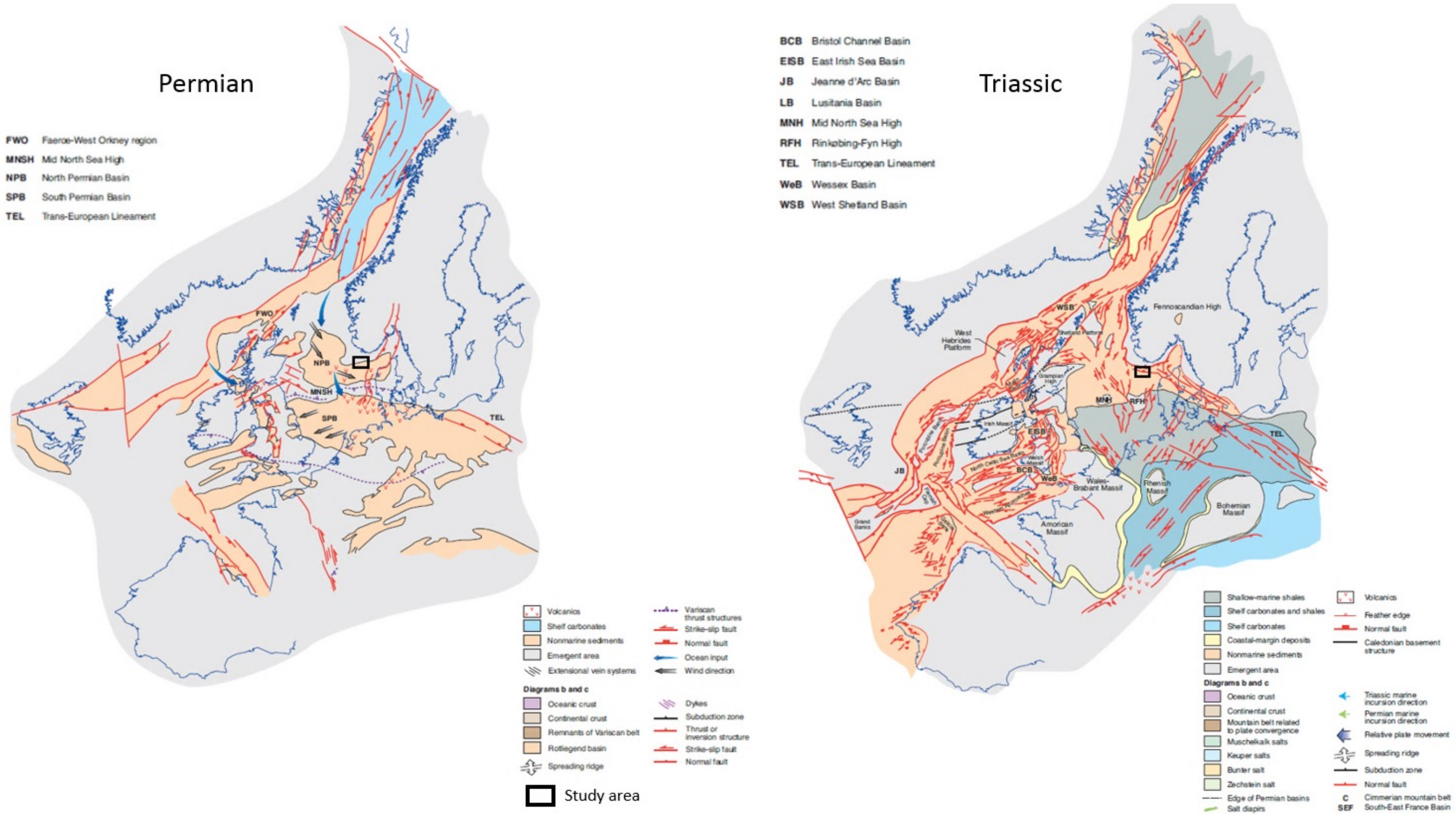


Figure 8: Paleogeographic maps showing the main structures and the lateral distribution of the different facies during Permian and Triassic (from Evans et a., 2003)

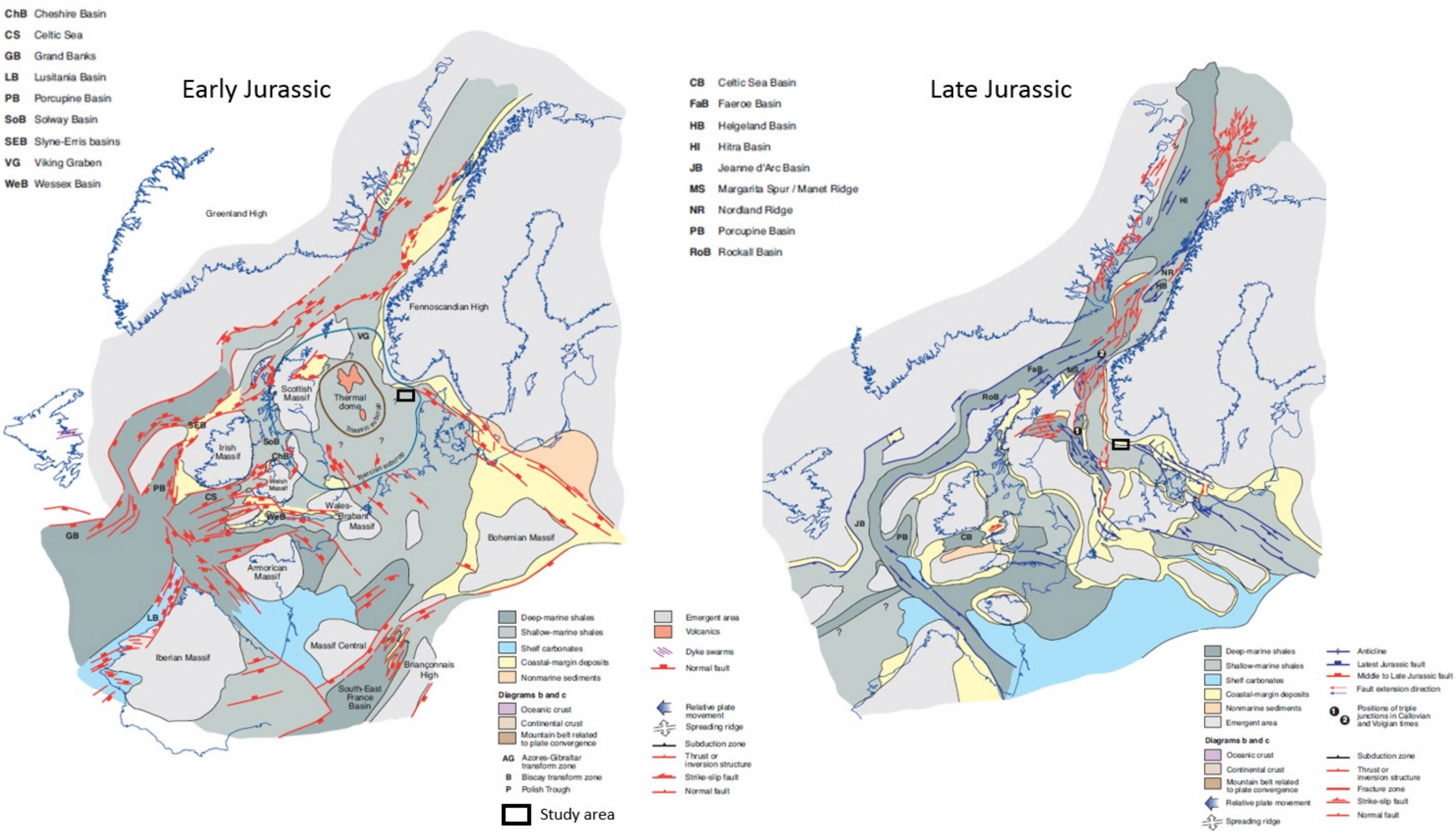


Figure 9: Paleogeographic maps showing the main structures and the lateral distribution of the different facies during Lower Jurassic and Upper Jurassic (from Evans et al., 2003)

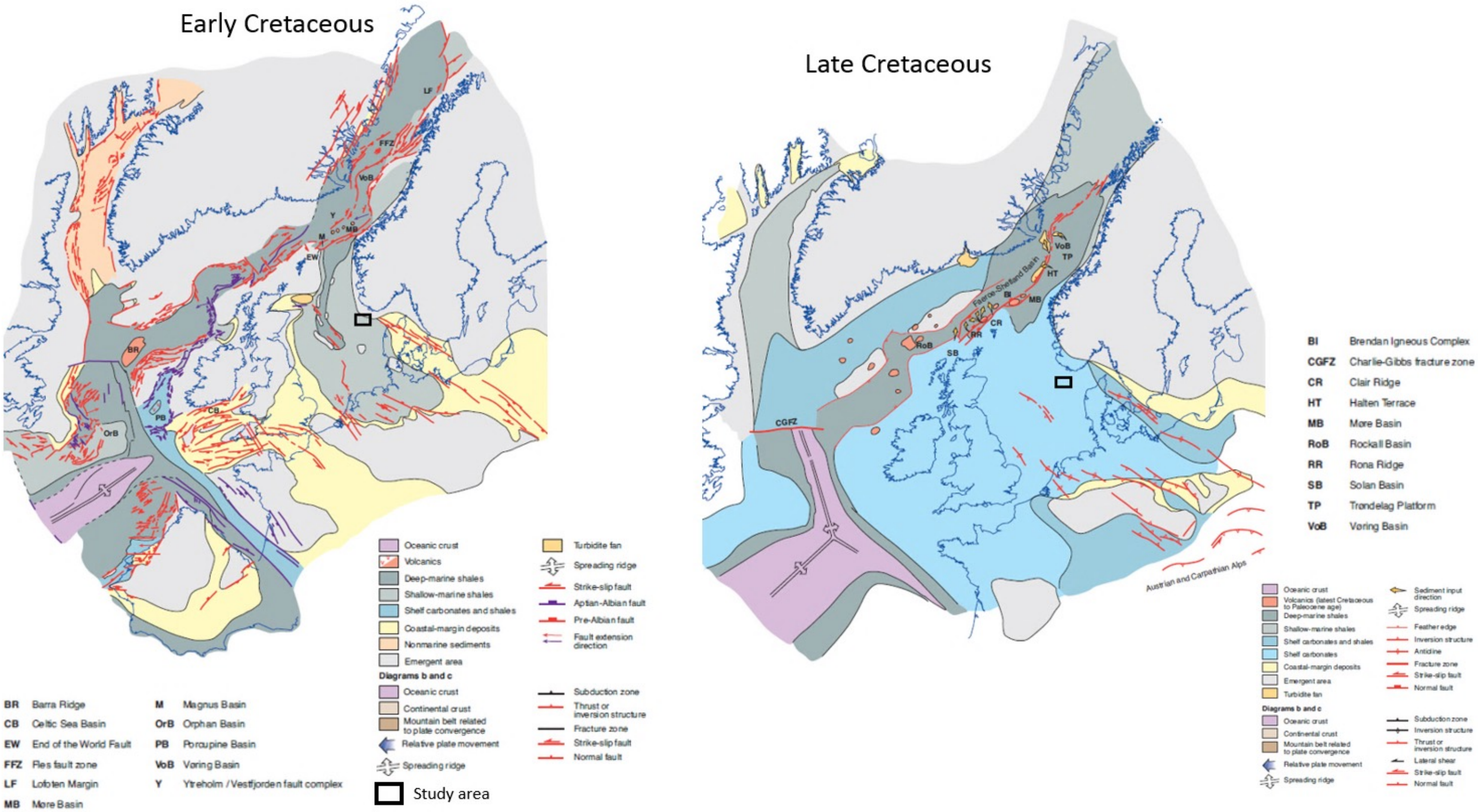


Figure 10: Paleogeographic maps showing the main structures and the lateral distribution of the different facies during Lower Cretaceous and Upper Cretaceous (from Evans et a., 2003)

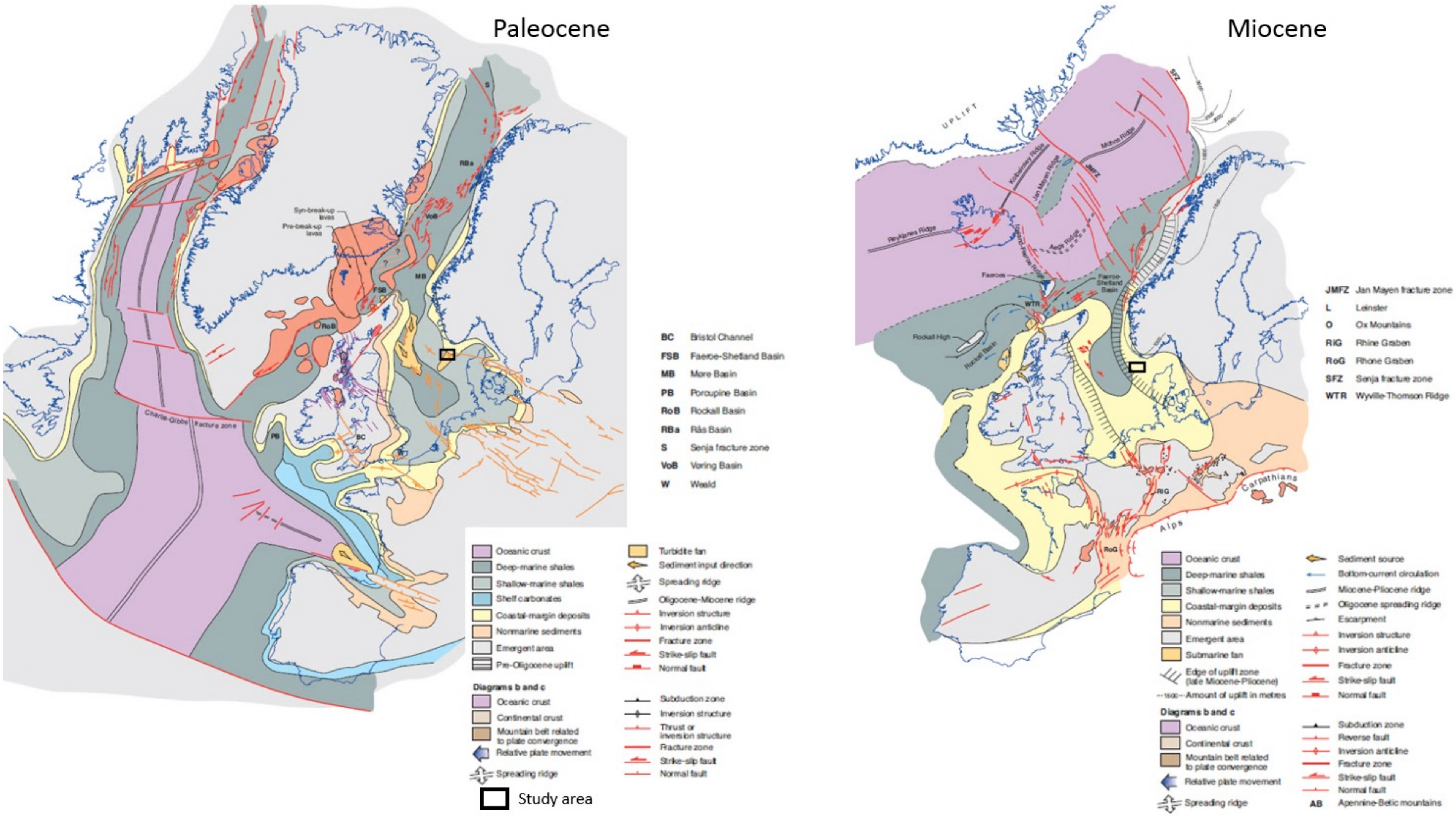


Figure 11: Paleogeographic maps showing the main structures and the lateral distribution of the different facies during Paleocene and Miocene (from Evans et al., 2003)

Stratigraphic elements

The following information about the stratigraphic and structural elements is retrieved from authors including Deegan & Scull (1977), Vollset & Dorè (1984), Isaksen & Tonstad (1989) and Ziegler (1975).

The basement is mainly metamorphic due to the Caledonian orogeny. The Devonian consists of the Lower, Middle and Upper Old Red Groups. The Lower Old Red Group was deposited following the significant episode of uplift and erosion that accompanied the Caledonian Orogeny, mainly consisting of volcanic rocks, sandstones, and conglomerates.

The transition from Lower to Middle Old Red Group marks the point at which most of the individual half-graben footwalls became submerged by sediments, and one large basin was created, with some local extensional faults ongoing. This group consists of conglomerates, sandstones, and lacustrine deposits.

The Upper Old Red Group consists of a succession of monotonous sandstones, mainly fluvial because of the basin that is evolving to a system with drainage.

Carboniferous consists of redbed fluvial deposits indicating an arid braided-river system in the lowermost part. Also, fluvial-deltaic sandstones are to be found, sourced by the erosion of the Devonian Old Red Sandstones and the uplifted basement horsts. In some areas, the Carboniferous appears to be deposited in a mixed-fluvial lacustrine environment. Areas where there was maximum subsidence, in general close to the major faults, periodic lakes formed and thick sequences of organic-rich oil shales were deposited.

The uppermost Carboniferous was dominated by more regional thermal subsidence and therefore the sediments deposited was a combination of lacustrine, channelized, crevasse-splay and overbank deposits with thick coals.

Lower Permian consists of the Roteliegend Group. The Roteliegend Group is recognized as unfossiliferous desert sandstone. This group consist of volcanics in the lowermost section and becomes more siliciclastic, mainly aeolian towards the upper part of the group.

Upper Permian consists of the Zechstein Group. This group consists of cyclic events of limestone, dolomite, anhydrite, and halite. The halite dominates in the basin center, while the limestone, dolomite, and anhydrite dominate in the basin margins. The depositional environment for Zechstein Group is a marine environment.

The Triassic consists of the Red Beds and the Grey Beds, both representing continental clastics. The Red Beds were deposited in an arid climate, while the Grey Beds were deposited in a humid climate.

While the Jurassic consists of the Tyne Group, which is mainly dominated by claystone. The color ranges from grey to brownish black and contains frequent silty, sandy and calcareous horizons. In some areas, the Tyne Group might consist of a sandy layer called Eldfisk Formation.

The Cretaceous consists of the Cromer Knoll and Shetland Group. The Cromer Knoll consists of mainly fine-grained, argillaceous, marine sediments with varying content of the calcareous material. The calcareous claystone, siltstone, and marls dominate, but there are some subordinate layers of limestone and sandstone occurring. The claystone is in general grey, olive grey, greenish and brownish becoming light olive-grey marlstones. Mica, pyrite, and glauconite are common in this group. The Shetland Group consists of chalky limestones, limestones, marls, calcareous shales, and mudstones. Chert (flint) occurs throughout the facies. The siliciclastic facies consist of mudstones and shales, partly interbedded with limestones. The shales and sandstones are slight to very calcareous.

The Lower Cenozoic consists of the Rogaland and Hordaland Group. Dominant lithologies of the Rogaland Group in the west are sandstones interbedded with shales. These sandstones form lobes which pass laterally into shales eastwards, and in most of the Norwegian sector of the North Sea, the Rogaland Group consists of argillaceous marine sediments. The basal deposits frequently contain reworked limestones and marls. Towards the top of the group, the shales become increasingly tuffaceous. The Hordaland Group consists of marine claystone with minor sandstones. The claystone is usually light grey to brown, fissile and fossiliferous. Red and green claystone sometimes occur at the base. Thin limestones and streaks of dolomite are present. Sandstones are developed at various levels in the group, which are very fine to medium grained, and are often interbedded with claystone.

The Upper Cenozoic consists of the Nordland Group. This group is dominated by marine claystone in the North Sea. They are grey, sometimes greenish-grey and grey-brown, soft, locally silty and micaceous. The uppermost part of the group consists of unconsolidated clays and sands with glacial deposits (Figure 12)

Structural elements

The Sørvestlandet High is located in the southern Central North Sea close to the Danish border. It is an Upper Jurassic horst bounded by the Upper Jurassic Coffee Soil fault complex on the west and the Triassic Hummer Fault Zone and Åsta Graben, and the Permian Danish-Norwegian Basin on the east. The structure that binds the Sørvestlandet High on the west is the Søgne Basin, an Upper Jurassic basin. Confining the Sørvestlandet High on the north is the Triassic Reke Fault Zone and the Jæren High. The northern part of the western Sørvestlandet High is bounded by the Upper Jurassic Ula-Gyda Fault Zone, Cod Terrace, and Steinbit Terrace (Figure 13).

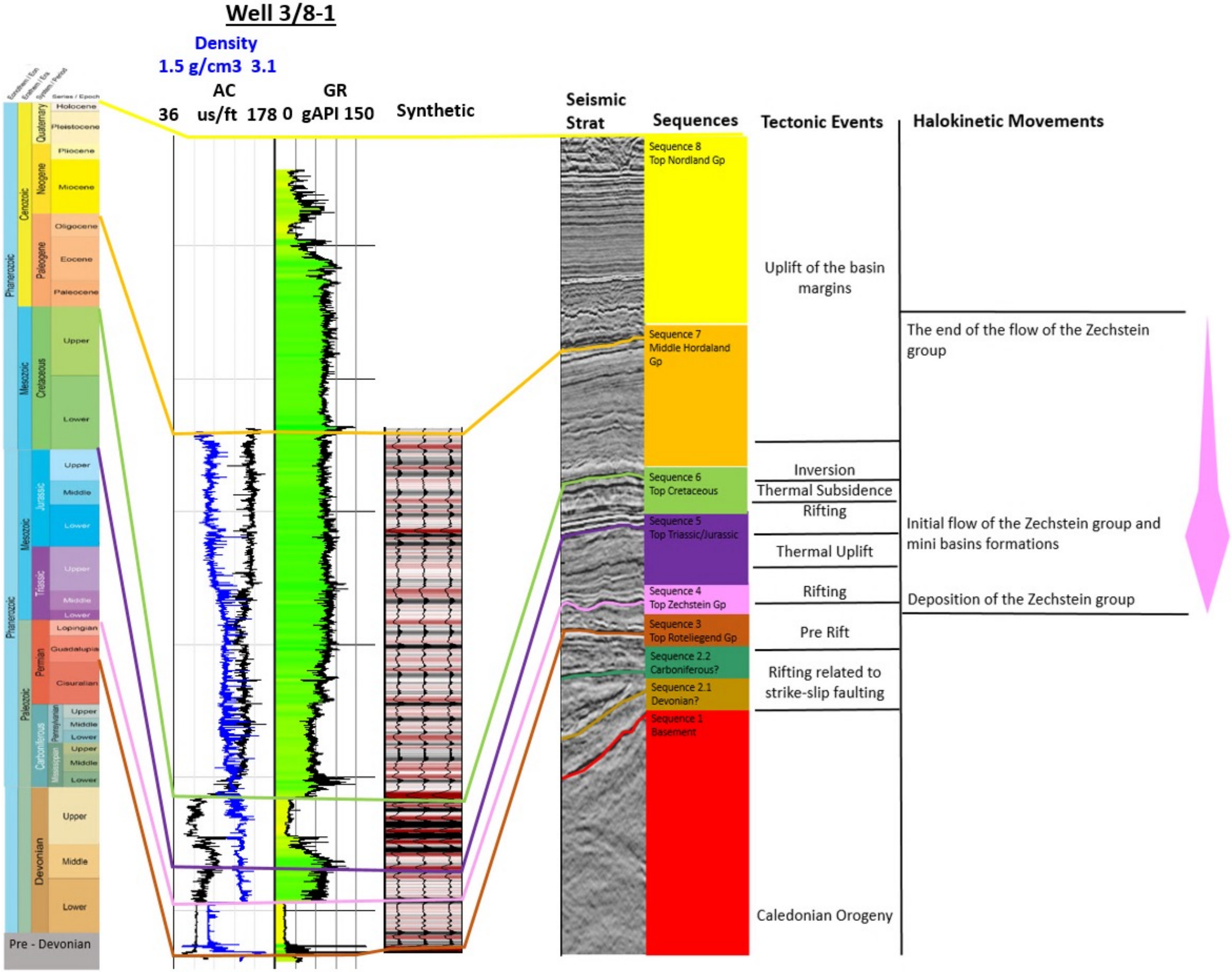


Figure 12: Chronostratigraphic column, along with seismic sequences, tectonic events and halokinetic movements

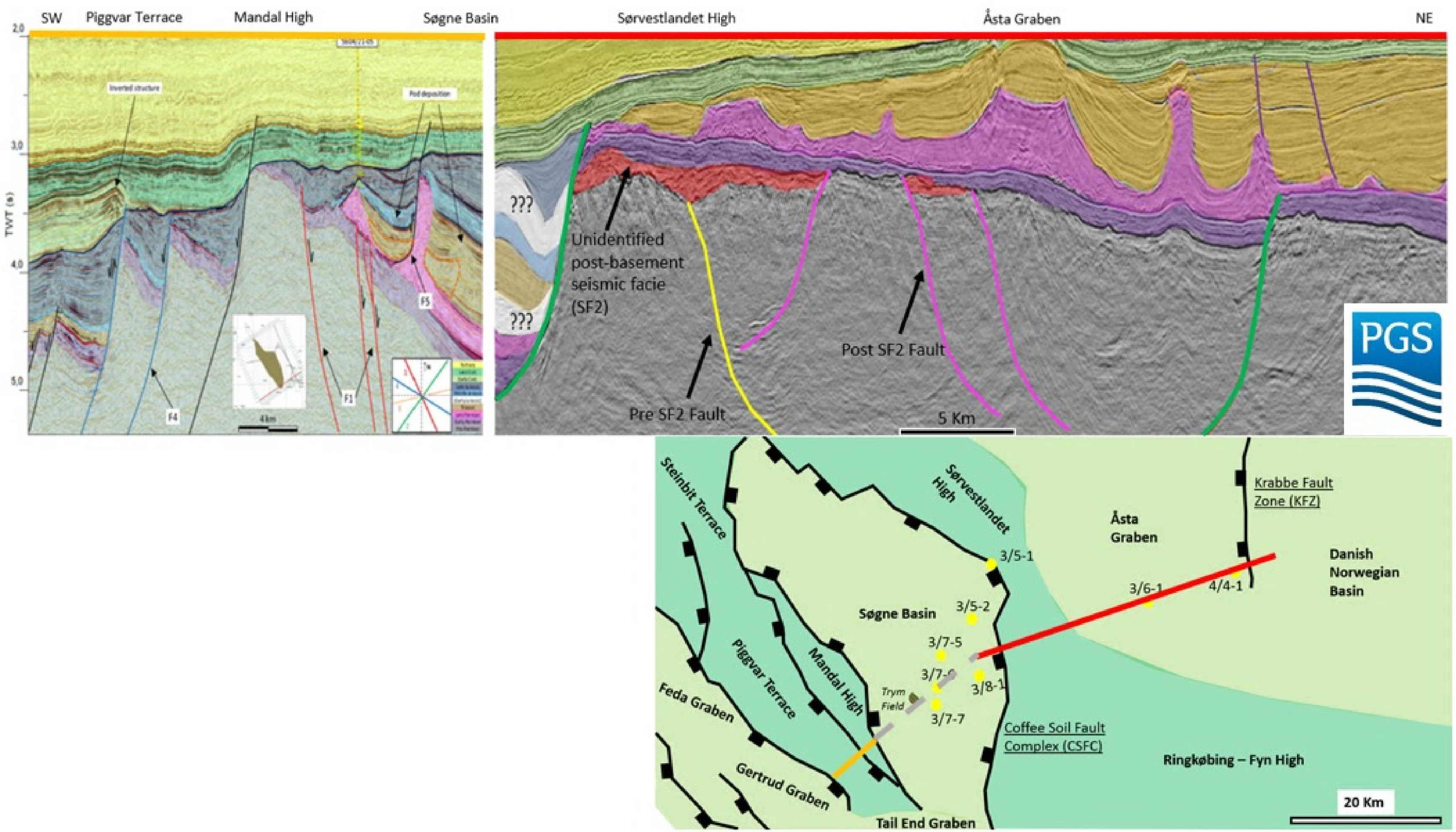


Figure 13: SW-NE Regional seismic cross-section across the North Sea, Norway where orange is the study area of Rossland et al. (2013) and red is the study area of this project.

Data and methodology

Dataset

The study area of this project is in the southern part of the Sørvestlandet close to the Danish border. It covers the eastern part of the Søgne Basin and the western part of the Åsta Graben. The data used in this project is provided by the Norwegian Petroleum Directorate and Petroleum Geo-Services (PGS) and includes (Figure 14):

MC3D – NDB2013 three-dimensional seismic cube

Well 3/6-1

Well 4/4-1

Well 3/5-1

Well 3/5-2

Well 3/7-5

Well 3/7-6

Well 3/7-7

Well 3/8-1

Seismic

The three-dimensional survey consists of 4264 east-west crosslines with a length of 50 km, and 3986 north-south inlines with a length of 53 km. The three-dimensional seismic cube is 2650 km^2. The seismic quality of the cube is excellent, but some noise around the salt structures is present due to the refraction and scattering of seismic ray paths traveling into and through the salt body, which increases the uncertainty of interpretation of the salt bodies.

Data Details:

Sample Rate: 4, 0 msec

Trace Length: 7000 ms

Data Type: Final post PSDM full offset stack

Polarity: Zero phase, reverse polarity (through= red hard kick, peak= black soft kick)

Inlines: 1319 – 3780, 12,50 m bin size

Xlines: 706 – 3816, 12,50 m bin size

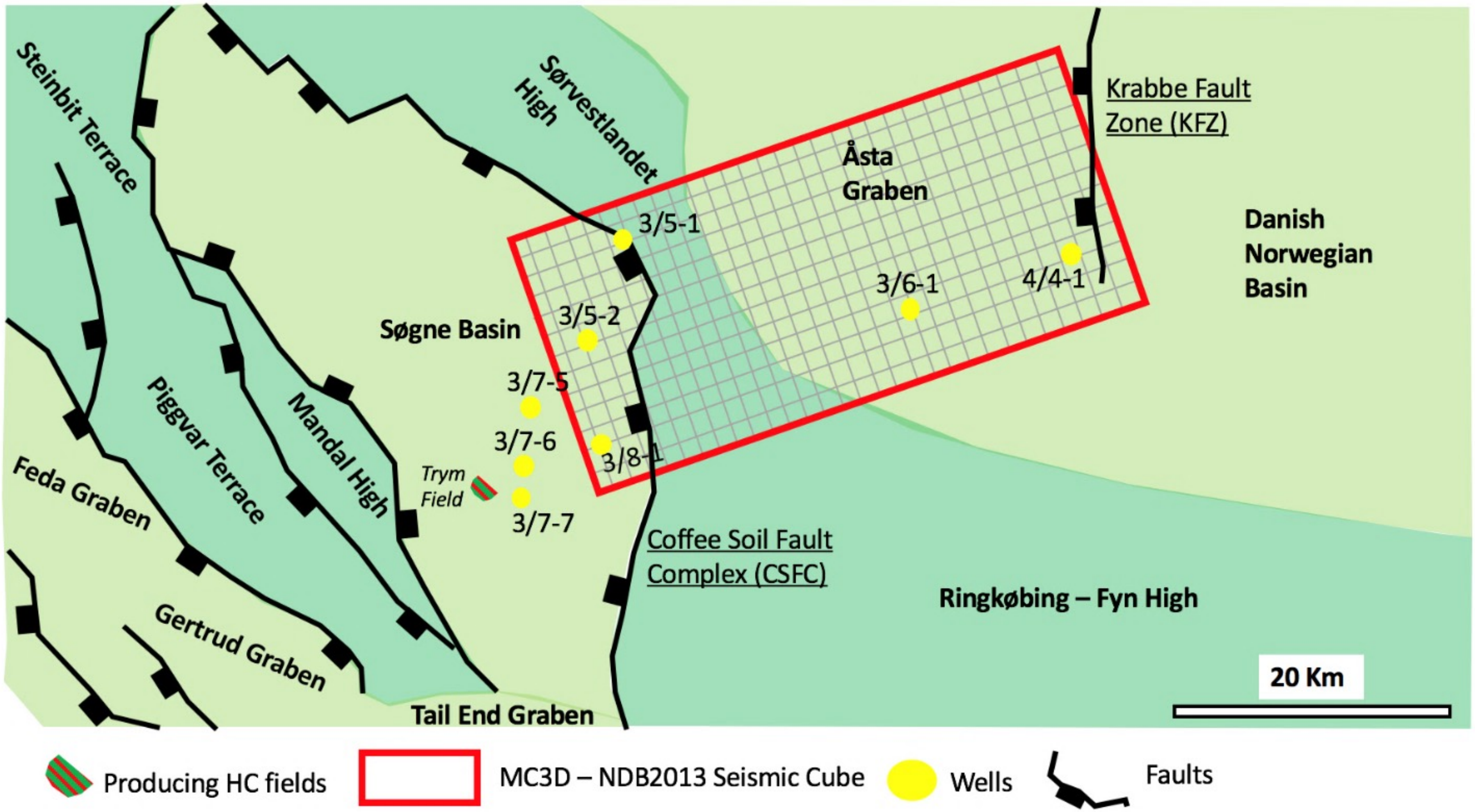


Figure 14: A structural map of the North Sea showing the main structures, oil fields, wells used in the study and the study area (red box)

Welldata

Published well-log data information from eight Norwegian wells was used in this project. The welldata consist of conventional logs, such as gamma ray, resistivity, density and others. Also, geochemical information, stratigraphic tops and core descriptions provided by NPD were used. The three-dimensional seismic cube does not cover four of the wells available. These wells are 3/7-7, 3/7-6, 3/7-5 and 3/5-2. However, it does cover well 3/8-1, 3/5-1, 3/6-1 and 4/4-1.

All the wells used in this study are wildcat wells that were drilled for exploration purposes. The wells will be divided into two groups based on their total depth and target. Group 1 is the wells that had their maximum depth to Triassic and Permian, 3/7-5, 3/8-1, 3/5-2 and 3/5-1. These wells are located near the Coffee Soil Fault Complex in the Søgne Basin. The primary targets for well 3/7-5 and 3/5-2 was to test the Jurassic HC potential, but both wells showed no HC presence. Well 3/8-1 and 3/5-1 had their primary target to test the Lower Permian Roteliegend sand, no HC shows were encountered here as well.

Group 2 are the wells that had their maximum depth to Jurassic and Cretaceous, 3/7-7, 3/7-6, 3/6-1 and 4/4-1. These wells were drilled in the western part of the Søgne Basin, Sørvestlandet High and Åsta Graben. Wells 3/7-7 and 3/7-6 primary targets were to test the HC potential of the Upper Jurassic shales. Both these wells had minor hydrocarbon in the sands within the Upper Jurassic shales. Wells 3/6-1 and 4/4-1 primary targets were to test the hydrocarbon potential of the Paleocene sands, but no to limited hydrocarbon shows were encountered. In general, it appears that there are no hydrocarbon potentials in the Mesozoic, Cenozoic and in the Roteliegend which is located in the Søgne Basin (Table 1).

Well	Type	Year	TD (MD) m	Oldest rocks penetrated	Discovery	Reservoir
3/5-1	Wildcat	28.06.1978	3426	Early Permian	No	Dry
3/5-2	Wildcat	20.08.1978	3825	Triassic	No	Dry
3/6-1	Wildcat	10.07.2000	2167	Late Cretaceous	No	Dry
3/7-5	Wildcat	07.02.1992	3666	Late Permian	No	Shows
3/7-6	Wildcat	30.11.1996	4120	Late Jurassic	No	Shows
3/7-7	Wildcat	27.10.2008	3930	Late Jurassic	No	Shows
3/8-1	Wildcat	29.12.2010	4070	Early Permian	No	Dry
4/4-1	Wildcat	13.10.2013	2012	Late Cretaceous	No	Dry

Table 1: A summary of the different well information (NPD)

Methodology

Seismic to welltie

To better constrain the age of the various seismic reflectors, a synthetic seismogram was generated for well 3/8-1, as it penetrates through all the formations from Cenozoic to the Lower Permian. An extracted wavelet from the seismic was used to create the synthetic seismogram. The dominant frequencies of MC3D – NDB2013 ranges from between 10 – 125 Hz. The RC calculation method is based on sonic velocity and density. The different interval velocities for the different sequences were based on literature for the three first sequences (the Pre-Permian) (Evans et al., 2003), and the rest of the sequences were obtained from the synthetic. The representative interval velocities for the nine different units are listed in Table 2.

Nine key seismic horizons were recognized based on their lateral and vertical seismic reflectivity (Figure 15). However, only six of the key seismic horizons were correlative and recognized on the well. Terminations such as toplap, downlap, onlap and truncations are often associated with boundaries separating the seismic units, and thus also distinct seismic events (Table 3). These differences often result in stratigraphic lithology and porosity variations. The nine chronostratigraphic sequences recognized are Basement, Devonian, Carboniferous, Lower Permian, Upper Permian, Triassic/Jurassic, Cretaceous, Lower Cenozoic and Upper Cenozoic.

Seismic Interpretation

The interpretation of the horizons was carried out in the interval of every 25th line using Schlumberger Petrel software. The interpreted grids were then 3D tracked to get a denser interpretation. An interpolation tool was then used to create time structural maps, and by subtracting these different structural maps isochrone maps were created. The Cosine of Phase seismic attribute was used to detect the continuity of the different reflectors (Figure 16). The Cosine of Phase attribute is the best indicator of lateral continuity. This attribute is also called Normalized Amplitude because this attribute doesn’t consider the different amplitude variations, therefore the enhancement of the seismic reflection continuity, especially in the areas adjacent to the salt structures where the area is poorly solved. Besides, this attribute is a great indicator of seismic facies and strata terminations.

However, to capture the Palaeozoic half grabens seismic flattening on the Top Roteliegend reflection was carried out (Figure 17). This technique removed younger deformation, and a more accurate interpretation of the original geometries and distribution of the graben was obtained.

Furthermore, to improve the interpretation of the salt bodies, multi-Z function in petrel was used instead of the conventional seismic interpretation method, since the conventional way of interpreting the salt structures leads to problems in the high dip velocity areas around the salt structures. The multi-Z algorithm solves issues related to the interpretation of objects that passes through a seismic trace twice (Figure 18). The structures this method is applicable for is, for instance, mushroom shaped salt dome, overhang or salt tongue (Warner, 2013). This algorithm allows one to have an accurate representation of the salt diapir, without creating multiple or overlapping interpretation patches that must be merged. The Multi-Z interpretation is then wrapped around with a triangular mesh to give a more accurate 3D model of the object (Figure 19).

Sequence	Minimum velocity (m/s)	Average velocity (m/s)	Maximum velocity (m/s)
Sequence 7		2066 m/s	
Sequence 6	1900 m/s	2000 m/s	3200 m/s
Sequence 5	1100 m/s	2500 m/s	11761 m/s
Sequence 4	3000 m/s	4000 m/s	5400 m/s
Sequence 3	3000 m/s	4500 m/s	5000 m/s
Sequence 2		3750 m/s	
Sequence 1.2		4000 m/s	
Sequence 1.1		4500 m/s	
Basement		5300 m/s	

Table 2: A summary of the velocities for the sequences defined in this study

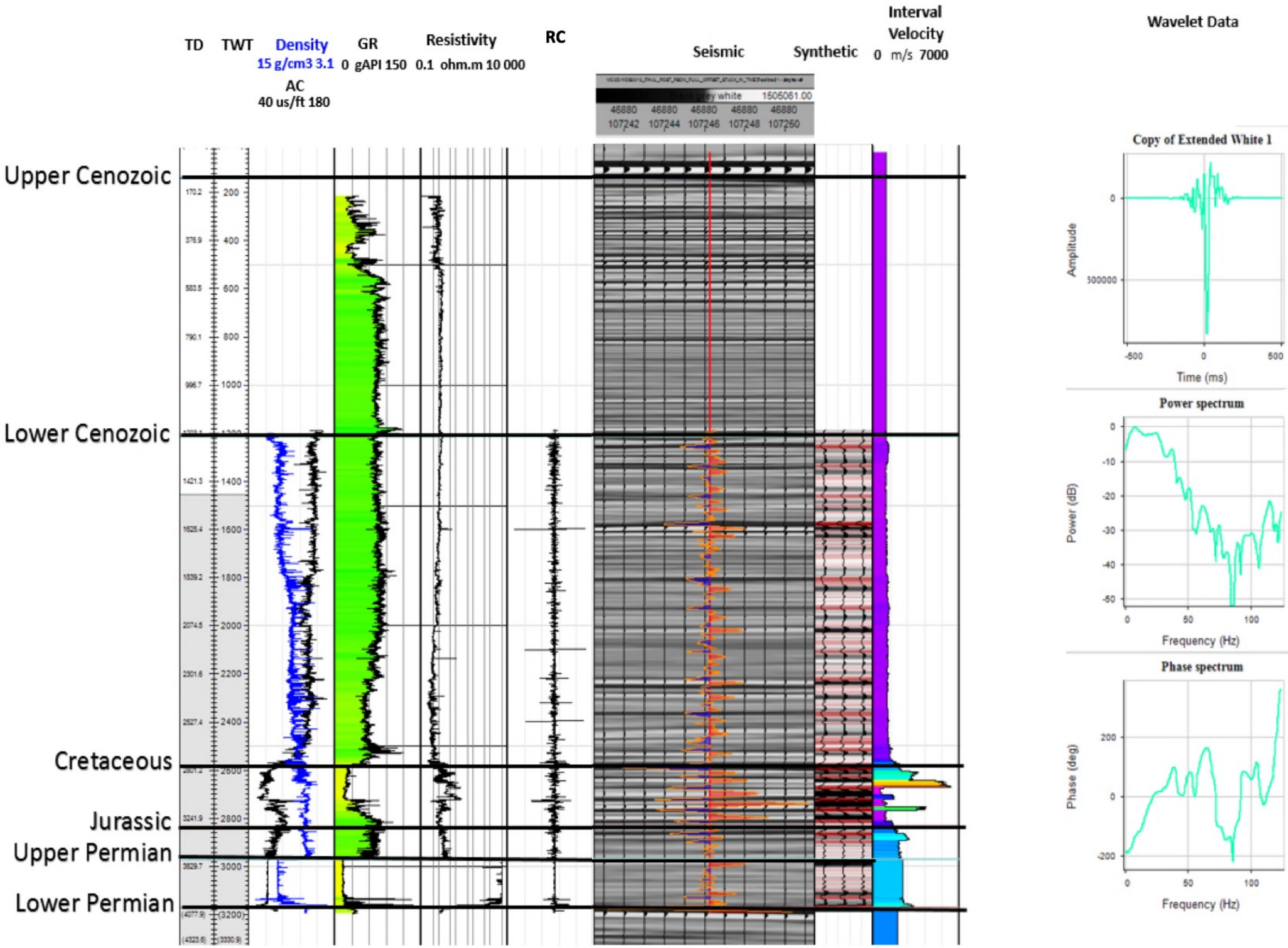


Figure 15: The synthetics of well 3/8-1 where align picked points was used as the correction method

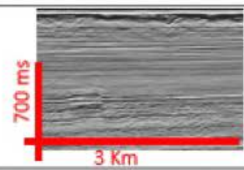
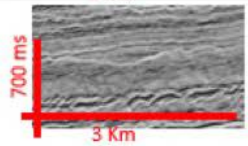
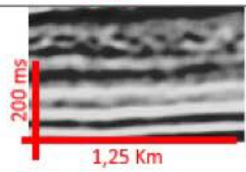
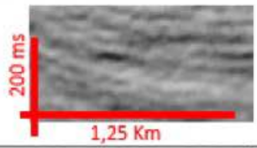
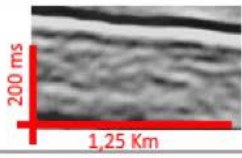
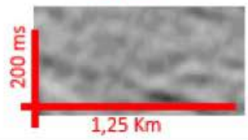
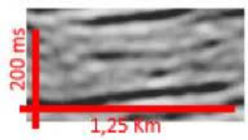
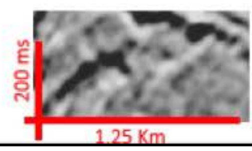
Seismic Facies	Reflection Configuration	Reflection Continuity	Reflection Amplitude and frequency	Example
SF 9	Parallel	Continuous	High amplitude	
SF 8	Parallel	Continuous	Medium amplitude	
SF 7	Parallel	Continuous	High amplitude and low frequency	
SF 6	Parallel	Continuous	Low amplitude	
SF 5	Chaotic, mound shaped, diapiric	Discontinuous	Low amplitude	
SF 4	Chaotic to Sub – Parallel	Continuous	High to medium amplitude	
SF 3	Chaotic	Discontinuous	Low Amplitude and low frequency	
SF 2	Sub - Parallel	Semi Continuous	High Amplitude and low frequency	
SF 1	Chaotic	Discontinuous	Low amplitude and low frequency	

Table 3: Table showing the different seismic facies with their seismic characters

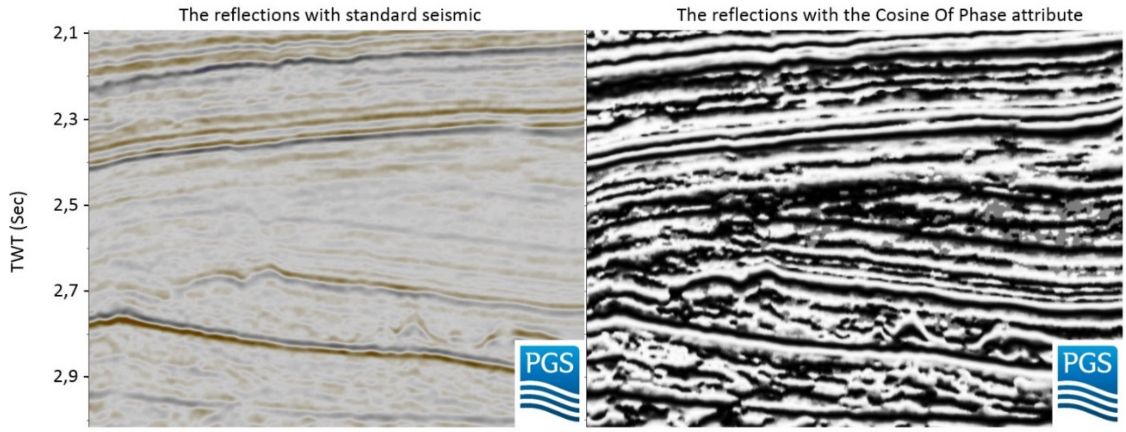


Figure 18: Before and after applying the Cosine of Phase function for enhancement of the reflection continuity

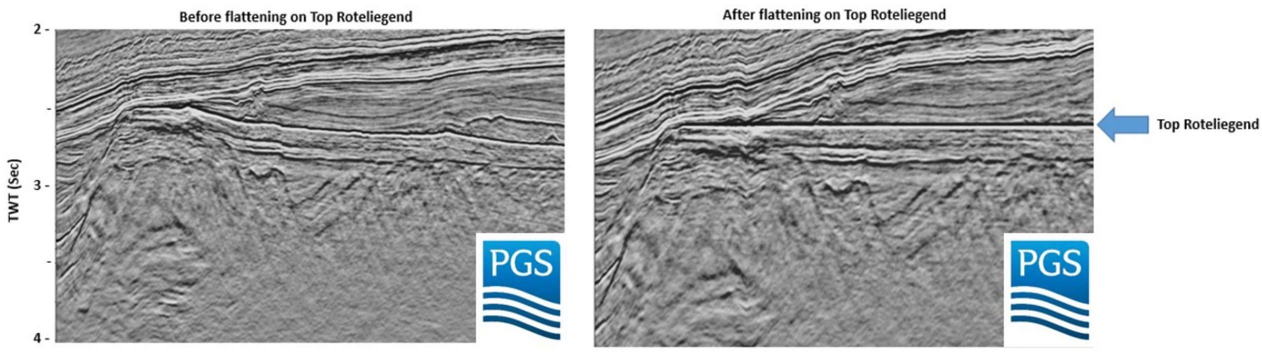


Figure 16: Shows the visually enhancement of the Pre-Permian half grabens by using flattening seismic cube on Top Roteliegend Gp.

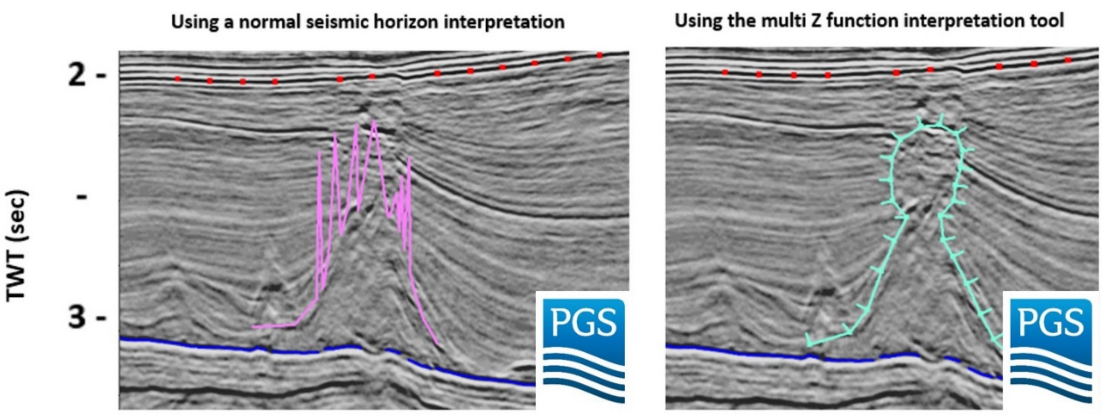


Figure 17: The solution for interpreting the mushroom shaped salt diapir as normal horizon didn´t work. The proper technique is show on the right-side picture and is called Multi Z Interpretation Technique.

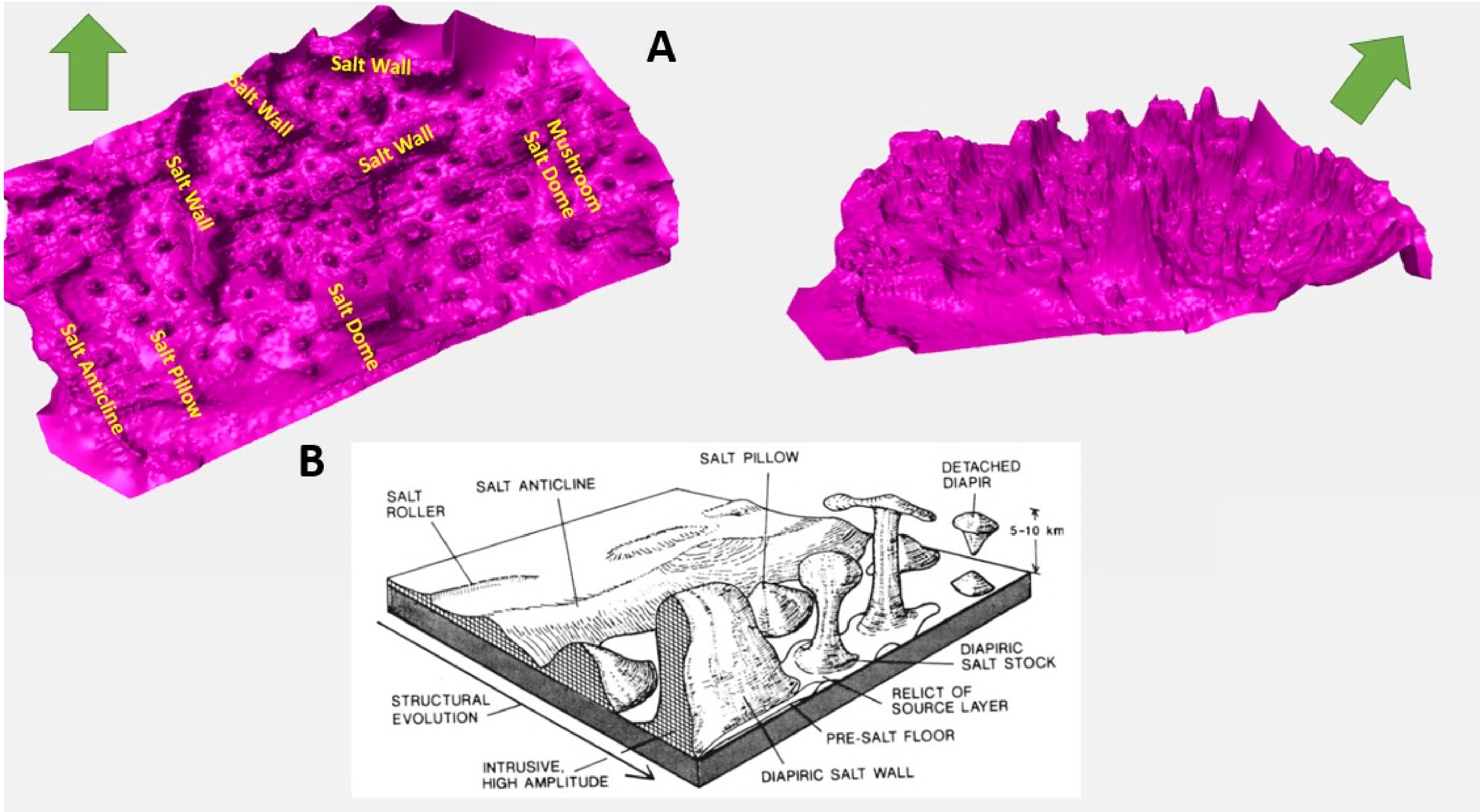


Figure 19: (A) The generated Multi Z that has been converted into triangular mesh to visualize the different types of salt bodies found in Zechstein Gp in the study area, B) A figure by Einsele (2010) that shows the different salts structures

Restoration

Restoration is a technique that allows one to restore a sequence of parallel profiles in a sedimentary basin margin. These profiles are restored along the strike and provides information about the total extension or shortening experienced by the basin (Lingrey & Vidal-Royo, 2015). Most of the restoration is done in either 3D or 2D, to generate the initial geometry of the cross section and provide the trail of realistic deformation between initial and final geometries (Moretti, 2007).

There are two main reasons for conducting a restoration. First balancing of a cross section provides validation that the cross section is restored by following a reasonable kinematic pathway to their un-deformed state. Second, the restored section gives information on how the structural deformation was developed. Restoring is vital to exploration industry as structural development influences the migration of hydrocarbons, development of traps, reservoir distribution, and hydrocarbon generation all.

The section balancing and restoration techniques suppose that the volume of hanging wall is preserved during deformation which is not realistic because tectonic stresses affect all the structures. Most important is the reduction in porosity due to the tectonic compaction (Yamada & McClay, 2003) which plays one of the major roles in petroleum systems of an area. A balanced cross section gives information about the gain and loss of sediments in sedimentary layers and the amount of extension or shortening. It provides great information about the compaction of the sediments and if there was a gain in porosity or not. But the restoration for salt will not represent the actual geometry since this is a 3D problem because the salt is flowing in all directions and not only one. Moreover, some of the main structural geology techniques used for restoring this section were:

Flexural slip used to unfold layers. This is a method which preserves length and bed thickness.

Simple shear was also used to remove the effect of faults. Beds are moved to the original position by selecting the same horizon in the hangingwall and footwall.

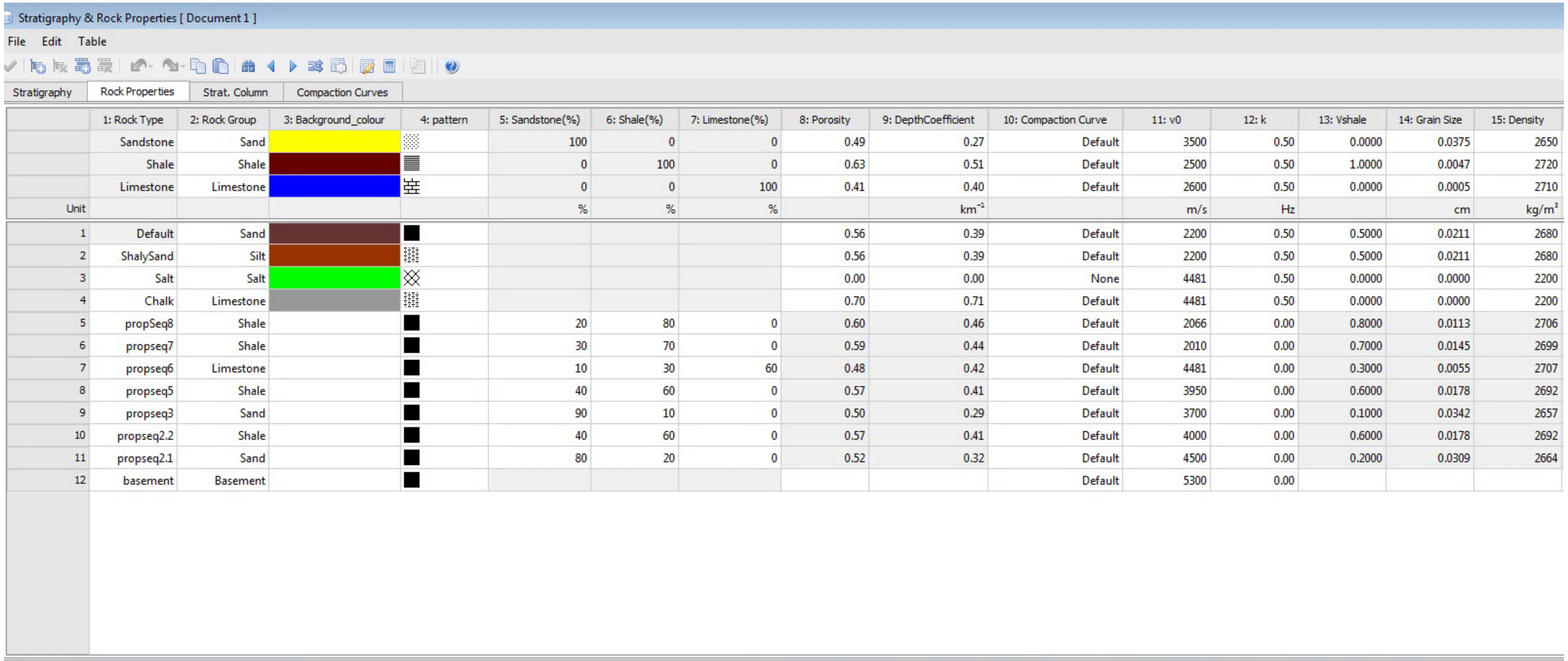
Block Restoration. The several fault blocks that were identified, were restored separately using flexural slip. Than all the blocks were joined together using simple shear. The last step was the decompaction.

Decompaction process works on the following equation (from Scalter et al, 1980)

$$\boldsymbol{f} = \boldsymbol{f0} * (\boldsymbol{e}^{-cy})$$

where f is the present-day porosity;
f0 is the porosity at the surface;
c is porosity-depth coefficient (Km^{-1}) and
y is the depth (m).
The principle behind this equation is to understand the decrease in porosity with depth i.e. when compaction takes place. When the layers are decompacted to the day of deposition they thicken and there is a gain in the sedimentary layer. But it is important to acquaint here that the effect of decompaction on shales is more than sandstones.

An interpreted seismic section was selected to perform the two-dimensional reconstruction & decompaction for which Move software; version 2017.1.0 was used. Once the seismic section was transferred to Move, the section was depth converted using the software´s default velocities or the velocities obtained from the synthetics. Since decompaction is mainly affected by the lithology, a stratigraphic chart of all the lithological percentages and the rock properties of each sedimentary layer was generated into Move database (Figure 20). Moreover, to restore a section with multiple layers, stratigraphic key horizons were identified. The youngest horizon was picked and typically brought to a flat, horizontal datum where it defines the geological time of its original position. When there were faulting and folding present, the sedimentary layer was first unfaulted where hangingwall rejoins the depth of footwall (Lingrey & Vidal-Royo, 2015) and the fault offset was removed. Than any folding present was removed. The sequence of restored stratigraphic layers was generated to provide information about the gain and loss of sediments in sedimentary layers and the amount of extension.



Stratigraphy & Rock Properties [Document 1]

File Edit Table

Stratigraphy | Rock Properties | Strat. Column | Compaction Curves

	1: Rock Type	2: Rock Group	3: Background_colour	4: pattern	5: Sandstone(%)	6: Shale(%)	7: Limestone(%)	8: Porosity	9: DepthCoefficient	10: Compaction Curve	11: v0	12: k	13: Vshale	14: Grain Size	15: Density
	Sandstone	Sand			100	0	0	0.49	0.27	Default	3500	0.50	0.0000	0.0375	2650
	Shale	Shale			0	100	0	0.63	0.51	Default	2500	0.50	1.0000	0.0047	2720
	Limestone	Limestone			0	0	100	0.41	0.40	Default	2600	0.50	0.0000	0.0005	2710
Unit					%	%	%		km^{-1}		m/s	Hz		cm	kg/m^3
1	Default	Sand						0.56	0.39	Default	2200	0.50	0.5000	0.0211	2680
2	ShalySand	Silt						0.56	0.39	Default	2200	0.50	0.5000	0.0211	2680
3	Salt	Salt						0.00	0.00	None	4481	0.50	0.0000	0.0000	2200
4	Chalk	Limestone						0.70	0.71	Default	4481	0.50	0.0000	0.0000	2200
5	propSeq8	Shale			20	80	0	0.60	0.46	Default	2066	0.00	0.8000	0.0113	2706
6	propseq7	Shale			30	70	0	0.59	0.44	Default	2010	0.00	0.7000	0.0145	2699
7	propseq6	Limestone			10	30	60	0.48	0.42	Default	4481	0.00	0.3000	0.0055	2707
8	propseq5	Shale			40	60	0	0.57	0.41	Default	3950	0.00	0.6000	0.0178	2692
9	propseq3	Sand			90	10	0	0.50	0.29	Default	3700	0.00	0.1000	0.0342	2657
10	propseq2.2	Shale			40	60	0	0.57	0.41	Default	4000	0.00	0.6000	0.0178	2692
11	propseq2.1	Sand			80	20	0	0.52	0.32	Default	4500	0.00	0.2000	0.0309	2664
12	basement	Basement								Default	5300	0.00			

Figure 20: The setup of velocity modellng in Move software, including properties of each sequence such as lithology fractions, porosities and velocities

Observations

Structural and stratigraphic framework of the Sørvestlandet High

In general, the present-day Sørvestlandet High is confined by the Upper Jurassic Søgne Basin and Coffee Soil Fault Complex to the west and the Triassic Åsta Graben and Krabbe Fault Zone to the east (Figure 21). The main chronostratigraphic sequences observed in the study area are the Metamorphic basement, sandy/fine grained Devonian, fine-grained Carboniferous, sandy Lower Permian, Upper Permian salt, Triassic/Jurassic sand and shale, Cretaceous chalk, Lower Cenozoic sandy shale and Upper Cenozoic shale (Figure 22).

Fault families

The fault families have been divided into two groups, the sub-salt fault families, and the supra-salt fault families. Within these two fault family groups, sub-fault families have been defined based on their trend. FF1, FF2, FF3, and FF4 are the sub-salt faults, while FF5, FF6, FF7, and FF8 are the supra-salt faults.

Fault Family one is NNW-SSE trending fault dipping both directions, towards SW and NE. These faults are low angle planar faults. The timing of these faults is post Sequence 1.2, since this fault cuts Sequence 1.2, for both the SE and NE dipping fault of FF1. This fault family is mainly found in the eastern part of the Sørvestlandet High, whereas the throw of these faults is relatively low, but can reach up to 250 ms.

Fault family two is trending NE-SW and mainly dips towards the N. These faults displace Sequence 1.1, and are planar and low to medium high angle, with a throw up to 100 ms. This fault family is mainly found in the northeastern part of the Åsta Graben and the north of the Sørvestlandet High (Figure 23).

Fault family 3 are the EEN-WWS striking faults, also dipping towards the N. These faults unlike FF2 is displacing Sequence 1.2, and are more listric, creating half grabens in the Sørvestlandet High with a throw up to 500 ms. FF3 are mainly found in the southern part of the Sørvestlandet High (Figure 24).

The last sub-salt fault family is fault family 4. These faults are striking NNE-SSW, and mainly dipping towards the west. This fault family includes the Upper Jurassic Coffee Soil Fault Complex and the Triassic Krabbe Fault Zone. The Coffee Soil Fault Complex displaces Sequence 4, while Krabbe Fault Zone displaces Sequence 2. The displacements of Coffee Soil Fault Complex and Krabbe Fault Zone are the largest ones in the study area, and especially

the Coffee Soil Fault Complex. These faults are planar high angle faults that can have a throw reaching almost 1500 ms. The Coffee Soil Fault Complex confines the Sørvestlandet High on the western side, while Krabbe Fault Zone is confining the Åsta Graben on the eastern side.
Fault family five are the first supra-salt fault family. This fault family is striking NW-SE dipping mainly towards SWW, and are high angle planar faults with throw up to 50 ms. This fault family displaces Sequence 5 in the southern part of the study area, while in the north they displace even Sequence 6. These faults are detached to Sequence 4, the Zechstein salt.
Fault family six are the high angle planar fault with throw up to 200 ms. This fault family is striking NWW-SEE and mainly dipping towards NNE (some towards SSW), displacing even Sequence 6. The larger displacements are found in the areas close to the transition between the Åsta Graben and the Sørvestlandet High, and in the areas where the salt diapirs are large (Figure 25).

Fault family seven are high angle planar faults with throw up to 20 ms. These faults are the E-W striking faults, dominantly dipping towards the north. These faults displace Sequence 5, but with an exception in the southeastern part of the study area, close to the major salt diapir, where it even displaces Sequence 6.

Fault family eight are high angle planar faults with throw up to 30 ms. This fault family is the NNE-SSW striking faults, mostly dipping towards NWW. FF8 displaces Sequence 6 and is mainly found in the Sørvestlandet High. These faults are detached to the Zechstein salt as well.

In general, the faults can be divided into two groups, the sub-salt, thick-skinned faults detaching to the basement, and the supra-salt thin-skinned faults dethatching to the salt. Most of the faults appear to be planar faults, except for the sub-salt FF3 listric ones. The faults with the larger displacements are the sub-salt faults ones, while the supra-salt faults appear to have smaller. Also, further division of the faults can be done based on the relations between the sub-salt and supra-salt. Some of the supra-salt faults seemed to follow the orientation of the sub-salt faults, with similar dip angle and fault curvature, while some of the supra-salt and sub-salt seem to have no relation to each other.

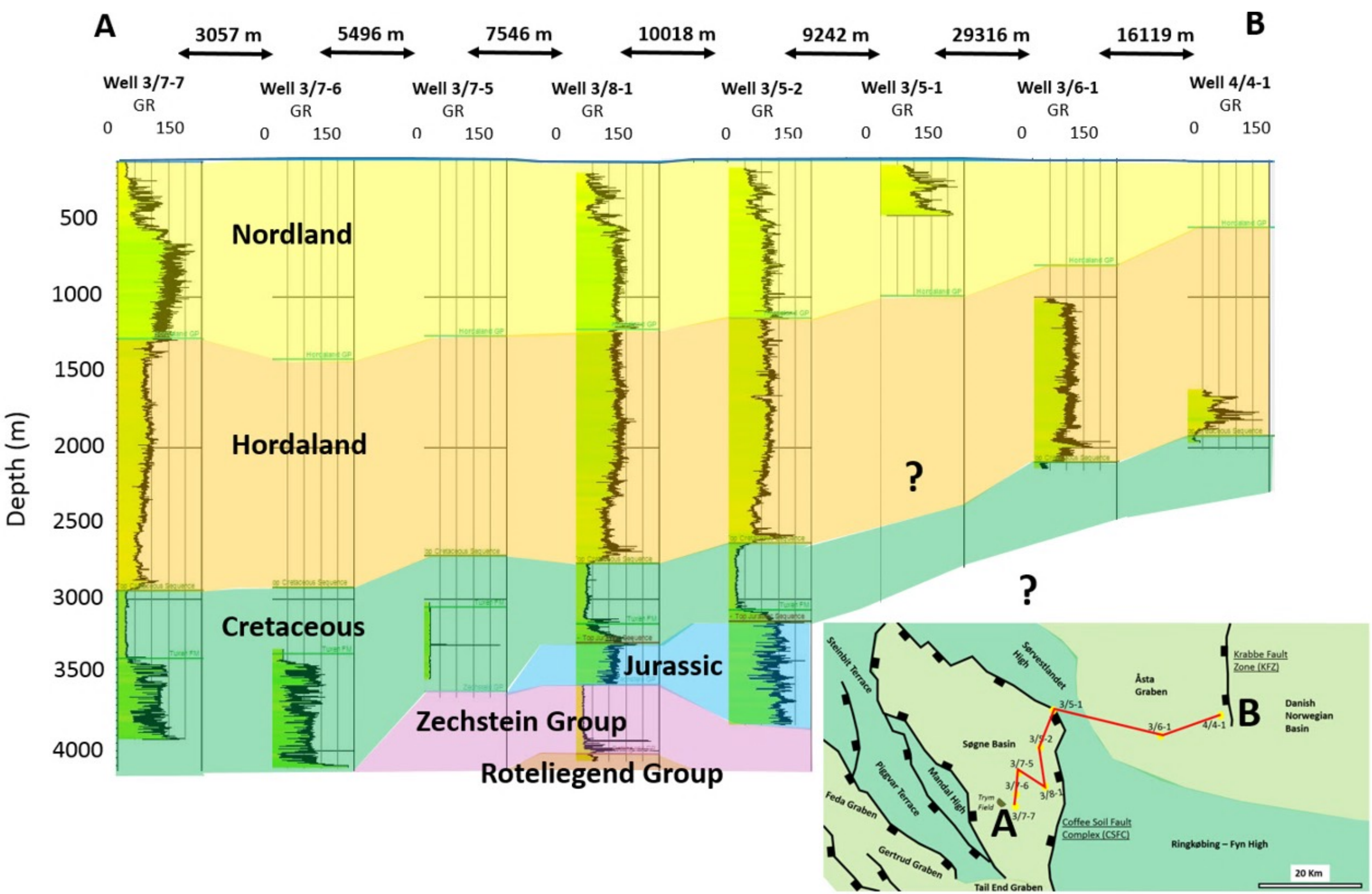


Figure 21: Well correlation diagram across the study area with GR log and the vertical and lateral distribution of the different chronostratigraphic sequences

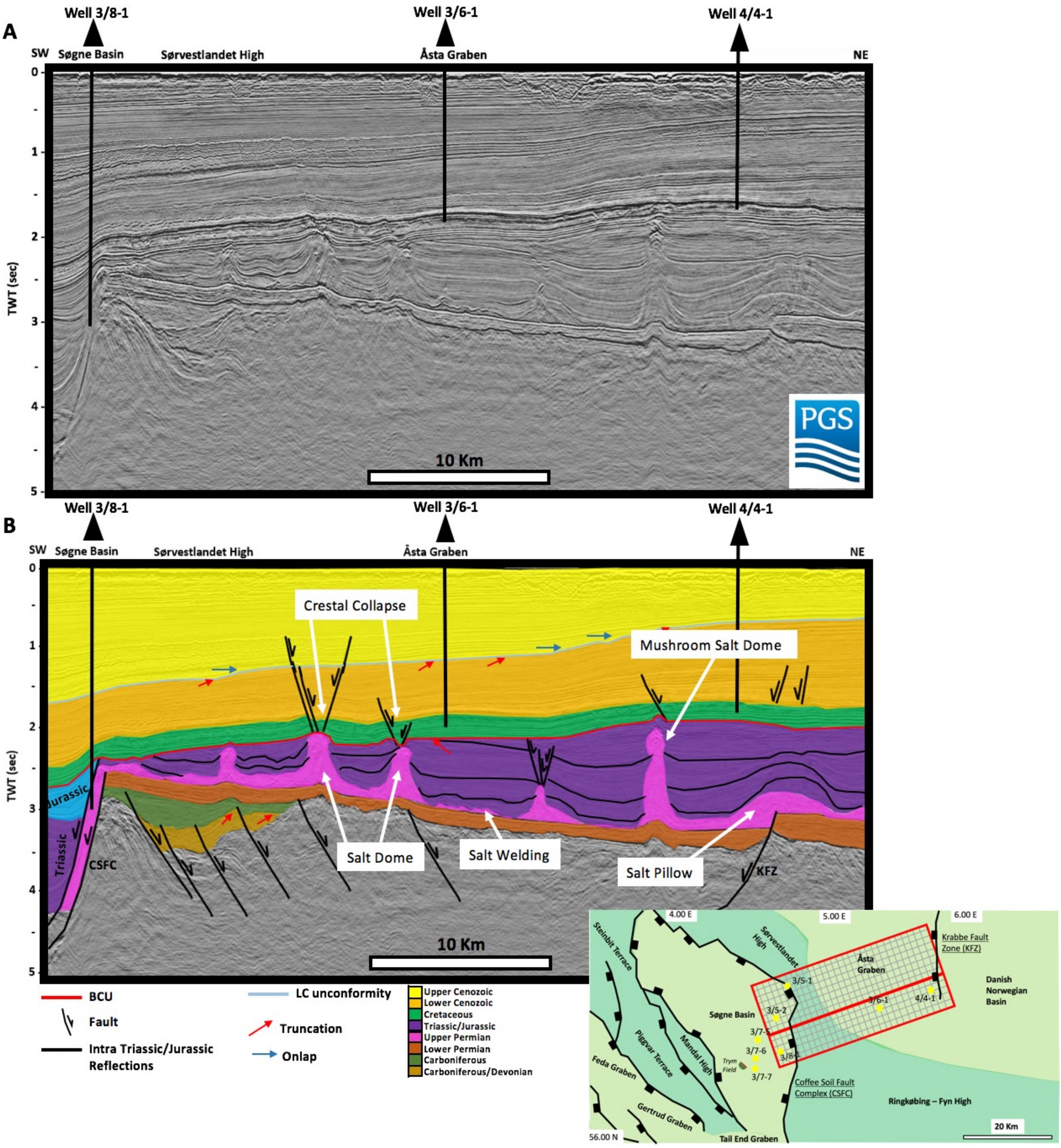


Figure 22: (A) Uninterpreted southwest-northeast three-dimensional seismic line from Søgne Basin to the Åsta Graben across the study area (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 4, 5 and 7. Clear truncations of the Devonian, Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like mushroom Salt Dome, salt welding and salt pillow. Also, seen here are the crestal collapse above some of the salt domes.

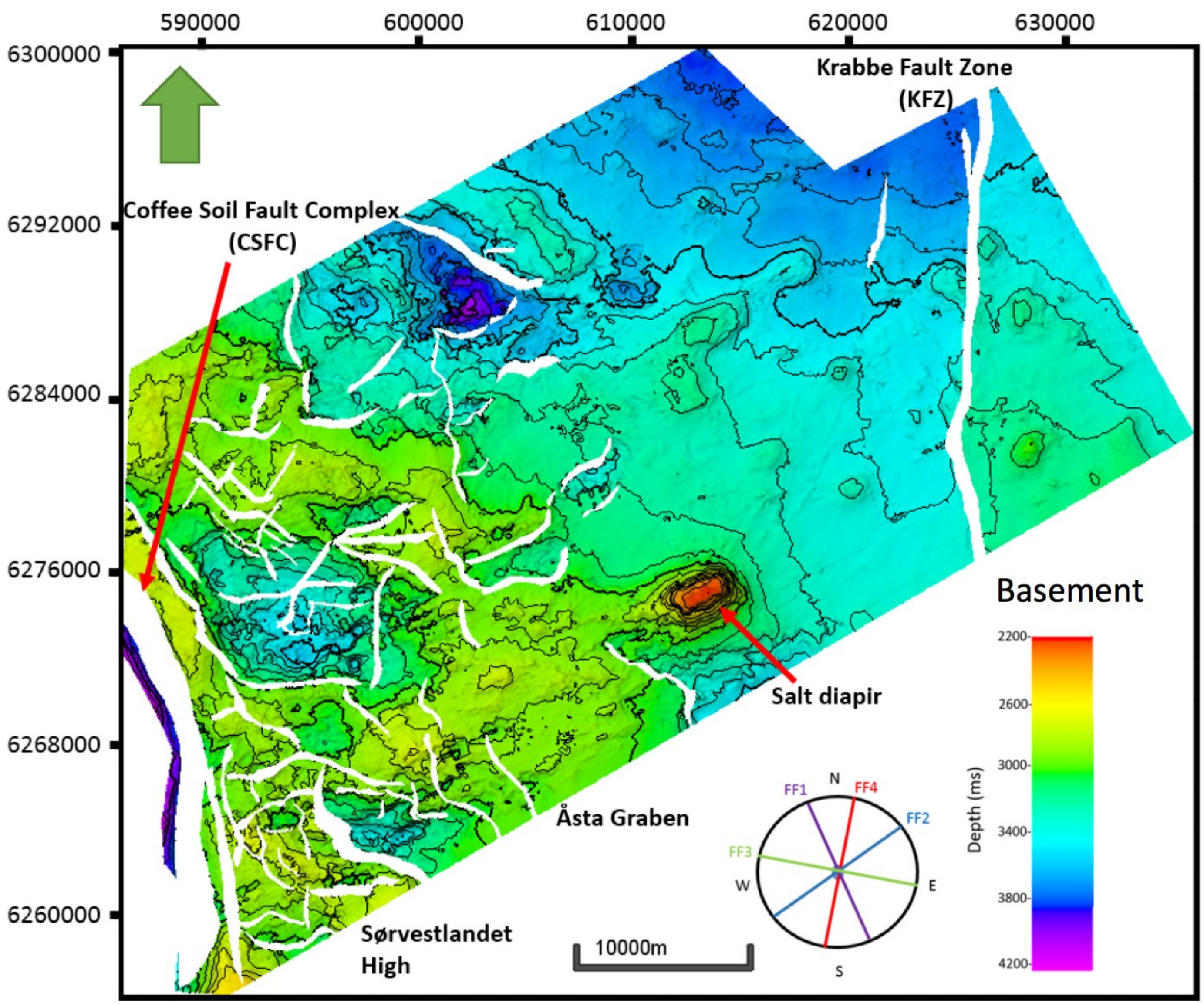


Figure 23: Structural Time Map (TWT) of Top Basement with the first four defined sub-salt fault families

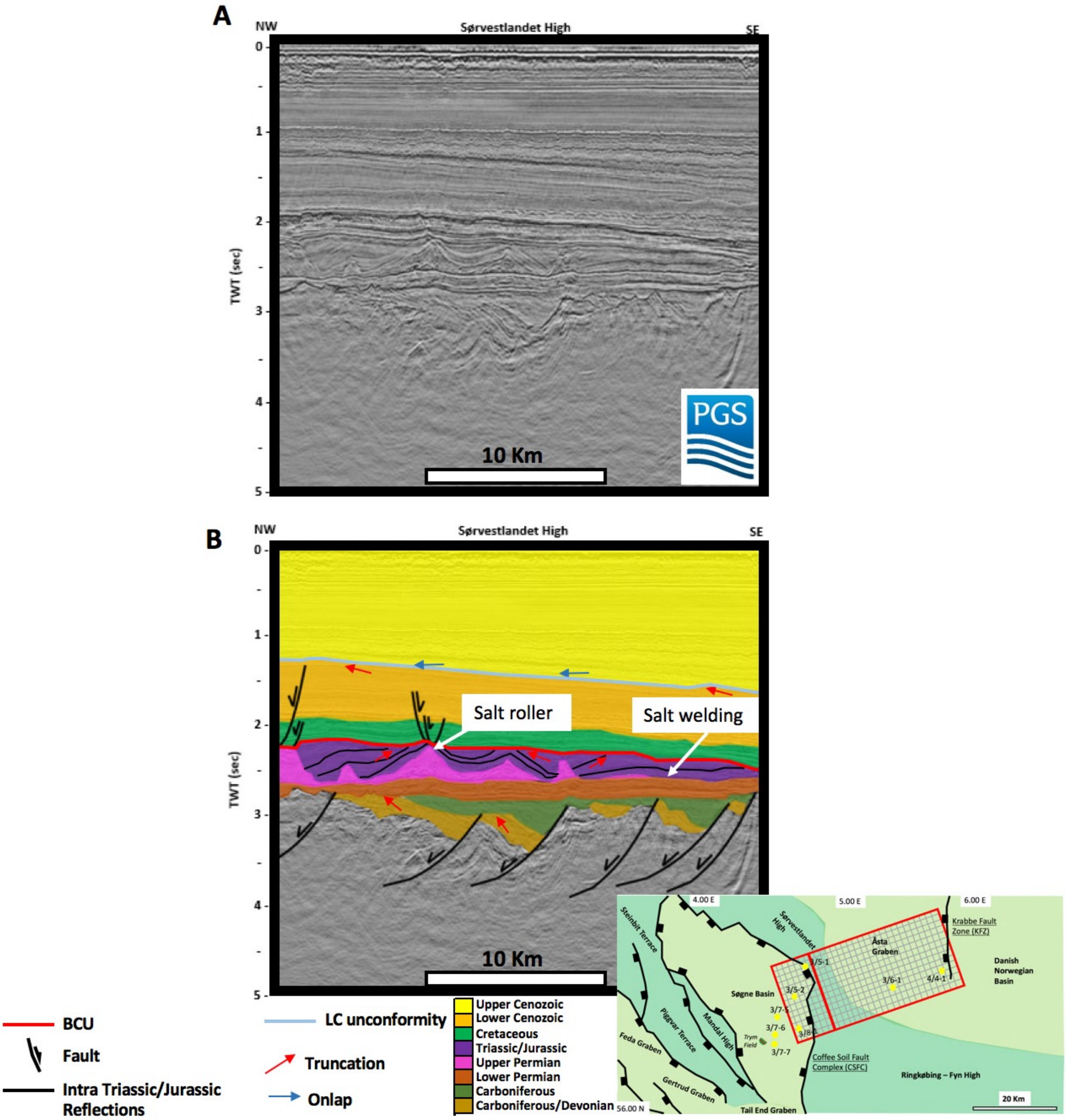


Figure 24: (A) Uninterpreted northwest-southeast three-dimensional seismic line of Sørvestlandet High (B) Interpreted northwest-southeast three-dimensional seismic line. Main faults interpreted in this line are fault families 2 and 8, where fault family 2 forms clear half grabens in the sub-Permian. Clear truncations of the Devonian, Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt welding and salt roller.

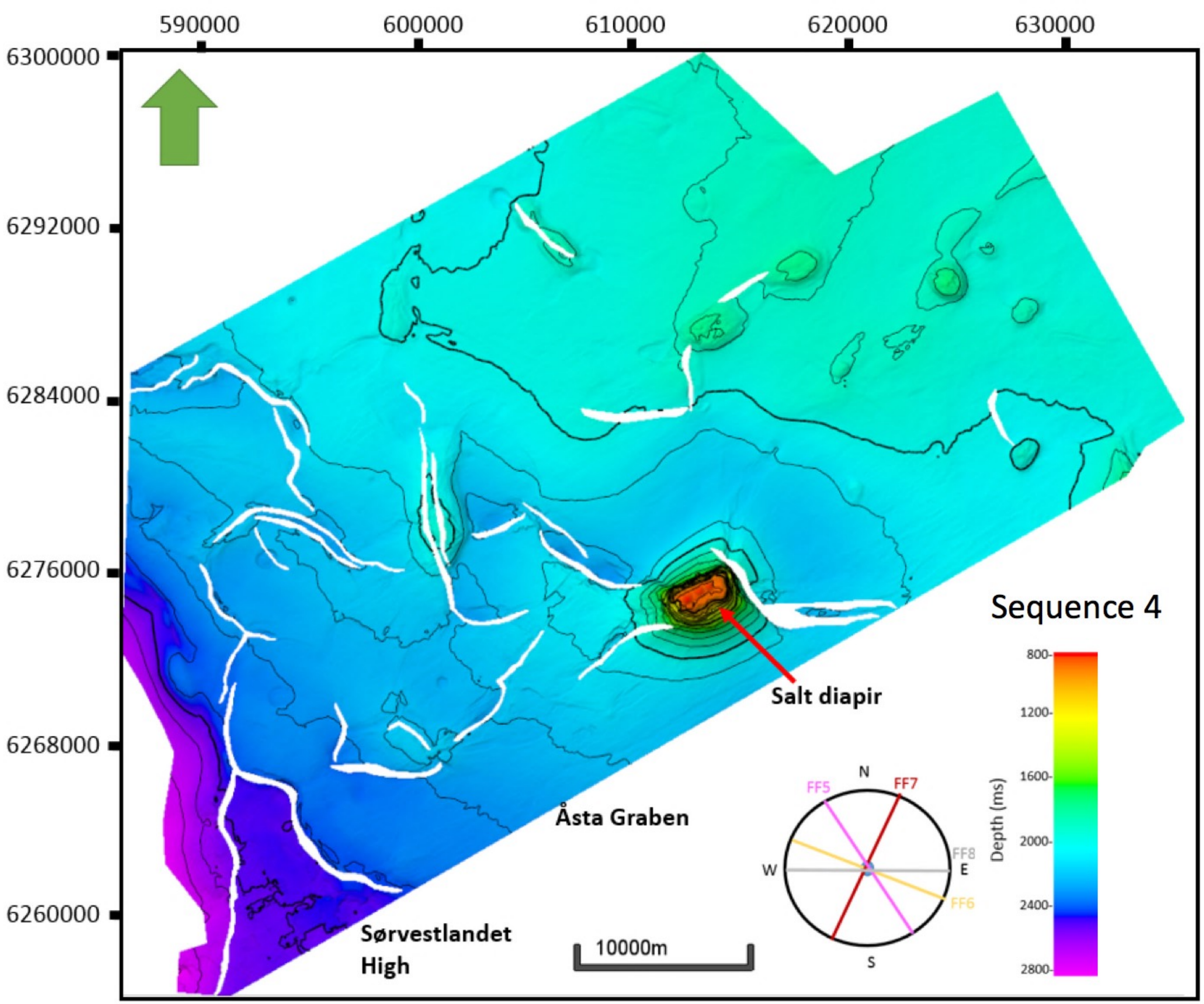


Figure 25: Structural Time Map (TWT) of Top Triassic/Jurassic (Sequence 4) with the last four defined supra-salt fault families

Basement

Seismic character

The top of the Basement shows weak downwards acoustic impedance in the areas where the basement is overlain by Sequence 1.1 and 1.2, while a stronger downwards acoustic impedance in the areas where the basement is overlain by Sequence 3. The top of the basement is identified with a weak through in the areas where it is overlain by Sequence 1.1 and 1.2, while a stronger through in areas overlain by Sequence 2. The pick of the basement is considered low to medium confidence, and particularly in the areas where the basement is covered by Sequence 1.1 and 1.2. The basement consists of mainly SF1, chaotic, discontinuous, low amplitude and low frequency, but might show slightly stronger intrabasement reflections. None of the wells have penetrated the basement, therefore the pick confidence of the basement is low.

Time structural and thickness map

The time structural map shows that the highest point of the basement is 2600 ms and the lowest point is 4000 ms. The highest areas of the basement are in the western part of the study area, while becoming lower eastwards towards the Åsta Graben. The deepest part of the basement is in the northeast part of the Åsta Graben. Fault families affecting the basement are sub-salt faults FF1, FF2, FF3, and FF4.

There are three synclines in the basement, the first one in the northwestern part of the Åsta Graben, with a total depth of 4200 ms. The second one is in the middle of the Sørvestlandet High with a depth of 3600 ms and, the last one in the southern part of the Sørvestlandet High with a total depth of 3300 ms. All these three synclines appear to be bounded by FF1. There is one major anticline like feature marked as salt diapir, which is just a side effect of the velocity pullup caused by the salt diapirs in Sequence 3.

Sequence 1.1 - Devonian

Seismic character

The top of the Devonian is identified with a medium strong downward acoustic impedance (through) that is clearer in some areas, while in other areas where Sequence 1.2 is present the impedance seems to be weaker. The pick of this sequence (both base and top) is of low to medium confidence. This sequence consists mainly of SF 2, with SF 3 at some parts, mostly sub-parallel, semi-continuous and high amplitude with low frequency (Figure 26). No wells in this area have penetrated the Devonian, making the interpretation confidence even lower. The reflections seem to be dipping upwards towards NE where some truncations are seen. These truncations are more evident in the south-easternmost of the Sørvestlandet High. These truncated reflections truncate towards both, the base of Sequence 3 and Sequence 1.2. No growth strata were observed in this sequence.

Time structural and thickness map

The time structural map shows that the highest point of Sequence 1.2 is 2500 ms and the lowest point is 3300 ms. This sequence is found on the Sørvestlandet High, and missing in the Åsta Graben and Søgne Basin (Figure 27). The trend of this sequence is N-S and mainly found in the synclines of the basement. This sequence is more widely distributed in the north part of the Sørvestlandet High. This sequence appears to be divided into portions. The southern "portion" of this sequence is dipping towards the north, into the deeper parts of the basement, while the northern portion dips towards the south to into the deeper parts basement. The dip of the sequence is gentler on the northernmost of the northern portion and the southern part of the southern portion, unlike the northern part of the southern portion and the southern part of the northern portion, that has a high dip angle (Figure 28). The main affecting faults in this sequence are FF2 and FF3. The time thickness map shows that the thinnest parts of this sequence (100-250 ms) is located on the higher elevations, while the main depocenter, with a thickness of 350-500 ms, is plunging into the basement controlled synclines that are beneath it.

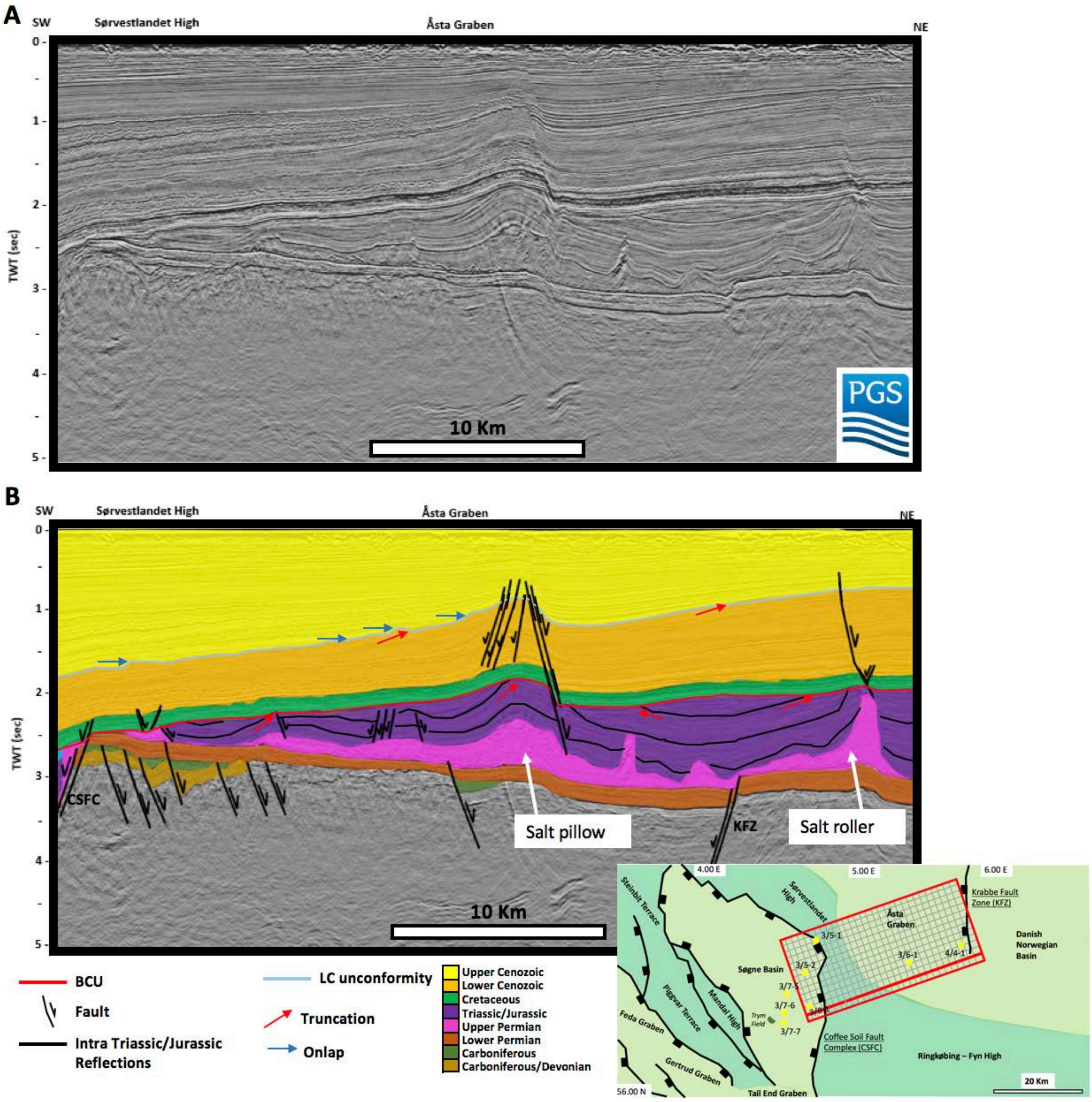


Figure 26: (A) Uninterpreted southwest-northeast three-dimensional seismic line of Sørvestlandet High and Åsta Graben (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 3, 4, 6 and 8. Clear truncations of the Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt roller and salt welding.

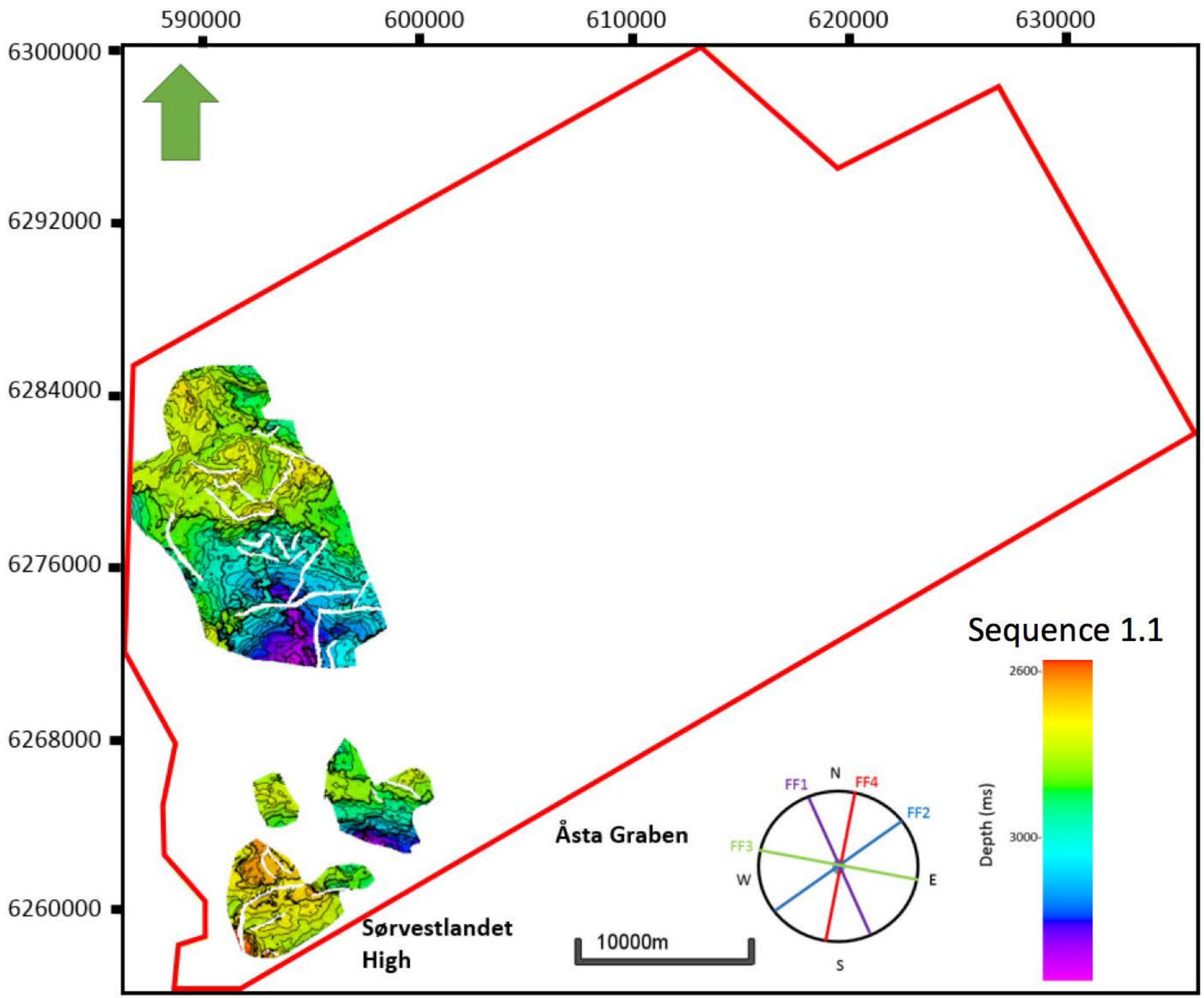


Figure 27: Structural Time Map (TWT) of Top Devonian (Sequence 1.1) with the fault family 1,2 and 3

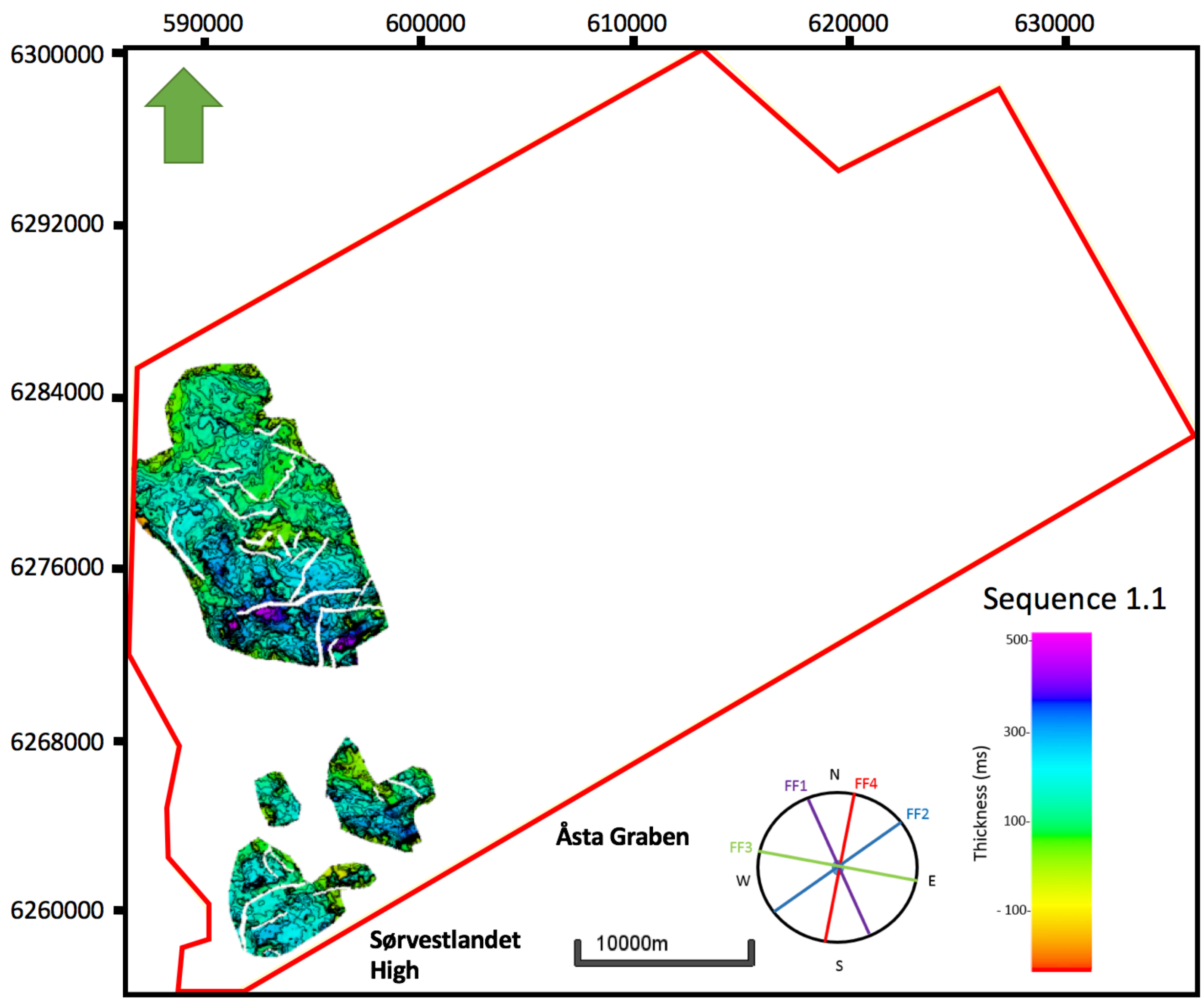


Figure 28: Time Thickness Map (TWT) of Top Devonian (Sequence 1.1) with the fault family 1,2 and 3

Sequence 1.2 - Carboniferous

Seismic character

The top of the Carboniferous is defined as a strong downward increase in impedance (through). The impedance contrast from Sequence 2 to the Carboniferous is strong, which gives a medium-high confidence pick (Figure 29). No wells have drilled the Carboniferous in the study area; therefore, the pick confidence is even lower. Carboniferous consists of mainly SF 3, chaotic, discontinuous low amplitude and frequency. The Carboniferous seems to fill in space above the half grabens. However, FF3 and FF4 is displacing this southwest.

Time structural and thickness map

The time structural map shows that the Carboniferous is more widely distributed compared to the Devonian, found in the Sørvestlandet High and the western Åsta Graben. The deepest part of the Carboniferous is in the northwestern Åsta Graben. Most of the faults that control the Carboniferous are in the westernmost part of the sequence, in the western Sørvestlandet High (Figure 30). The highest points of the Carboniferous are in the southwestern part of the Sørvestlandet High with a maximum elevation of 2800 ms, while the deepest point of this sequence is in the northeast, in the Åsta Graben with an elevation of 3400 ms. The general dip of this sequence appears to be towards the ENE, dipping from the Sørvestlandet High and into the Åsta Graben.

The time thickness map shows that the Carboniferous has three depocenters, in the southern part of the Sørvestlandet, in the central part of the Sørvestlandet High and the northeastern part of the Åsta Graben. The main depocenter of the Carboniferous is in the central part of the Sørvestlandet High, with a diameter of approximately 7 Km (Figure 31). This depocenter is plunging into the Devonian depocenter. In general, these depocenters are about 550-700 ms, while the thinner parts, the flanks, are about 50-100 ms.

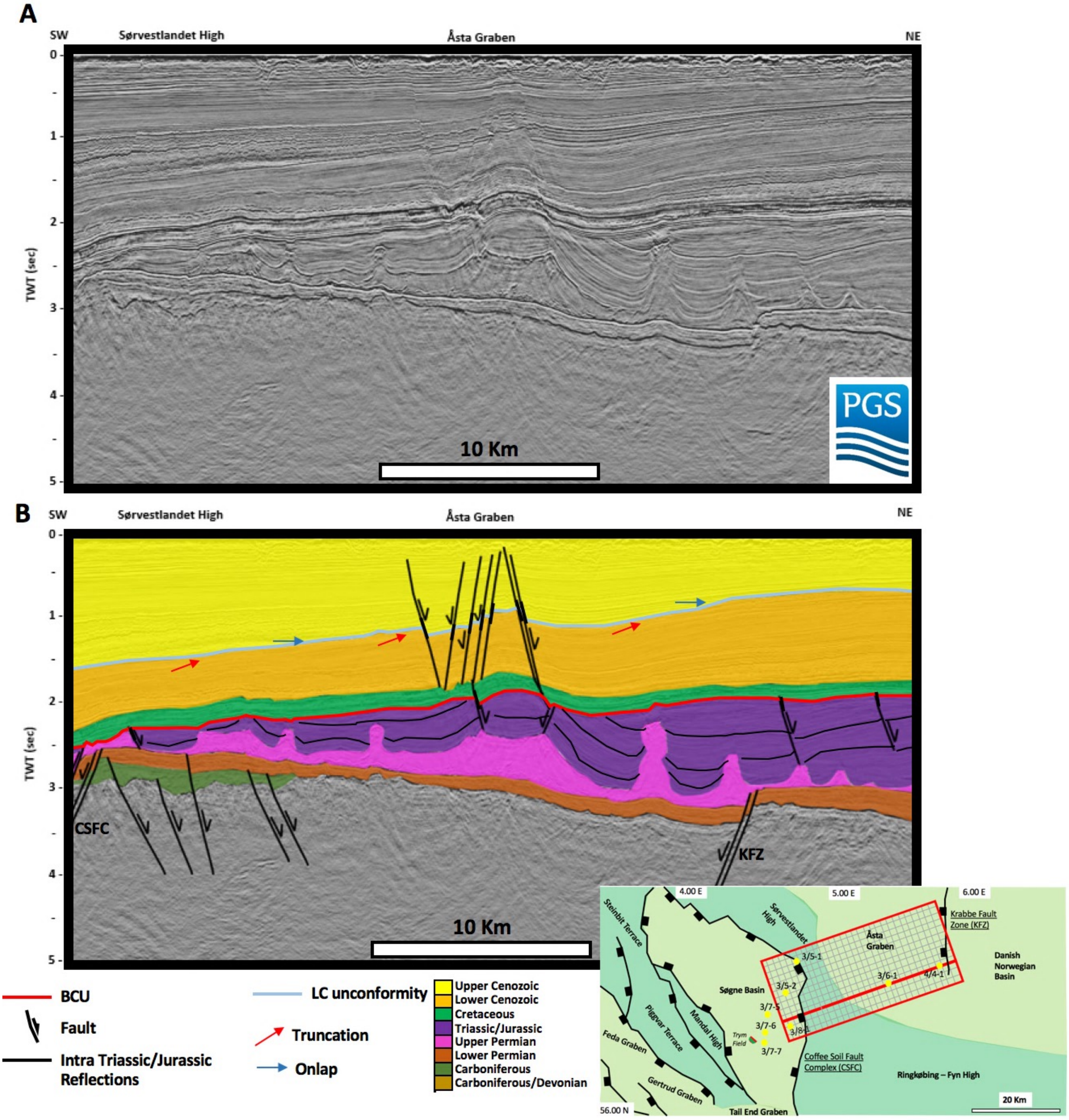


Figure 29:(A) Uninterpreted southwest-northeast three-dimensional seismic line of Sørvestlandet High and Åsta Graben (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 3, 4, and 6. Clear truncations of the Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt pillow, salt roller, and mushroom salt domes.

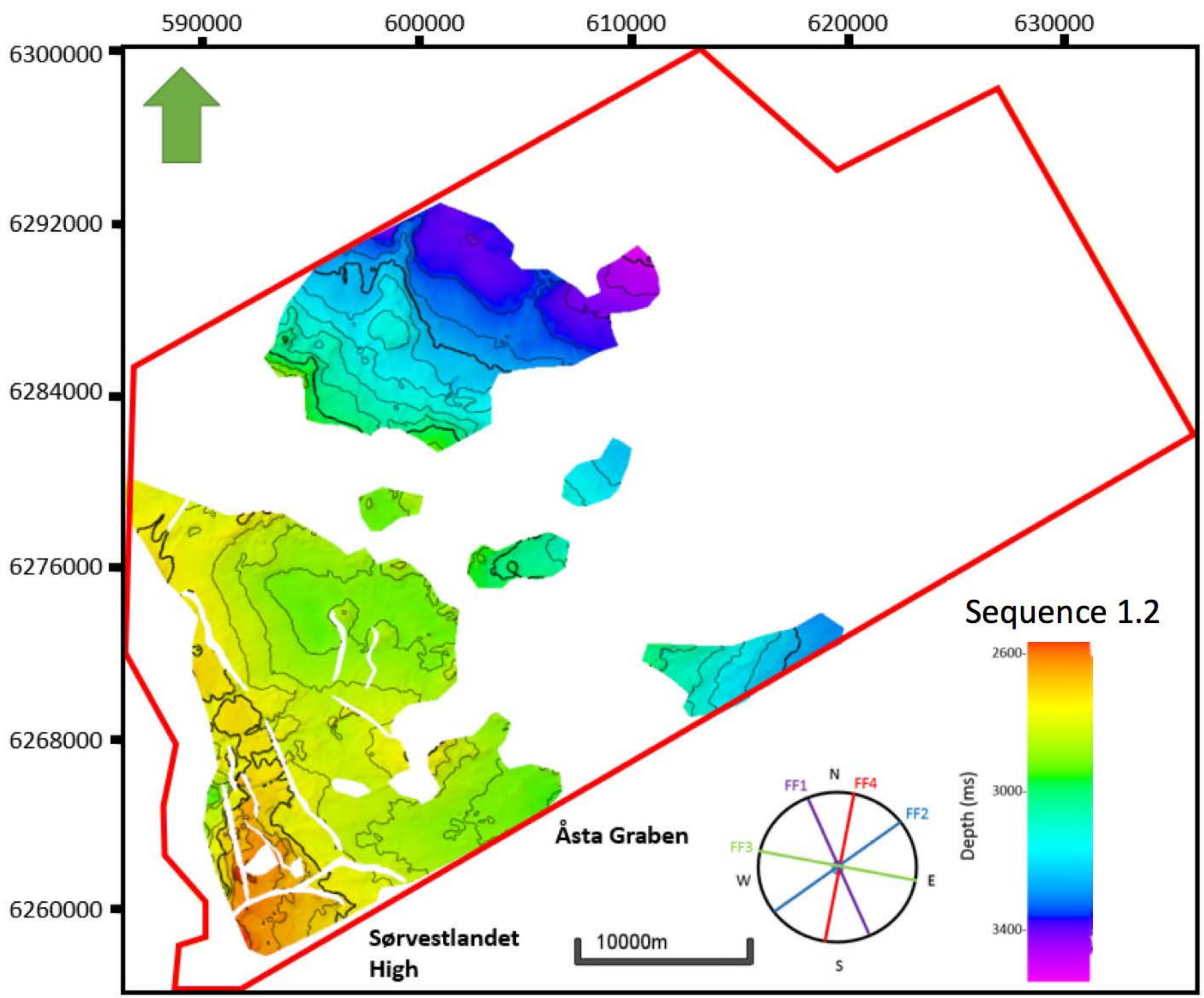


Figure 30: Structural Time Map (TWT) of Top Carboniferous (Sequence 1.2) with fault family 1 and 2

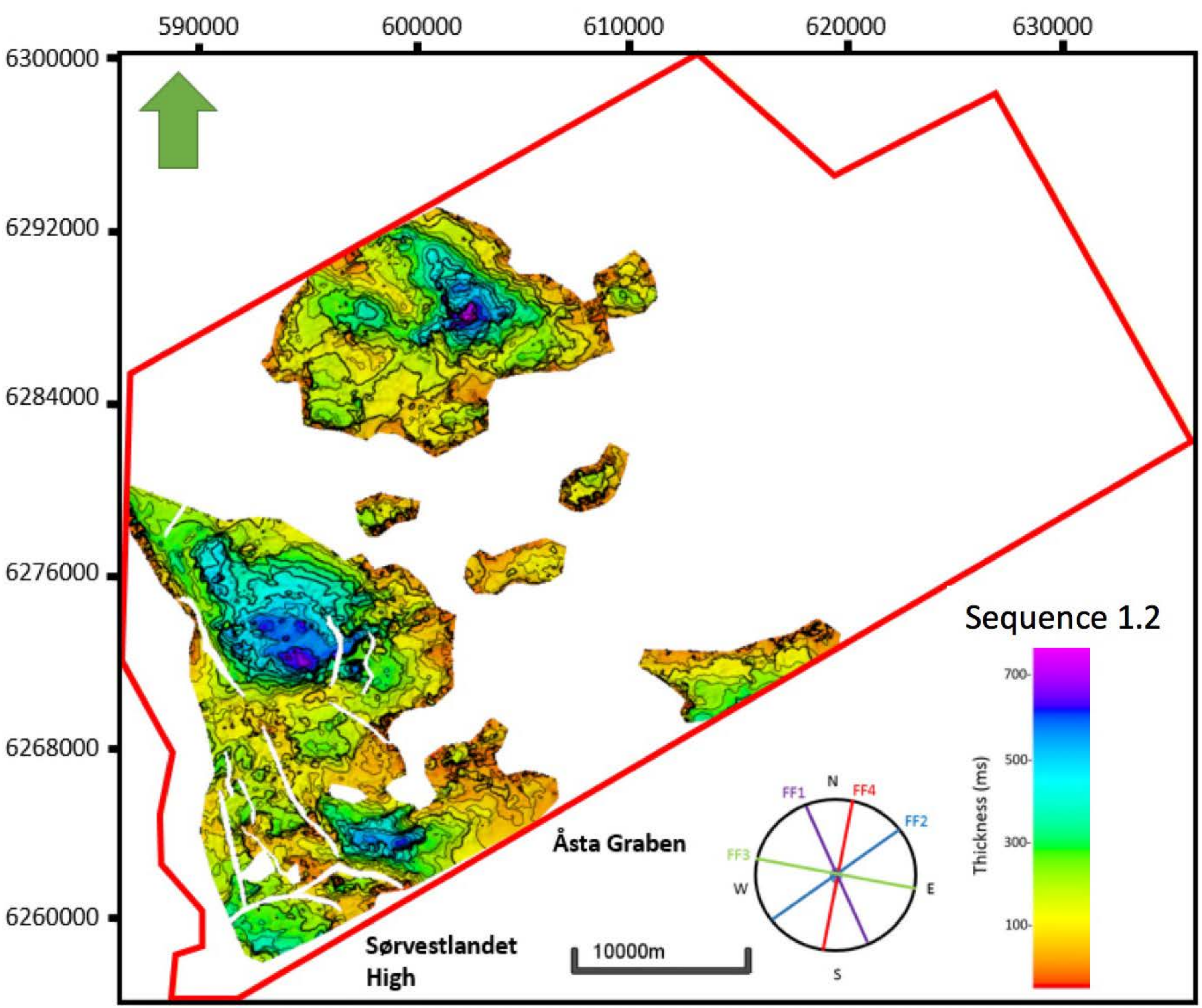


Figure 31: Time Thickness Map (TWT) of Top Carboniferous (Sequence 1.2) with fault family 1 and 2

Sequence 2 – Lower Permian Roteliegend Group

Well character

The Lower Permian was encountered in well 3/8-1 only, where the thickness was 50 m (Figure 21). The GR response of this sequence shows low values with maximum 40 gAPI and a very homogenous and blocky GR. The average density value is 2.5-2.6 g/cm3 signifying a sandier unit. The resistivity values are low, with a mean value of 2 ohm.m, which could be due to the unit not being highly compacted. The sonic readings of this sequence show a higher reading, compared to the later Sequence 3.

Seismic character

The top of the Roteliegend was picked on a through, a strong downward increase in acoustic impedance, and there for a very high interpretation confidence throughout the whole study area. Even though the well that drilled the Lower Permian was drilled in the Søgne Basin, correlating it to the Sørvestlandet High was done with high confidence because of the strong reflection that was recognizable (Figure 32). The Roteliegend consists of mainly SF 4, a chaotic to sub chaotic, continuous, and high to medium and medium frequency seismic body. The Roteliegend seems to have a constant thickness in the entire study area, and only the Coffee Soil Fault Complex and Krabbe Fault Zone is displacing this sequence.

Time structural and thickness map

The time structural map shows that the Lower Permian is widely distributed over the entire study area. The highest points of the Lower Permian are located along the Sørvestlandet High and dipping down into the northeastern Åsta Graben. The highest points of this sequence are 2500 ms in the southwestern Sørvestlandet High, while the deepest part of the Lower Permian is in the northeastern Åsta Graben with a depth of 3500 ms. The main faults controlling this sequence are FF4, including the Coffee Soil Fault Complex and the Krabbe Fault Zone as mentioned earlier (Figure 33). The throws seem to be more prominent in the Krabbe Fault Zone where the elevation of the footwall is 3100 ms compared to the adjacent hangingwall at 3500 ms. Also, in the time structural map of the Lower Permian, many anticline like features are observed, but these are not “real” as they are only an effect of the velocity pullup induced by the salt.

The time thickness map shows little thickness variation in the Lower Permian. The overall thickness is 400 ms, but some depocenters are observed in the northeastern Åsta Graben and the Sørvestlandet High with a thickness of 600 ms (Figure 34). These depocenters seem to follow the structural relief of the previous sequences. There is also a red part with negative thickness, which is just an algorithm problem due to the velocity pullup that is caused by the salt.

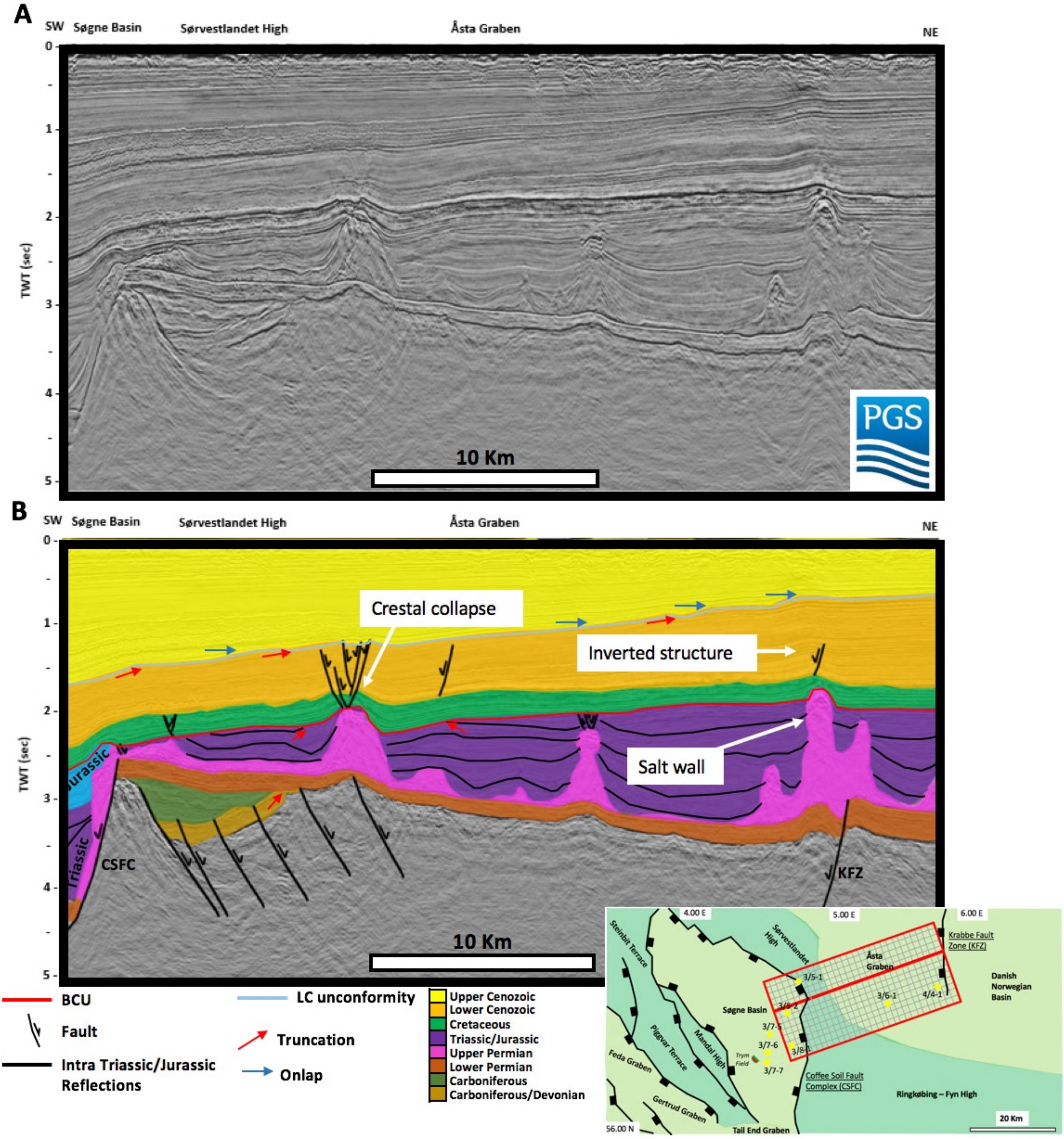


Figure 32: (A) Uninterpreted southwest-northeast three-dimensional seismic line of the Søgne Basin, Sørvestlandet High and Åsta Graben (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 3, 4, and 6. Clear truncations of the Devonian, Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt walls. Also, inverted structure and crestal collapse are observed in this section.

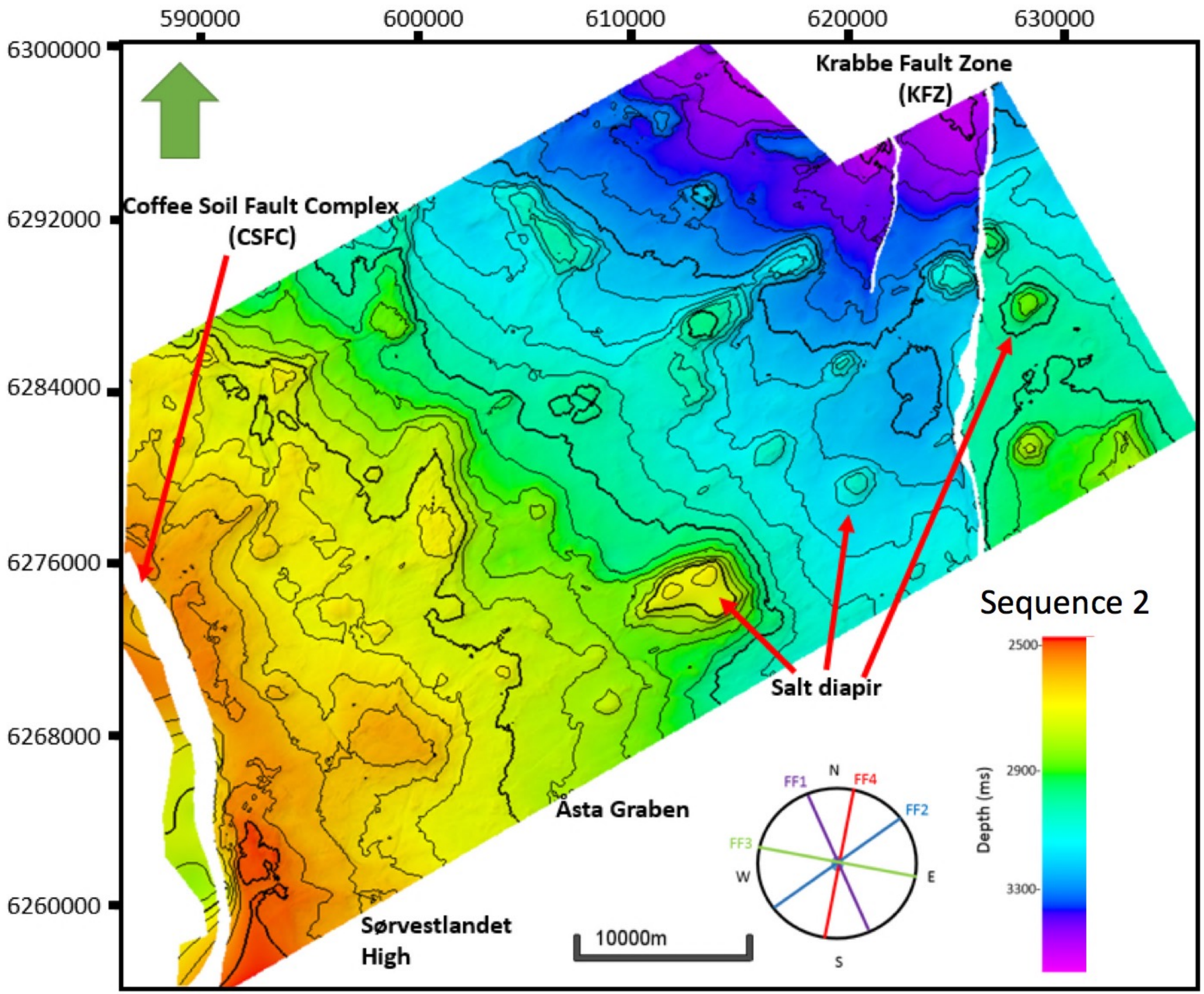


Figure 33: Structural Time Map (TWT) of Top Lower Permian (Sequence 2) with fault family 4

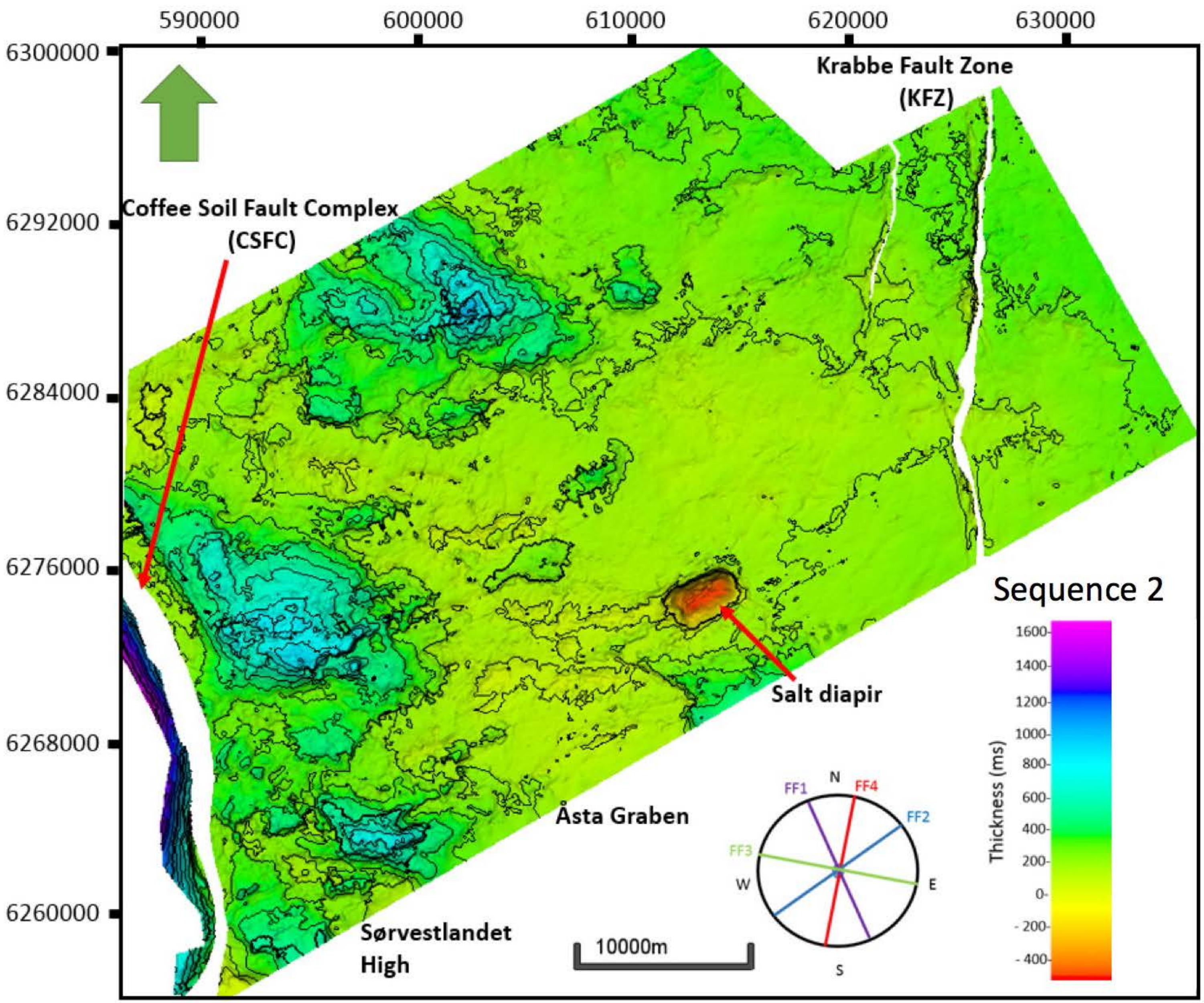


Figure 34: Time Thickness Map (TWT) of Top Lower Permian (Sequence 2) with fault family 4

Sequence 3 – Upper Permian Zechstein Group

Well character

The sequence is only found in well 3/8-1 where the thickness was 460 m. The GR response of this unit can be divided in two, the lower half showing spikes of high gamma ray readings, and the upper part showing very low GR readings. The spikes high readings observed are due to high content of potassium salt, and the low readings are due to the high amount of the halite (Figure 21). The density readings are higher for the lower most of this unit but then decreases when moving into the halite (the upper part of the sequence). The resistivity increases when moving from the lower part to the upper part of the sequence, and this is because the halite has much higher resistivity than the potassium salt. In general, the halite has the highest resistivity in the entire log compared to all the sequences. However, the sonic log shows lower reading in the lower section of the sequence, compared to the upper section.

Seismic character

The top of Zechstein is picked at a through, a major increase in downward acoustic impedance. The through is clearer on the synthetic than in the seismic. The seismic vertical sections show that there are different salt structures formed after the halokinetic movements, structures such as mushroom salt diapirs, salt pillow, and massive salt walls (Figure 35). The top of the salt structures seems to give stronger reflection rather on the adjacent mini-basins. The interpretation of the flanks of the salt bodies is difficult due to the velocity pullups, the high reflection dip and the deformation of the surrounding formations (Figure 36). The pick confidence of the salt is medium in smaller scale, but high regionally. Zechstein salt body consists of SF5 chaotic, discontinuous and low amplitude and frequency.

Time structural and thickness map

The time structural map shows that the Upper Permian salt is distributed in the entire study area, dipping towards the northeastern Åsta Graben, from the southeastern Sørvestlandet High. The highest elevations of the base without the high salt structures are 2450 ms, and the deepest elevations are 3500. It appears that the massive salt walls are more concentrated on the northern and northwestern part of the study area, while the less massive salt diapirs are in the eastern and southeastern part of the study area (Figure 37). The general strike of the salt walls is north-south or east-west. Some of the salt diapirs reach even 1200 ms, but the average reaching point for the diapirs are 2000 ms. The longest salt wall has a length of 8-9 km and a width of 3-4 km.

The time thickness map shows that the average thickness of the Upper Permian is less than 100 ms, but then having thicknesses of around 1250 ms in the diapirs and the salt walls on the northeastern part of the study area. The western salt walls seem to have thicknesses of 600-700 ms (Figure 38).

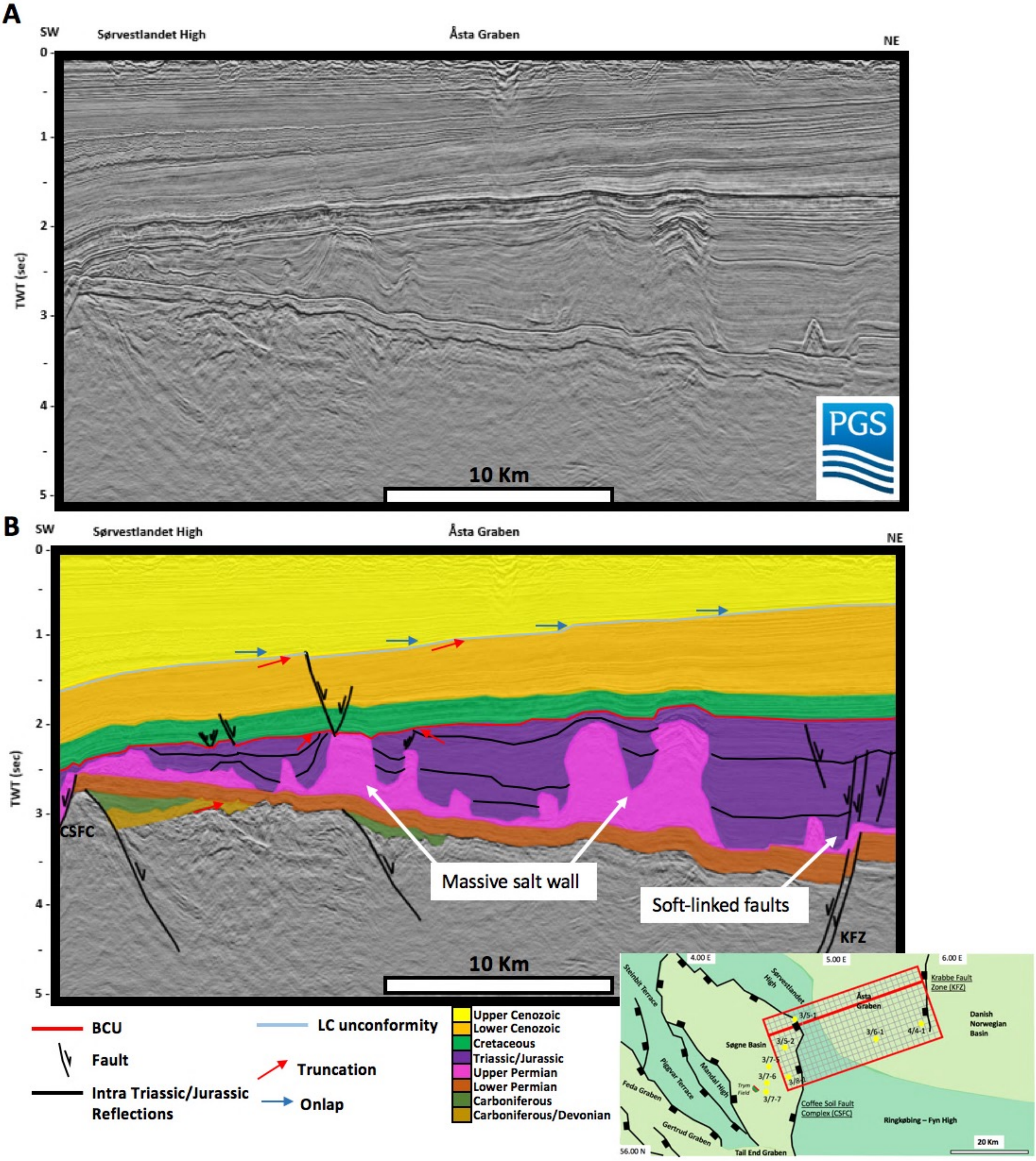


Figure 35: (A) Uninterpreted southwest-northeast three-dimensional seismic line of the Sørvestlandet High and Åsta Graben (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 3, 4, 5 and 7. Soft linkage between the sub-salt and supra-salt faults are observed. Clear truncations of the Devonian, Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like massive salt walls.

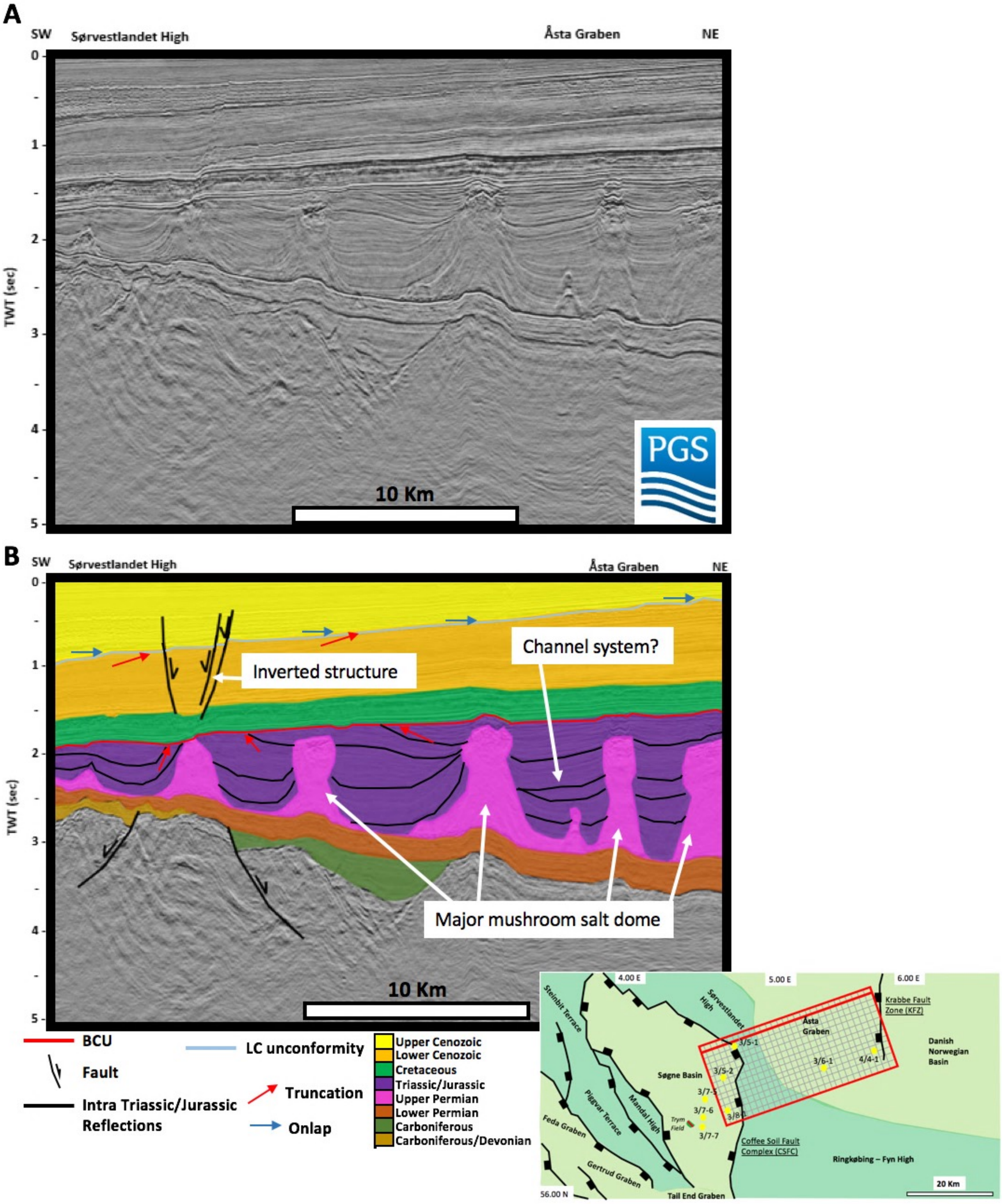


Figure 36: (A) Uninterpreted southwest-northeast three-dimensional seismic line of the Sørvestlandet High and Åsta Graben (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 3, and 7. Clear truncations of the Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like massive mushroom salt domes. Inverted structure is also observed here.

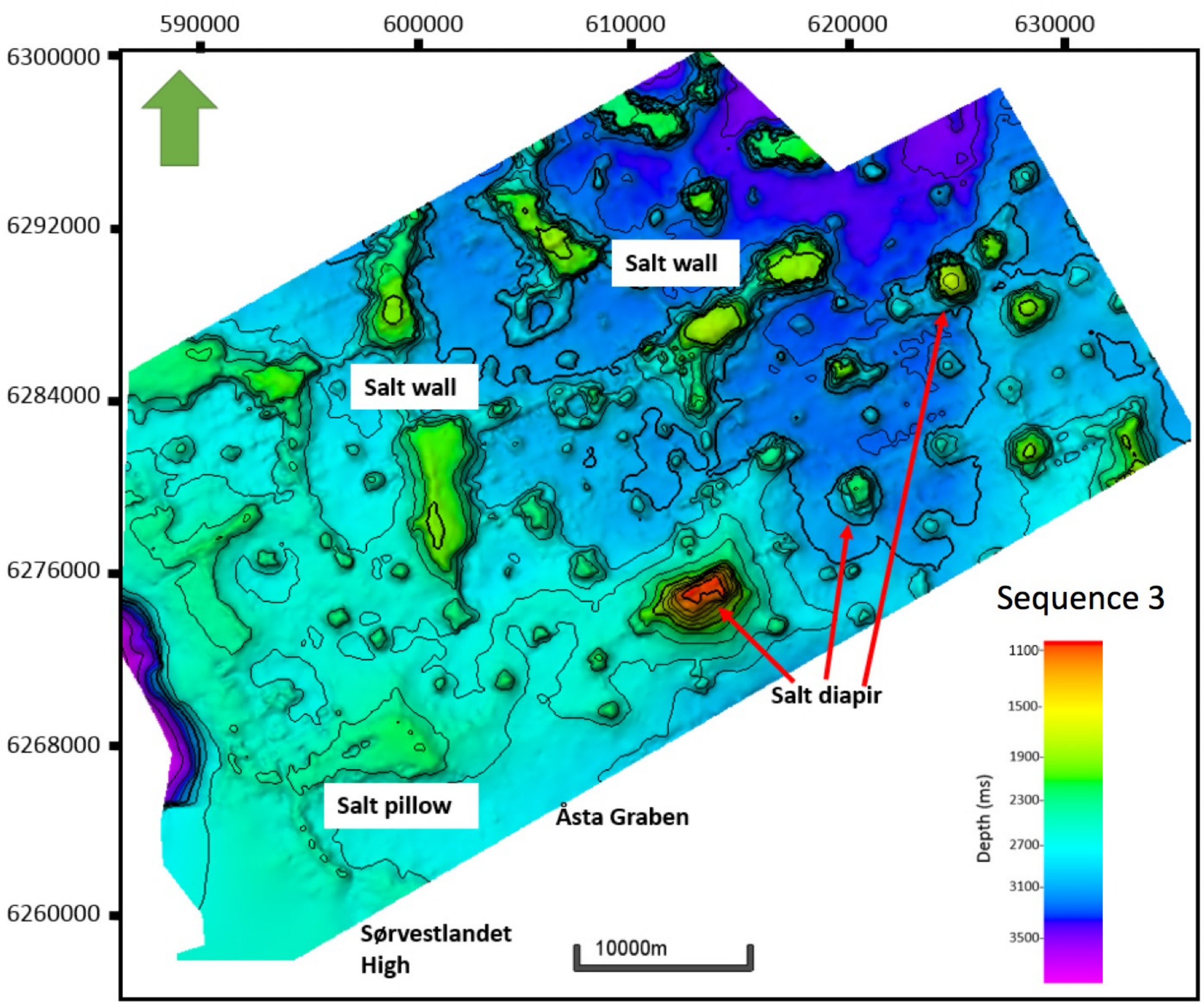


Figure 37: Structural Time Map (TWT) of Top Upper Permian (Sequence 3) showing some of the main salt structures including salt wall, salt pillow and salt diapir

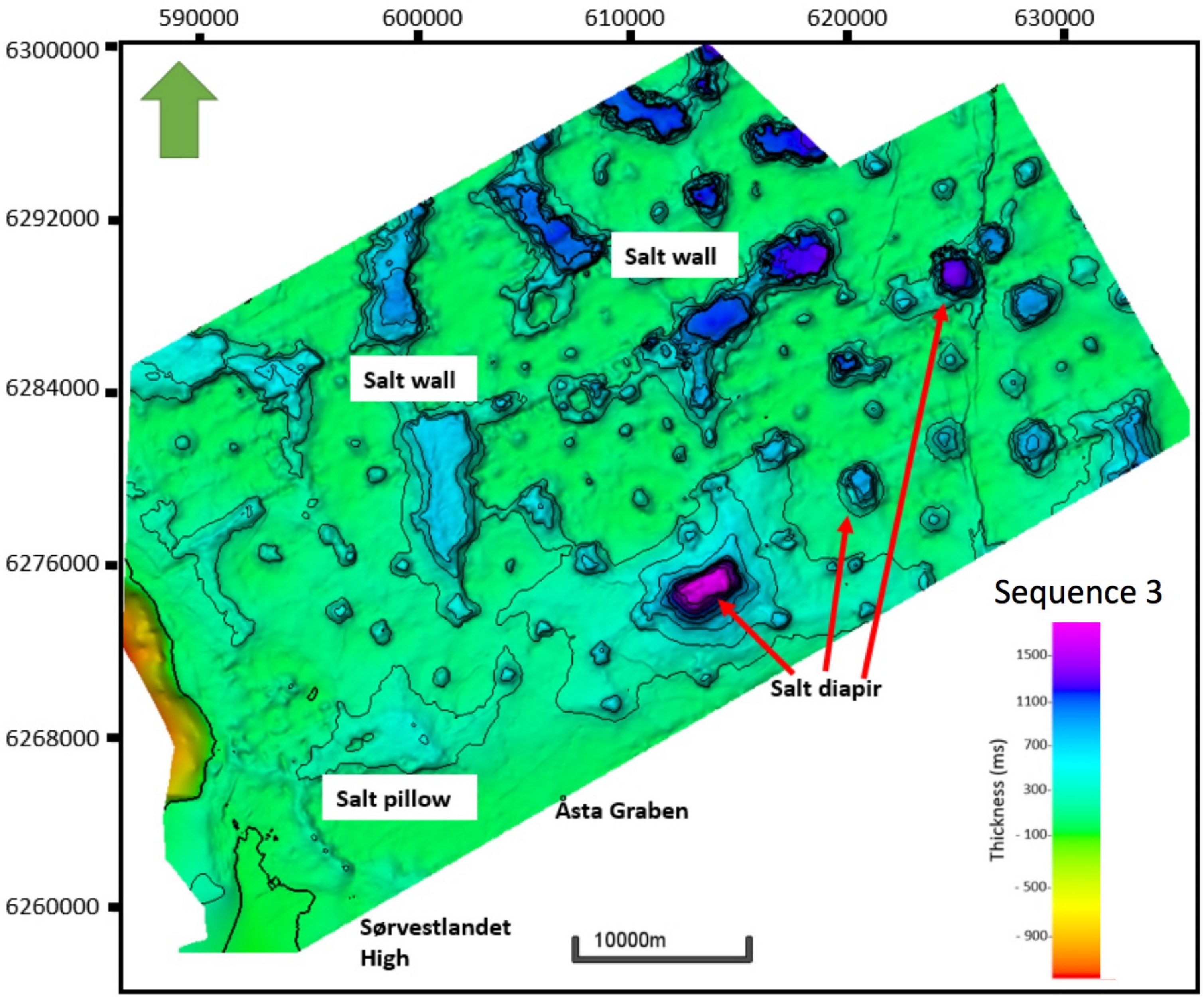


Figure 38: Time Thickness Map (TWT) of Top Upper Permian (Sequence 3) showing some of the main salt structures including salt wall, salt pillow and salt diapir

Sequence 4 – Triassic/Jurassic

Well character

No well has penetrated the Triassic, and therefore only well characters of the Jurassic will be observed here. Two wells penetrated the Jurassic, well 3/5-2 and 3/8-1. The Jurassic is thinning towards the east, since well 3/5-2 shows a thickness of 684 m, while 3/8-1 shows a thickness of 274 m. The GR response of this sequence is very high and blocky because it is a fine-grained homogenous sequence. Compared to Sequence 3, the density increases when entering Sequence 4, while the resistivity decreases. The sonic log shows a slight increase when moving from the previous sequence to this one (Figure 21).

Seismic character

The top of this sequence has been picked on a strong through, a strong downward increase in the acoustic impedance. The top of this sequence is the BCU, which is a regional unconformity throughout the whole study area that is characterized by truncations of the intra Triassic/Jurassic reflections, Zechstein salt, and Roteliegend. The truncations are easily seen on the crest of the Sørvestlandet High footwall (Figure 39). Well 3/8-1 drilled the Jurassic in the Søgne Basin, but as the top reflections are more parallel on the basin setting, interpreting the Triassic and Jurassic as two separate sequences on the Sørvestlandet High is very challenging. The pick of the BCU is with high confidence throughout the entire study area. The body of this sequence consists of mainly SF6, with SF2 in some areas, but mainly parallel, continuous low amplitude and frequency in general, with some strong sub-parallel internal reflections. The whole Triassic/Jurassic sequence seems to be pinching out from eastern Åsta Graben towards western Sørvestlandet High.

Time structural and thickness map

The time structural map shows that the Triassic/Jurassic is distributed in the entire study area, the Søgne Basin, Sørvestlandet High and the Åsta Graben. The sequence seems to dip downwards towards CSFC and the Søgne Basin from the northeastern Åsta Graben. The highest elevations are around 1700 ms and the lowest elevations, found in the Søgne Basin, is 2600 ms. The two main fault families that seems to affect the Triassic/Jurassic is the FF6 and FF7.

The time thickness map shows that the average thickness of the sequence in the northeastern Åsta Graben is 1400 ms. The average thickness reduces when moving towards the

Sørvestlandet High, with some minor erosion on the southwestern Sørvestlandet High (marked as red "negative thickness" in the time thickness map). The average thickness of the sequence in the western part of the Åsta Graben and the Sørvestlandet High is 200-400 ms (Figure 40). The thinnest parts of this sequence are above the salt walls and diapirs where the thicknesses are less than 100 ms, and it seems that the thinnest parts of the sequence are always adjacent to the faults, furthermore it appears like the faults are following the trends of the salt walls and diapirs.

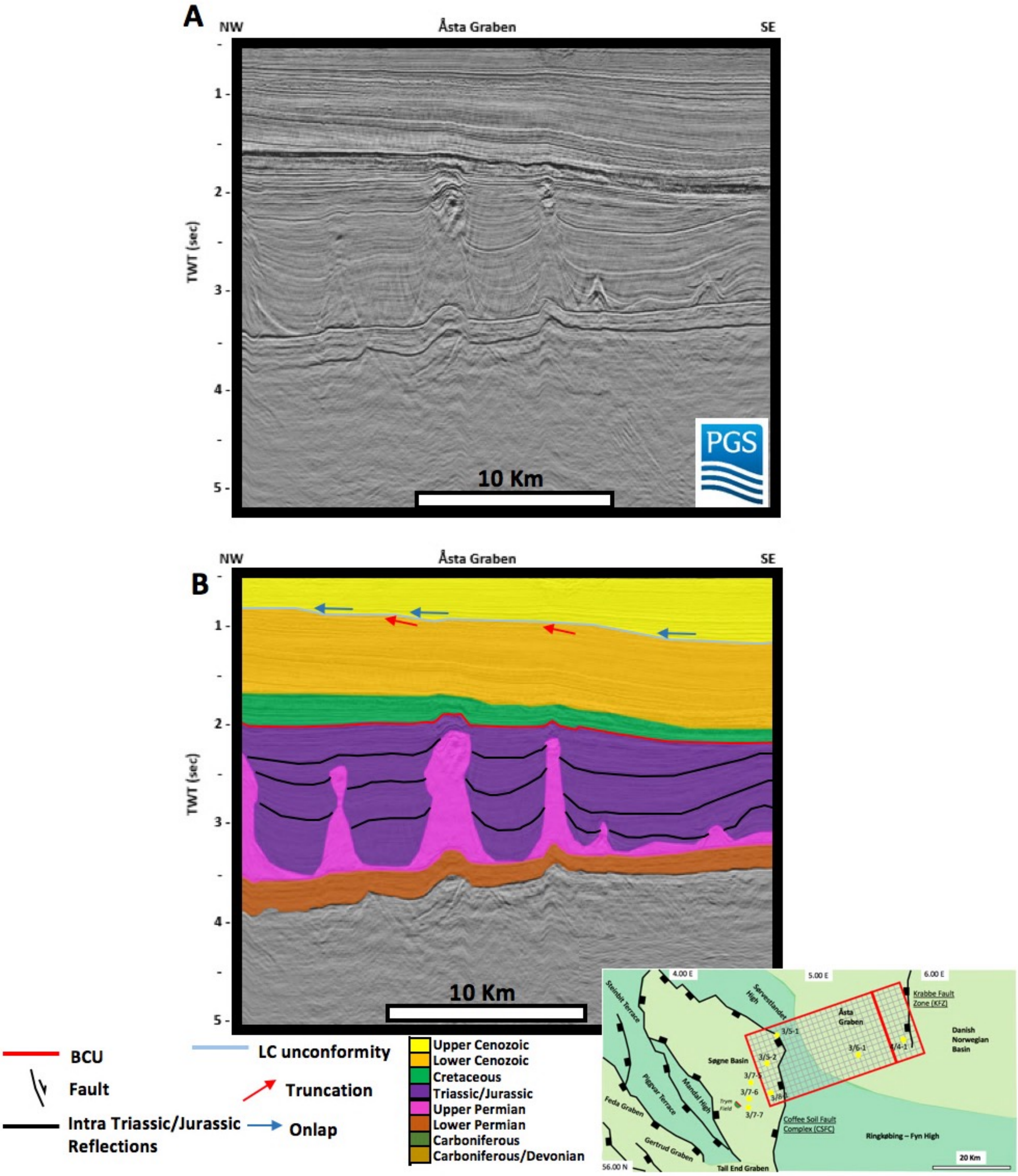


Figure 39: (A) Uninterpreted northwest-southeast three-dimensional seismic line of Åsta Graben (B) Interpreted northwest-southeast three-dimensional seismic line. Clear truncations and onlaps on the Top Lower Cenozoic is observed here.

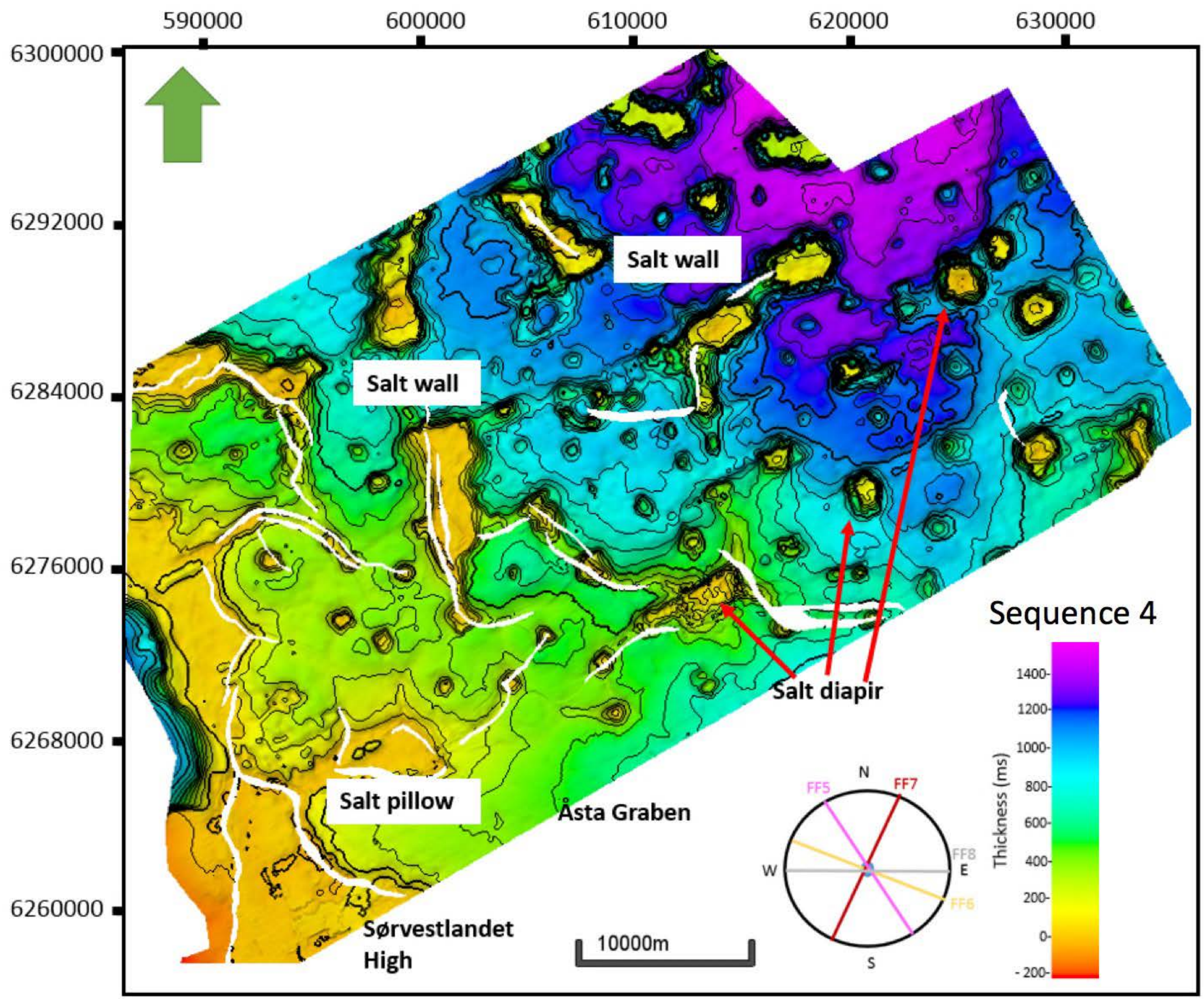


Figure 40: Time Thickness Map (TWT) of Top Triassic/Jurassic (Sequence 4) with the four last defined supra-salt fault families

Sequence 5 – Cretaceous

Well character

All wells drilled the Cretaceous, except for 3/5-1 only reaching the Cenozoic. Well 3/6-1 and 4/4-1 drilled only the upper part of the Cretaceous, approximately 50 m down into the sequence. The rest of the wells has the Cretaceous varying in thickness between 500 m to 1200 m. The thickest part of Sequence 5 is observed in Søgne Basin. The two wells that drilled only 50 m into the Cretaceous are the ones on the Åsta Graben, a therefor determining a thickness of the Cretaceous here in this area is challenging. The wells that drilled the entire Cretaceous has a GR response with two different characters. The lower most of the Cretaceous shows a high GR reading, while the upper part shows a low GR reading, this is due to the more clastic dominated lower section, though more calcareous and chalky dominated upper section (Figure 21). The density readings seem to be constant throughout the entire Cretaceous sequence, whereas the sonic decreases and the resistivity increase when moving from the lower to the upper section of the Cretaceous.

Seismic character

The top of this sequence is identified as a strong downward increase in the acoustic impedance, a strong through. This sequence is picked over the entire study area, and because of the strong response to the impedance and the strong through, the pick of this sequence is with very high confidence. The main seismic facies of this sequence are SF7, parallel, continuous, high amplitude and low frequency. The upper part of this sequence appears to have a lower frequency than the lower part. The internal reflections of this sequence dips slightly downwards towards west (Figure 41), therefor this is the first sequence that covers the Sørvestlandet High on the crest of the Sørvestlandet footwall where the Triassic/Jurassic is absent. The thickness of this sequence appears to be constant throughout the entire study area, except for some local variation on the Søgne Basin.

Time structural and thickness map

The time structural map shows that the surface has the highest point in the northeastern Åsta Graben plunging downwards towards the west and into the Søgne Basin. The highest elevation of the surface is 1500 ms and descending to 2400 ms in the west. The main faults affecting this sequence are FF6 and FF7, where the FF7 seems to follow an SW-NE pattern, cutting the NW-SE trending FF6 pattern in half (Figure 42). The red dome-like shape is just an artifact due to the velocity pullup.

The time thickness map shows that the northern part is the thickest with an average thickness of 400 ms, thinning towards the south with the thinnest part having an average thickness of 200 ms. Also, it appears that some of the thinnest parts of this sequence are adjacent to the faults (Figure 43). FF6 on the northwestern Åsta Graben seem to form a mini graben, providing this mini graben a thickness of 350 ms. There are some round and elongated thickness anomalies, in the central and northern part of the study area, which is due to the salt domes and walls being right underneath the surface, creating these thin parts in the Cretaceous.

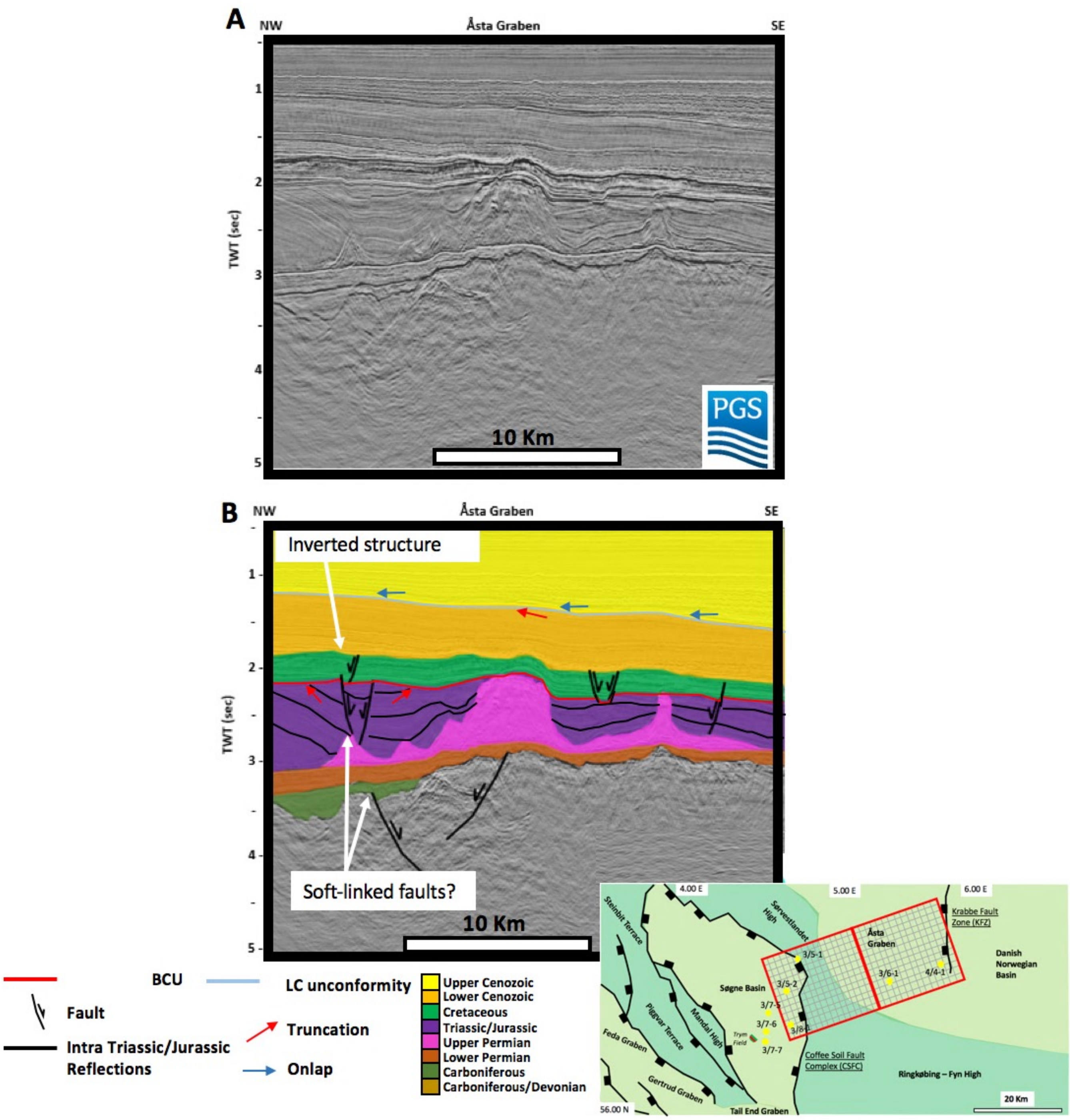


Figure 41: (A) Uninterpreted northwest-southeast three-dimensional seismic line of Åsta Graben (B) Interpreted northwest-southeast three-dimensional seismic line. Main faults interpreted in this line are fault families 2, 3, 6 and 8. Clear truncations of the Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt walls. Inverted structure and soft – linkage between sub-salt and supra-salt fault are also interpreted.

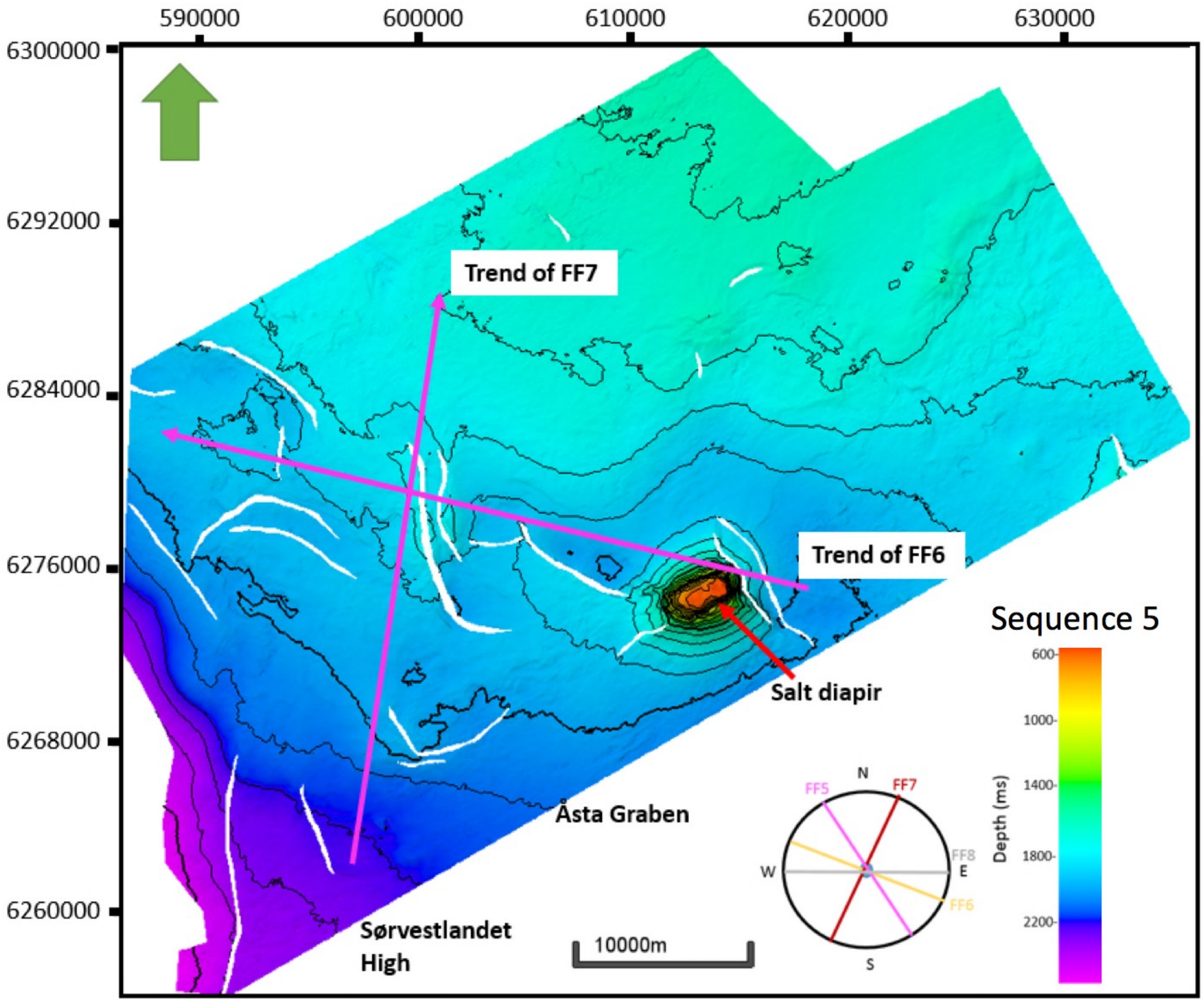


Figure 42: Structural Time Map (TWT) of Top Cretaceous (Sequence 5) mainly affected by fault family 5 and 7

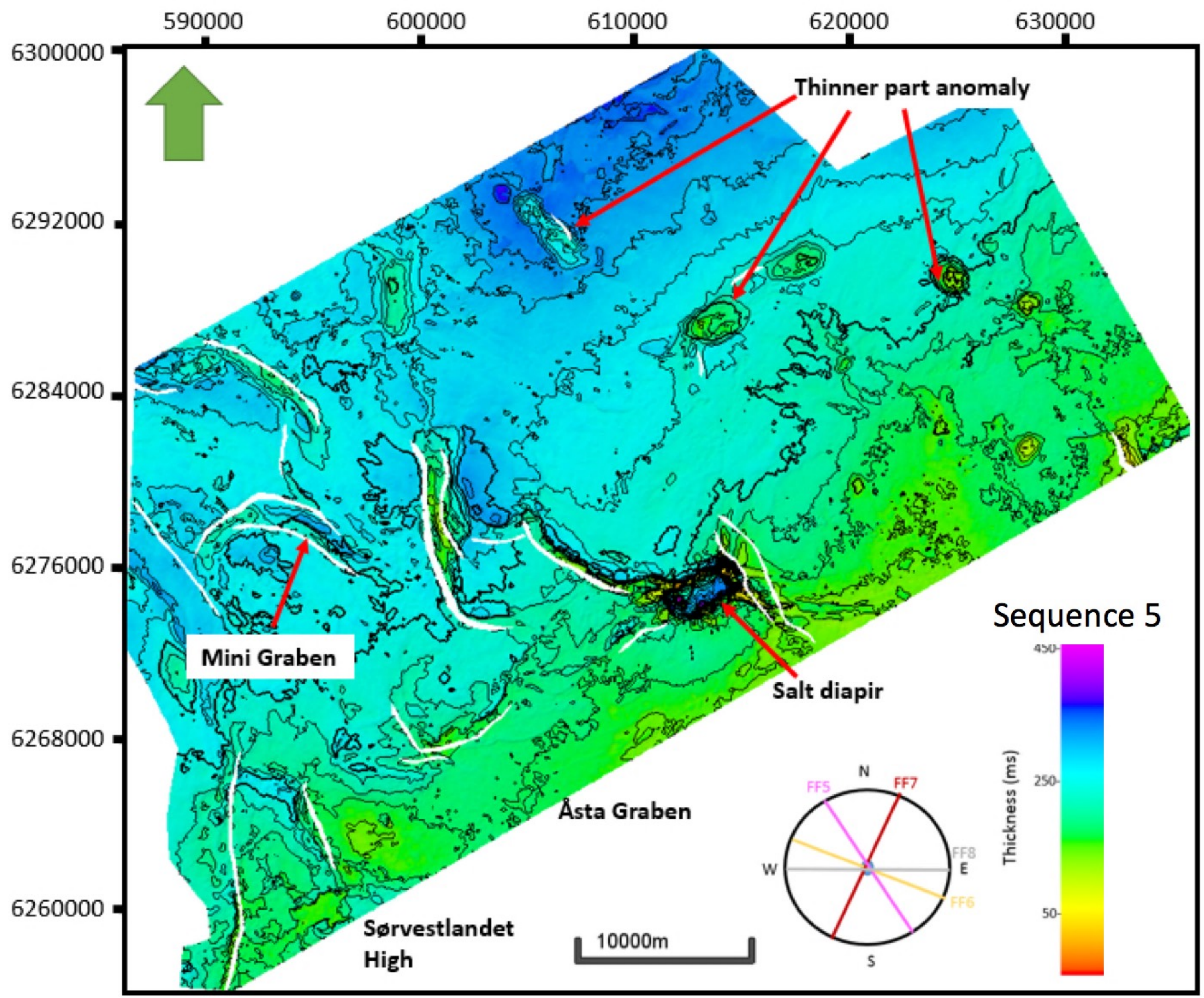


Figure 43: Time Thickness Map (TWT) of Top Cretaceous (Sequence 5) with fault family 5 and 7 mainly affecting it

Sequence 6 – Lower Cenozoic Hordaland Group

Well character

All the wells, except for 3/5-1 has penetrated Lower Cenozoic, and the thickness of this sequence appears to get thinner towards the east, with the maximum thickness in the Søgne Basin being 1668 m and a minimum thickness of 1380 m in the Åsta Graben. In general, the GR pattern of this sequence is also blocky with a semi-funnel shape, because of the vertical homogeneousness in the sequence. There is some variation in the GR readings, where the lower part of this sequence seems to have lower GR reading than the top, because of the sandier Rogaland Group unit in the bottom. The density, sonic, and resistivity log is constant throughout the entire sequence. However, the sonic has increased when moving from the Cretaceous to this sequence (Figure 21).

Seismic character

The top of this sequence is picked on a weak through, a downward increase in the acoustic impedance. The confidence of the pick is weak to medium. The surface is an unconformity as reflections seem to truncate on it from below, while the sequence over seems to onlap it (Figure 44). This body seems to prograde towards the west, where also the thickness of this sequence decreases towards west. The main seismic facies of this sequence are SF 8 and SF 9, mostly parallel, continuous, and high to medium amplitude and frequency. The lower part of this sequence seems to be dominated by polygonal faults, while the upper section is more of the prograding character.

Time structural and thickness map

The time structural map shows that the highest parts of the Lower Cenozoic are in the eastern Åsta Graben with an elevation of 600 ms, plunging downwards toward the west, to the Søgne basin with the deepest point being at 1800 ms (Figure 45). The Lower Cenozoic is distributed in the entire study area, and the main faults affecting this sequence are FF5 and FF6. The red dome-like feature is just as mentioned earlier, an effect due to velocity pullup.

The time thickness map shows that the thickest part of this sequence is in the eastern Åsta Graben with an average thickness of 1100 ms, thinning towards the west with the thinnest average thickness being 550 ms (Figure 46). It appears that the maximum thickness is in the southeastern Åsta Graben, compared to the previous sequences 4 and 5, where their thickest part was in the northeastern Åsta Graben.

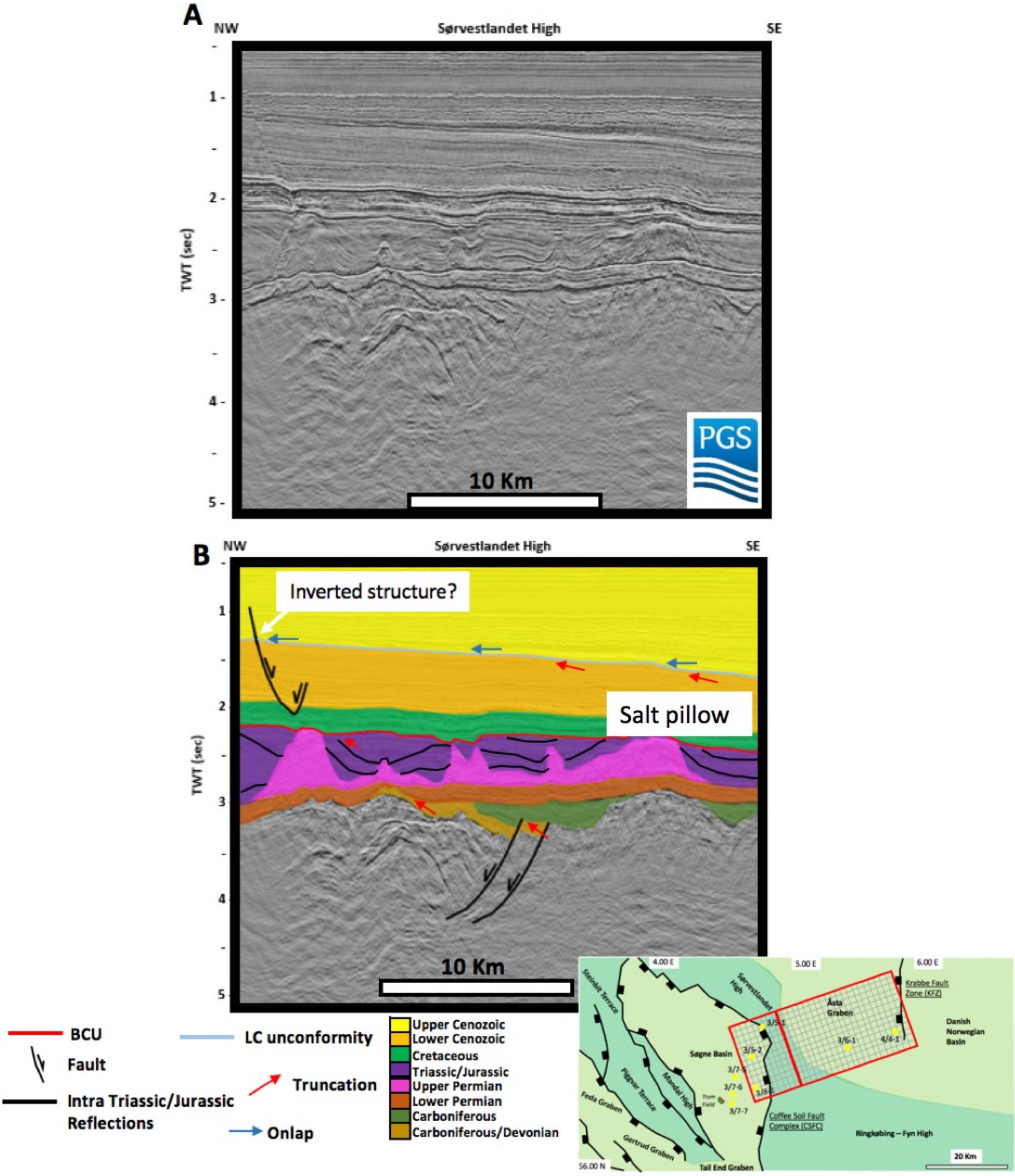


Figure 44: (A) Uninterpreted northwest-southeast three-dimensional seismic line of Åsta Graben (B) Interpreted northwest-southeast three-dimensional seismic line. Main faults interpreted in this line are fault families 3 and 8. Clear truncations of the Devonian, Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt pillows. Inverted structure is also interpreted.

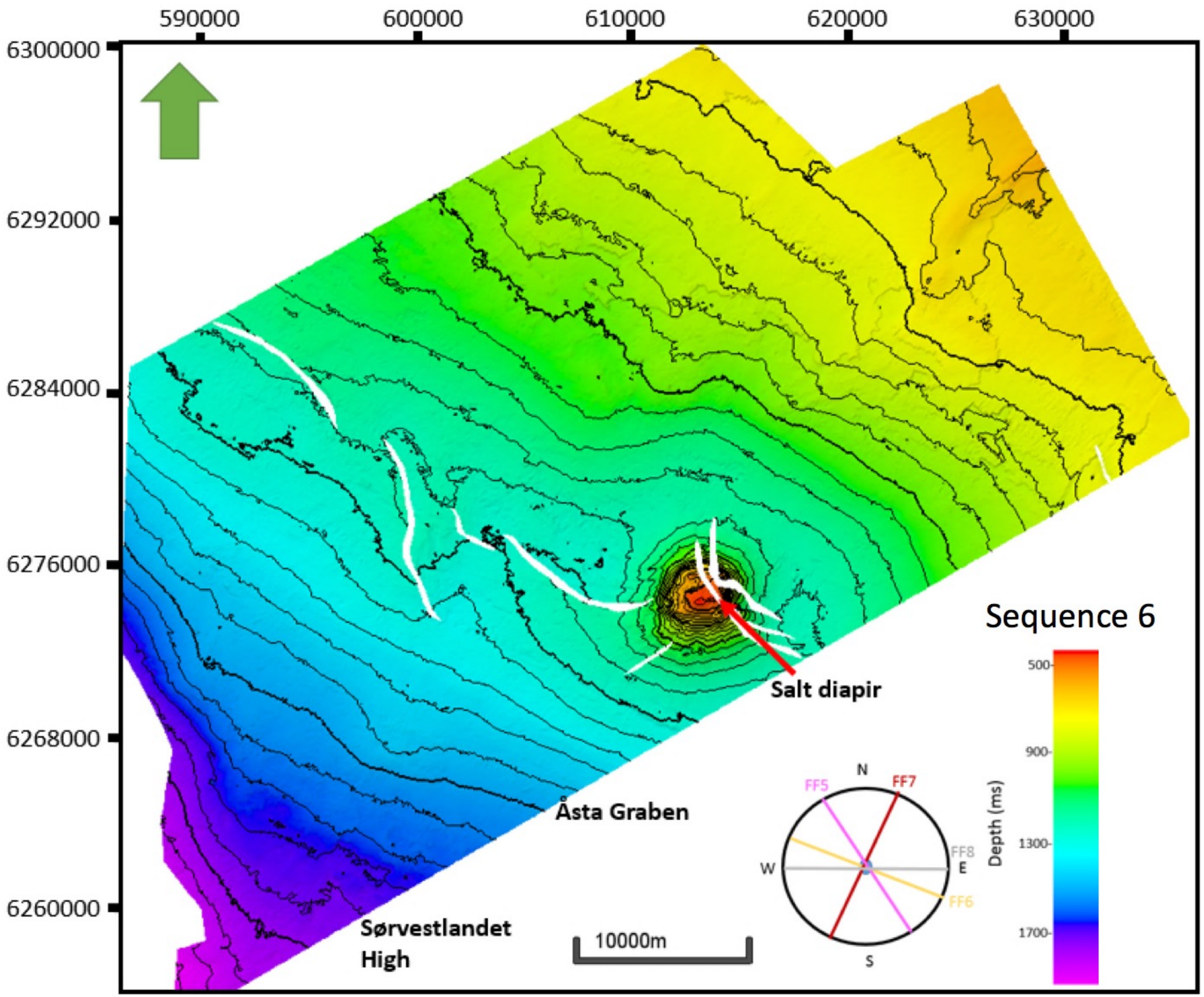


Figure 45: Time Thickness Map (TWT) of Top Lower Cenozoic (Sequence 6) with fault family 5 and 6 mainly affecting it

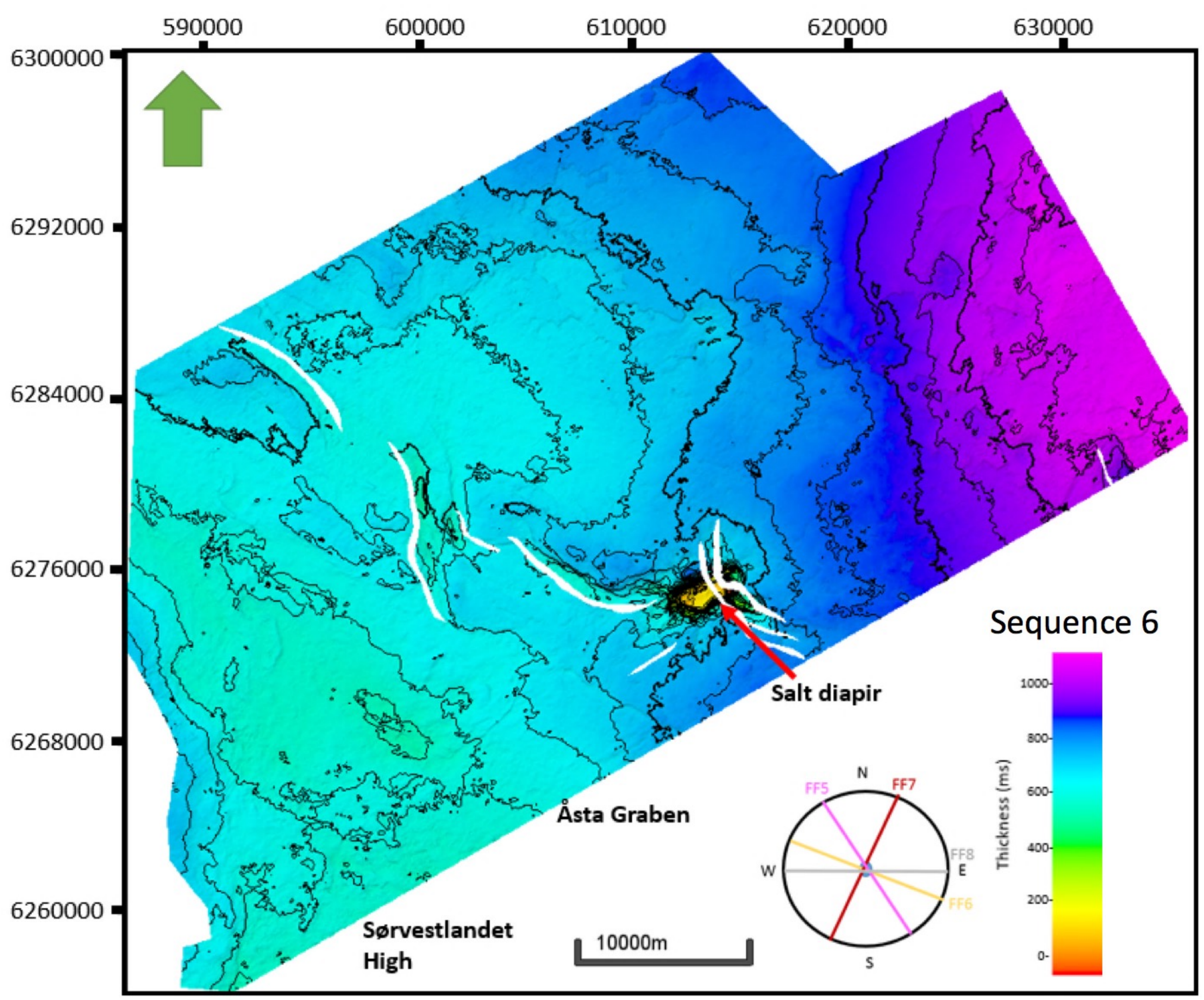


Figure 46: Structural Time Map (TWT) of Top Upper Cenozoic (Sequence 6) with fault family 5 and 6 mainly affecting it

Sequence 7 – Upper Cenozoic Rogaland Group

Well character

All the wells penetrated the Upper Cenozoic. The maximum thickness is in the Søgne Basin with 1328 m thickness, thinning towards the Åsta Graben with a minimum thickness of 435 m. Two GR patterns are recognized in the GR log, whereas the lower part is a blocky GR pattern with high GR readings, and the upper part has a funnel-shaped GR pattern with lower GR readings compared to the lower section. The GR characters in the upper part of this sequence is a result if glacial deposits. No density or sonic log was available for this sequence, but the resistivity log shows low constant readings (Figure 21).

Seismic character

The top of this sequence is picked on the seafloor, an adamant through and therefore the pick of this top is of high confidence. The main seismic facies of this sequence are SF8 and SF10, where SF8 dominates in the lower section, while SF10 is more common on the upper section (Figure 47). In general, the reflections are parallel, continuous and high amplitude, however, the lower part has more of discontinuous reflections because of the polygonal faults present. Some clinoforms are observed in the upper part of the sequence in the west of the study area, with a height of 50 ms. The internal reflections of this sequence seem to be dipping down towards the west on the lower part, but then becoming more sub-horizontal in the upper part.

Time structural and thickness map

The time structural map shows that there is not a major variation in elevation, having the maximum elevation at the northwest with a value of 70 ms and the deepest point at 90 ms (Figure 48). This surface has no faults affecting it and is distributed over the entire study area. The time thickness map shows that the thickest part is in the Sørvestlandet area with a thickness of 1750 ms and thinning towards the northeast with a minimum thickness of 600 ms (Figure 49). Again, the velocity pull is creating a red dome in this thickness map.

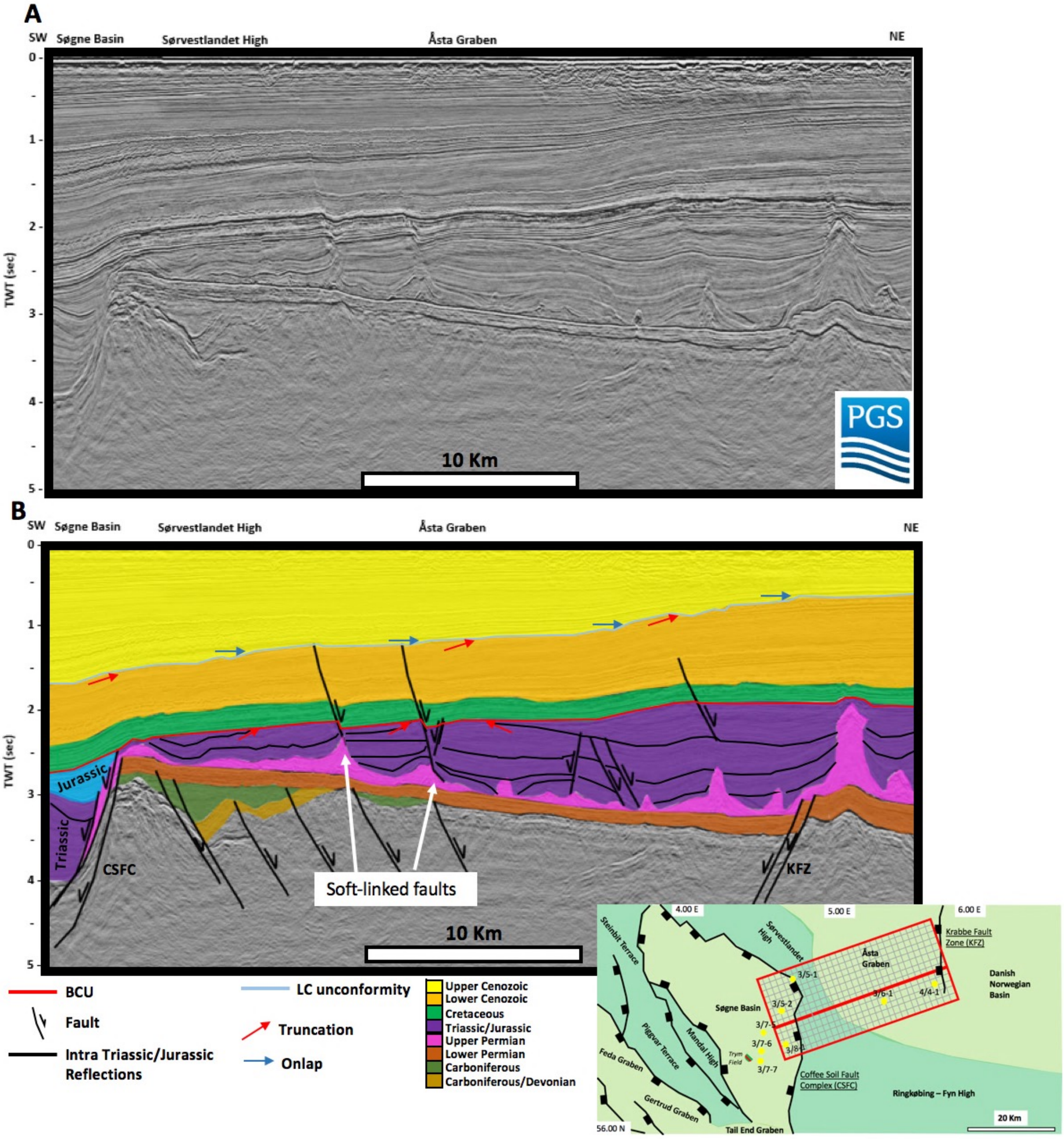


Figure 47:(A) Uninterpreted southwest-northeast three-dimensional seismic line of Søgne Basin, Sørvestlandet High and Åsta Graben (B) Interpreted southwest-northeast three-dimensional seismic line. Main faults interpreted in this line are fault families 1, 3, 4, and 6. Clear truncations of the Triassic/Jurassic and Lower Cenozoic are interpreted along with the salt structures like salt roller, salt welding and salt pillow are observed, along with soft-linkage of the sub-salt and supra-salt faults

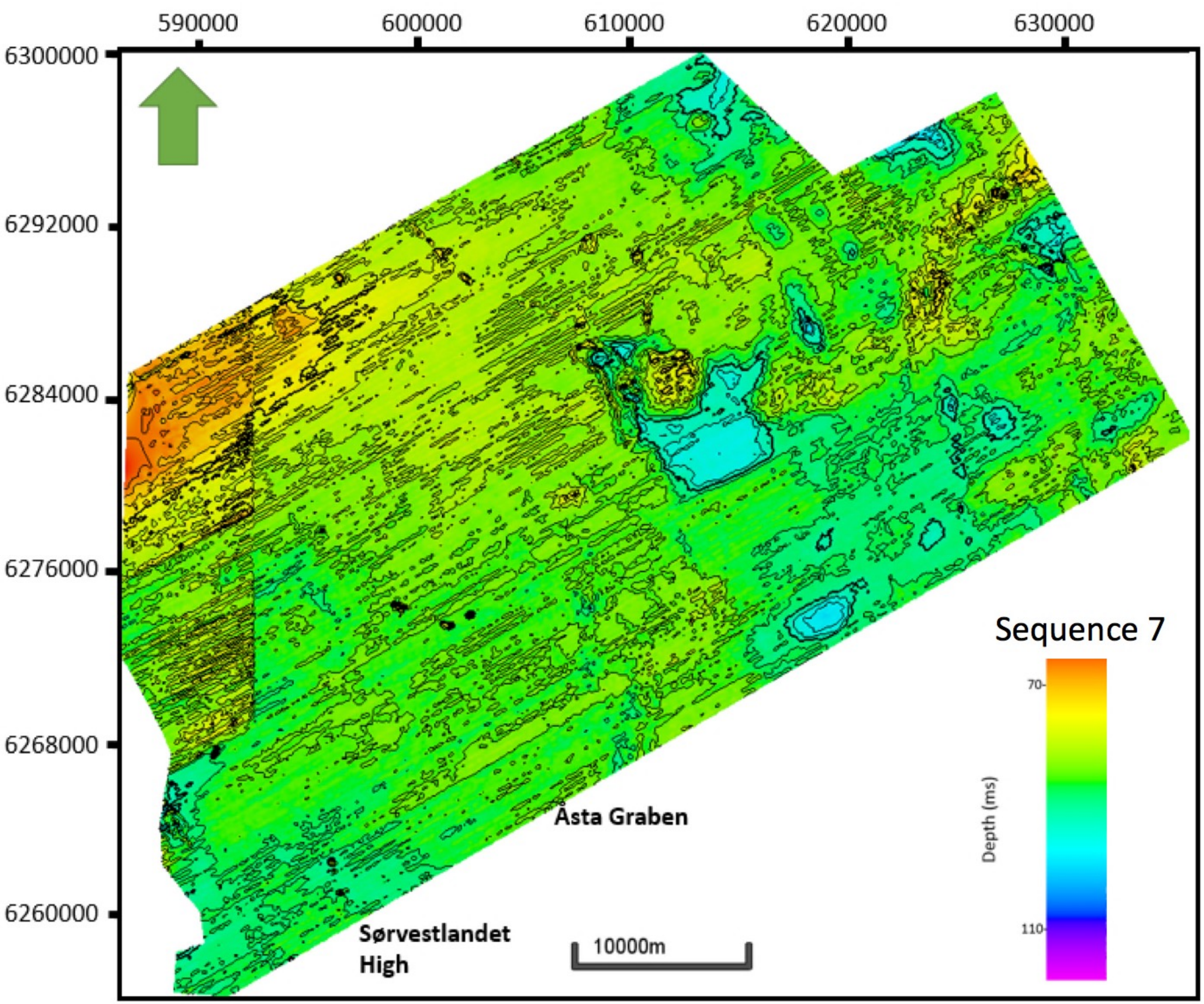


Figure 48: Structural Time Map (TWT) of Top Upper Cenozoic (Sequence 7)

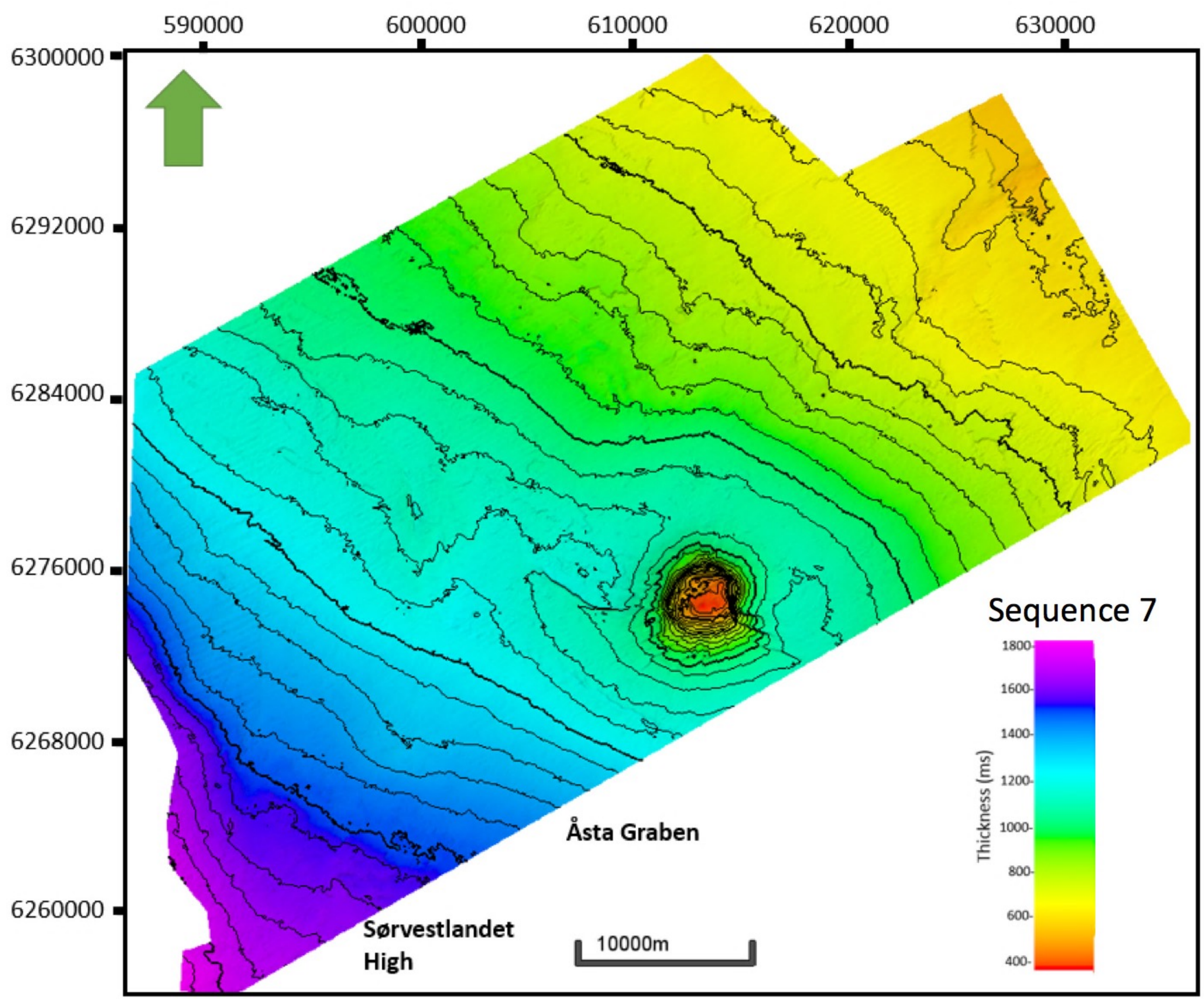


Figure 49: Time Thickness Map (TWT) of Top Upper Cenozoic (Sequence 7)

Restoration of the Sørvestlandet High and the Åsta Graben

A vertical seismic section was restored, and all the sedimentary layers were decompacted in the Move software. All the sequences showed higher area when after decompaction. Moreover, the decompaction effects shale intervals more than sand intervals (Roberts et al., 1998), which was observed. When mudstones where decompacted, porosity increased and hence resulted in a larger area. The areas of shale intervals become bigger after they are decompacted (Table 4). All the layers showed a gain. To simplify the process of restoring this section, the Devonian and Carboniferous has been treated as one section.
The total amount of extension the study area suffered was 5,5 km, and the three most important extensional phases were: Pre-Upper Palaeozoic extensional phase with an extension of 2,1 km, where the main controlling faults are the sub-salt FF1 (Figure 50). Then second extensional phase during the Devonian/Carboniferous with an extension of 189 m, and as the previous extensional phase, the main controlling fault family is FF1 (Figure 51). The third and last extensional phase was during the Upper Permian, with an extension of 2,8 km where the main controlling faults are the FF1 and FF4 (which includes the Coffee Soil Fault Complex). A quantitative calculation has been done to give a rough estimate on the amount of area that was uplifted and exposed during the different times in the study area. During the Upper Devonian/Carboniferous, both the basement and Devonian has an exposed and uplifted area of approximately 14,3 km2 in total. During the Upper Jurassic, new and exposed uplifted footwalls were dominating the study area. During this time, about 2,7 km2 of the footwalls were uplifted and exposed.

Sequence	Present Area	Deformed Area	Extension
Sequence 7	65606891 m²	65606891 m²	0 m
Sequence 6	34919210 m²	47672944 m² (Gain)	0 m
Sequence 5	18329665 m²	26188479 m² (Gain)	0 m
Sequence 4	44228863 m²	64636848 m² (Gain)	0 m
Sequence 3	14471440 m²	54490196 m² (Gain)	451 m
Sequence 2	13741966 m²	28377292 m² (Gain)	3288 m
Sequence 1.2	7541721 m²	14885394 m² (Gain)	3477 m
Sequence 1.1	3198199 m²	5494824m (Gain)	-
Basement	378162290 m²	786195051 m² (Gain)	5565 m

Table 4: A summary of the gain of sediments after decompaction for each sequence and the amount of extension during the different times

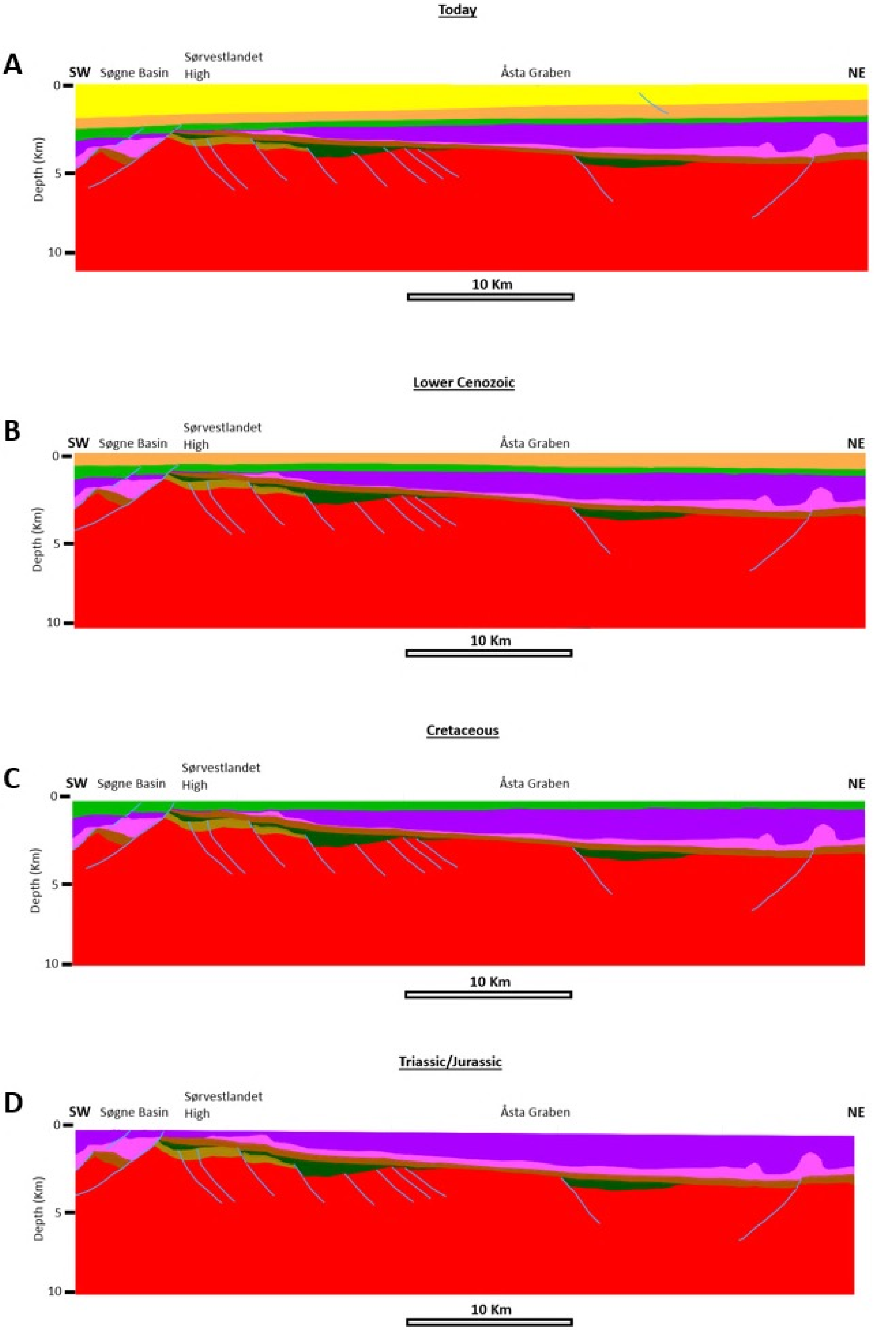


Figure 50: Two- dimensional restored sections for sequence (A) Upper Cenozoic, (B) Lower Cenozoic, (C) Cretaceous and (D) Triassic/Jurassic

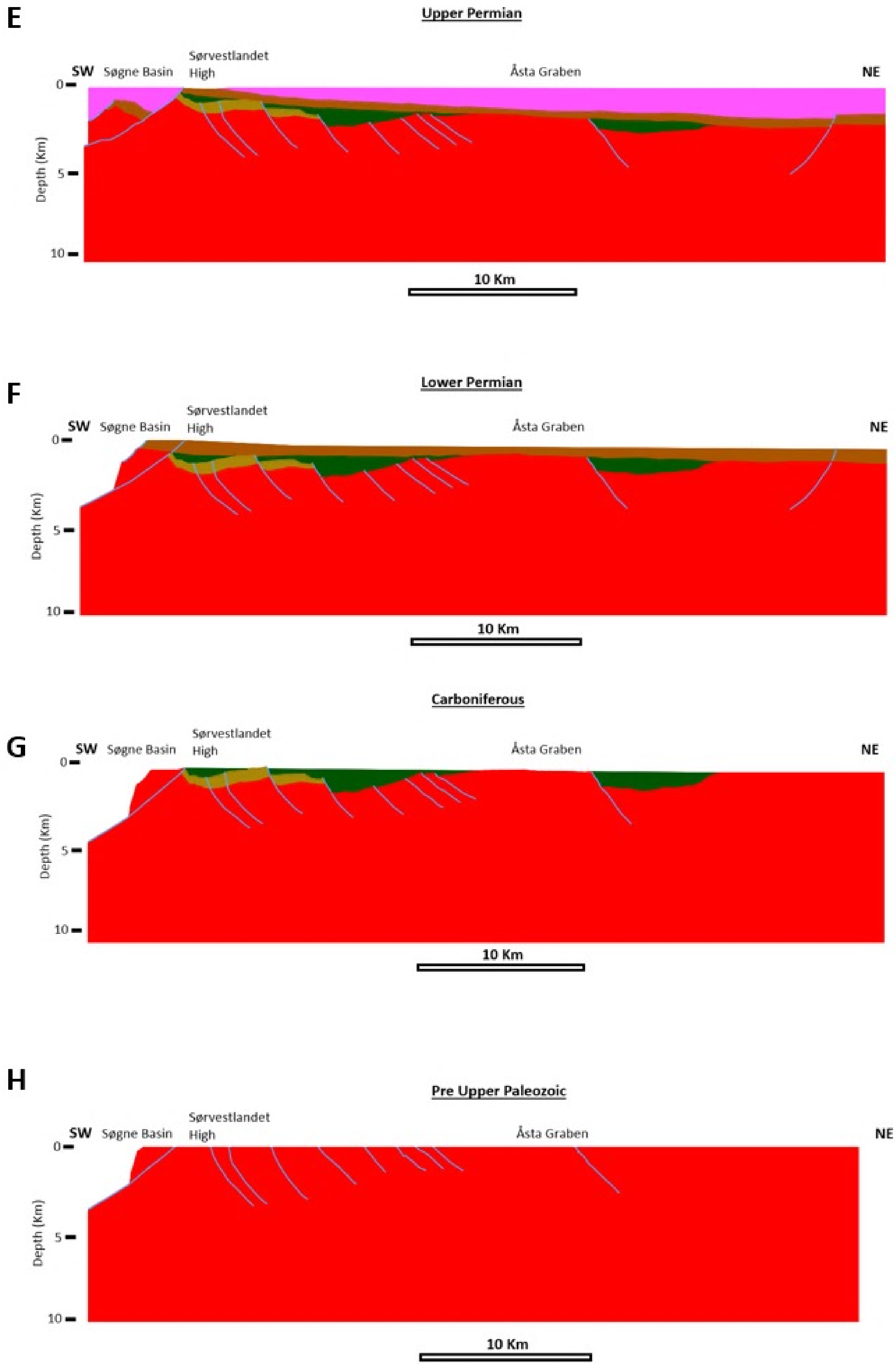


Figure 51: Two- dimensional restored sections for sequence (E) Upper Permian, (F) Lower Permian, (G) Devonian/Carboniferous (H) Basement

Discussion

Geological evolution of the Sørvestlandet High and Åsta Graben

Devonian Carboniferous folding and rifting

The observed preservation of the Devonian and Carboniferous sediments in the Sørvestlandet High and Åsta Graben indicates that the Sørvestlandet High was not a high during the Devonian and Carboniferous. However, as observed in figure 26 and 27, the Devonian is only preserved in the Sørvestlandet High and not in the adjacent Åsta Graben. The proposed theory for this is that both the Sørvestlandet High and Åsta Graben were on the same uplifted footwall dipping towards the east (Figure 52) in such a manner that initially the Devonian was in both the Sørvestlandet High and the Åsta Graben. This uplifted footwall was subaerially exposed, and the crest of the footwall was eroded away, leaving the Devonian only to be preserved in the Sørvestlandet High (Figure 52B, C, D). Then faulting within the uplifted footwall, which also follows the same dip as the uplifted footwall, was initiated (Figure 52E). These faults are the observed as FF1 and FF2 in figure 32.

Moreover, in some areas, the Devonian appears to have undergone some deformation. To justify this is observed curvature that the Devonian tend to have (Figure 44). This curvature could be a result of a folding related to the Variscan Orogeny (Ziegler, 1975). This same folding character of the Devonian has been observed in other places such as Ål Basin, where the Embla Field is located (Figure 6). Furthermore, some truncations of this sequence were also observed (Figure 35), indicating that there was an erosive event that was post-Devonian and pre-Carboniferous. This erosive event observed could be due to the post-orogenic uplift with the collapse of the Caledonian mountains (Ziegler, 1975).

After rifting and folding during the Devonian (Wilson et al., 2004), the Carboniferous was deposited filling the topography (Figure 52F). The source of the Carboniferous is interpreted to be the uplifted footwall eroding both the Devonian and the crystalline basement (Figure 53). However, what is interpreted to be the Devonian and Carboniferous could also be the lowermost Roteliegend, the conglomerates, and volcanics. Usually, the volcanics usually to show a random distribution of short, strong amplitudes seismic reflections in the formation (Evans et al., 2003). However, due to fact that these random reflections are not observed this unit is interpreted with high confidence as Devonian and Carboniferous, rather than the lowermost Roteliegend. Therefore, it is more likely that both Carboniferous and Devonian is preserved in the Sørvestlandet High (Figure 54).

Lower Permian Pre-Rift

The creation of the Southern and Northern Permian Basins took place during the Lower Permian. The GR log of the welldata from this period shows a blocky pattern with density values close to the value of Quarts (Figure 21), indicating a very sandy unit. According to the description of the formation, the depositional environment for this sequence should be an arid aeolian dune (Gautier, 2003). Furthermore, the Sørvestlandet High was yet not defined as a structural high, this being confirmed by the observed minor erosion of the Roteliegend Group in the crest of Sørvestlandet High. The erosional surface that has the Roteliegend internal reflections truncating to it is the Upper Jurassic BCU (Figure 26). The narrow thickness variation of this sequence, as well as the dip of this sequence observed seems to follow the Basement. Also, as seen in figure 33, the Lower Permian seems to be widely distributed over the entire study area, suggesting that the Lower Permian represents a tectonic quiescence time.

Upper Permian Rifting

During the transition to the Upper Permian the Roteliegend Basins were submerged, and the Zechstein seas were flushed into the area. A significant amount of salt in these Roteliegend Basins observed by the welldata (Figure 15) and seismic data (Figure 36) correlates to the fact that there was a connection to the open seas. It was during this time that the Søgne Basin began to partially subside and become separated from the Sørvestlandet High (Figure 51E). This means that the Coffee Soil Fault Complex was active at that time. This conclusion is based on the observed thickness variation of the Zechstein salt during the Upper Permian between the Sørvestlandet High and the Søgne Basin as seen in figure 51E. Based on these observations the Upper Permian Zechstein Group is interpreted as a time of rifting.

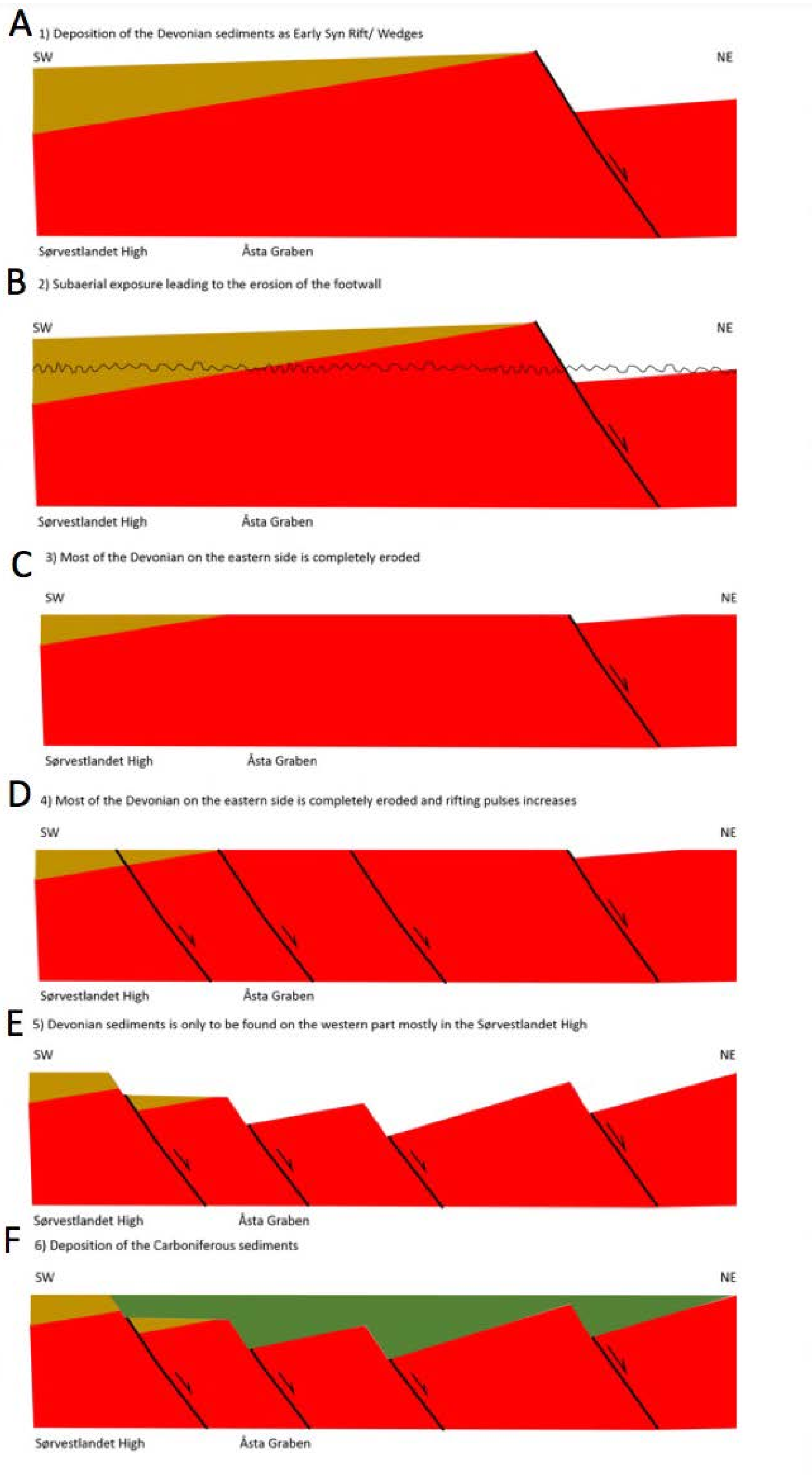


Figure 52: Proposed evolutionary model of the Pre-Permian explaining the preserved Devonian sediments in the Sørvestlandet High where A) The deposition of the Devonian, B) Subaerial exposure of the Devonian, C) Erosion of the Devonian initiates, D&E) The Devonian has been completely eroded in the Åsta Graben, but preserved in Sørvestlandet High, F) The deposition of the Carboniferous

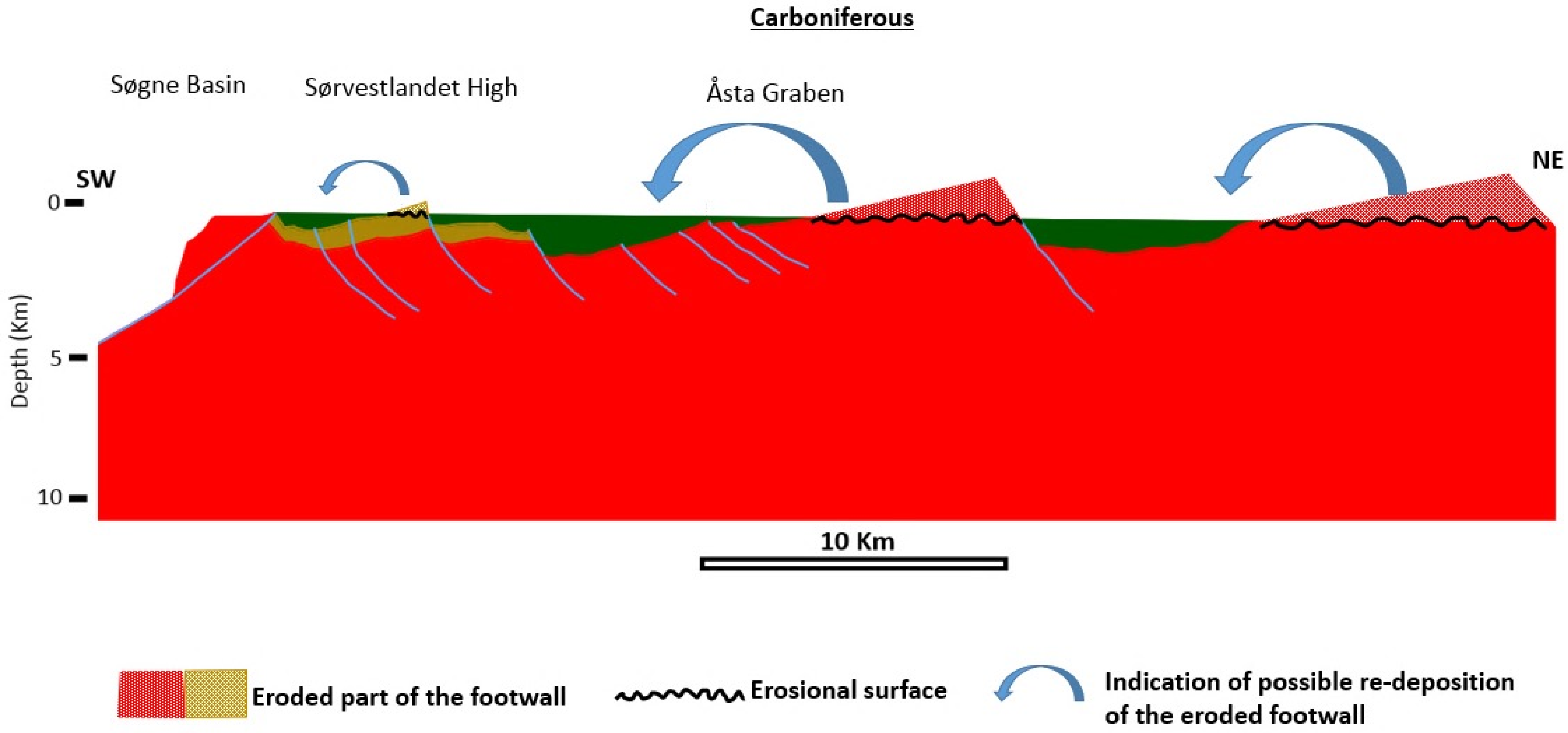


Figure 53: Two-dimensional cross section of the study area showing how the carboniferous is locally sourced by the Devonian and basement uplifted footwall

Triassic/ Jurassic intracratonic rifting with salt movements

The Triassic time indicates a continental depositional regime. The North Sea was in an intracratonic setting with minor faulting (Ziegler, 1975). The Coffee Soil Fault Complex did not appear to be active during this time since the thickness of the Triassic is similar in the eastern Søgne Basin and Sørvestlandet High (Figure 55). However, the Krabbe Fault Zone appears to have been active during the Triassic. It is observed that the Krabbe Fault Zone displaces the Roteliegend (Lower Permian), but not the Triassic/ Jurassic. In addition to this, the Triassic/Jurassic appears to be thicker on the hangingwall of the Krabbe Fault Zone compared to the footwall (Figure 35). The Triassic/Jurassic is thicker in the areas where salt is welding as well as in between the different salt structures (Figure 41). This indicates that it was during the Triassic that the salt started to withdraw while deposition of sediments was continuing, leading to the development of the major salt structures (Rossland et al., 2013). This is also apparent when observing the Triassic sub-basins adjacent to the salt diapirs (Figure 39) and how they seem to flank up towards the diapirs. However, at the same time, the salt mobilization seems to have controlled the distribution of the Triassic sediment simultaneously. Subsequently no well drilled the Triassic/Jurassic on the high, and no distinctive seismic character differences were recognized within the Triassic/Jurassic, therefore differentiating the Triassic and Jurassic as two separate events on the high is considerably challenging. Well 3/8-1 drilled in the Søgne Basin encountered the Roteliegend, but not the Triassic (Figure 21). This could be due to the salt withdrawal, as the salt replaces the Triassic in the area where the well was drilled (Figure 22). However, the Triassic is present in the Søgne Basin according to Rossland et al. (2013). The other possibility is that the Sørvestlandet High has no preserved Jurassic as a result of the erosion related to the Upper Jurassic North Sea Dome (Ziegler, 1975). The thickness of the Jurassic in the Søgne Basin appears to thicken from west of the Søgne Basin towards the Coffee Soil Fault Complex in the east (Figure 21). This thickening towards the east could be due to the reactivation of the Coffee Soil Fault Complex during the Jurassic, which then explains the uplift of the Sørvestlandet High and the absence of the Jurassic in the high. The lack of sand in the Jurassic indicated by the high GR reading (Figure 12) in the Søgne Basin might reflect the first marine transgression during the Mid Jurassic. This could also indicate that the source of these Jurassic sediments in the Søgne Basin are long transported sediments (Rossland et al., 2013). If this is the case, then the Sørvestlandet High might not be the source of these sediments seeing that the Jurassic did not deposit here, or no erosion of the Jurassic occurred.

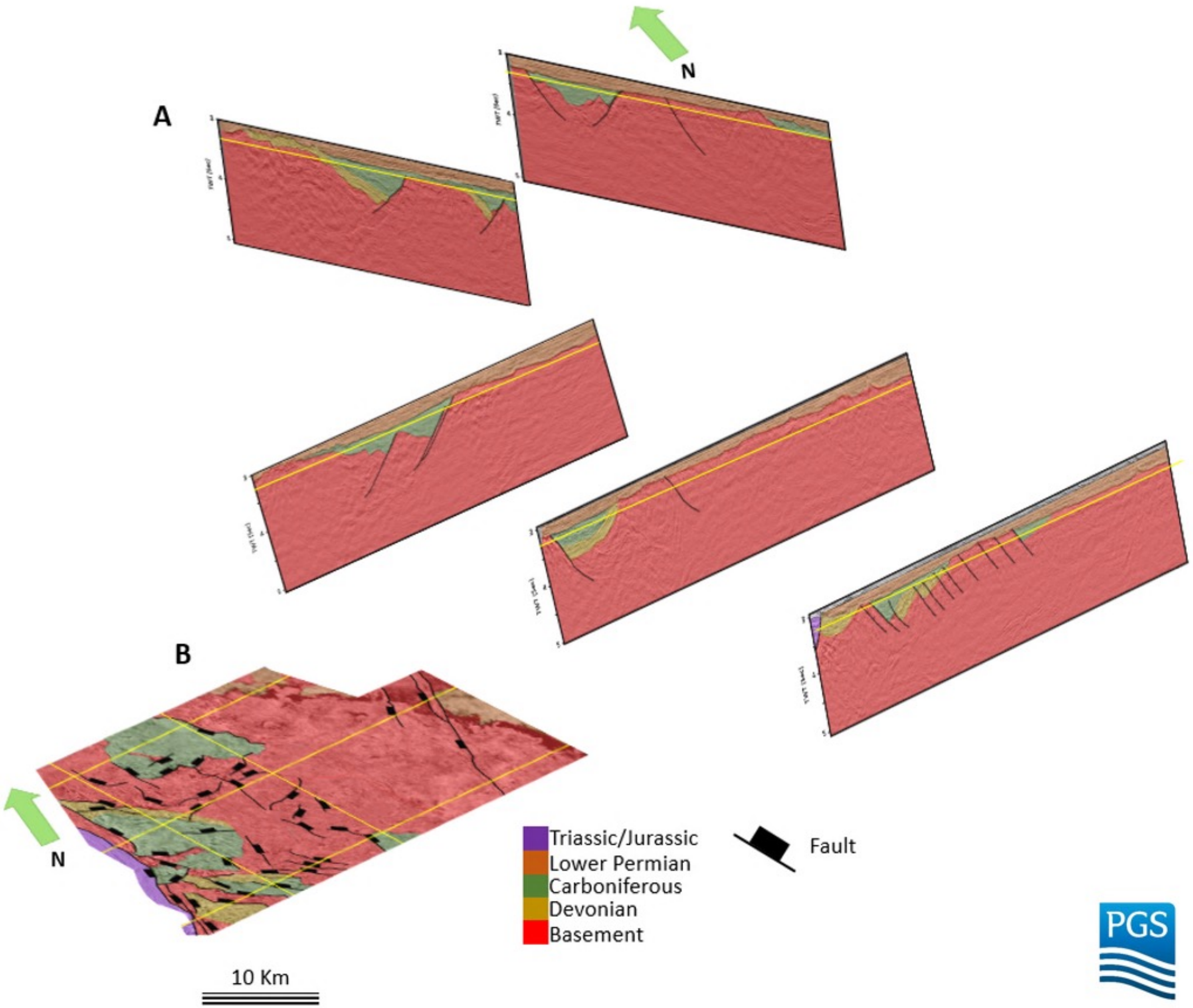


Figure 54: (A) Seismic vertical cross line from the main areas of interest to show how the different sequences differs vertically in the study area (B) Seismic time slice flattened at 3100 ms showing the lateral distribution of the different sequences and the main faults controlling these distributions

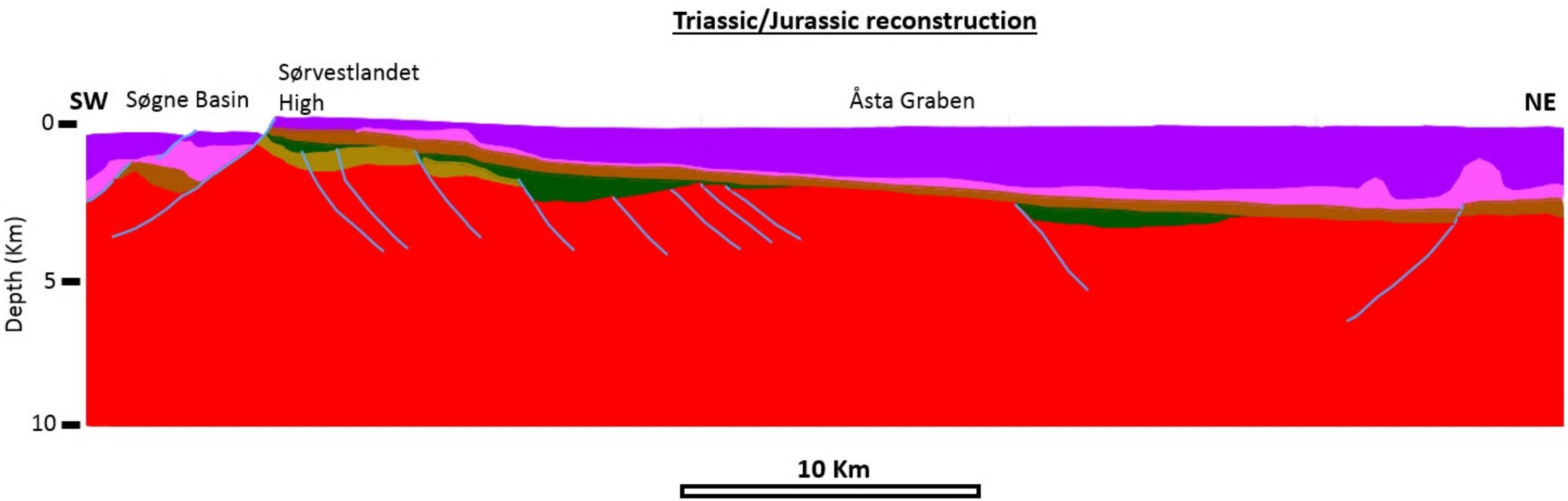


Figure 55: Two-dimensional cross section of the study area showing the reconstructed part of the Sørvestlandet High during the Triassic/Jurassic

Cretaceous Post Rift and flooding

The uniform thickness of the Cretaceous in the study area indicates little tectonic activity, which might be an indication of the end of a rifting stage (Gowers & Sæbøe, 1985). Still, FF6 and FF7 (Figure 41) are present in the Cretaceous, but no growth strata are observed, indicating that these faults are Post-Cretaceous (Figure 42). Some inverted structures however are interpreted in both the Cretaceous and Lower Cenozoic (Figure 44) which could be due salt movements, or are related to the creation of the Alpine Orogeny (Rossland et al., 2013). The observed small anticline like features in Cretaceous and Lower Cenozoic (Figure 39) is also indicating salt movements during the Cretaceous. However, the halokinetic intensity is not as high as in the Triassic/Jurassic (Figure 50C).

From well 3/8-1, 3/7-7 and 3/5-2 it is observed that the lower part of the Cretaceous has in general high GR reading and erratic log shape, which indicates a shallow marine with beds of marls and shales (Rossland et al., 2013). The wells that have this GR character of the Cretaceous are all observed in the Søgne Basin due to the ceased subsidence of the basin. Moving towards the east, to the Sørvestlandet High, only the high GR reading are found (Figure 21), in well 3/6-1, and 4/4-1, representing the Upper Cretaceous chalk facies (D´Heur, 1986).

Cenozoic basin subsidence

The Cenozoic marks a time of post-rifting intracratonic setting with minor fault activity of FF5 and FF6. According to Ziegler (1975), the Lower Cenozoic had a minor tectonic activity that was accompanied by global drop in sea level, that resulted in down warping of the North Sea Basins, mainly centered above the main Mesozoic rift system. This down warping of the Lower Cenozoic can be seen in figure 36, how the Cenozoic is dipping towards the SW, and into the Mesozoic Central Graben. Further basin subsidence of the study area led to sedimentation of the Upper Cenozoic. The boundary between Upper Cenozoic and Lower Cenozoic is marked by an unconformity where clear truncations from the Lower Cenozoic and the onlaps from the Upper Cenozoic is observed (Figure 39).

Triassic halokinesis and the development of mini basins

When salt is present in extensional tectonics, a group of different salt structures is formed (Ten-Veen et al., 2012). The faults propagate from the more brittle sequences until they encounter, the more ductile salt as observed in figure 29. This is what has prevented the four sub-salt fault families to prograde into the Triassic/Jurassic. However, as the displacement of the faults continues, the base of the salt becomes more and more deformed which is causing flexural bending in the Triassic/Jurassic, and the creation of mini basins (Figure 24). The sub-Salt fault families stress also causes bending resulting in the development of FF5, FF6, FF7, and FF8 (Figure 25). This creation of the supra-salt fault families is also related to the present thickness of the salt and the doming of the salt (Lewis et al., 2013).

Some of the sub-salt fault families and supra-salt fault families appear to be unlinked as there is no spatial relationship between them (Figure 44). Additionally, some of the supra-salt faults are created due to the crestal collapse of salt diapirs and ridge collapse because of either dissolution or differential compaction above the salt (Figure 22), resulting in the radial pattern of these faults (Ten-Veen et al., 2012). There are several soft linked faults observed (Figure 41), especially in the Triassic/Jurassic sequence. These soft linked faults are present in areas where the salt is around 100-300 ms thick, and where the supra-salt faults and pre-salt faults are spatially related but might show some lateral offset (Stewart, 2007) (Figure 56). A soft-linkage is also observed between sub-salt fault family FF1 and supra-salt fault family FF5 as shown in figure 47.

As observed these soft linked fault systems appears to be formed in the thick-skinned setting due to the deformation of Triassic/Jurassic and the diapirs, which are directly related to the pre-salt faults in several places (Figure 35). The major salt structures such as salt walls and massive salt domes are widely distributed in the Åsta Graben (Figure 37), as a result of the load from the thicker Triassic/Jurassic package (Figure 38). Unlike Sørvestlandet High where the Triassic/Jurassic has less thickness. According to Ten-Veen et al. (2012), basin or graben-like structures will intensify the halokinetic movements (Figure 57), while the platforms and highs will have salt structures that require little halokinetic intensity (Jackson & Talbot, 1986) (Figure 32).

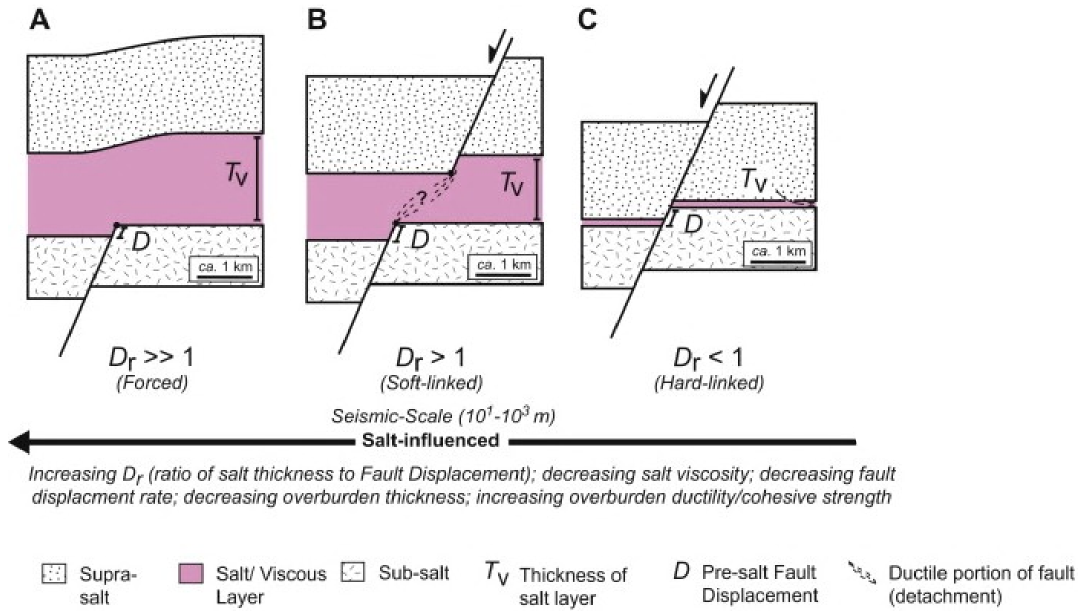


Figure 56: How the salt thickness influences the connection between the sub-salt and supra-salt fault where (A) is when the sub-salt fault offset is low relative to the salt thickness prior to fault growth, inducing a basinward dipping monocline formed in the overlying supra-salt strata. (B) Is when initial salt thickness is greater than the sub-salt fault throw. (C) Is when sub-salt fault throw is greater than initial salt thickness and a through-going fault is formed (from Lewis et al., 2013).

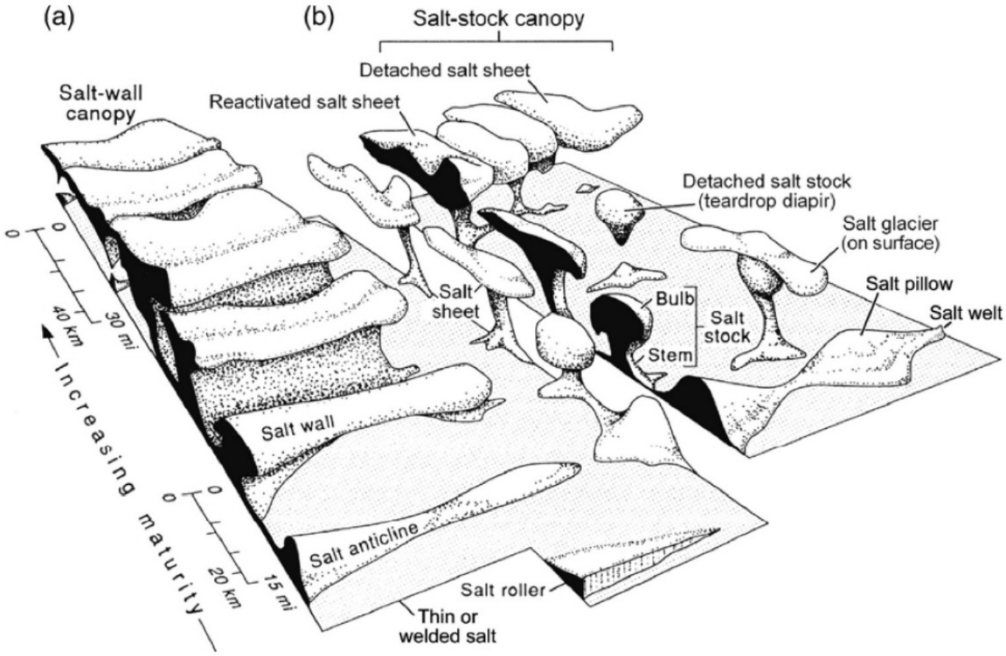


Figure 57: The relation between salt structure maturity and salt structures (from Hudec & Jackson, 2007) where (A) are salt structures developed from linear sources and (B) point sources.

Implications for the petroleum system

Unlike the Upper Jurassic Mandal and Utsira highs analogs, the Sørvestlandet High does not seem to have a working petroleum system in the Mesozoic, but rather in the Paleozoic. However, the geological histories are similar for these three Upper Jurassic highs, and the three highs are underlain by Caledonian weathered and fractured crystalline basement rocks (Figure 2). Nevertheless, the Paleozoic seems to be only preserved in the Sørvestlandet High, which can be further proved with more data and knowledge.

Source Rock and Migration

The organic-rich lacustrine shales of the Devonian and Carboniferous are well established as an excellent source rock in the UK and Dutch sector of the North Sea (Gautier, 2003). The Carboniferous is the main source rock for gas and coal. The Devonian acts more as an oily lacustrine source rock (Figure 58). Therefore, both oil and gas might be present in the Palaeozoic petroleum system. Though, according to Ohm et al. (2012), these Devonian source rocks might also source the non-movable hydrocarbons, bitumen, which was one of the cases in the Embla Field. The bitumen was found in the weathered and fractured rhyolite (Lundmark et al., 2012) due to biodegradation during the Middle Jurassic uplift. In this case, a Devonian sourced hydrocarbon migration will not occur, and only Carboniferous gas and coals might have migrated from the Paleozoic source rocks.

Furthermore, the present Mesozoic formations that tend to be main source rock in the Central Graben are Jurassic Mandal, Haugesund and Farsund Formations (Glennie, 2009). These formations are mainly found in the Søgne Basin. However, these source rocks seem immature in the Søgne Basin, as no hydrocarbons have migrated from this basin to the Sørvestlandet High or to Mandal High. According to Rossland et al. (2013), the main problem regarding no hydrocarbon generations in the Søgne Basin is the shallow burial of the source rock. Another possibility is that the source rock could have been generating hydrocarbons in the Søgne Basin, but because of the salt structures, the migration to the Sørvestlandet High of this hydrocarbon could not happen as the passageway was probably sealed by the salt. Accordingly, due to Zechstein salt being a regionally barrier covering the entire study area (Evans et al., 2003), a vertical migration within the Sørvestlandet High from the Paleozoic source rock to the Triassic/Jurassic and Cretaceous is not possible. Based on this, the Mesozoic will not be able to work as a petroleum system in the Sørvestlandet High and therefore only the Paleozoic petroleum system is working.

The Palaeozoic source rock is present in the Sørvestlandet High as well as the western and central part of the Åsta Graben, making the possible migration path for the HC from the Paleozoic source more local. The main migration path will be through the sub-salt fault families. This is due to these faults not being sealed, as a result of the Roteliegend sand dunes being juxtapositioned to the Paleozoic source rocks. Another migration route would be through the fractured and weathered crystalline basement. As seen in figure 54, the seems to be a basement high where the source rock is adjacent on the western side, and the Roteliegend is sub adjacent on the eastern side. Therefore, a sub-horizontal hydrocarbon migration from the west to the east through these fractures might be another possibility.

Reservoir

The different tectonic and stratigraphic episodes that have occurred in the Sørvestlandet High and Åsta Graben provides different hydrocarbon plays. As mentioned earlier, no migration to the Mesozoic could have occurred, therefore the main traps and reservoirs are only found in the Paleozoic. The main reservoir rock in the Palaeozoic is the Lower Permian Roteliegend Group, sandy aeolian formation (Figure 59). The main trap of this system is the tilted bed of the Roteliegend, confined by the non-permeable salt and Jurassic shale to the east in the Søgne Basin. Since this is a bed dipping upwards towards the west, the main hydrocarbons will be found in the Sørvestlandet High and western part of the Åsta Graben. Nonetheless, like the Embla Field, the Devonian sand could also work as a reservoir rock. The Devonian reservoir rock in the Embla Field seems to contain two types of oils, Devonian black oil and Jurassic light oil (Ohm et al., 2012). As mentioned earlier no Jurassic sourced hydrocarbon has been generated, therefore only Devonian oils might be in the sands, or the Carboniferous gas. The third option will be like the Utsira and Mandal highs analogs, where the fractured and weathered crystalline basement might also work as a reservoir rock (Rossland et al., 2013). The seal rock of this system is the Upper Permian Zechstein Halite (Figure 60), which is present in the entire study area. In conclusion, there is the Devonian and Carboniferous source rocks that are locally sourcing (Figure 61): the Devonian sands, the Lower Permian Roteliegend sand dunes, and the weathered crystalline basement. This whole petroleum system is regionally sealed by the Upper Permian Zechstein salt (Figure 62).

Risks and recommendations

The main risk in this petroleum system is the presence of the source rock. Since no well is drilled deeper than the Cretaceous and the presence of the Carboniferous and Devonian is only based on seismic data, the possibilities for the main source rock being present is of high risk. Also, type of hydrocarbons (movable vs. non-movable hydrocarbons) present in these Paleozoic source rocks is also a risk of whether migration into the reservoir happened or not. Further recommendations would be to drill below the Lower Permian in the Sørvestlandet High and the western part of the Åsta Graben, as well as to obtain geochemical data of the Devonian/Carboniferous source rocks. Gravity and magnetic data over the study area would also help excluding the possibility of whether what is believed to be Devonian and Carboniferous is just a different seismic reflection character of the basement or not.

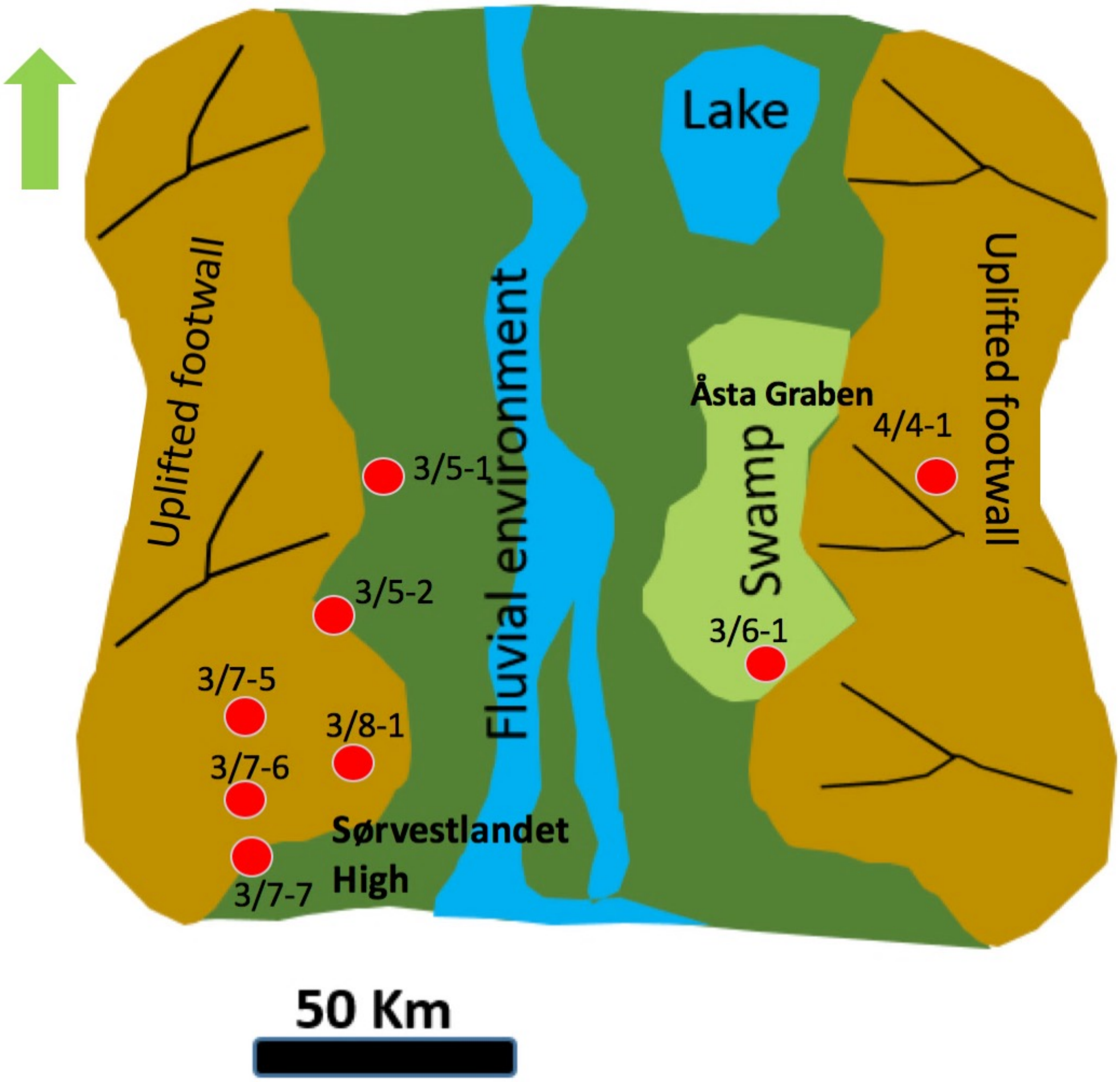


Figure 58: The depositional environment in the study area during the Carboniferous/Devonian with the positions of the wells

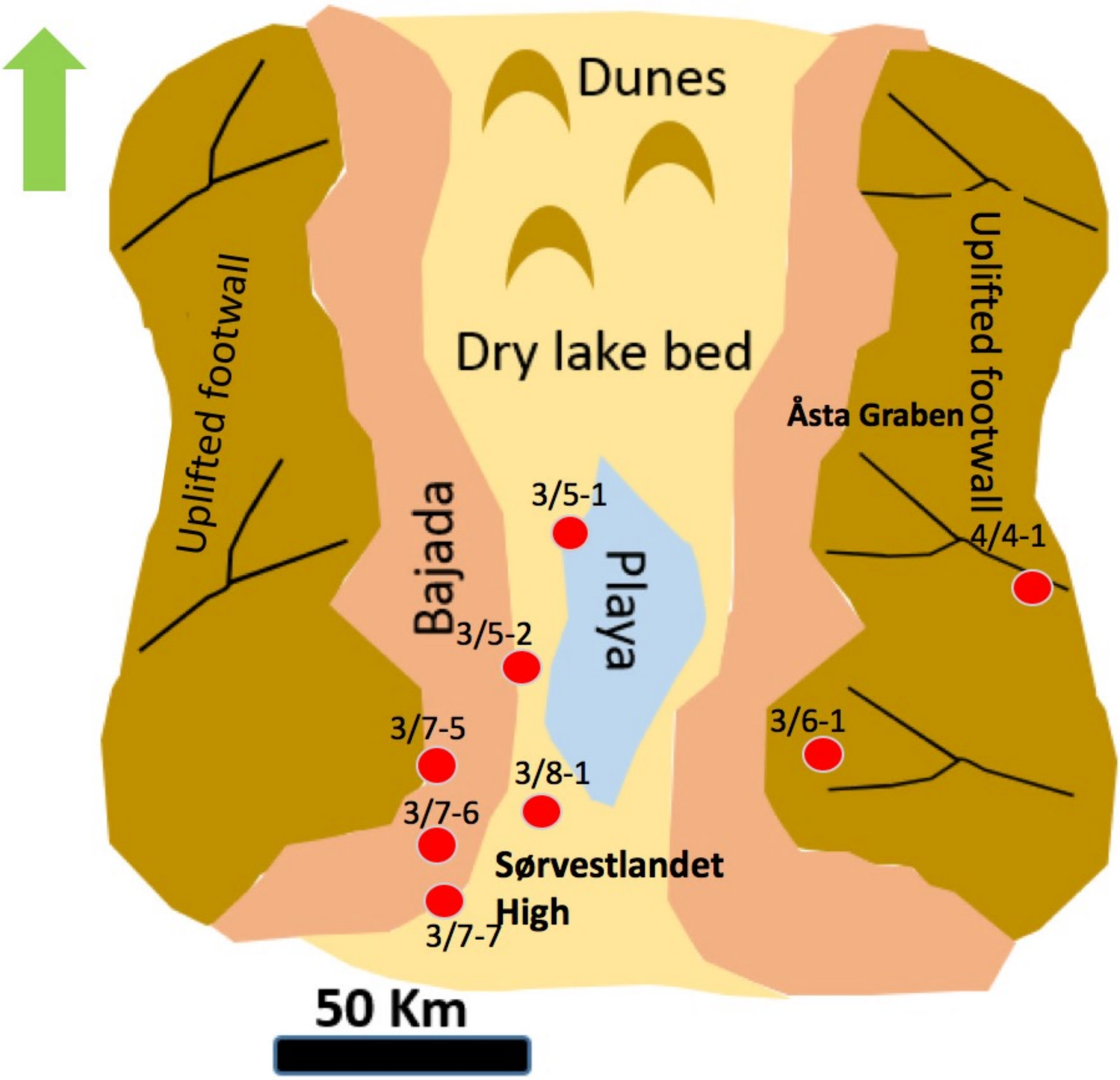


Figure 59: The depositional environment in the study area during the Lower Permian with the positions of wells

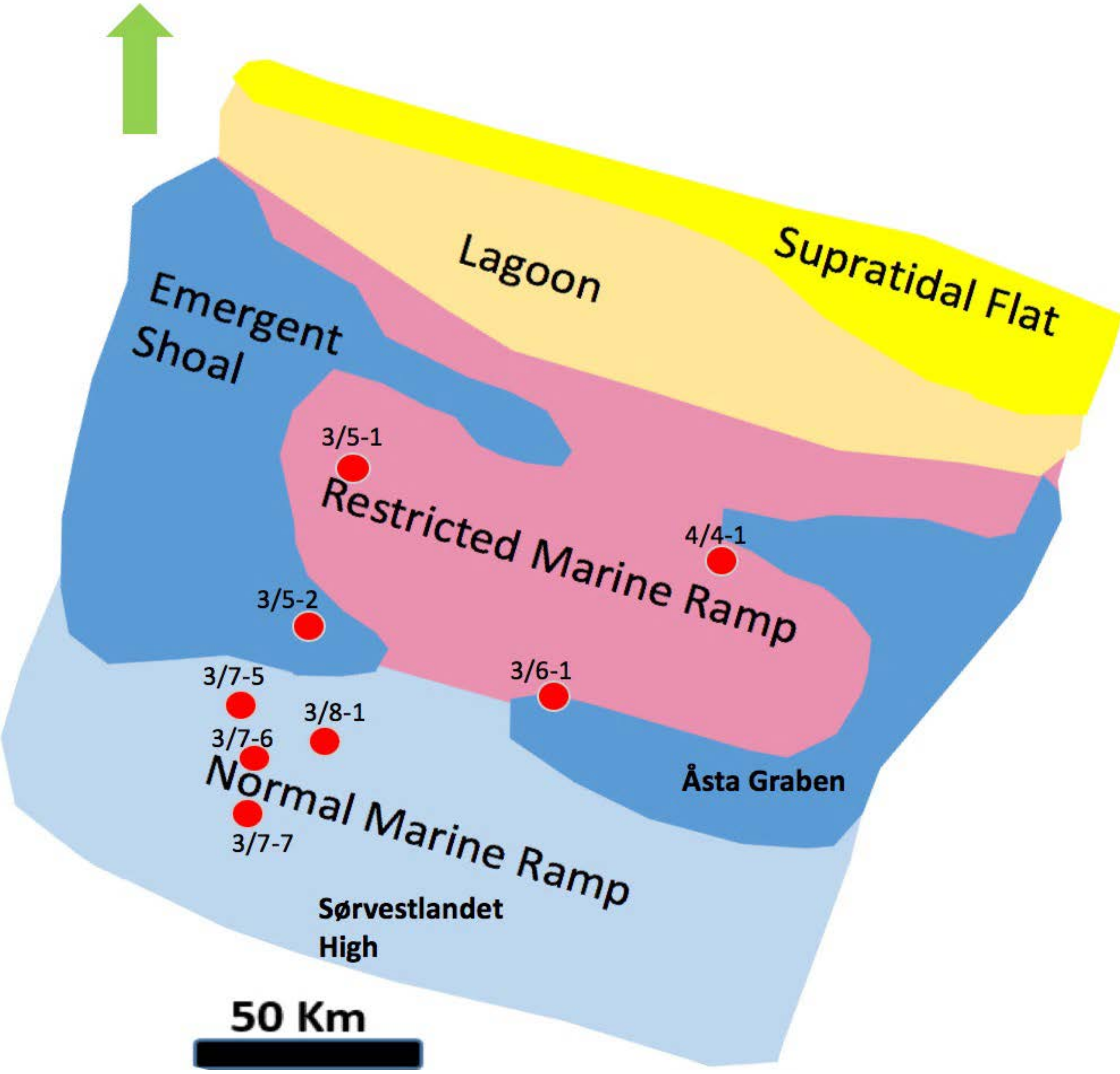


Figure 60: The depositional environment in the study area during the Upper Permian with the positions of the well

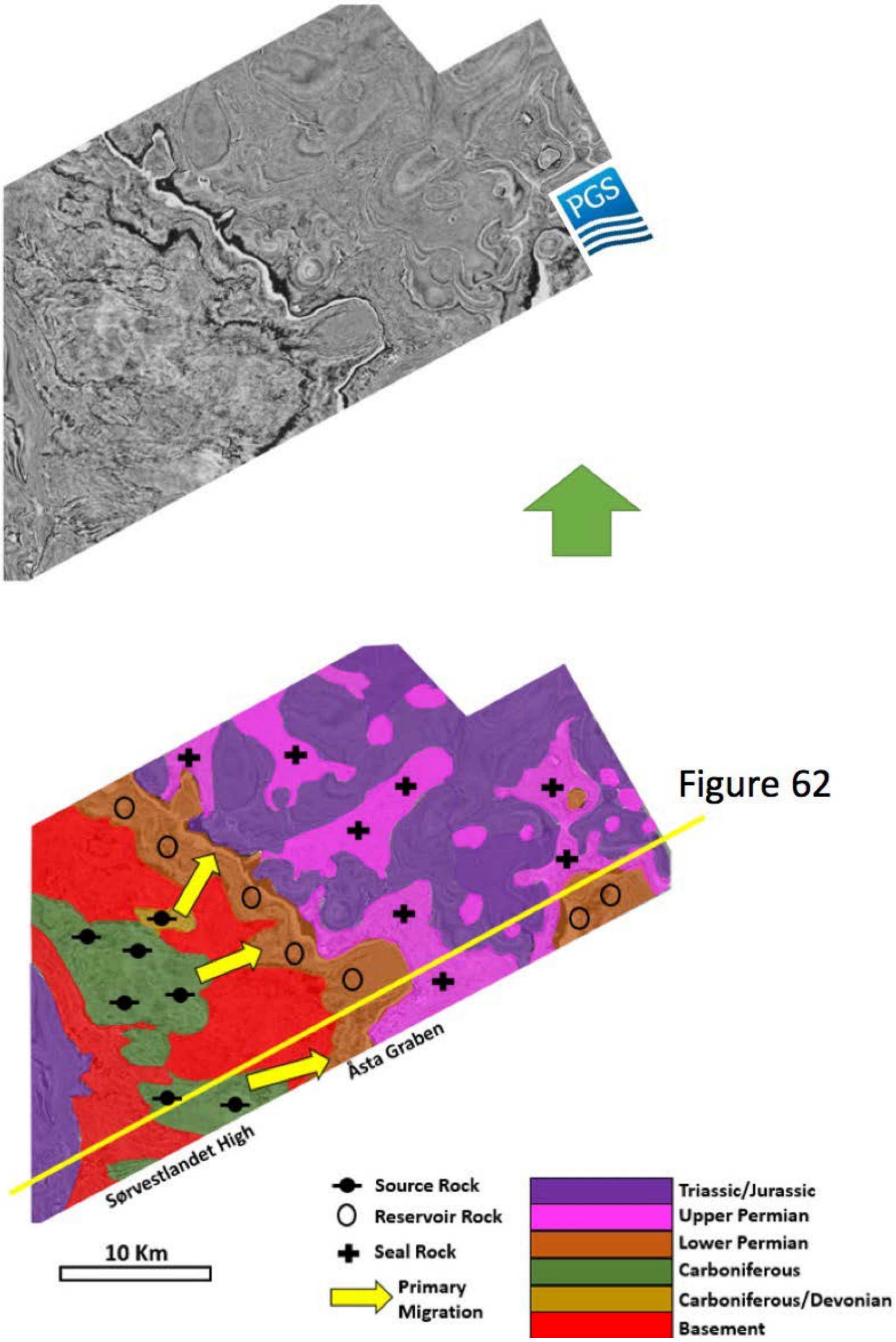


Figure 61: Seismic time slice at 2940 ms showing the lateral distribution of the different petroleum elements (source, reservoir and seal rock) and the lateral migration pathways

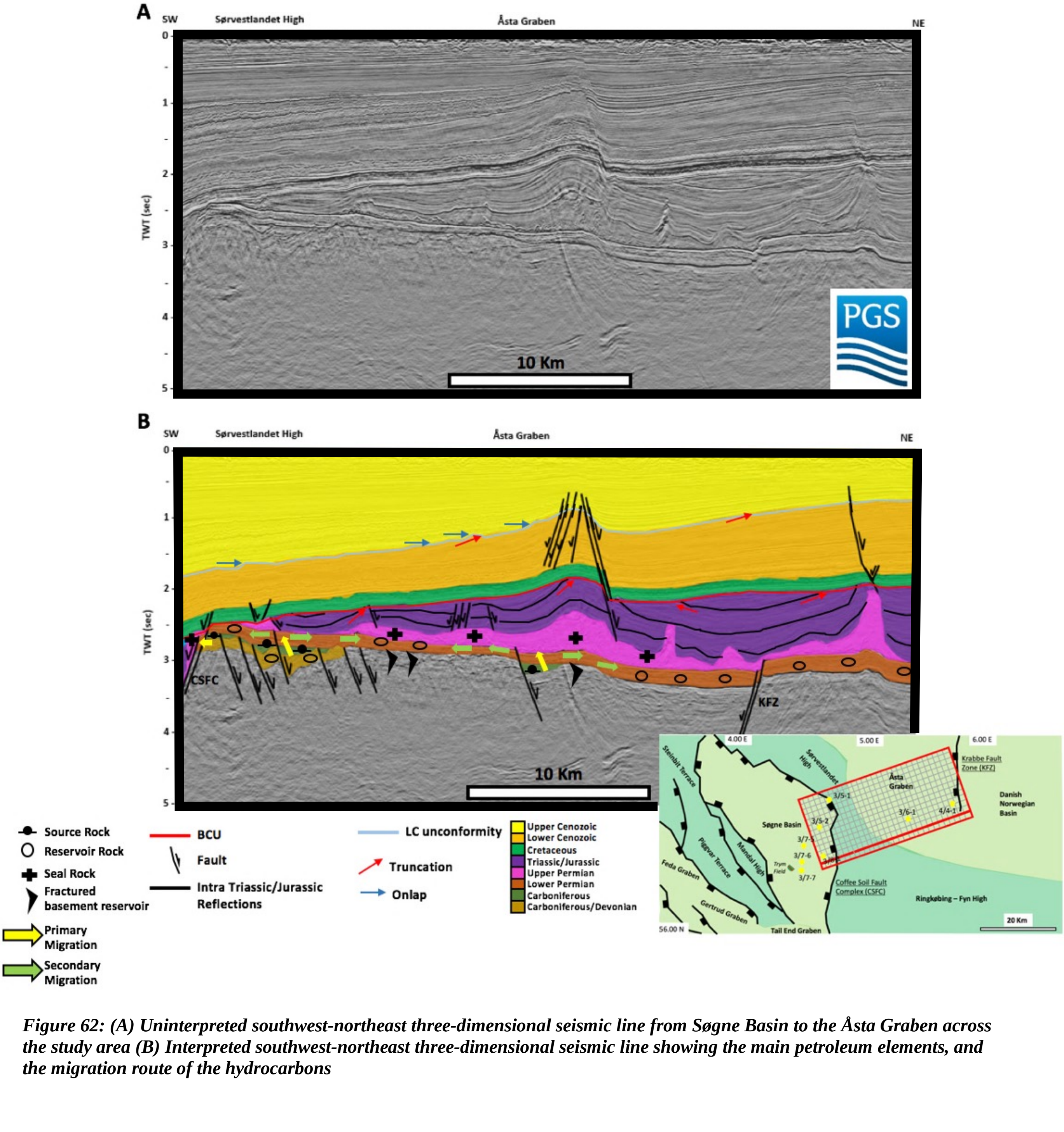


Figure 62: (A) Uninterpreted southwest-northeast three-dimensional seismic line from Søgne Basin to the Åsta Graben across the study area (B) Interpreted southwest-northeast three-dimensional seismic line showing the main petroleum elements, and the migration route of the hydrocarbons

Conclusions

The newly acquired three-dimensional seismic cube covering the Sørvestlandet High and Åsta Graben has been the basis for this study. Using different seismic interpretation technique, along with a two-dimensional restoration of the study area, a detailed study of the geological evolution and petroleum system has led to these conclusions:

A. The Sørvestlandet High is an Upper Jurassic high shaped as northwest-southeast-trending horst separating the Søgne Basin to the west from Åsta Graben to the east. The main faults bounding the high are the Upper Jurassic Coffee Soil Fault Complex to the west and the Triassic Krabbe Fault Zone to the east.

B. Eight normal fault families have been identified in the study area. Four sub-salt fault families and four supra-salt fault families. Sub-salt fault families include: (1) a north-northwest-south-southwest striking fault family, (2) a northeast-southwest striking fault family, (3) an east-northeast-west-southwest striking fault family, (4) a north-northeast-south-southwest, including the Coffee Soil Fault Complex and Krabbe Fault Zone. The supra-salt faults include: (5) a northwest-southeast striking fault family, (6) a north-northwest-west-south-southeast striking fault family, (7) an east-west striking fault family, (8) north-northeast-south-southwest striking fault family.

C. The salt mobilization occurred during the Triassic to Cretaceous, with a climax in the Upper Triassic/Jurassic. The intensity of the mobilization is highly connected to the structures formed and the connection between the sub-salt fault families and the supra salt-salt fault families. The main salt structures are found in the Åsta Graben, while most of the salt is welding or minor salt pillows is present in the Sørvestlandet High. The major salt walls and diapirs are found in the northern Åsta Graben indicating a more intense halokinetic movement here compared to the rest of the study area, where there are only salt diapirs, pillows, roller or salt welding present. But there is more soft linkage between the sub-salt fault families and the supra-salt faults families in the southern part of the Åsta Graben compared to the northern Åsta Graben. No linkage between the sub-salt fault families and the supra-salt families dominates in the norther Åsta Graben.

D. The petroleum system of the Sørvestlandet High is an analogue of the Mandal High and Utsira High, in the sense that the three structures are Upper Jurassic horsts and that the fractured and weather crystalline basement might act as a trap in the petroleum system. In addition, a Paleozoic petroleum system is proposed in the Sørvestlandet High. The main source rock in this play is the Devonian and Carboniferous lacustrine shale with local migrations to the Lower Permian Roteliegend aeolian sand, weathered crystalline basement and perhaps Devonian sand. These are regionally covered and sealed by the Upper Permian Zechstein salt. The main risk for the petroleum system in this area is the presence of the source rock, and the type of hydrocarbons (movable vs non-movable hydrocarbons) Therefore, it is recommended to drill deeper in the Sørvestlandet High to target the sub-Permian and to get geochemical samples of the oil types in these source rocks.

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