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Interpretation of Upper Jurassic sandstone in the area between Statfjord and Tordis field, Northern North Sea

by

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Abstract

Interpretation of Upper Jurassic sandstone in the area between Statfjord and Tordis field, Northern North Sea

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The University of Stavanger, 2014

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The study area is located in the half graben between the Statfjord field and the Vigdis development on the Tampen Spur, northern North Sea. The petroleum systems in the central and northern North Sea are mainly Jurassic-sourced. The Late Jurassic sandstones are one of the major reservoirs in the study area and formed during the Late Jurassic rifting as syn-rift sediment which also formed syn-rift plays. The sedimentary source came from erosion of the footwall exposed during the rifting event, and the source directions are north and east. Late Jurassic was the time of the widespread Kimmeridge Clay Formation that constitutes a world class of oil source rock. Late Jurassic reservoirs are very good potential petroleum plays which can be seen form the oil fields in the northern North Sea. This thesis will focus on the Late Jurassic sandstone in the Draupne Formation of Viking Group. The depositional environments of the Late Jurassic sandstones are shallow-marine system and deep-marine fan system. The interpretation of the Late Jurassic sandstones is based on well data and seismic data. Two methods of surface attribute are used to interpret the sandstone in the seismic data. The analysis of the Late Jurassic sedimentary model is very important for the exploration process in this area. The result of this thesis would support exploration decision in the future.

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1. INTRODUCTION

The North Sea area is though time the one of the most productive hydrocarbon provinces in the world. Since 1993, the study of uplift footwall and structural highs has been focused in the exploration activity in the areas of the northern North Sea (Brennand, 2009). From Mid to Late Jurassic, the effects of extensional tectonics formed variable patterns of footwall uplift and hanging wall subsidence, with a variety of syn-rift reservoir plays (Dawers et al., 1999).

In the northern North Sea, three main rift tectonic phases occurred and are related to the Late Jurassic rift structure. In accordance with these tectonic phases and the reservoir ages, the event in this area can also be grouped into pre-rift, syn-rift and post-rift phases (Johnson, 2009). Almost 80% of the hydrocarbon accumulation belongs to both pre- and syn rift phases in the North Sea (Fraser et al., 2002). There have been some shows of hydrocarbon in the Upper Jurassic syn-rift plays, which reserved in the reservoirs formed of shallow marine sandstone facies in the northern North Sea (Nøttvedt et al., 2000). The Late Jurassic syn-rift phase has been proven to consist of important reservoirs with considerable volumes, which is the main reason to develop the basin-infill models. In this study project, the syn-rift Upper Draupne sandstone is the main target, which is the reservoir of Borg, Borg Northwest and Statfjord North oil fields. However, the distribution of sandstones and its source from nearby exposed footwall blocks has been poorly understood. Therefore, the distribution of the syn-rift plays will be focused in this study.

The main objectives of this thesis are to interpret the Upper Draupne sandstone, and to build a depositional model for the Upper Jurassic syn-rift depositional packages in the half-graben between the Statfjord field and the Vigdis development. To develop the depositional model, seismic/geophysical mapping of the Upper Jurassic Draupne reservoir sandstone will be one of the most essential inputs. The Upper Jurassic Draupne stratigraphic discovery will be the key known seismic facies/signal, which will be used as an analogue/guidance for the interpretation in the areas without well control. In this study area, the Upper Draupne sandstone and Draupne shale are deposited during the same time. Hence, how to distinguish the Upper Draupne sandstone and Draupne shale in the seismic data both horizontally and vertically is a main topic of this investigation.

The study area is located on the Tampen Spur, in the northern North Sea (Figure 1.1). Several oil and gas fields have been discovered in this area (Figure 1.2) which is Statfjord field in the west, Tordis field in the east. In addition, there are also some fields outside and close to the study area, which are Vigdis field, Snorre field to the north, and Gullfaks field to the southeast. Snorre, Statfjord, and Gullfaks fields are three major oil fields and have been estimated recoverable reserves of 5.5 billion barrels oil and natural gas liquids (Karlsson, 1986).

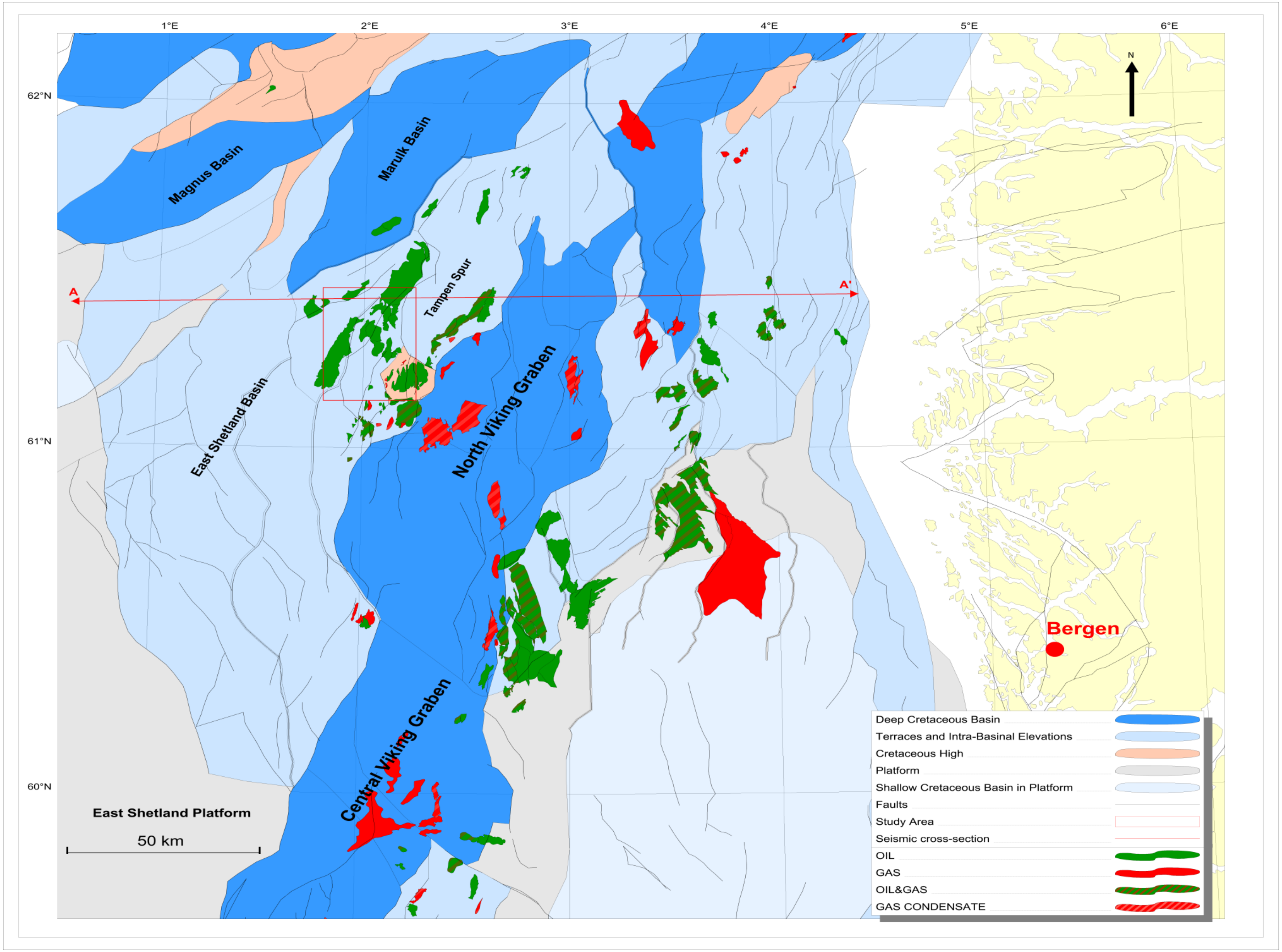


Figure 1.1. Main structural element from the NPD, showing the location of the study area in Norwegian North Sea, displayed in the red rectangular.

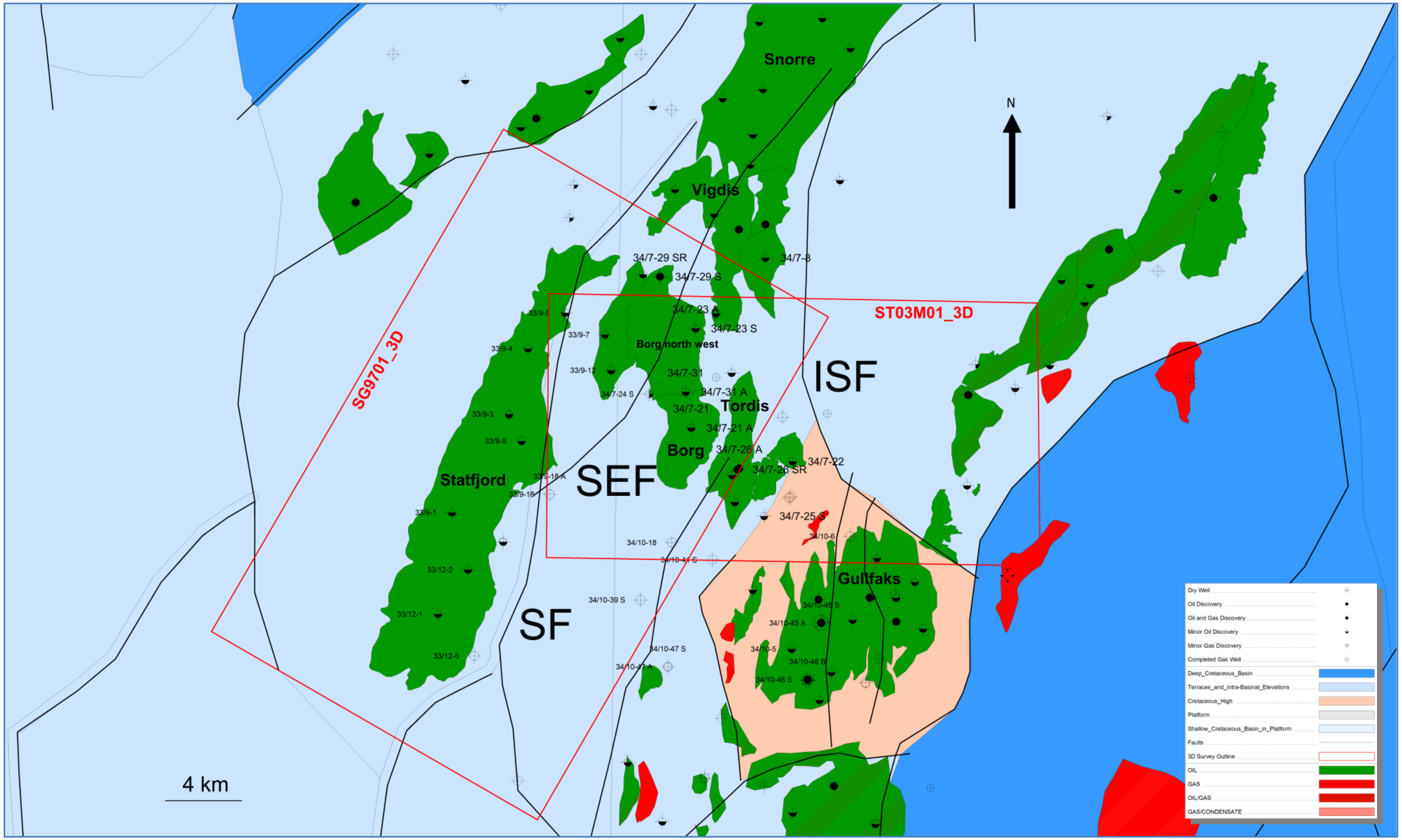


Figure 1.2. Map showing the main geologic elements (basins, high, and faults), hydrocarbon fields, exploration wells and fields, and the data used in this study (three-dimensional seismic coverage and exploration wells). SF=Statfjord Fault, SEF=Statfjord East Fault, ISF=Inner Snorre Fault.

2. GEOLOGICAL SETTING

2.1 Present-day structural elements

The main structural elements in the study area are shown in Figure 1.1. To the west, the Shetland Basin and two major faults which are Statfjord Fault and Statfjord East Fault are located. Both faults are normal faults dipping to the east with northeast-southwest striking direction. The Statfjord East fault and the Inner Snorre fault both truncated to the north. A regional major normal extensional fault named as Inner Snorre Fault formed the eastern boundary of this area, which is also the west boundary of Northern Viking Graben (Figure 1.2). The Tampen Spur where the study area is mainly located is a rift basin formed in the Late Jurassic, and is located at the footwall block of Inner Snorre Fault (Fraser et al., 2002).

The North Viking Graben is the major structure of the northern North Sea (Figure 2.1). The north-northeast trending structure consists of three main individual segments named as the North, Central, and South Viking grabens. The development of the Viking Graben started during Permo-Triassic, which was formed by the rifting and thermal subsidence (Underhill, 1998).

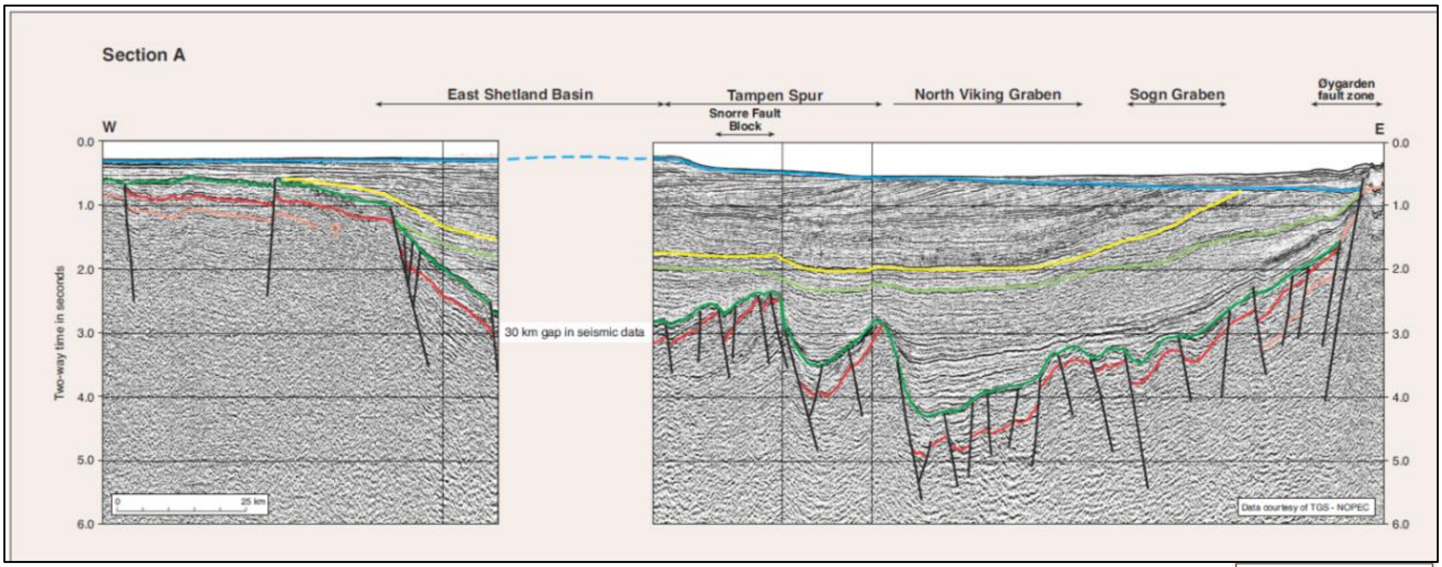


Figure 2.1. Regional seismic cross-sections illustrate the different structural styles of the northern North Sea (Zanella et al., 2003). The location of the seismic cross section is shown on Figure 1.1.

2.2 Tectonic evolution of the study area from Late-Permian to Recent

This study focuses on the deposition of Upper Jurassic sandstones, therefore, only the main tectonic events from Permian to Early Cretaceous are included for the tectonic evolution.

2.2.1 PERMAIN

During Late Permian, rifting events occurred in the Faeroe-East Greenland area and in the northern North Sea (Figure 2.3). There was a seaway which was developed through the southern North Sea to the Arctic Ocean due to the rifting events. A Zechstein Sea formed caused by the marine transgression and then formed the Permain salt basins in the large part of northern and central Europe (Coward et al., 2003). The Northern and Southern Permian basins formed which were separated by the Mid-North Sea High in the Permain basin (Figure 2.3).

2.2.2 TRIASSIC

The Triassic rifting affect the Northern and Central North Sea Basins, which were controlled by north-south direction faulting, followed by the distinct and deep grabens formed (Fisher and Mudge, 1998). In the northern North Sea, the Triassic faults were opened by the dominant northwest-southeast rift direction (Coward et al., 2003). Based on Figure 2.5, the Northern North Sea Basins were located at the north outside of the Permain salt boundary, and then there is no halokinetic influence in the study area. A triple junction formed in the north-west Europe (Figure 2.3), caused by the different rift systems with different extensional directions between the Arctic and Atlantic regions, a triple junction formed in the north-west Europe (Figure 2.3).

2.2.3 JURASSIC

During the Early Jurassic, there are some minor rifting activities in the northern North Sea. Callovian volcanics indicate the presence of a mantle hot spot during Middle Jurassic, in the northern North Sea (Figure 2.3). The uplift caused by the hot spot and formed the erosion of the lower Triassic strata (Coward et al., 2003).

In the northern Viking Graben, the crustal extension initiated as almost at the same time as the deltaic depositions of the Brent Group in the Bathonian stage, which cross the newly developed north to north-easterly trending faults along with the thickness and facies changes (Coward et al., 2003).

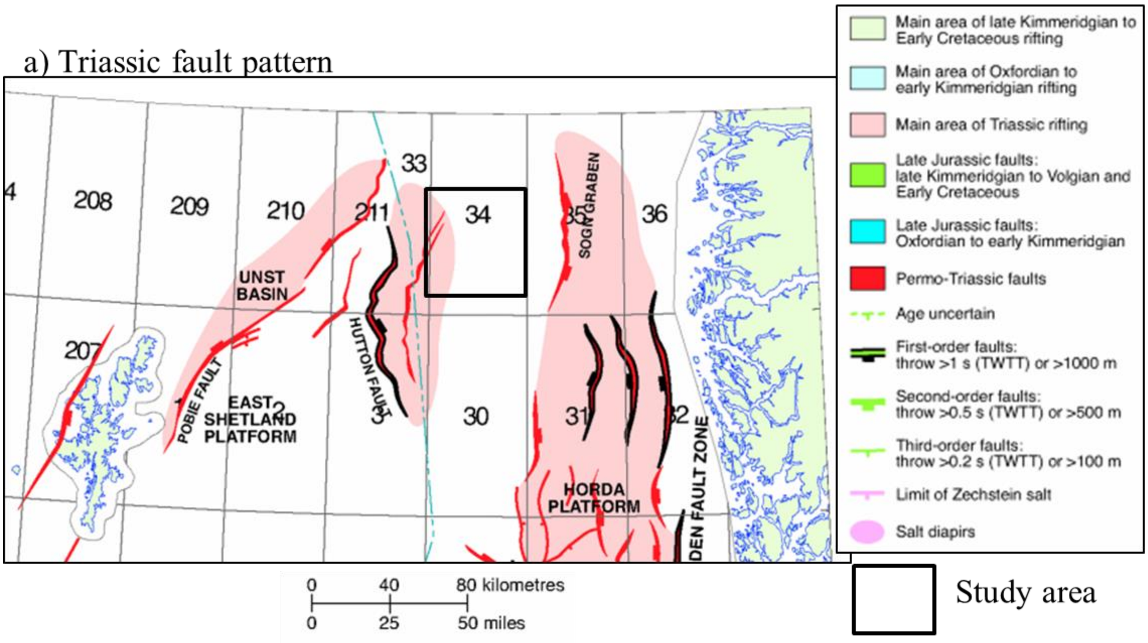
From Middle to Late Jurassic, the most significant rifting event took place in the northern North Sea (Figure 2.3), forming the rifting phase and establishing the basic structural framework in the North Sea Basin. Lower extent of extension had started in the Viking Graben during Bajocian to Bathonian stages. The Arctic extensional system expanded into the North Sea from Callovian to early Kimmeridgian, which formed the north to north-east normal faults in this area. The extension continues on processing during Oxfordian in the northern North Sea parts of mid-Norway shelf and Viking Graben (Coward et al., 2003).

During Latest Jurassic, the central North Sea experienced a change of extensional direction, to northeast-southwest. In the Viking Graben, the old northwest-west normal faults, coupled with Volgian and Early Cretaceous extensions, were superimposed on the new north-east Late Jurassic normal faults, and made the old faults reactivate. For example, the old north to north-east trending faults show as strike-slip faults caused by the reactivation. The Viking Graben shows the action as a left-lateral transfer system due to the northeast-southwest extensional phase in the Central Graben and to the rifting along the Norwegian margin (Coward et al., 2003).

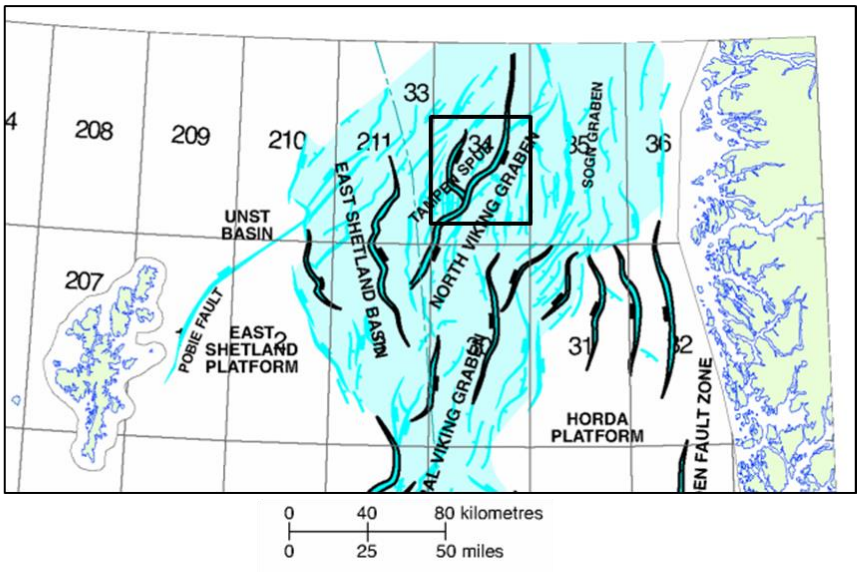
In the North Sea, from Triassic to Jurassic extension, since the main extensional direction is changed, there is an ‘extension-vector-triangle’ model took place during the North Sea rift. During the Triassic age, the dominant extensional direction was northwest-southeast in the northern North Sea, and the extension of northeast-southwest direction opened the Triassic normal faults in the Central Graben. Late-Jurassic rifting extensional structures are mainly located in the northern North Sea, forming large, north to northeast trending tilted fault blocks. In addition, faults originated in Triassic show reactivation in Jurassic (Coward et al., 2003).

The Permo-Triassic and Late-Jurassic rift periods are different at structural style. In the northern Viking Graben, the tectonic extensional periods changed both in space and time, which indicate the variance in architecture and composition of the syn-rift infill (Ravnås et al., 2000). In additional, the depositional environment varied as a result of the complex extensional phase and crustal thinning, mainly from continental environment during Permo-Triassic rifting to marine environment during Late-Jurassic rifting (Figure 2.2) (Zanella et al., 2003). The Triassic rifting is widely extensive in the northern North Sea with extensional direction of east-west, and formed the north-south trending faults (Figure 2.2 (a)). During the Late Jurassic rifting, the extensional structures mainly took place in the northern North Sea (Figure 2.2(b)). This result caused by change of extensional direction to northwest-southeast, and new faults formed with north-northeast trending direction. In addition, the older major Triassic faults were reactivated by this extension (Figure 2.2 (b) and (c)) (Zanella et al., 2003).

a) Triassic fault pattern



b) Oxfordian to early Kimmeridgian fault pattern



c) Late Kimmeridgian to early Cretaceous fault pattern

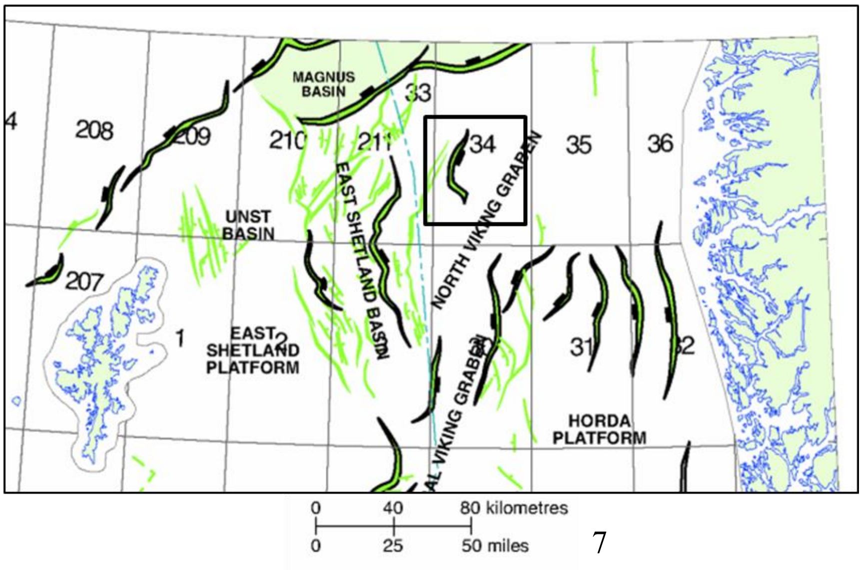


Figure 2.2. Rifting fault pattern during Triassic to Early Cretaceous (Zanella et al., 2003).

2.2.4 CRETACEOUS

During the earliest Cretaceous, Late Jurassic faults were still active, associated with deposition of clastic sediments against the fault scarps in the central and northern North Sea. From Jurassic to Early Cretaceous, the extension ceased with the onset of passive thermal subsidence, and the syn-rift topography was covered by transgressive sediments that also formed the Base Cretaceous Unconformity. The dominant deposition was marine shale, and these uplifted footwalls were covered and were gradually onlapped by the Base Cretaceous Boundary, although there were numerous phases of minor faults reactivation; however it may be caused by the compaction of earlier sediments (Coward et al., 2003).

2.2.5 PALEOCENE TO RECENT

There are some anomalous subsidence events partially attributed to igneous underplating shown in some back-stripped wells, which are located in the North Sea and Faeroe–Shetland Basin during Paleocene (White and Latin, 1993). In the North Sea and west of Shetland, the presence extensive erosion was followed by the submarine-fans deposition, which was contributed by the uplift process of northern Scotland and probably associated with the Iceland plume (Zanella et al., 2003).

From Eocene to Oligocene, the North Atlantic Ocean formed in the middle of Greenland and Scotland. In the North Atlantic, the Labrador Sea showed the ceased opening and a minor change in opening trend direction. Therefore, the local basin inversion was caused by large transform faults, which is affected by compression (Doré, et al., 1999). The basin inversion may affect the north-eastern North Sea. During Pleistocene, the regional uplift event explained the rapid erosion and deposition of glacial period (Coward et al., 2003).

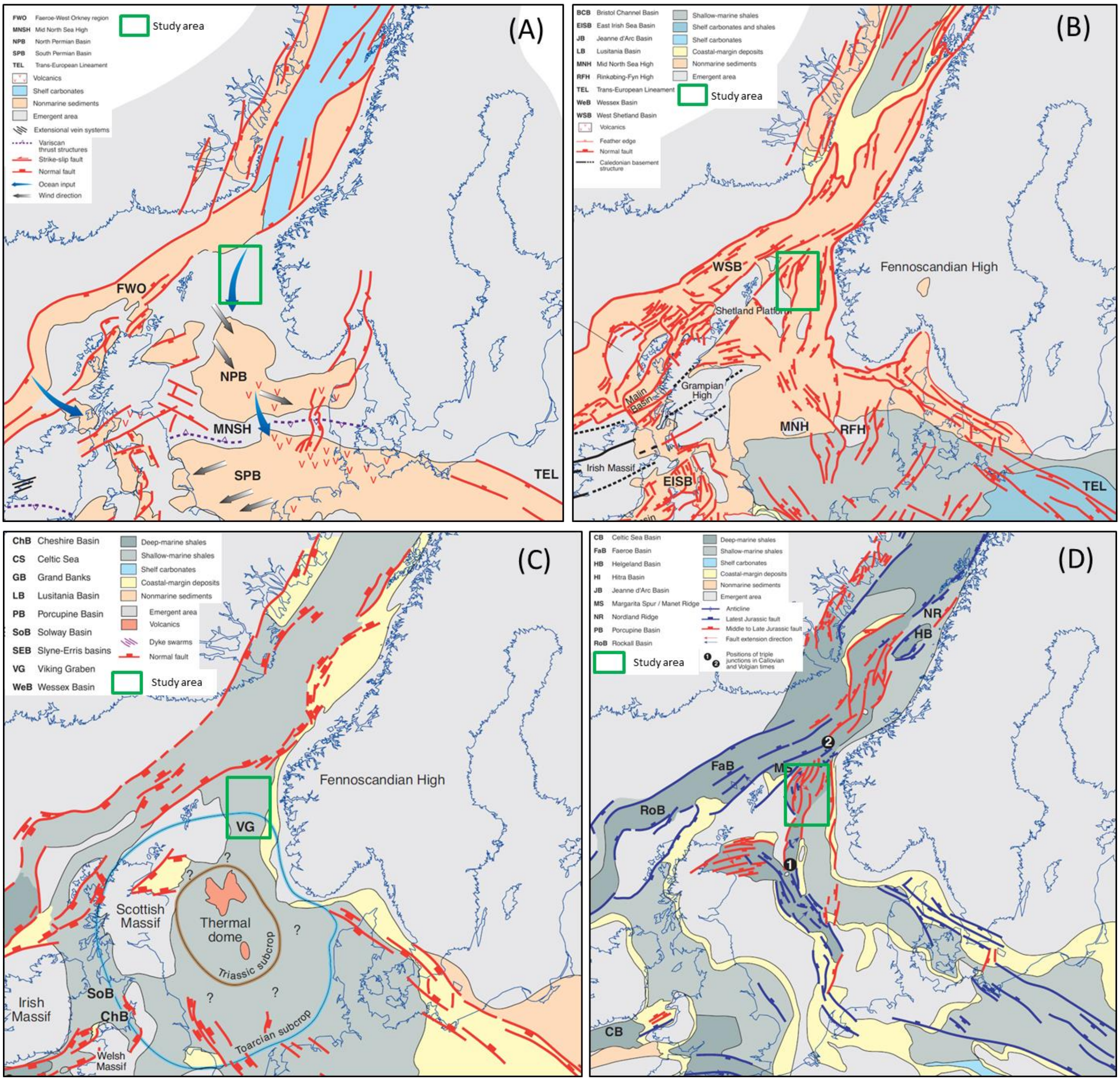


Figure 2. 3. Tectonic evolution of the study area graben and its surrounding area of A)Permian B)Triassic C)Early to Middle Jurassic and D) Late Jurassic time (Coward et al., 2003)

2.3 Stratigraphy Late Jurassic – Early Cretaceous of the study area

The main successions of regional lithostratigraphy in the Tampen Spur area during Jurassic age are shown in Figure 2.4. The syn-rift Draupne formation is the focus which was deposited during the Late Jurassic age. The Draupne formation was overlain by the Heather formation which is the regional source rock, and was underlain by the Cromer Knoll group which deposited during the Early Cretaceous. The Base Cretaceous Unconformity is the boundary between these two formations and marks the transition from syn-rift to post-rift episodes. In the Draupne formation interval, the Upper Draupne sandstone is the major sand body present in the upper part during the Late Volgian to Early Ryazanian (Nøttvedt et al., 2000).

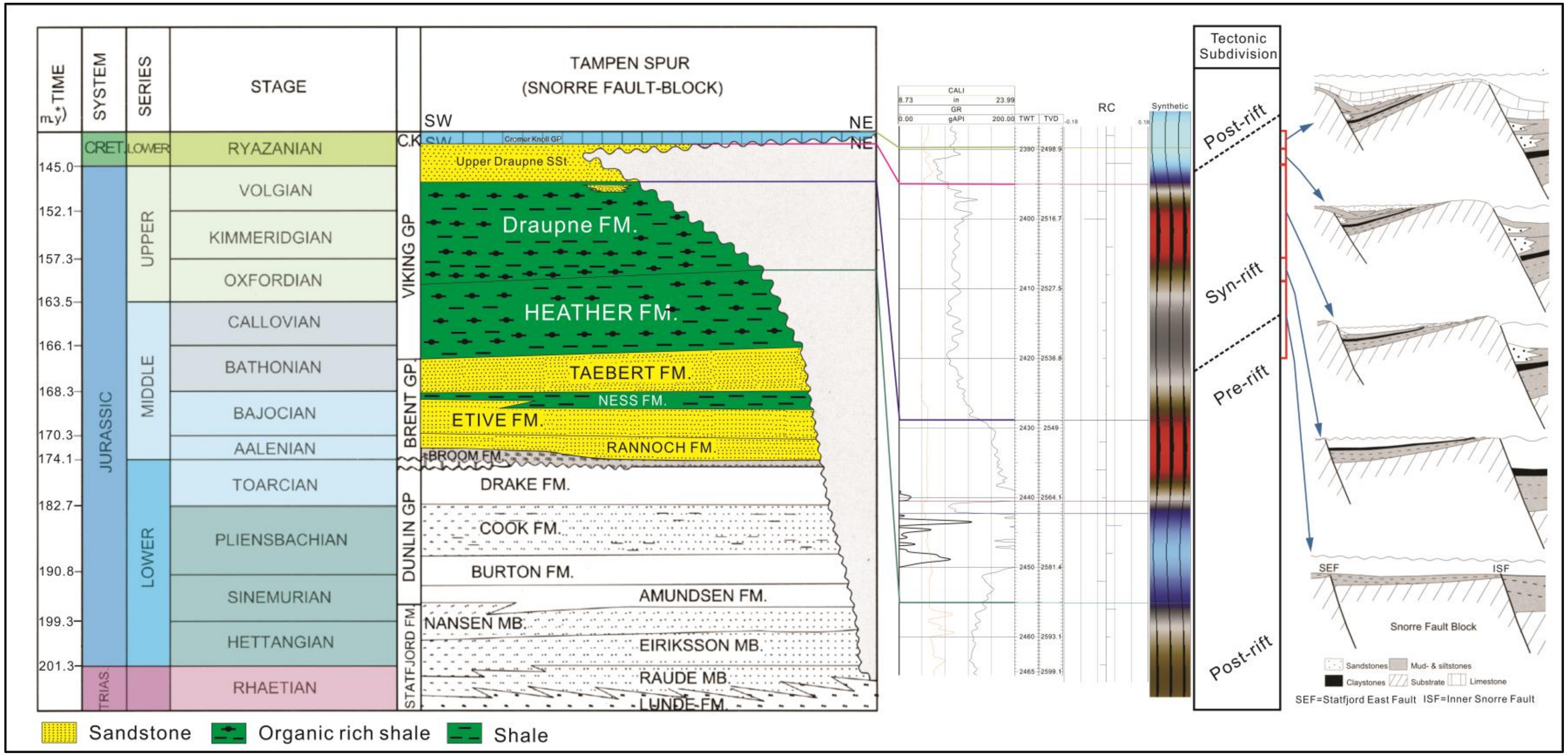


Figure 2. 4. Lithostratigraphy of the Tampen Spur area with the well log data and main faults rotational stages on the right column modified after Nøttvedt et al., 2000.

2.4 The Upper Jurassic depositional system

Upper Jurassic reservoir sandstones were deposited in two main depositional environments during the Late Jurassic. The first is shallow-marine/coastal-shelf system, of which the evidences are in the Fulmar, Ula/Gyda, Heno, Piper, and Borg fields. The second depositional environment is the deep-marine slope-apron and fan systems which are evident up in the Magnus Sandstone Member and the Brae Formation (Fraser et al., 2002). There are two general depositional models below showing these two depositional environments in the North Sea. However, the sandstones formed in the shallow-marine system are the main target of this investigation.

The shallow-marine/coastal-shelf systems are significant sequences formed during the rapid rise of relative sea level (Figure 2.5). The shallow-marine sandstones are formed in an extensive coastal-shelf depositional system, as good reservoir sand bodies located at basin margins, and were deposited in different environment as shoreline, shoreface and shelf. These sandstone bodies are characterized as progradational upward-coarsening sequence and aggradational fining-upward sequence (Fraser et al., 2002).

In the deep-marine slope-apron and fan systems (Figure 2.6), the sandstones are mainly deposited in submarine fans to deep-marine basins. These sandstones can be divided into gravel rich and sand rich fans, which formed related to the Late Jurassic rift activities (Fraser et al., 2002).

Both of these types of sandstones above were deposited related to the footwall uplift and hanging wall subsidence during rifting, and were sourced from erosion of the locally uplifted footwall.

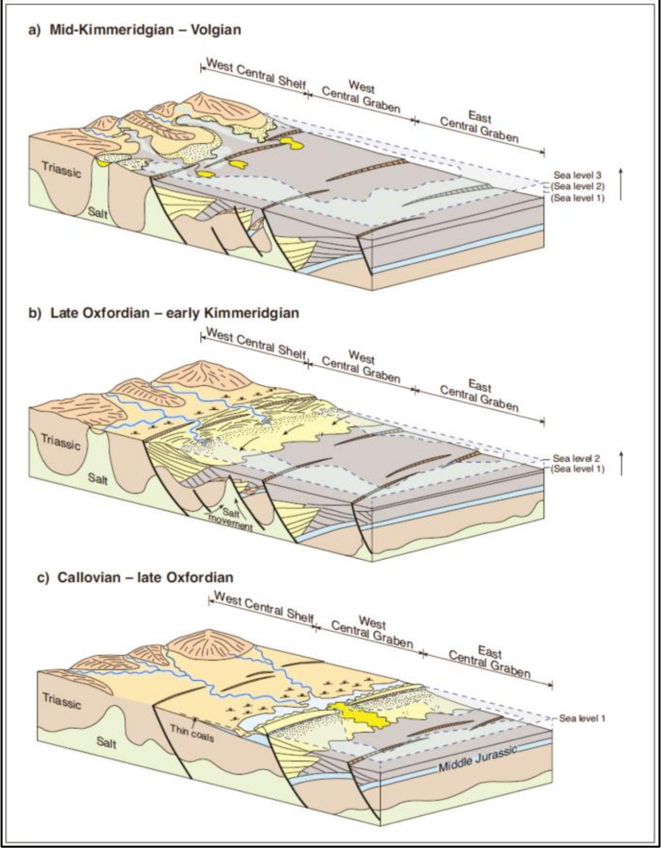


Figure 2.5
Schematic illustration of the development models of shallow-marine sandstones in the Central Grabenm, during Callovian to Volgian from c) to a) (from Fraser et al., 2002).

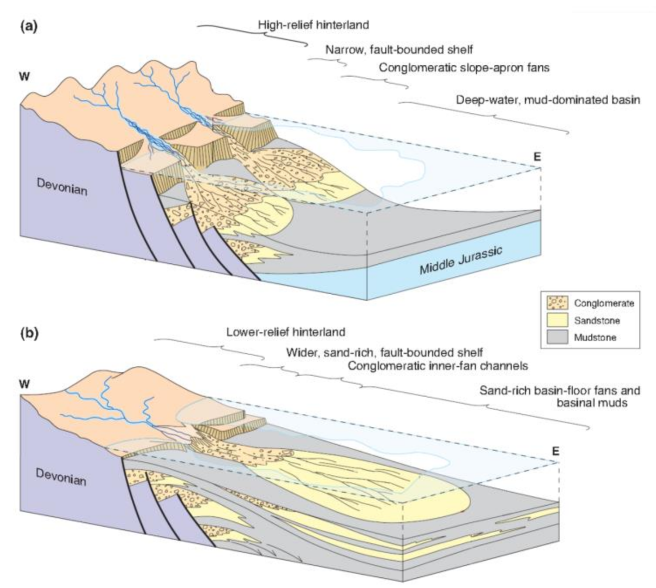


Figure 2.6
Schematic illustration of two submarine fan models; a) gravel-rich and b) sand-rich (from Fraser et al., 2002).

3. DATASET AND METHODOLOGY

3.1 Dataset

The dataset used in this project are provided by Suncor Norge AS, which consists of well data and 3D seismic data.

3.1.1 WELL DATA

All of the related exploration wells in the area have been used for this study (Figure 1.2) with different uses (Table 1). The core pictures are available in some wells which were only used for the Upper Jurassic formation, and will be shown in next chapter.

Table 1. List of exploration wells and main use of the wells

Well name	Main use	Well name	Main use	Well name	Main use
33/9-1	S	34/7-8	O	34/7-30 S	O
33/9-3	S	34/7-12	S	34/7-31	T, S
33/9-4	S	34/7-14	S	34/7-31 A	S
33/9-5	S	34/7-17	S	34/7-33	S
33/9-7	S	34/7-17 A	S	34/10-12	S
33/9-9	S	34/7-18	S	34/10-18	C, T, S
33/9-12	S	34/7-21	C, T, S	34/10-34	S
33/9-18	C, S	34/7-21 A	C, T, S	34/10-41 S	S
33/9-18 A	S	34/7-22	O	34/10-45 A	S
33/12-1	S	34/7-23 A	C, T, S	34/10-45 S	O
33/12-2	S	34/7-23 S	C, T, S	34/10-46 B	S
33/12-3	S	34/7-24 S	T, S	34/10-46 S	S
33/12-4	S	34/7-25 S	O	34/10-47 A	S
33/12-5	S	34/7-26 A	C, T, S	34/10-47 S	S
34/7-2	S	34/7-26 SR	C, S		
34/7-5	S	34/7-29 S	C, T, S		
C, well core description; S, applied in seismic interpretation; T, applied for well tie; O, applied for general information					

Nine wells are used for the seismic well tie, which are significant for the seismic interpretation, and contain wireline logs, stratigraphic well tops, and parts of checkshot data. The rest of the wells are used for seismic interpretation and providing additional information. The key wells data are from well 34/7-21 and well 34/7-21A, which are located in the Borg discovery. These wells together with well logs and the stratigraphic well tops have been used in the seismic interpretation.

3.1.2 CORE PHOTOGRAPHY DATA

Core photographs from six key wells in the Draupne Formation (Table 2), used to do the lithology description and build the general facies model. The source of Core photographs is the NPD database.

Table 2. The core photography intervals from the wells

well name	Core interval (MD)
34/7-26 A	4129-4130m, 4132-4216m
34/7-29 S	2701-2724m
34/7-23 A	3199-3222m, 3223-3278m, 3279-3291m
34/7-23 S	3079-3095m, 3106-3116m, 3117-3136m
34/7-21	2515-2522m, 2530-2588m
34/7-21 A	2867-2873m, 2874-2885m, 2890-2900m, 2901-2920m, 2943-2953m

3.1.3 SEISMIC DATA

There are four 3D seismic survies used in this study, which are SG9701, ST03M01, CTM94 and MC3D_PGS_MEGASURVEY. SG9701 and ST03M01 seismic survies cover most of the study area (Figure 1.2), and the other two seismic survies are used for the eastern part of the study area. The frequency of SG9701 and ST03M01 are 30Hz and 20Hz, the interval velocity of Draupne Formation is 2900 m/s, and then the velocity resolutions are 24m and 36m respectively. All of them are used for the seismic interpretation. The interpretation is targeted at the Draupne formations from Late Jurassic to Early Cretaceous.

3.2 Methodology

The analysis of the well data was the first step of this study. Well correlation and sequence stratigraphy interpretation were finished in this step, which are significant for analysis of the depositional sequence. The description and interpretation of the photographic core intervals indicate additional information about the lithology and depositional environment of the focused Draupne Formations during the Late Jurassic.

From these important wells shown in the well correlation Figures 4.1 and 4.2, the lithological interpretation was based on these wireline logs, which are GR log, Neutron log, Sonic log, Density log and so on. Besides, the wireline logs were also used for well correlation and sequences stratigraphy interpretation. These results built a good framework for the lithology variance and depositional environment.

The sequences depositional model was built based on observation and interpretation of sequence stratigraphy and core photographs together.

Before the horizons interpretation, the process to build the correlation between the well data and the seismic data are very critical. To apply well data to the seismic data, wireline logs and checkshot data in Petrel are needed to construct the synthetic seismogram in the Petrel software, and then to recognize the seismic response of key horizons in this well tie process, especially in the Draupne Formations. In this process, synthetic seismogram was applied to these key wells 34/7-21, 34/7-21A, 34/7-26A, 34/7-31, 34/7-23A, 34/7-23S, 34/7-24S, 34/7-29S and 34/10-18, creating a good correlation between well data and seismic data.

The seismic interpretation, both in in-line and x-line, was performed using the Petrel software from Schlumberger. The seismic interpretation was used to perform the time structural maps of the main surface and time thickness map. The faults interpretation was focused on the major faults activities. Based on the seismic interpretation, time structural maps and thickness maps of the formations are both to estimate the location of the Upper Jurassic sandstones.

The seismic facies map is shown the distribution of Upper Draupne sandstone in these exploration wells. Surface attribute method was selected based on the observation of the seismic data of the Upper Draupne sandstone. The interpretation of potential Upper Draupne sandstones was finished applied by surface attributes data.

The Upper Draupne sandstone depositional map was finished based on the results of sequence stratigraphy and surface attributes.

4. WELL CORRELATION AND SEQUENCE STRATIGRAPHY

4.1 Well correlation

Well correlation (Figure 4.1) was done in this part based on the general well tops. The well tops in the interval of Draupne Formation consist of Top_Heather FM, Top_Intra Draupne SS, Top_Draupne SH, Top_Upper Draupne SS and Top_Viking GP. The correlation Figure 4.1 where the Top_Viking GP was flattened, shows the Draupne Formation turning thicker from south (34/10-47S, 34/7-39S and 34/10-18S) to north. The thickest part of the Draupne Formation presents in well 34/7-24S, but no Upper Draupne sandstone is present. In Figure 4.1, the Upper Draupne sandstone appeared in wells 34/7-23A and 34/7-31, and pinched out in the well 34/7-24S. In wells 34/7-26A, 34/7-21 and 34/7-21A, Intra Draupne sandstone was found being deposited in the Draupne shale, and pinches out to north and south seperately.

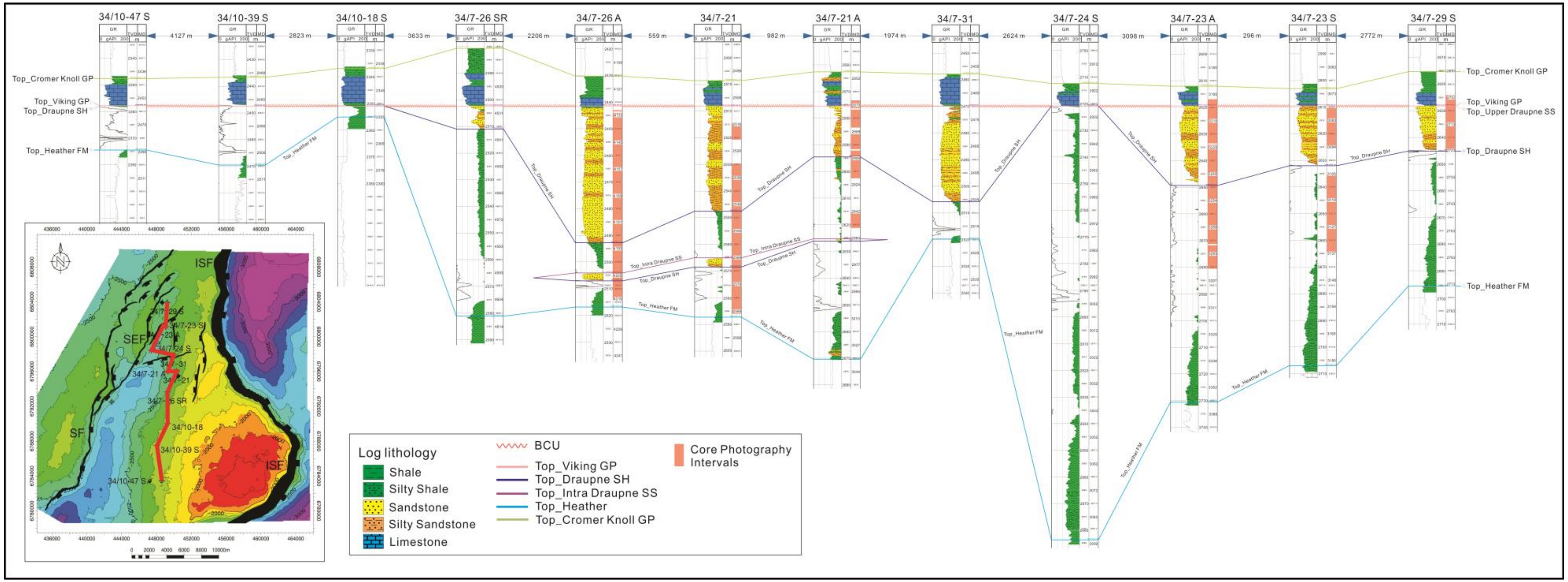


Figure 4.1. Well correlation based on main general well formation tops. Location is shown at left low side.

4.2 Sequence stratigraphy

Five bounding surfaces have been interpreted for the sequence stratigraphy (Figure 4.2). Three surfaces of which are flooding surfaces, FS1, FS2 and FS3, and the other two are Parasequence boundaries, 2A and 4A. From younger to older, the bounding surfaces are FS1, 2A, FS2, FS3, 4A. The interval between top Heather Formation and Base Cretaceous Unconformity (BCU) is divided by these surfaces into three stratigraphic sequences and two Parasequences. The first Parasequence boundary 2A is present in wells 34/7-21, 34/7-21A and 34/7-26A, and the second Parasequence boundary 4A is only shows in wells 34/7-23A and 34/7-23S. The sequences correlation is shown in Figure 4.2.

From the top Heather Formation to Base Cretaceous Unconformity (BCU), the Draupne Formation can be divided into three stratigraphic sequences as Sequence 1, Sequence 2 and Sequence3, and two Parasequences, 2A and 4A (Figure 4.2). The sequence correlation of these wells is shown as Figure 4.2.

4.2.1 SEQUENCE 1

Bounding surface: FS1 is the first flooding surface above Heather Formation, indicated by the obvious high gamma ray data signal in Draupne Formation (Figure 4.2). FS1 is shown in Well 34/7-26SR at 2574m (TVD), and is correlated to well 34/10-18S at 2353.3m (TVD) to the south. The depth of FS1 turned shallower from well 34/7-26SR to well 34/10-18, and then deeper to well 34/10-39S and well 34/10-47S. To the north, FS1 is correlated to well 34/7-26A at 2509m (TVD), well 34/7-21 at 2580m (TVD), well 34/7-21A at 2651m (TVD), and well 34/7-31 at 2516.1m (TVD). FS1 is located in Draupne Formation with uniform lithology around this surface. FS1 also shows in well 34/7-24S at 2792.6m (TVD), well 34/7-23A at 2670.8m (TVD), well 34/7-23S at 2648m (TVD), and well 34/7-29S at 2667.1m (TVD). The deepest part of FS1 occurred in well 34/7-24S, turned shallower to both southeast and northeast (Figure 4.2). FS1 is a flooding surface may indicating the deepening basin deposition with high accumulative rate and relative low sediments filling rate, which may be caused by increased or high rotation rate of the fault block.

Sequence character: Sequence 1 is bounded by top of Heather Formation and FS1, and deposited from late Early Oxfordian to Kimmeridgian (Nøttvedt et al., 2000). Shale present in Sequence 1 and turns finner upward in the whole well correlation, with different thickness in different wells (Figure 4.2). The thickest part of sequence 1 appears in the well 34/7-24S which is located almost in the mid of the study area, and it may be caused by the deepening of depositional environment and the relative low sedimentary rate. The thickness of sequence 1 turns thinner to the north (wells 34/7-23A, 34/7-23S and 34/7-29S) and much thinner and shallower to the south (34/7-26A, 34/7-26SR, 34/10-18, 34/10-39S and 34/10-47S) (Figure 4.2). Besides, to the south, a very thin sequence 1 shows up in the well 34/7-31 and is located at the upper part of the gradual depositional gradient shoreface.

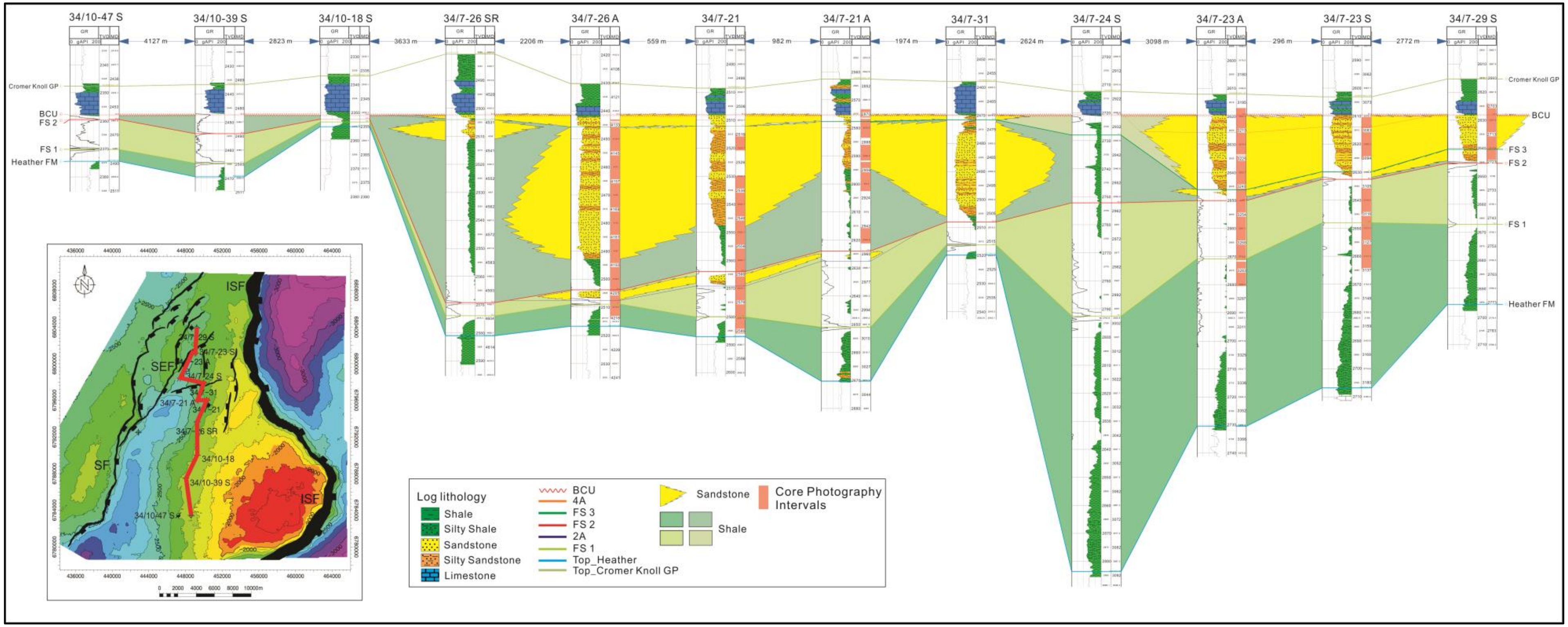


Figure 4.2. Stratigraphic correlation with facies infill. Location is shown at left low side.

Similar thickness of thin Sequence 1 was detected in well 34/7-21 and was proven by similar but thicker sequence 1 in well 34/7-21A, which is located in the lower part of the gradual depositional gradient shore face nearby 982 meters to the east of 34/7-21A (Figure 4.2).

Lithological character: From the well logs data, it shows high gamma ray signal and upward increasing in the Sequence 1 (Figure 4.3). The core photographs which were extracted from the interval of Sequence 1, indicats the main sedimentary lithology as dark black shale. The core photographs are described as very low density bioturbation, and thin low angle sandy lamination (Figure 4.3, part B). In some intervals, ripple cross lamination was found, showing sharp based deposition (Figure 4.3, part D). In addition, shell, carbonate debris and some light yellow debris are also present in this formation (Figure 4.3, part A and C). This shale interval was interpreted as being deposited in low to medium energy water, of which the depositional environment can be offshore of the deep marine.

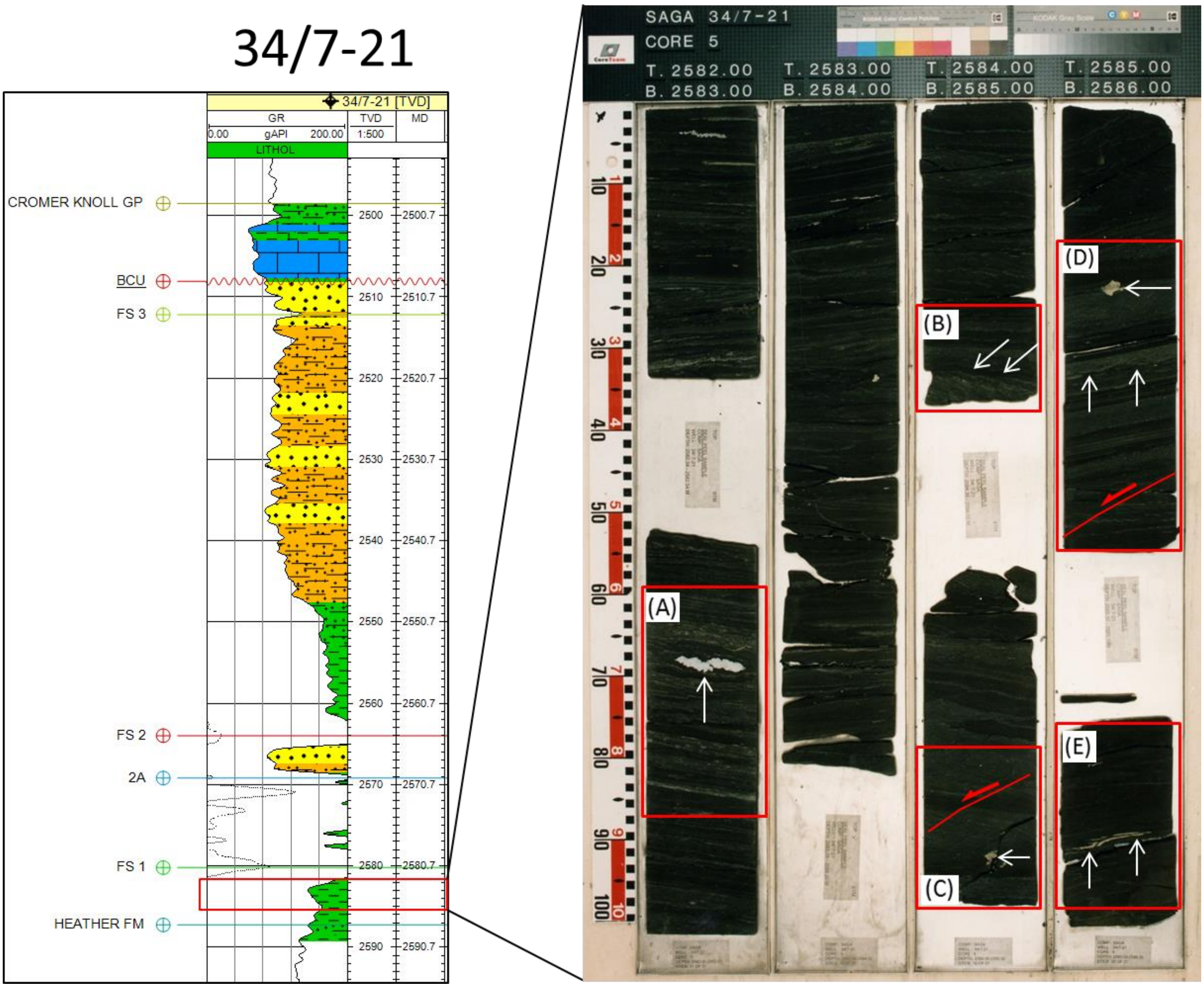


Figure 4.3. Photographs of core intervals from well 34/7-21, showing the deep marine dark black shale in Sequence 1 and corresponding with the lithology log at left.

In general, FS1 is interpreted as the boundary of the climax of fault block rotation. Sequence 1 was deposited during the increasing of the fault block rotation, leading to increase of relative sea level, accumulative space and relative low sediment supply rate, and therefore formed the fining upward shale in sequence 1.

4.2.2 SEQUENCE 2

Bounding character: FS2 is the second flooding surface as the top boundary of Intra Draupne sandstone and the base boundary of the Upper Draupne Formation appeared in this area. FS2 (Figure 4.2) shows up with both Intra Draupne sandstone and Upper Draupne Formation (lithology changing upwards from shale to sandstone), at 2503.8m in the well 34/7-26A, at 2563.9m (TVD) in well 34/7-21 and at 2623.9m (TVD) in the well 34/7-21A as well. To the south, FS2 presents in well 34/7-26SR at 2569.4m (TVD), however without Intra Draupne sandstone shows in this well. FS2 is interpreted with distinct high gamma ray signal in well 34/7-26SR, which happens also in well 34/10-18, 34/10-39S, and 34/10-47S to the north. To the north, Upper Draupne Formation exists overlying FS2 in wells 34/7-31, 34/7-24S, 34/7-23A, 34/7-23S, and 34/7-29S. The highest depth that FS2 surface has reached is in well 34/7-24S (Figure 4.2). FS2 is interpreted as a flooding surface because of the distinct high gamma ray signal indicated. FS2 as the base boundary of the upward coarsening succession, also indicates the climax of the fault block rotation happened which lead to the high accumulative space and relative low sediment supply.

Sequence character: Sequence 2 is bounded by the FS1 and FS2, ranges from lower Volgian to the lower Middle Volgian (Nøttvedt et al., 2000). Sequence 2 mainly contains shale in all of these investigated wells (Figure 4.2). In this sequence, the gamma ray shows particular high value indicates organic rich shale. Near the bottom of Sequence 2, the gamma ray value shows continue decreasing, followed by the value of Upper Draupne sandstone. In wells 34/7-23A, 34/7-23S and 34/7-29S, it can be seen that Sequence 2 was overlain by the sandstone immediately after being deposited (Figure 4.2). Therefore, the Sequence 2 can be interpreted as the climax of the fault block rotation, which produced high accumulation space and relative sea level.

Lithological character: Observation of the well logs tells that the lithology is organic rich with high gamma ray signal decreasing upward (Figure 4.4). From the core interval photography (Figure 4.4, part A, B and C), it can be seen that the main sedimentary lithology in Sequence 2 is black shale, and with sandy lamination (1-2cm) in the lower part. Besides, the sandy lamination shows an upward increasing trend both in thickness and frequency.

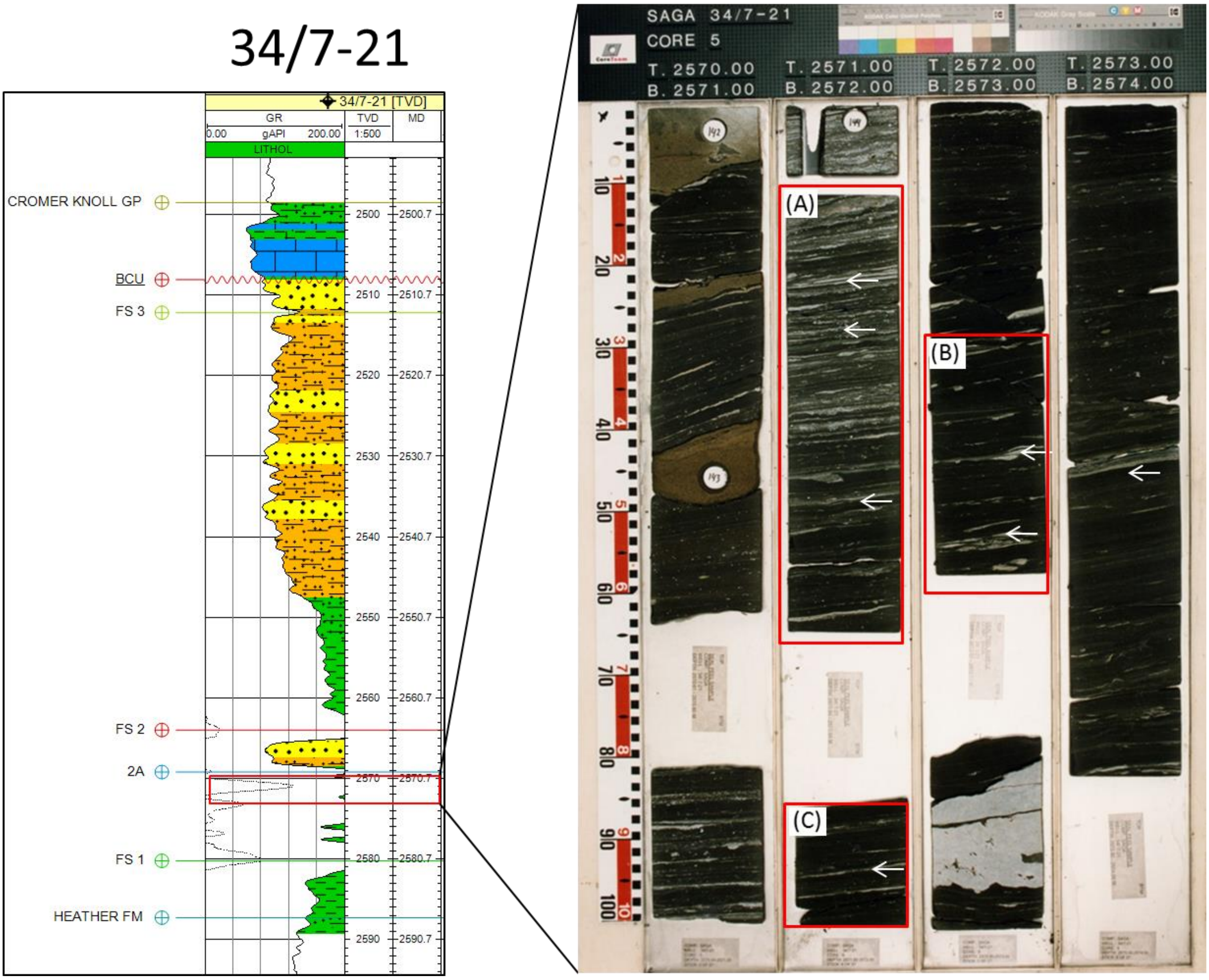


Figure 4.4. Photographs of core intervals from well 34/7-21, showing black shale in Sequence 2 and corresponding with the lithology log at left.

4.2.2.1 Parasequence 2A

Bounding character: Surface 2A is a Parasequence bounding surface shown in well 34/7-26A at 2507.6m (TVD), well 34/7-21 at 2569.2m (TVD), and well 34/7-21A at 2627.6m (TVD), as a base surface of the Intra Draupne sandstone, and is interpreted with a high gamma ray signal below the intra Draupne sandstone (Figure 4.2). This surface may pinch out near well 34/7-26SR to southwest and well 34/7-31 to north.

Sequence character: Parasequence 2A, as Intra Draupne sandstone, is a subsequence between surface 2A and FS2 at the top of Sequence 2, which is only present in wells 34/7-26A, 34/7-21 and 34/7-21A (Figure 4.2). This subsequence is absent in the other wells, which therefore indicates that it may pinch out to the north and south. The well data indicate the upper part of Intra Draupne sandstone was eroded, and replaced by the Draupne shale of Sequence 3.

Lithological character: This is the only core showing the Intra Draupne sandstone (Figure 4.5), in which it displays yellow silty sandstone with grain size changing upward from fine, medium to coarse. In this core interval, the sandstones shows planar bedding, oblique and ripple cross lamination (Figure 4.5, part B and D), with present of coal fragment and flake, black mud clast (Figure 4.5, part A and C). Besides, the shale fragment, flake and black mud clast observed in this interval may come from the underlying black Draupne shale.

The Intra Draupne sandstone was interpreted as a syn-rift formation. Therefore it indicates the high rate of fault rotation causing the increase of the gradient and fall of the relative sea level (Nøttvedt et al., 2000).

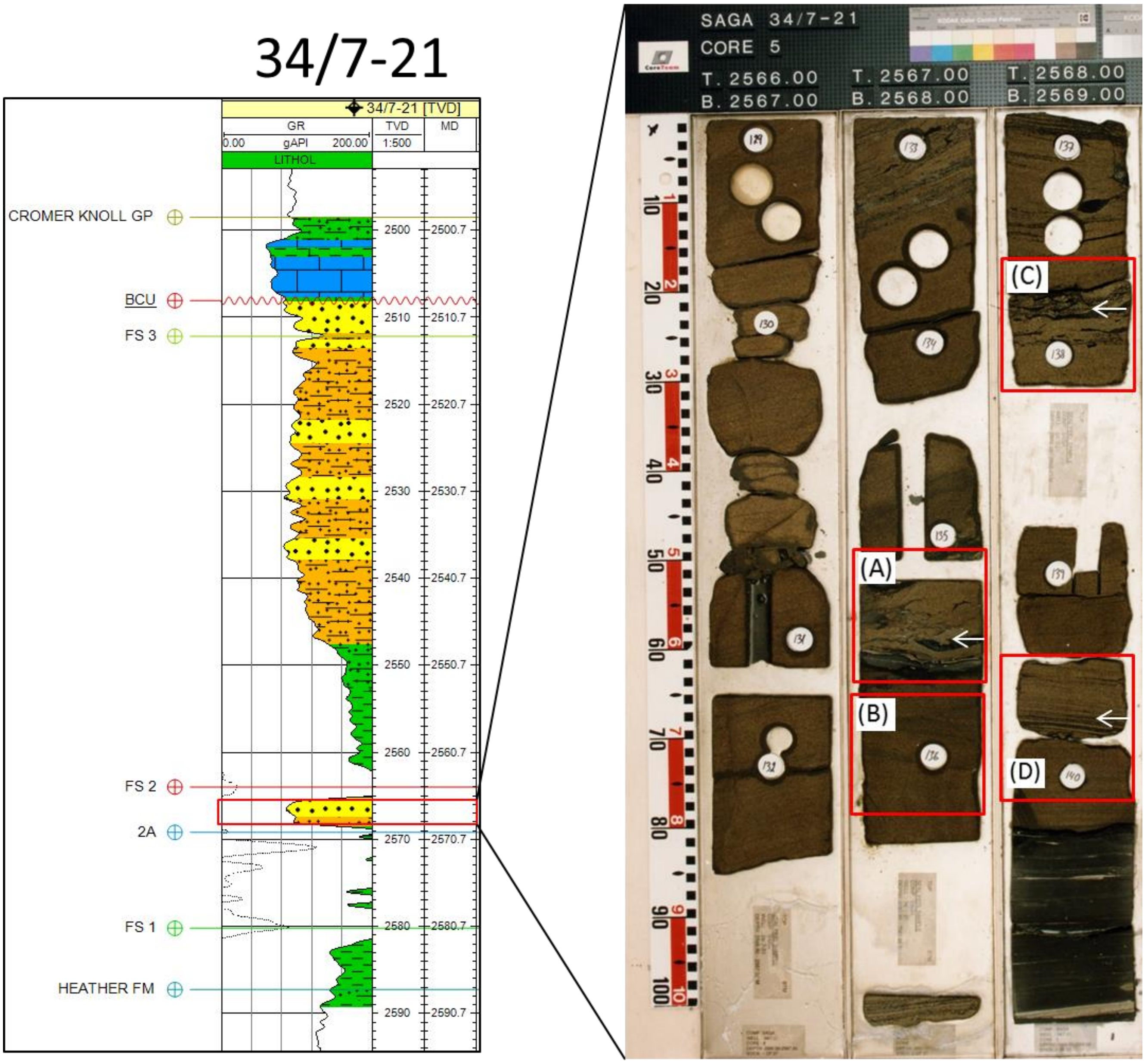


Figure 4.5. Photographs of core intervals from well 34/7-21, showing the yellow silty sandstone in Parasequence 2A and corresponding with the lithology log at left.

4.2.3 SEQUENCE 3

Bounding character: FS3 is the third flooding surface shown in well 34/7-21 at 2512.2m (TVD), well 34/7-21A at 2577.8m (TVD), well 34/7-24S at 2728m (TVD), well 34/7-23A at 2646.1m (TVD), and well 34/7-23S at 2629.8m (TVD) (Figure 4.2). FS3 in these five wells listed above is referenced from Nøttvedt et al. 2000, and it is considered as the top boundary of the Late Volgian which is a biostratigraphical sequence, but with some modification on the depth (Nøttvedt et al., 2000). This surface is also interpreted with a relative high gamma ray signal, and therefore is indicated as a flooding surface. Extending FS3 to other wells in this correlation, this surface is also shown in well 34/7-26SR at 2504m (TVD), well 34/7-26A at 2445.7m (TVD), but is absent in well 34/10-18, well 34/10-39S and well 34/10-47S to the south, which suggest a pinch-out near wells 34/7-26SR and 34/10-18. To the north, FS3 is shown in well 34/7-31 at 2471.5m (TVD), well 34/7-29S 2640.4m (TVD). FS3 is interpreted as the biostratigraphical boundary between Upper Volgian and Lower Ryazanian, and a flooding surface (Nøttvedt et al., 2000) (Figure 4.2). Therefore, this part of the Upper Draupne sandstone is deposited during Late Volgian.

Sequence character: Sequence 3 is bounded by flooding surface FS3 and FS4, and was deposited from Middle to Late Volgian (Nøttvedt et al., 2000). In the southern part of the study area, there is only shale shown in sequence 3 in wells 34/10-47S, 34/10-39S and 34/10-18 (Figure 4.2). In the middle part of the study area, the Upper Draupne sandstones in the lower part of the sequence coarsen upward from Draupne shale to progradational shoreface sandstone, and it changed to gradual fining upward retrogradational sandstone in the upper part of the sequence (wells 34/7-26SR, 34/7-26A, 34/7-21, 34/7-21A and 34/7-31). The thickness of sequence 3 in well 34/7-26A is 58 meters with 9 meters upward coarsening shale and 49 meters sandstone above the shale. To the southwest, the well 34/7-26SR shows 42 meters coarsening upward shale and 8 meters sandstone above, which may indicate the location of well 34/7-26SR at the lower part of the shoreface. The same lithology variance of Sequence 3 also shows in wells 34/7-21, 34/7-21A and 34/7-31. It shows 11 meter upward coarsening shale and 36 meters sandstone in well 34/7-21. In well 34/7-24S, sequence 3 has only 23 meters shale succession and no sandstone at the upper part, indicating the location of this well at the deepening area. In the northern part of the study area, sequence 3 shows thickness of respectively 3 meters in well 34/7-23A and 2 meters in well 34/7-23S. Well 34/7-21A is located at 982 meters west of well 34/7-21, the Sequence 3 in which shows 29 meters shale and 15 meters sandstone (Figure 4.2). Associated with Sequence 3 in well 34/7-21, it indicates the terminating direction of the sandstone in this sequence.

Lithological character: It shows Gamma ray decreases in the lower part and increases in the upper part of Sequence 3 (Figure 4.6). The sedimentary lithology of Sequence 3 can be divided into two different types.

The lithology appeared in the lower part of the sequence is black silty shale (Figure 4.6), which is described as thin lower angle sandy lamination in opposite dipping angle (Figure 4.6, part A), gray shale debris presented, and structural influence. The average thickness of sandy lamination is 1 to 2 cm, and it shows the upward increasing in both thickness and frequency (Figure 4.6, part A, B and C).

The other main lithology existed in the upper part of Sequence 3 is yellow silty sandstone which constitutes Upper Draupne sandstone (Figure 4.7). This lithology is described as upward changing from fine, medium to coarse grain, with low density of bioturbation, showing ripple cross shaly lamination of low angle (Figure 4.7, part A), and decreasing upward both in thickness and frequency. Several irregular sandstone depositions show debris in the middle of shaly lamination (Figure 4.7, part B and C), which may originate from the erosion of the uplift footwall.

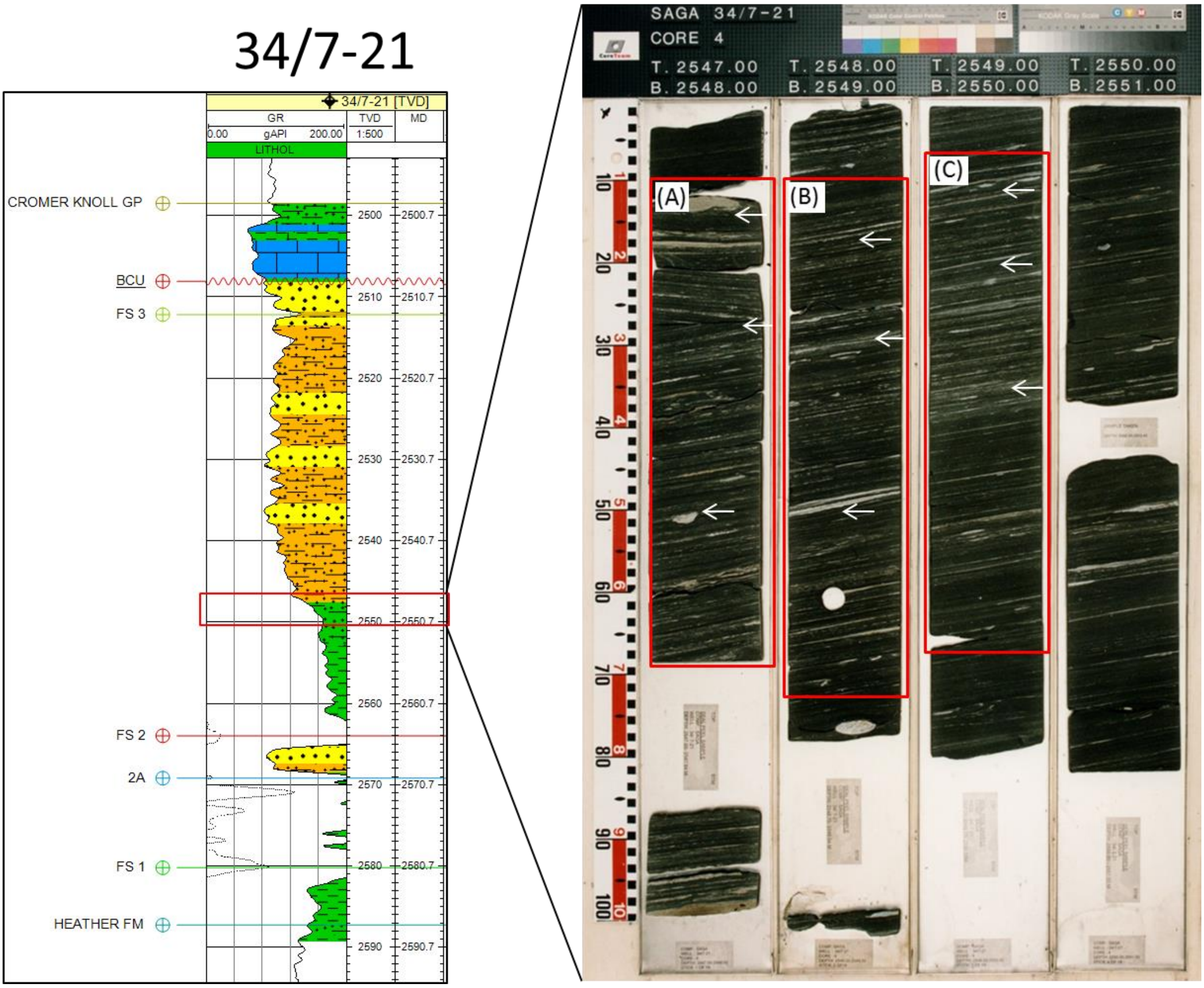


Figure 4.6. Photographs of core intervals from well 34/7-21, showing the black silty shale in Sequence 3 and corresponding with the lithology log at left.

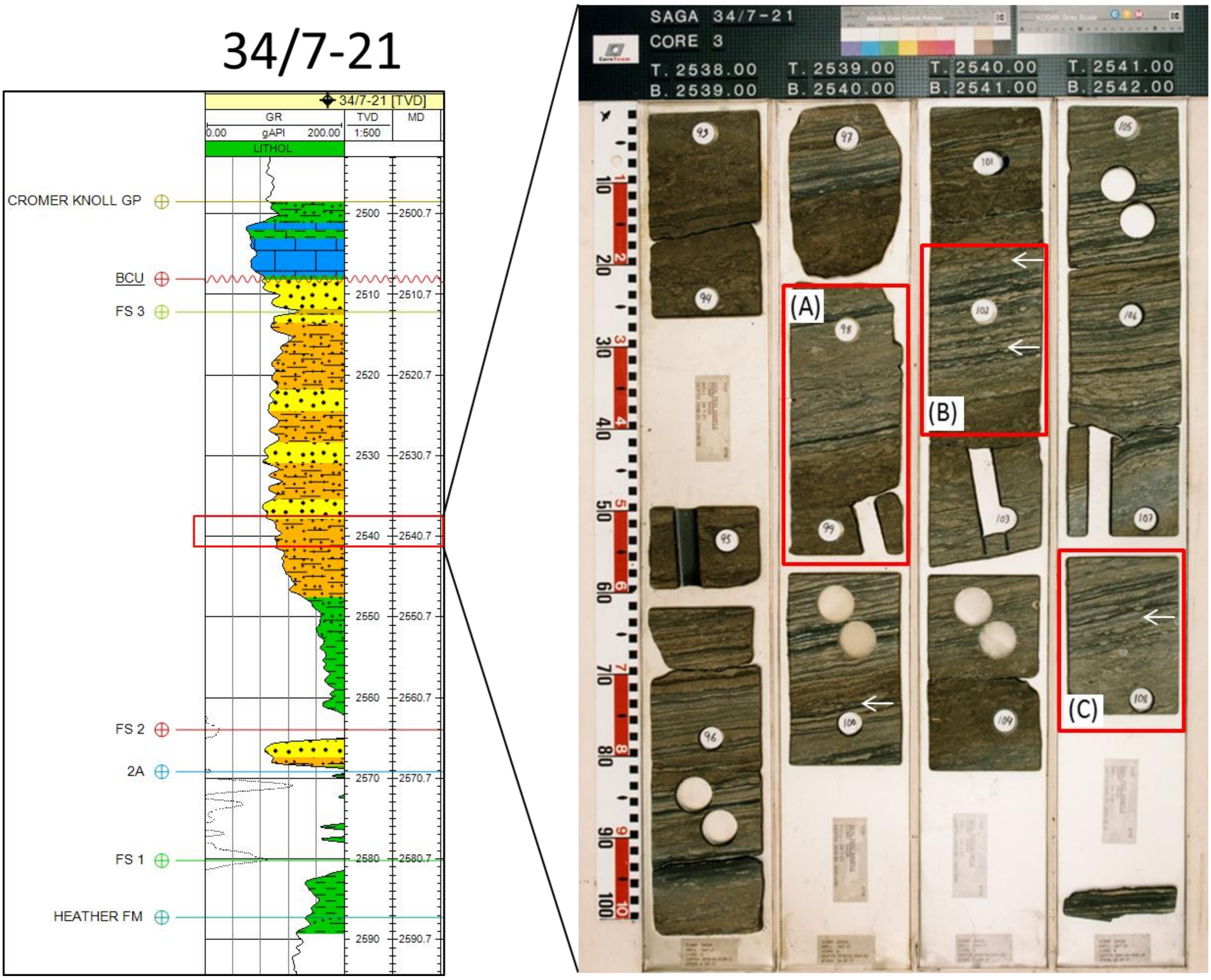


Figure 4.7. Photographs of core intervals from well 34/7-21, showing the yellow silty sandstone in Sequence 3 and corresponding with the lithology log at left.

From description and analysis above, the lower part of Sequence 3 can be interpreted as coarsening upward regression, progradational sequence formed in the shallower basin during the force regression, and it indicates falling of the relative sea level and climax of the fault block rotation. The upper part is shown as the upward fining transgression, retrogradational sequence, which indicates the cease of the fault block rotation. The sediment of the sandstones is come from east, the erosion of the uplift footwall of ISF.

4.2.4 SEQUENCE 4

Sequence character: Sequence 4 which was deposited during Ryazanian (Nøttvedt et al., 2000) is bounded by FS3 and BCU (Figure 4.2). In this sequence, it shows more sediment deposited in wells 34/7-23A，34/7-23S and 34/7-29S to the north and it turns to be thinner and pinches out to BCU in the well 34/10-18 to the south. Sequence 4 shows more deposition of shoreface sandstone with upward coarsening and thinner thickness compared with sequence 3 in wells 34/7-31, 34/7-21, 34/7-21A, 34/7-26A and 34/7-26SR (Figure 4.2).

Lithological character: In the lower part of Sequence 4, it shows that the gamma ray decrease upward (Figure 4.8). The main sedimentary lithology in the lower part of Sequence 4 is yellow sandstone (Figure 4.8), which changes upward from fine to medium grain and shows thin shaly lamination (Figure 4.8, part A and D), with bioturbated burrows of very low density (Figure 4.8, part C). In the upper part of Sequence 4, the lithology changes to light yellow silty sandstone, and the grain size changes upward from fine to medium grain, with bioturbation absent (Figure 4.8, part B), showing abundant debris sediment flow and low angle shaly lamination but absent upward. This type of sandstone in the Sequence 4 was interpreted as deposited in the medium to high water energy environment, with high accumulation rate, and progradational sequence. Therefore the depositional environment is Upper shoreface.

Sequence 4 is interpreted a progradational process in an overall back stepping shoreline system, and it is younger than Sequence 3. The Upper Draupne sandstone in Sequence 4 is mainly deposited at the northern area, and pinches out in well 24/7-24S. Therefore, the source for the sediment in the northern area is from the northwest, the erosion of the fault block.

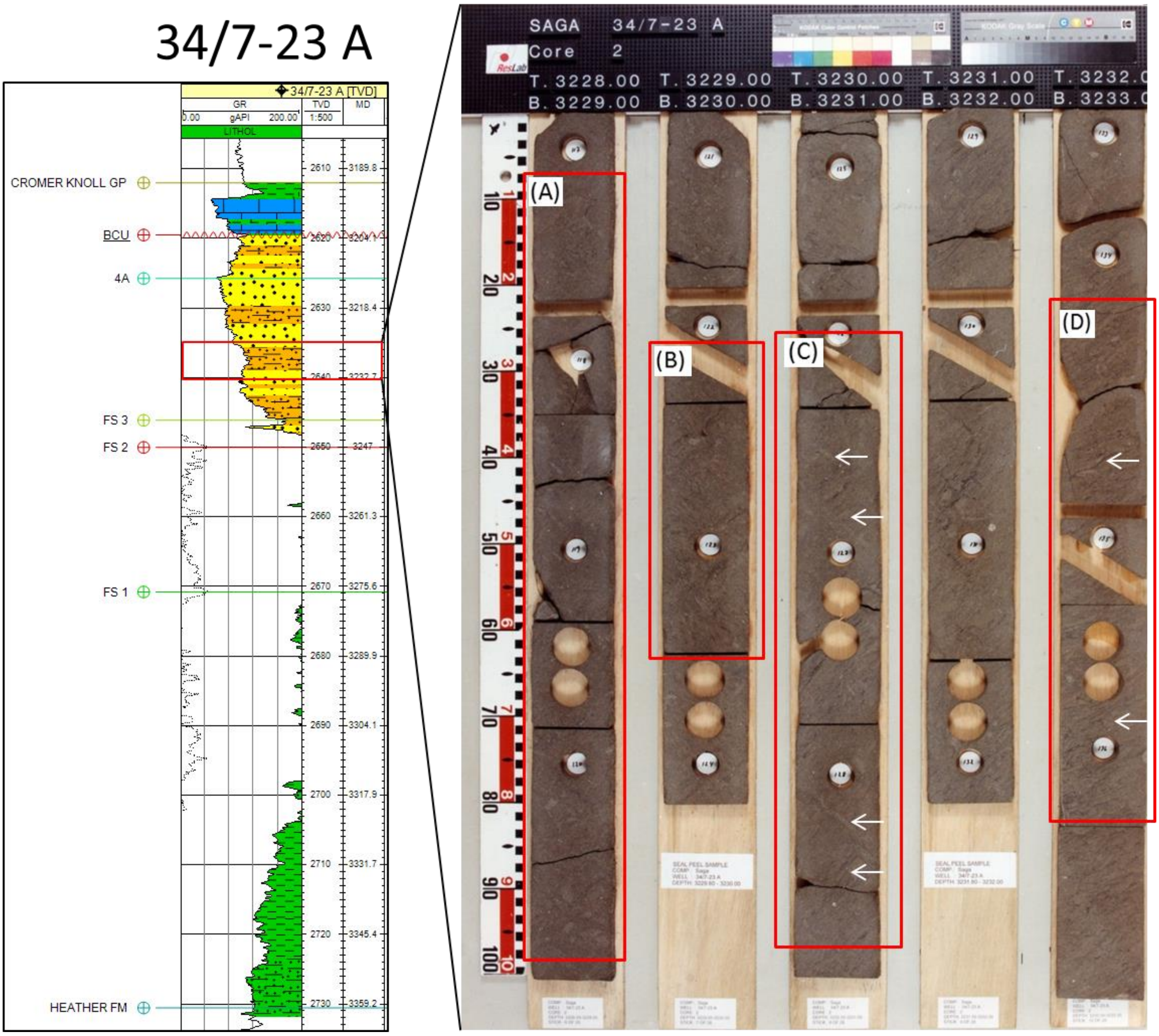


Figure 4.8. Photographs of core intervals from well 34/7-23A, showing the yellow sandstone in Sequence 4 and corresponding with the lithology log at left.

4.2.4.1 Parasequence 4A

Bounding character: Surface 4A is a parasequence bounding surface shown in well 34/7-23A at 2625.7m (TVD) and well 34/7-23S at 2613.9m (TVD) (Figure 4.2). Surface 4A is located within the Upper Draupne sandstone, and is the boundary between upward coarsening sandstone and upward fining sandstone. This surface may pinch out to BCU in well 34/7-29S because there is no upward fining sandstone detected in this well. In addition, it may also pinch out in well 34/7-24S, which can be seen from the well location of 34/7-24S in the deepening area without any sandstone deposited (Figure 4.2).

Sequence character: Parasequence 4A is the other subsequence and it is bounded by surface 4A and truncated by BCU in wells 34/7-23A and 34/7-23S (Figure 4.2), which deposited during latest Ryazanian (Nøttvedt et al., 2000). The thickness of this sequence is 6 meters and 5 meters detected in well 34/7-23A and 34/7-23S respectively (Figure 4.2). In these two wells, it shows upward fining sandstone which indicates the retrogradation process. The sequence 4A indicates the likely rise of the relative sea level.

Lithological character: The gamma ray within Parasequence 4A interval shows upward increase (Figure 4.9).

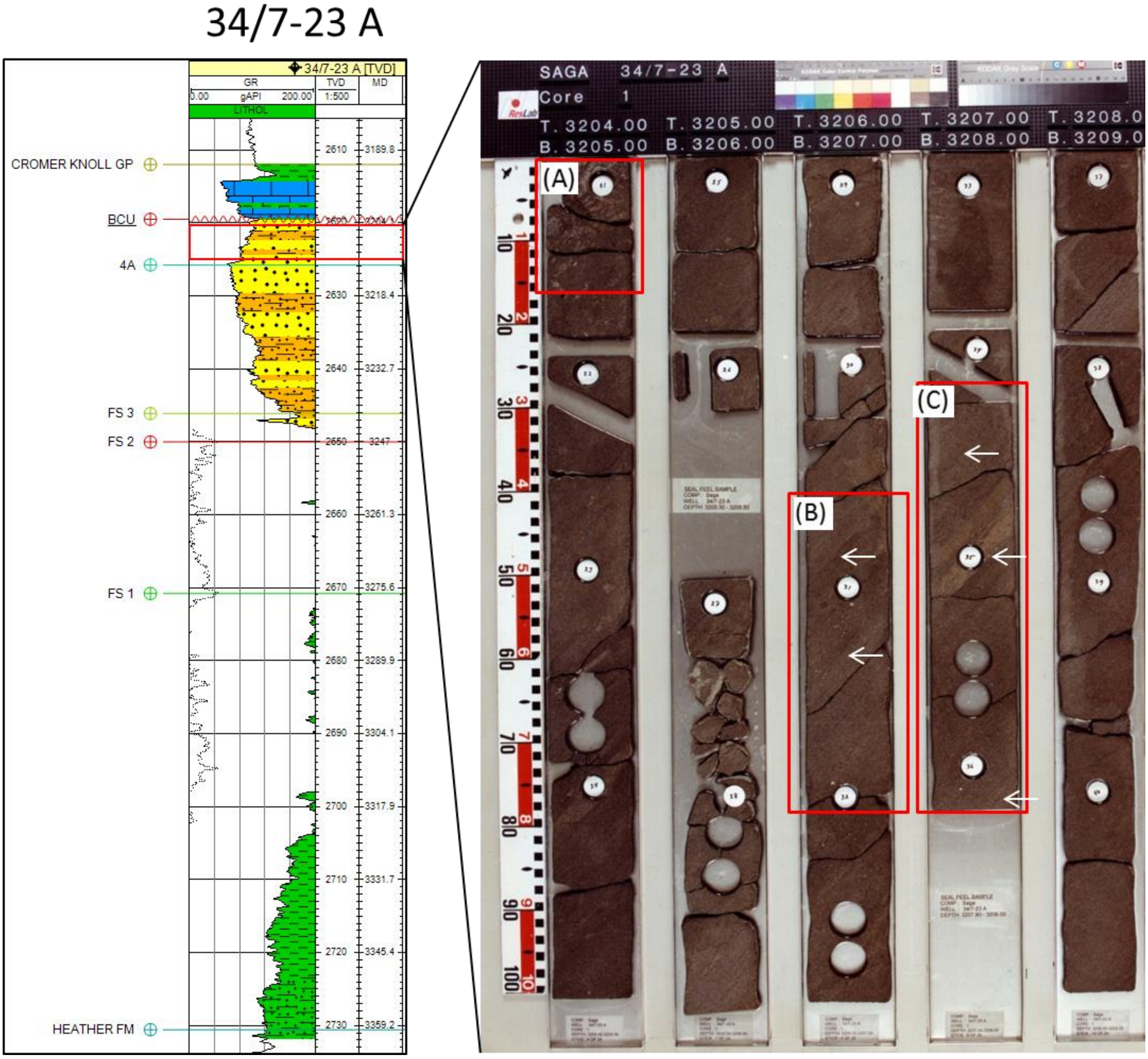


Figure 4.9. Photographs of core intervals from well 34/7-23A, showing the yellow sandstone in Parasequence 4A and corresponding with the lithology log at

The lithology in Parasequence 4A is mainly yellow sandstone (Figure 4.9), with grain size changing upward from fine to medium, and with low density of bioturbation, and with thin shaly lamination but absent upward (Figure 4.9, part A, B and C).

4.2.5 SANDSTONE SEQUENCES INTERPRETATION

From the observation and analysis above in the sequence stratigraphy, the sandstones are present in both Sequence 3 and Sequence 4, all as progradational sandstone sequence. However, only the strike directions of these sandstones have been shown above (Figure 4.2). As to the dipping direction of these sandstones, in this part of study, 6 wells are chosen, which are wells 34/7-29S, 34/7-23A and 34/7-24S to the north for sandstone in Sequence 4 (Figure 4.10) and wells 34/7-26A, 34/7-21A and 34/7-24S to the south for sandstone in Sequence 3 (Figure 4.11).

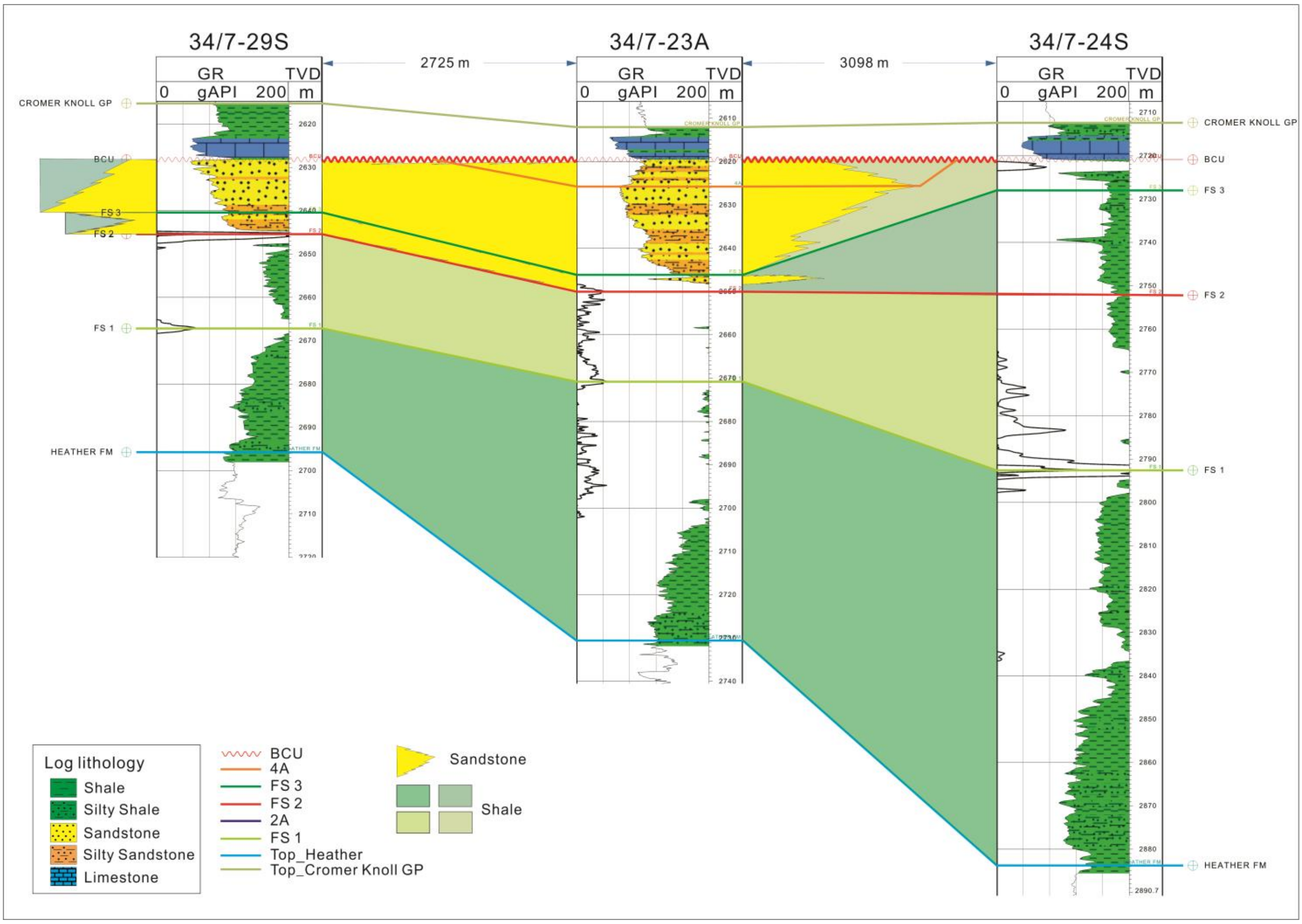


Figure 4.10. Well correlation for the sandstone dipping direction to the north.

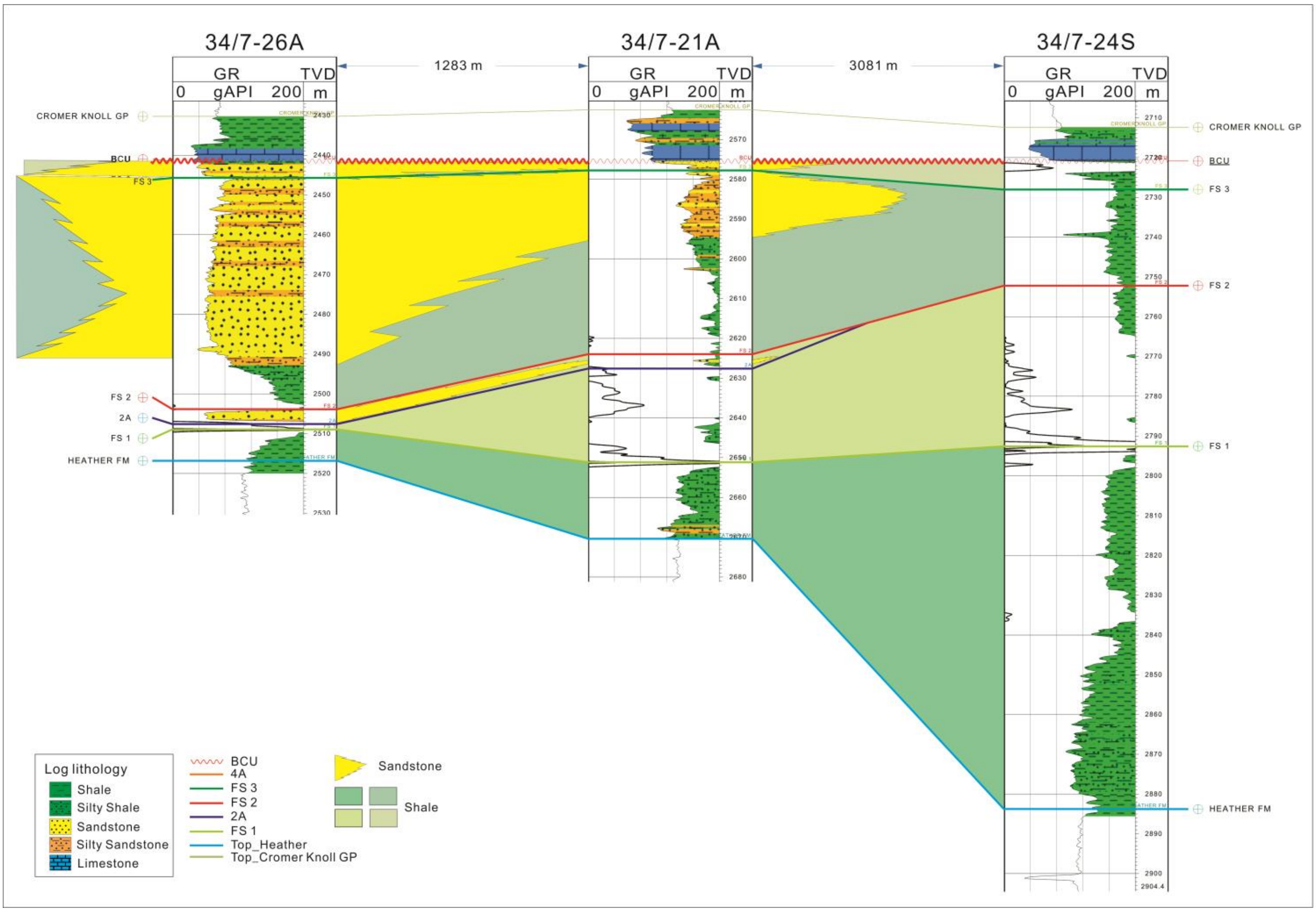


Figure 4.11. Well correlation for the sandstone dipping direction to the south.

Therefore, sandstones in Sequence 3 and Sequence 4 show similar character, which is the similar progradational sequence in the lower part, formed during the force regression, and a retrogradational sequence in the upper part, formed during the transgression (Figure 4.10 and 4.11). The sandstones indicate the back stepping process. In the northern area, the sandstone sourced from the northwest direction (Figure 4.10). However, in the southern area, the sandstone sourced from the east direction (Figure 4.11).

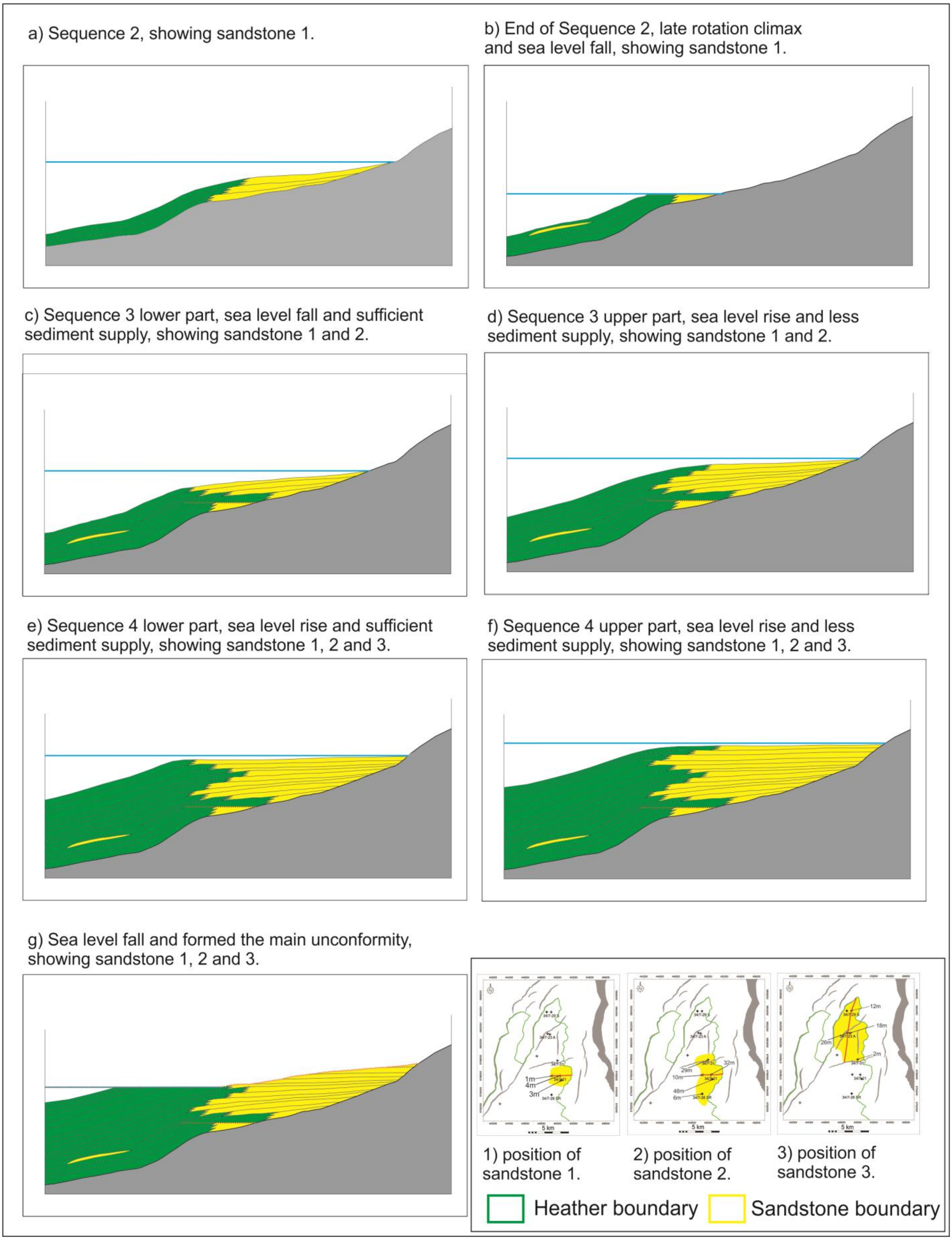
From description of the sandstones in the chapters above, the sandstones in Sequence 3 and Sequence 4 have shown similar characters. In the lower part of both sequences, they are progradational sequence formed during the force regression. While in the upper part of both sequences, they are retrogradational sequences formed during the transgression. All the sandstones in Sequence 3 and Sequence 4 indicate a back stepping process. In the northern area, the sandstone was sourced from the northwest (Figure 4.10). However, in the southern area, the sandstone was sourced from the east (Figure 4.11).

4.2.6 DEPOSITIONAL MODEL OF THE SEQUENCES

From the chapters above, there are three sandstones in the sequences. Sandstone 1 is the Intra Draupne sandstone, showing in three wells only. Sandstone 2 is belongs to Upper Draupne sandstone in the Sequence 3. Sandstone 3 is the Upper Draupne sandstone as well, but is showing in Sequence 4 and mainly deposited at the wells in the northern area.

Based on the observation and analysis of the depositional processes of these sequences, a depositional model was built (Figure 4.12).

The process of the sequential deposition is shown from (a) to (g) in the Figure 4.12. The initial rifting is shown in sub-figure (a), the Sequence 2 was deposited. The deposition of Sequence 2 ended (Figure 4.12, b) at climax of the late rotation. At the climax of the fault blocks rotation, the relative sea level was falling, which lead to the erosion of the upper part of Sequence 2, and the sandstone 1 was left after erosion. After that, the Late Jurassic rifting ceased, and the relative sea level rise back, sufficient sediment started to deposit which came from the erosion of the uplift footwall, and it shows a sedimentary facies of a progradational process in lower part of Sequence 3 (Figure 4.12, c). The sea level continued rising and formed the retrogradational upper part of Sequence 3(Figure 4.12, d) as sandstone 2 in well 34/7-21. Sandstone 3 has the similar forming function as sandstone 2, which is located at the northeastern sub-basin area (Figure 4.12 e) and f)). At the end of the depositional stage, the relative sea level fell again, and the upper part of Sequence 4 was eroded as shown in wells 34/7-23A and 34/7-29S.



a) Sequence 2, showing sandstone 1.

b) End of Sequence 2, late rotation climax and sea level fall, showing sandstone 1.

c) Sequence 3 lower part, sea level fall and sufficient sediment supply, showing sandstone 1 and 2.

d) Sequence 3 upper part, sea level rise and less sediment supply, showing sandstone 1 and 2.

e) Sequence 4 lower part, sea level rise and sufficient sediment supply, showing sandstone 1, 2 and 3.

f) Sequence 4 upper part, sea level rise and less sediment supply, showing sandstone 1, 2 and 3.

g) Sea level fall and formed the main unconformity, showing sandstone 1, 2 and 3.

Figure 4.12. Depositional model of sandstone in Sequences (out of scalar).

5. SEISMIC INTERPRETATION

Main objectives for the seismic interpretation in this study are to interpret the sedimentary distribution of the Upper Draupne sandstones, and to interpret the syn-rift depositional patterns.

5.1 Seismic well ties

Gamma ray, sonic and density logs have been used for building the synthetic seismogram. The checkshot was also used for the time-depth relationship. An example of a well tie is presented in Figure 5.1. The same well tie process is applied to other wells mentioned above, and shows the synthetic seismogram with key well tops on the 3D seismic data (Figure 5.2). The seismic well ties marker the key tops of the formations, which is the basis for the seismic interpretation.

The characters of these main seismic horizons are demonstrated in Table 3. The sea bottom shows positive RC (reflection coefficient) and negative in the seismic, which indicates the seismic data in reverse polarity.

Normally, Top of Upper Draupne sandstone is shown at the zero crossing and the Upper Draupne sandstone reflector shows positive amplitude in the seismic data (Figure 5.2). In well 34/7-24S, only Draupne shale is deposited, which is shown in Figure 5.2 (B). The Draupne shale is shown positive amplitude in the seismic data as same the Upper Draupne sandstone mentioned above.

The Upper Draupne sandstone and Draupne shale have the same polarity of amplitude (Table 3), varying AI(acoustic impedance) and RC, which means it is difficult to distinct them in the seismic data.

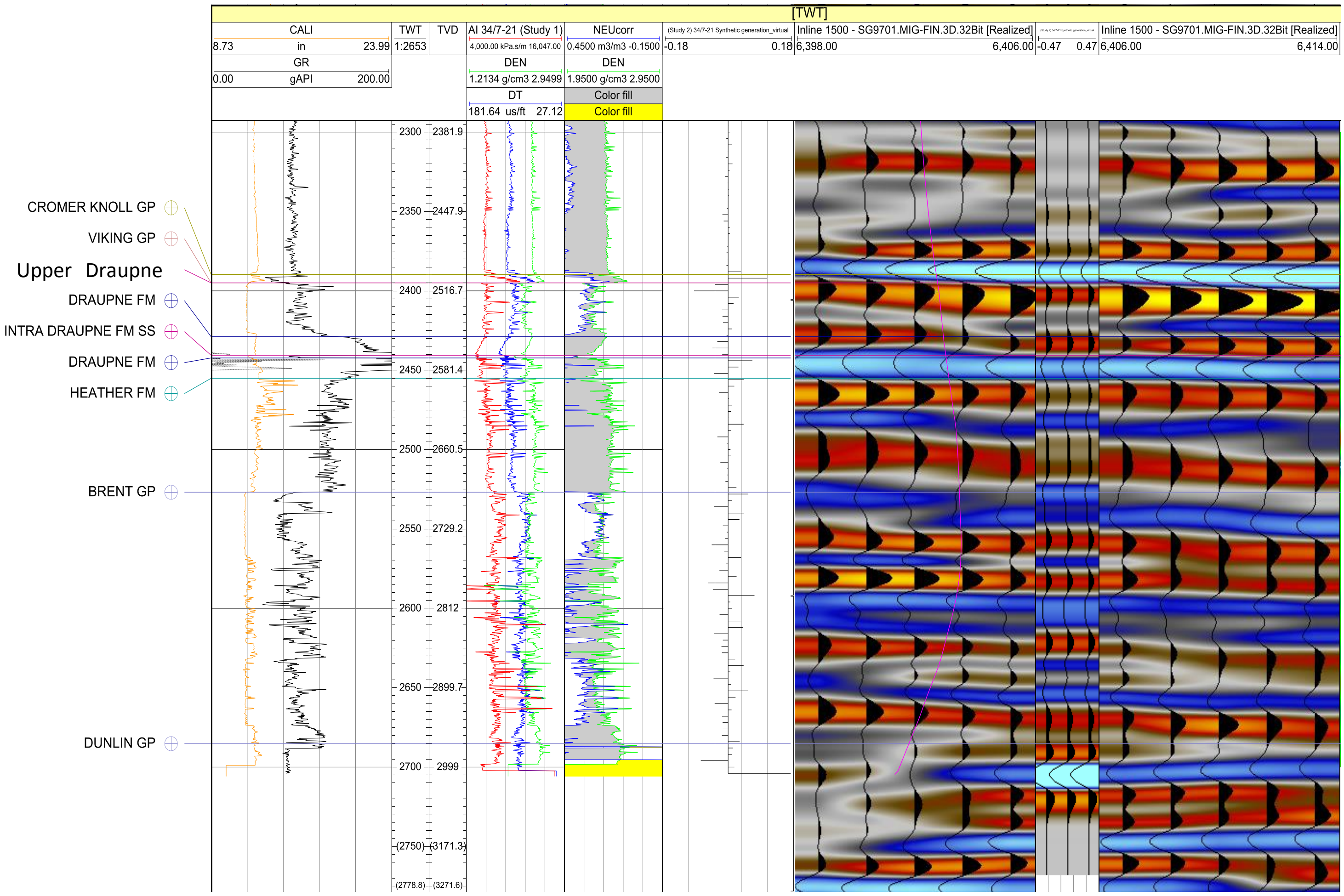
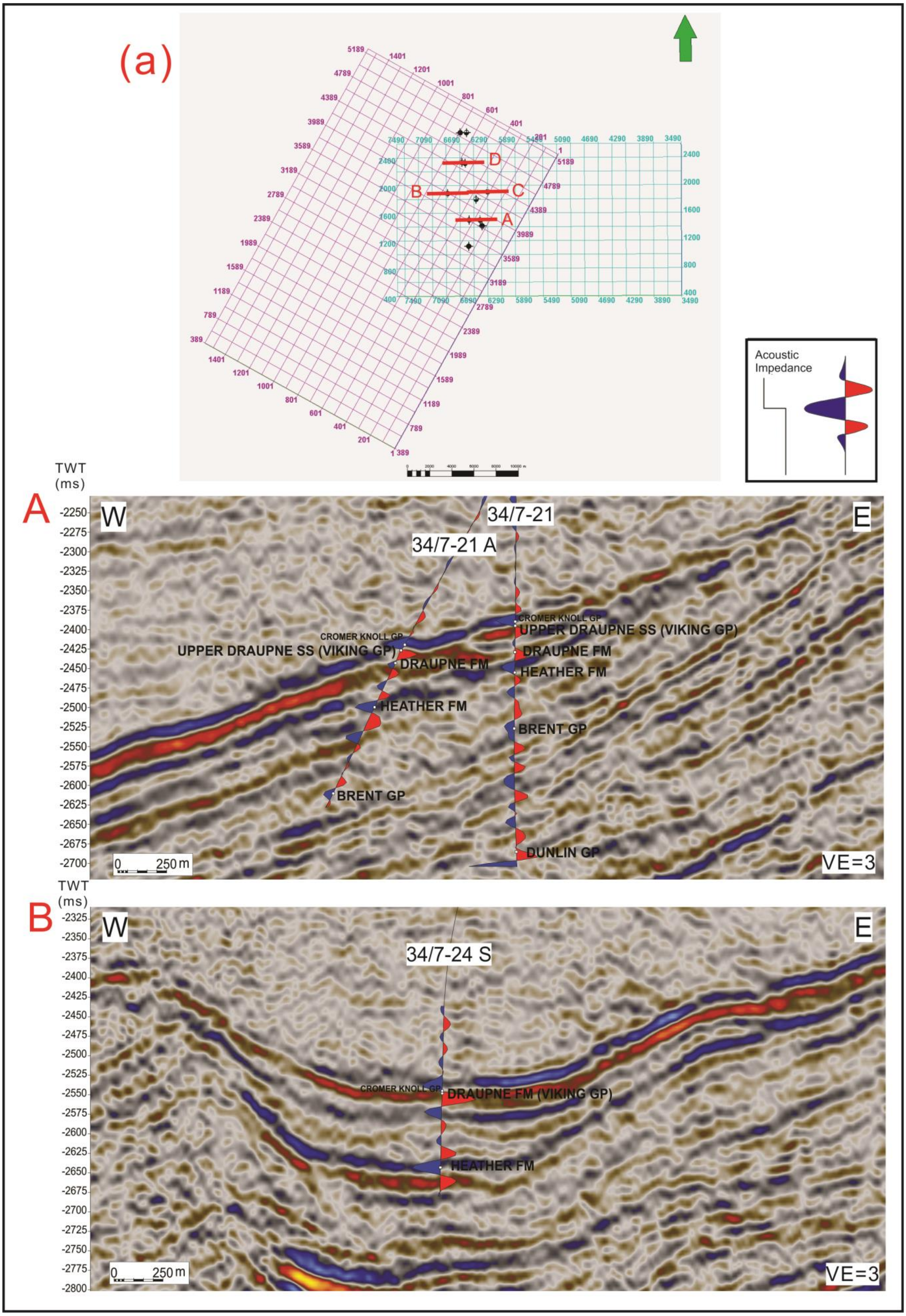


Figure 5.1. Synthetic seismogram for well 34/7-21 with main well tops.

Table 3. Characters of key seismic horizons and seismic facies

Horizons	Amplitude (in the seismic)	AI	RC	Correlation
Sea Bottom	Negative	Increase	Positive	NA
Base Cretaceous Unconformity	Negative	Increase	Positive	Good
Upper Draupne Sandstone	Positive	Decrease	Negative	Good
Draupne Formation	Positive	Decrease	Negative	Medium
Heather Formation	Negative	Increase	Positive	Good


(a)
A
B
C
D
Acoustic Impedance
TWT (ms)
A
W
E
34/7-21
34/7-21 A
CROMER KNOLL GP
UPPER DRAUPNE SS (VIKING GP)
DRAUPNE FM
HEATHER FM
BRENT GP
DUNLIN GP
0 250 m
VE=3
TWT (ms)
B
W
E
34/7-24 S
CROMER KNOLL GP
DRAUPNE FM (VIKING GP)
HEATHER FM
0 250 m
VE=3

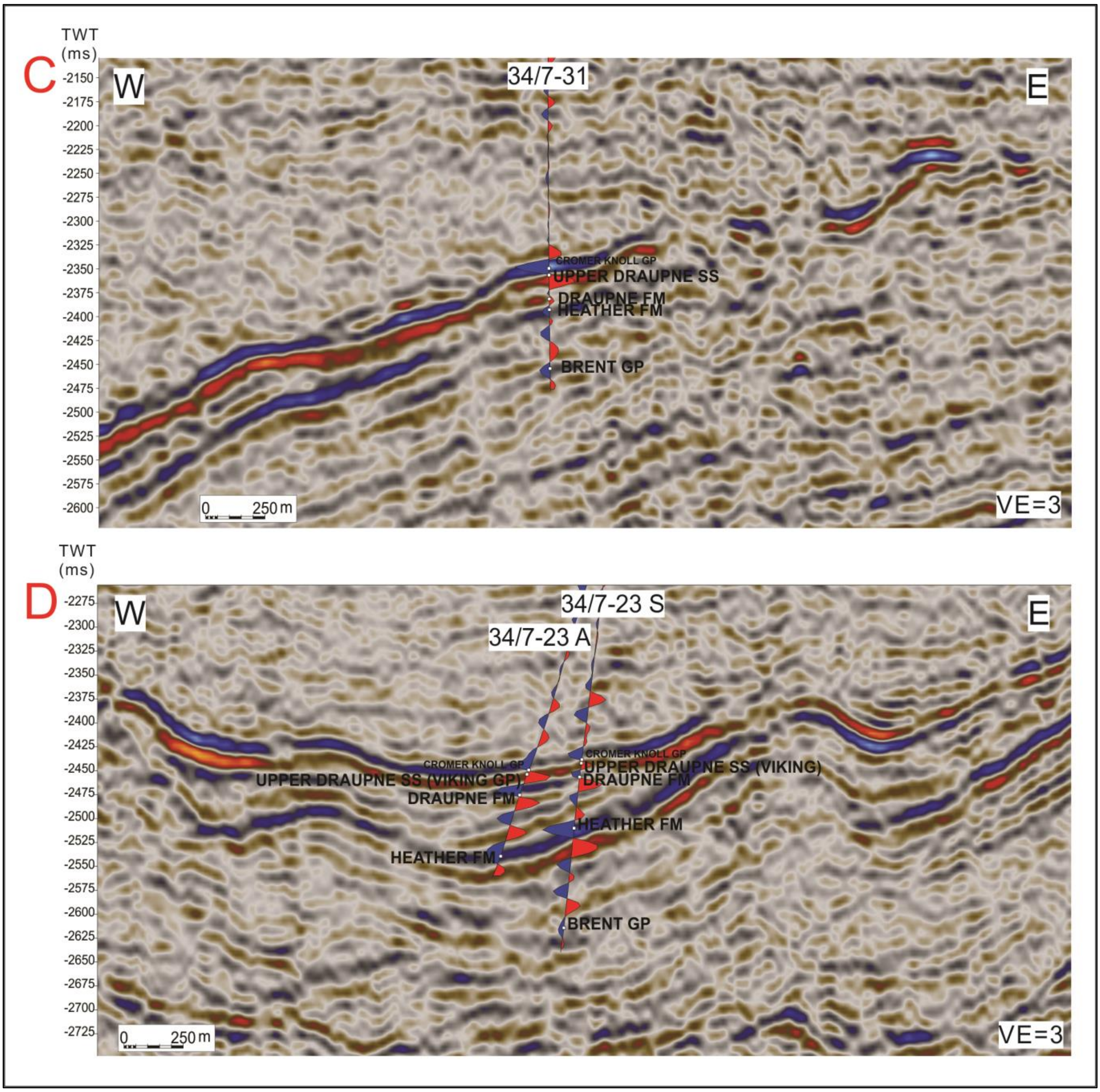


Figure 5.2. Well ties result are displaying in the seismic cross sections with key well tops, (a) show the location of these seismic lines.

5.2 Faults interpretation

During the rifting event, half graben was formed by the rotation of the fault block which also defined the boundary of the half graben.

Fault family1 (F1) is a set of northeast-southwest striking and eastern dipping faults, which formed during the Late Jurassic rifting (Figure 5.3). In the eastern part, the Inner Snorre Fault (ISF) is the eastern boundary of the half graben, and formed the footwall uplift with a large dip throw (Figure 5.3, 5.4 and 5.5). In the western part, there are two major faults which are Statfjord East Fault (SEF) and Statfjord Fault (SF) (Figure 5.3, 5.4 and 5.5). The SEF is interpreted to be older than SF in the northern part. Therefore, the area between SF and SEF turned to be the fault degraded area when the SF formed and truncated in the north (Figure 5.7). There is an east-northeast-west-southwest-striking fault (Figure 5.3 and 5.6) and is interpreted as formed during the end of the rifting event and in the group of Fault Family 1.

Fault family 2 (F2) consists of a set of north-south-striking normal faults, which are interpreted as younger faults formed by the following subsidence (Figure 5.3).

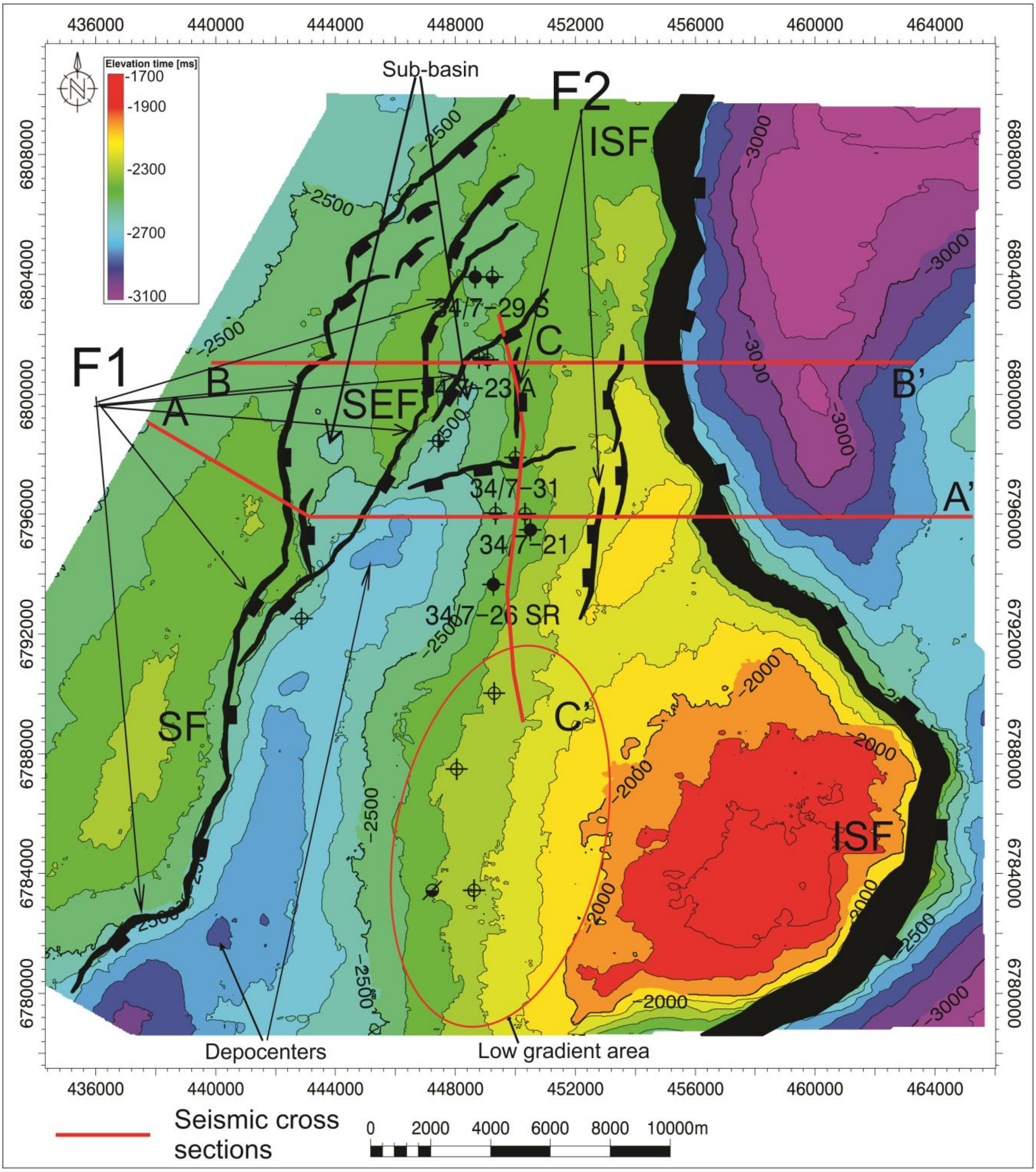


Figure 5.3. Time structural map of BCU.

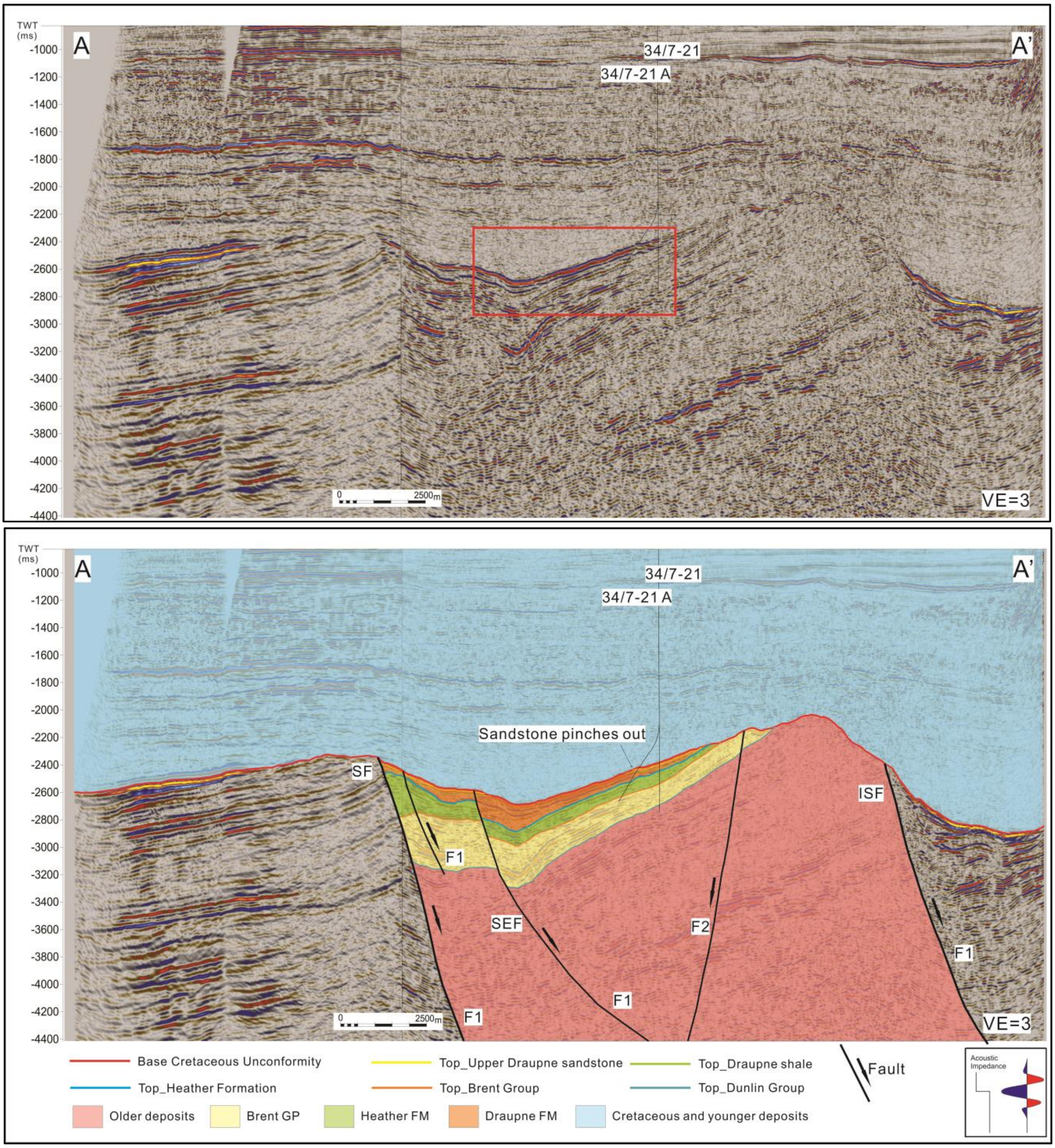


Figure 5.4. Seismic cross section A-A', original seismic data at up and interpreted cross section at low, the location is in Figure 5.3. And the red box is the location of Figure 6.5.

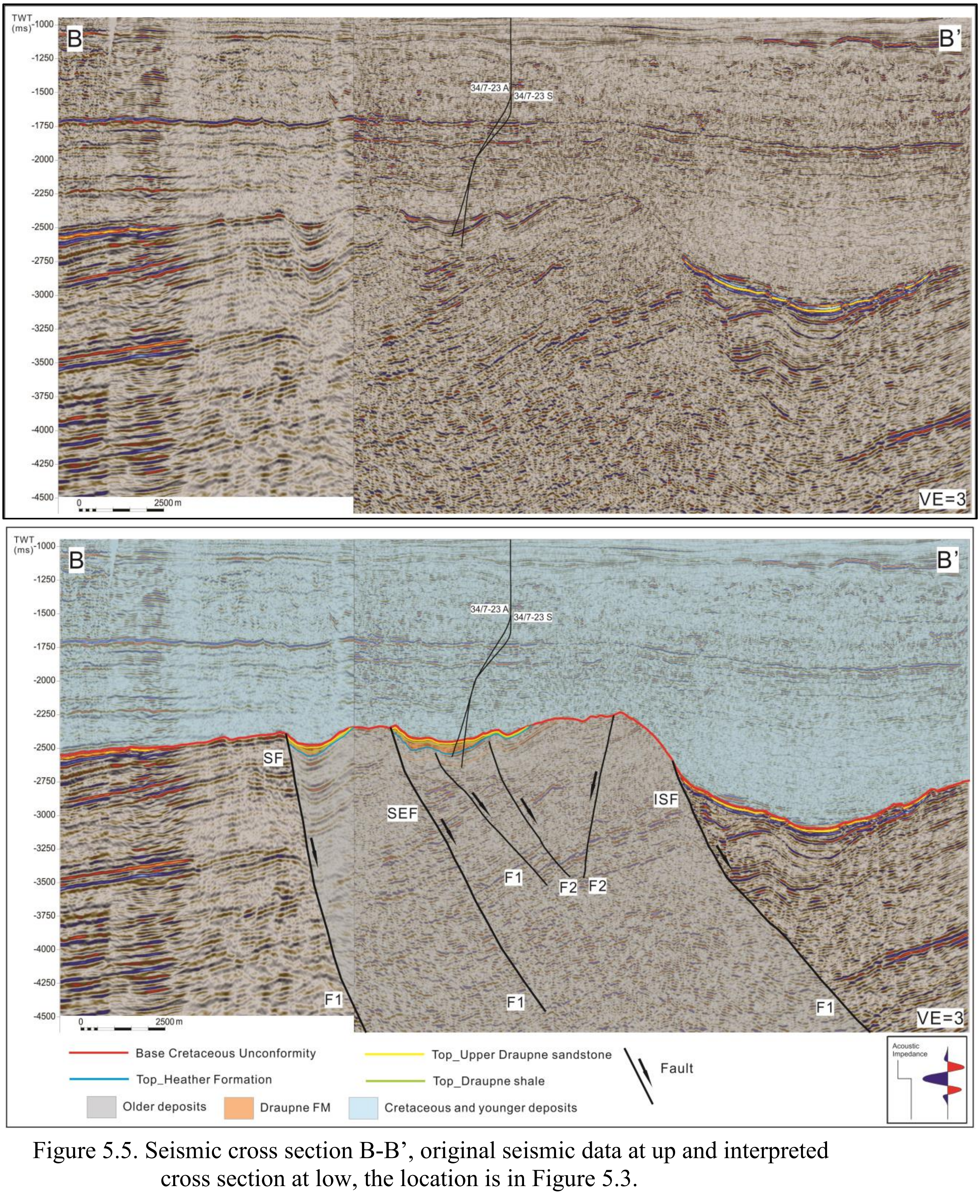


Figure 5.5. Seismic cross section B-B’, original seismic data at up and interpreted cross section at low, the location is in Figure 5.3.

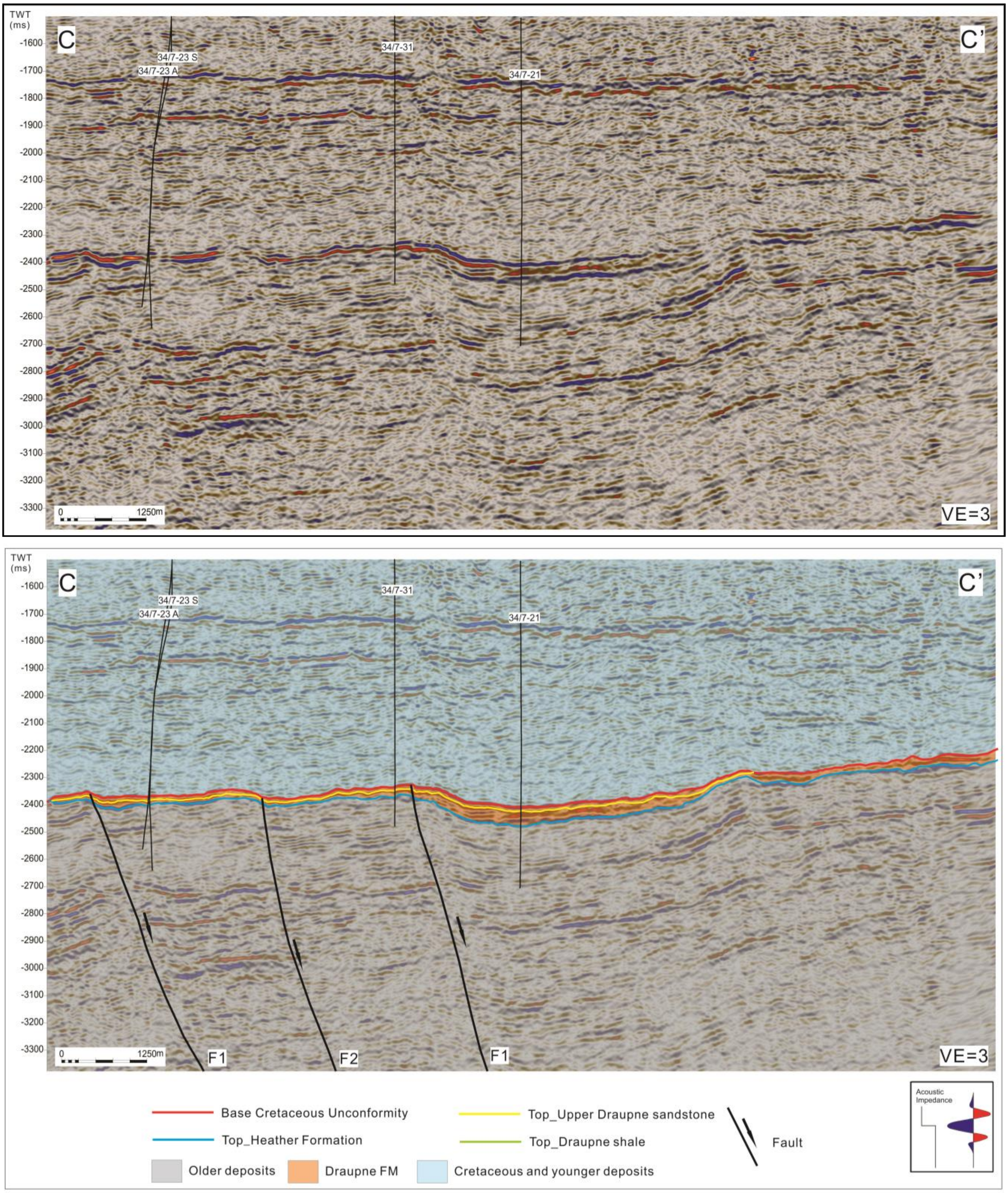


Figure 5.6. Seismic cross section C-C', original seismic data at up and interpreted cross section at low, the location is in Figure 5.3.

5.3 Horizon interpretation

The horizon interpretation in this chapter focuses on the BCU and Top Heather. They have similar characters and clear reflectors in the seismic data. Seismic cross sections are shown in Figure 5.4 and Figure 5.5 in the W-E direction and Figure 5.6 in the N-S direction, with the locations shown in Figure 5.3.

The interpretation of the Upper Draupne sandstone and Draupne shale in these cross sections are based on the well data.

In Figure 5.4, the Upper Draupne sandstone was interpreted at the wedge area based on wells 34/7-21 and 34/7-21A. The wedge is formed during the fault block rotation, and truncated buy BCU to the east. The Upper Draupne sandstone was stopped nearby the western part of well 34/7-21A as the interpretation in the Figure 5.4. The cease of the Upper Draupne sandstone is caused by the depositional environment change to deeper to the west, as the change from shoreface to shelf. Additional, the Upper Draupne sandstone in these two wells is shallow-marine sandstone.

Figure 5.5 is shown the seismic cross section through these two sub-basins in the northern area (Figure 5.3). These two wells 34/7-23A and 34-7-23S were drilled in the northern east sub-basin. The Upper Draupne sandstone was deposited in both wells 34/7-23A and 34-7-23S. The source of the sandstone is northwest that was interpreted in the sequence stratigraphy. Therefore, the Upper Draupne sandstone was deposited in the entire shallow part of these sub-basins as the interpretation in Figure 5.5. And the Upper Draupne sandstone was stopped at the location of well 34/7-24S, which is based on the result from the sequence stratigraphy (Figure 4.10).

The N-S cross section is shown in Figure 5.6, which indicate the variance of the thickness of Draupne Formation.

5.3.1 BASE CRETACEOUS UNCONFORMITY

The interpreted time structure map of BCU is shown in Figure 5.3. BCU is a regional unconformity covering the whole study area. On the other hand, BCU is the key boundary between Late Jurassic and Early Cretaceous, which indicates the halt of the Late Jurassic rifting. BCU is interpreted in a strong negative though reflector tied in the seismic data at the well locations, and interpreted confidently (Figure 5.2).

The Upper Draupne sandstone formation is overlaid by BCU immediately within a short period, therefore the BCU is assumed to indicate the depositional environment for the upper part of the Draupne formation. In the Figure 5.3, the half-graben is located at the southwest of the figure, which was bounded by SF and SEF in the west. There are two depocenters, one of which in the south is deeper. The Gullfaks high is located at the southeastern part in this area (Figure 5.3), which was formed by the footwall uplift and rotation of ISF block. To the north, the BCU turned to shallow and was separated as two sub-basins by SEF. In the process of forming these two sub-basins, the SF and SEF were both truncated to the north, and therefore the hanging wall subsidence and fault block rotation were weaker than that in the central and southern parts. The northwestern sub-basin is located at the fault degraded area. These two shallower basins could be the potential area for sandstone deposits. To the eastern part of the half graben, it showed gradual coastal facies. The line of the coastal facies follows the trend direction of SF and SEF (Figure 5.3).

5.3.2 HEATHER

The interpretation of Heather is shown in Figure 5.7. The erosion line of Heather is shown as the orange dash line, which means the truncation of Top Heather by BCU. Discovery of the depositional area of the Heather is significant, because the boundary of Top Heather defined the area that the Upper Draupne sandstone could possibly deposited in and preserved from the erosion of BCU.

Top Heather seismic horizon is tied in a negative though and is interpreted confidently (Figure 5.2). Heather formation was truncated by the erosional BCU in the eastern part, and was bounded by SF and SEF in the western part (Figure 5.4). The Top Heather surface is the base of the Draupne Formation showing the depositional area of the Draupne Formation. The Top Heather surface is not only the depositional area of Heather Formation, but also the limit of the Draupne Formation deposition.

5.3.3 ISOCHORE OF DRAUPNE FORMATION

Isochore map was built to show how variance in structural situation, which controlled the depositional processes of Upper Draupne sandstone during the latest Jurassic. The isochore of Draupne Formation is from Top Heather to BCU. This is not only the thickness of the Draupne Formation, but also indicate the accumulate space of the Upper Draupne sandstone (Figure 5.8). Thickness of this interval varies from 0ms to about 210ms. Showing in the Figure 5.8, the thickest part is located at the northern depocenter. In the half-graben area, the value of the thickness is high, and increasing to these two depocenters, decreasing to these two sub-basins in the northern area. The thickness in the fault degraded area varied from about 20ms to about 100 ms. The low gradient area shows the thickness range from about 10ms to 50 ms (Figure 5.8).

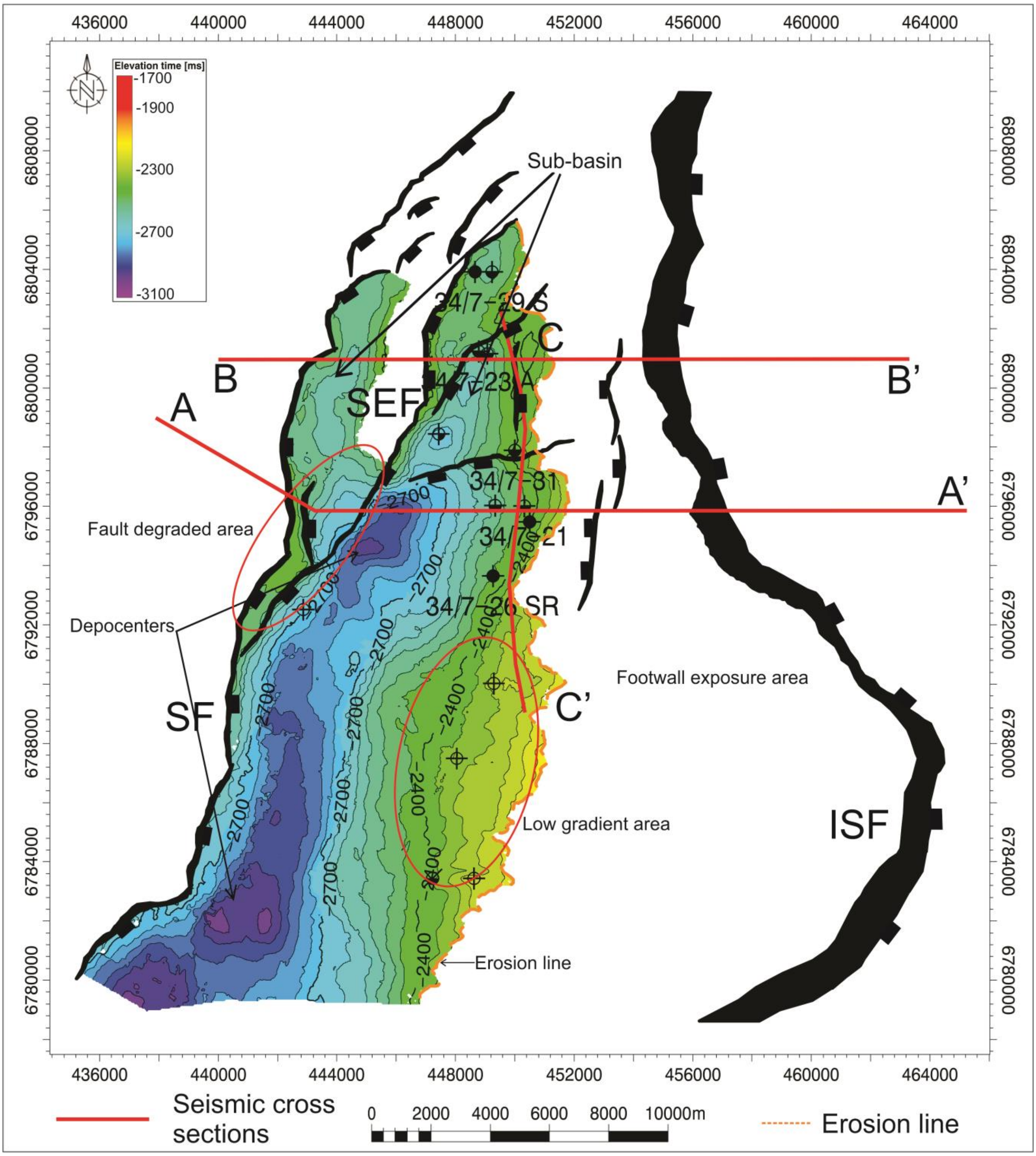


Figure 5.7. Time structural surface of Top Heather.

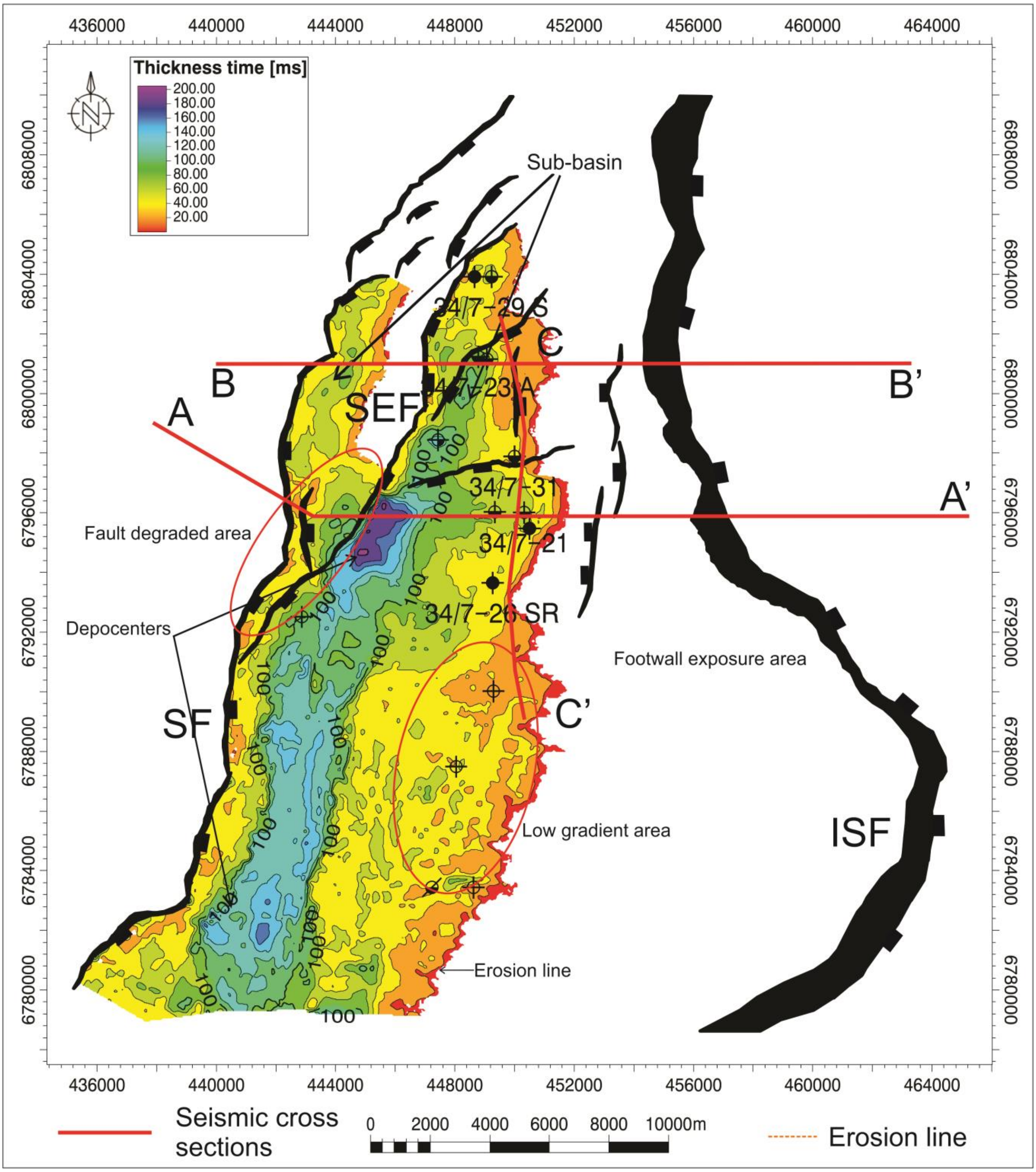


Figure 5.8. Time isochore map of Draupne Formation.

6 UPPER DRAUPNE SANDSTONES INTERPRETATION

To interpret the Upper Draupne sandstone, it is very important to distinct the sandstone and shale within the Draupne Formation correctly. Therefore to interpret the transition from sandstone to shale in the same seismic reflector is a critical work. To achieve the aim above, how to select a proper surface attribute method is significant.

6.1 Upper Draupne sandstone distribution in the exploration wells

In the study area, the Upper Draupne sandstone shows in some exploration wells (Figure 6.1) with certain thickness (Table 4). The sandstone was concentrated at the northeastern sub-basin which is located at the uplift footwall of ISF, and close to the erosion line of Heather Formation.

Table 4. Thickness of Draupne Formation and Upper Draupne sandstone in wells

well name	Total thickness of Draupne FM (m)	Thickness of Upper Draupne SS (m)
34/7-26 A	75	54
34/7-26 SR	78	8
34/7-29 S	68	17
34/7-31	45	31
34/7-31 A	11	10
34/7-23 A	111	30
34/7-23 S	97	21
34/7-21	79	39
34/7-21 A	95	17

6.2 Distribution of Upper Draupne sandstone in the seismic data

To do the interpretation of Upper Draupne sandstone, the seismic data observations need to be finished. Based on the location of these exploration wells, and the thickness of the Upper Draupne sandstone in these wells, the characters of the Upper Draupne sandstone in the seismic data are shown in Figure 6.2. The observation is in chapter 6.3.

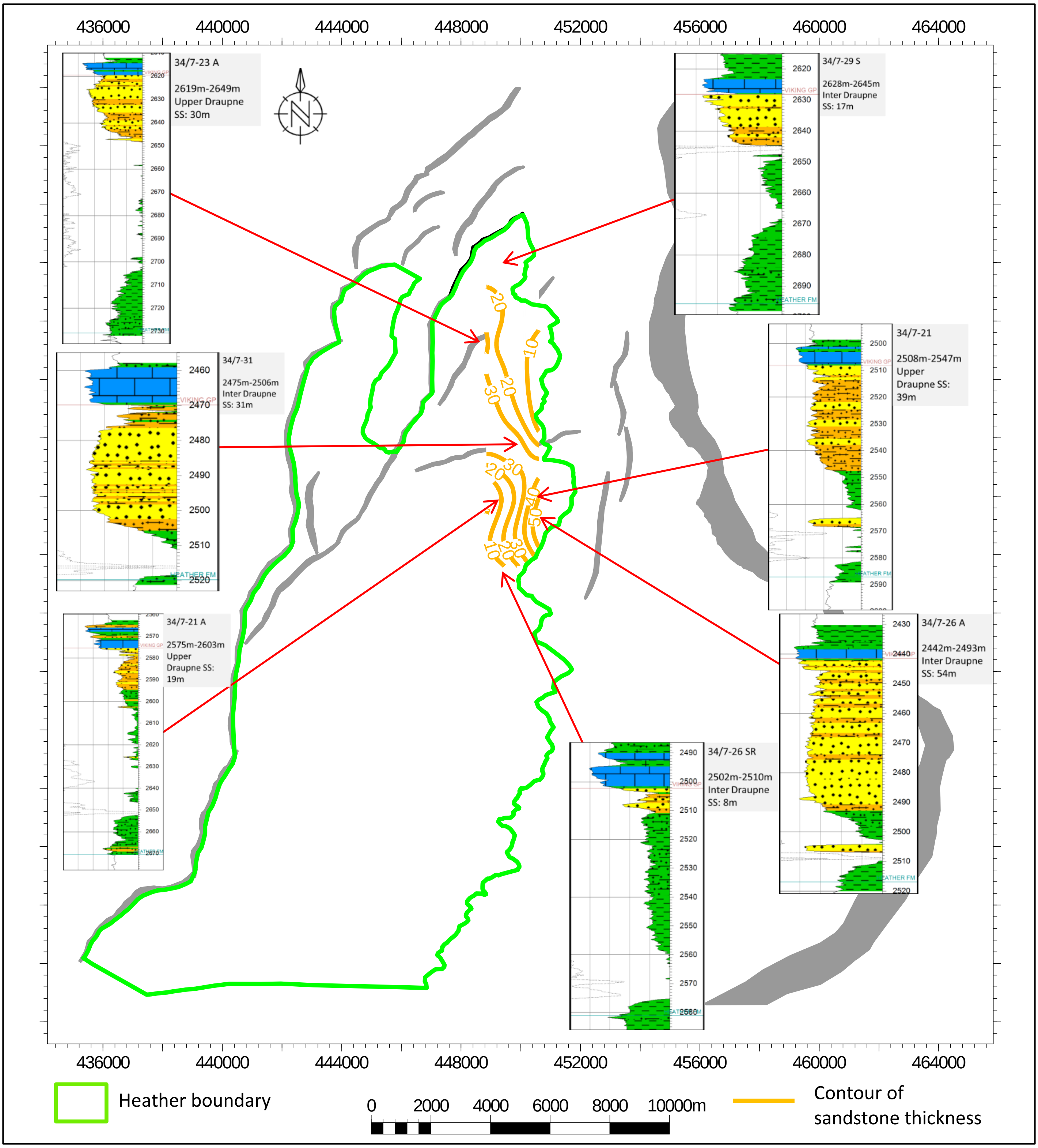


Figure 6.1. Facies map of Upper Draupne sandstone in these exploration wells.

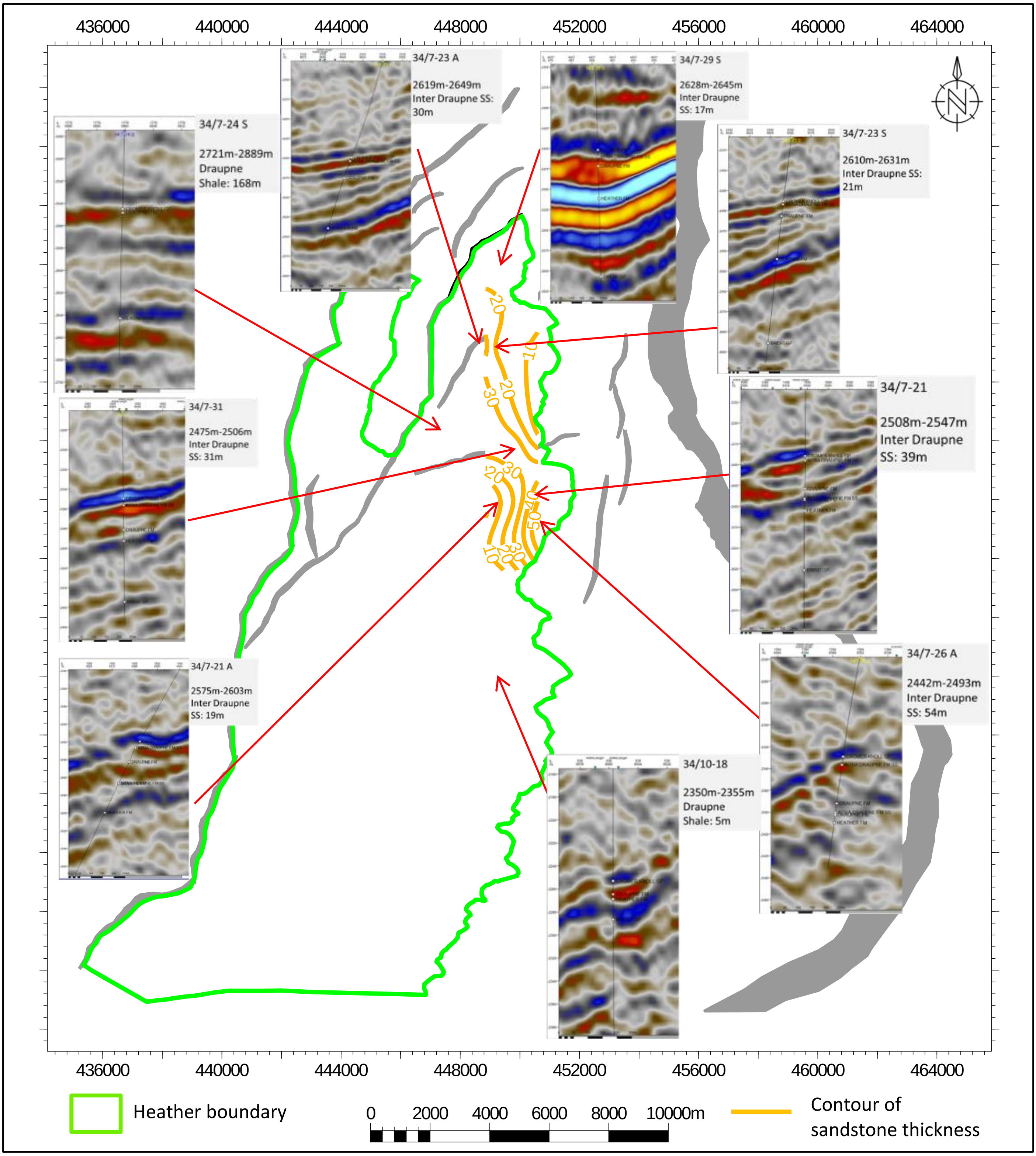
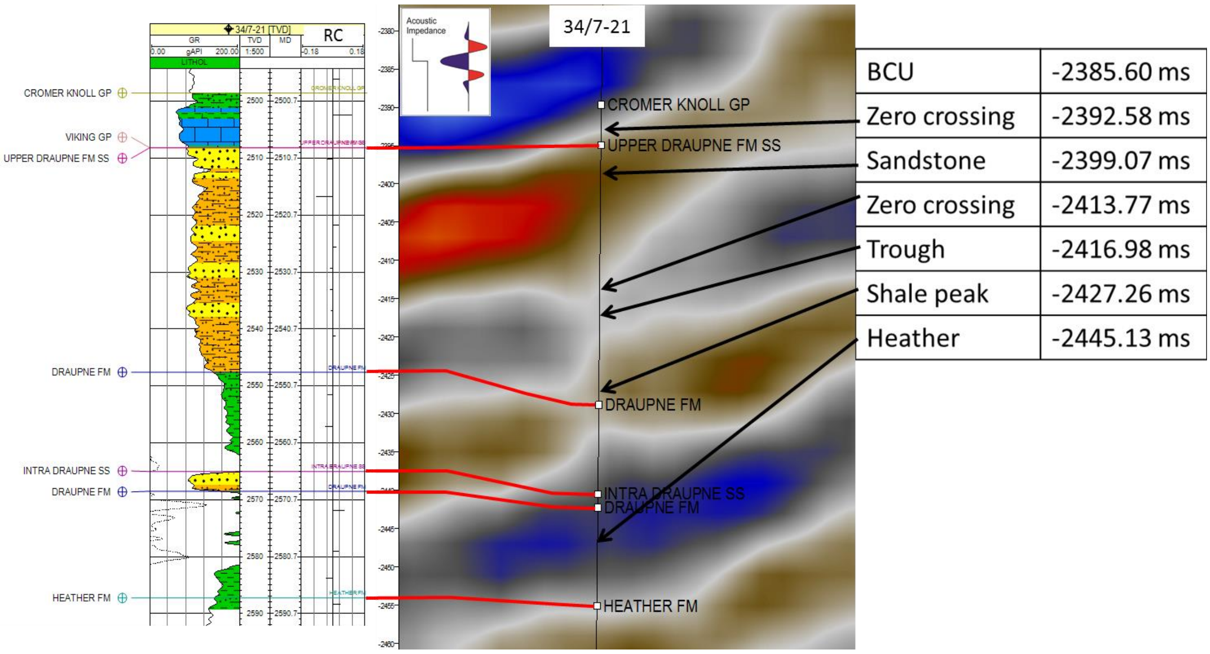


Figure 6.2. Seismic Facies map of Upper Draupne sandstone.

6.3 Seismic facies interpretation of Upper Draupne sandstone

In the Chapter 6.2, the distribution of sandstone seismic facies was described. In this chapter, the observation of seismic data was finished, and based on the characters and results of the seismic facies of the sandstone, an applicable surface attribute method will be chosen.

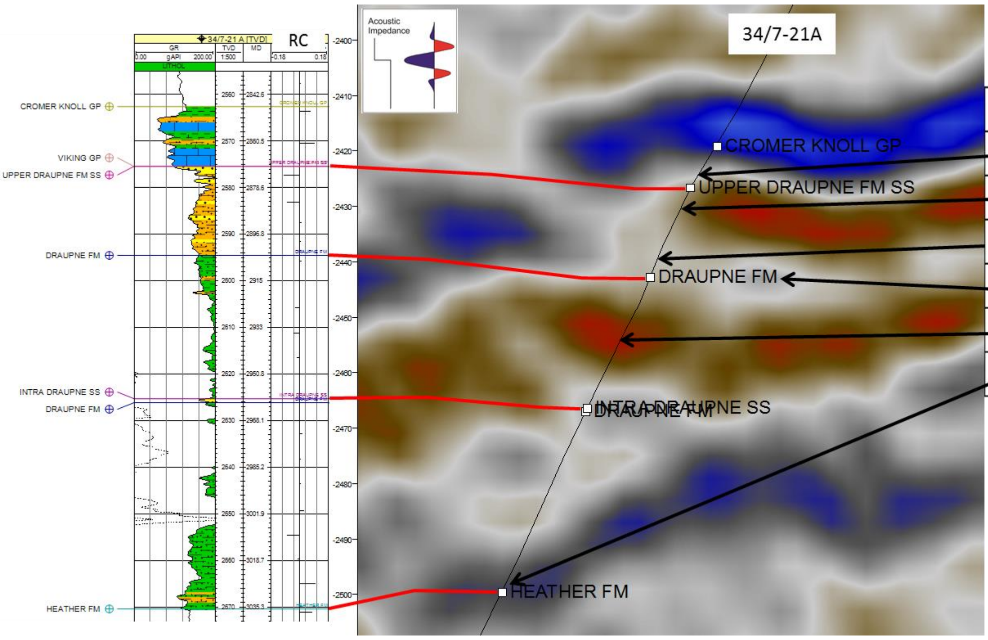
In well 34/7-21 (Figure 6.3) and well 34/7-21A (Figure 6.4), the RC log shows negative RC value below the Upper Draupne sandstone well top, and positive loop in the seismic data which mean the sandstone formation is soft compare with that overlying. Similarly, the Draupne Shale formation below the Upper Draupne sandstone shows negative RC value and positive loop in seismic data as well. Draupne Shale which below the Intra Draupne sandstone show positive value in RC log below the formation well top and negative loop in seismic data which indicates a hard seismic event.



BCU	-2385.60 ms
Zero crossing	-2392.58 ms
Sandstone	-2399.07 ms
Zero crossing	-2413.77 ms
Trough	-2416.98 ms
Shale peak	-2427.26 ms
Heather	-2445.13 ms

Figure 6.3. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-21, corresponding with the lithology log (left) and two-way time (right).

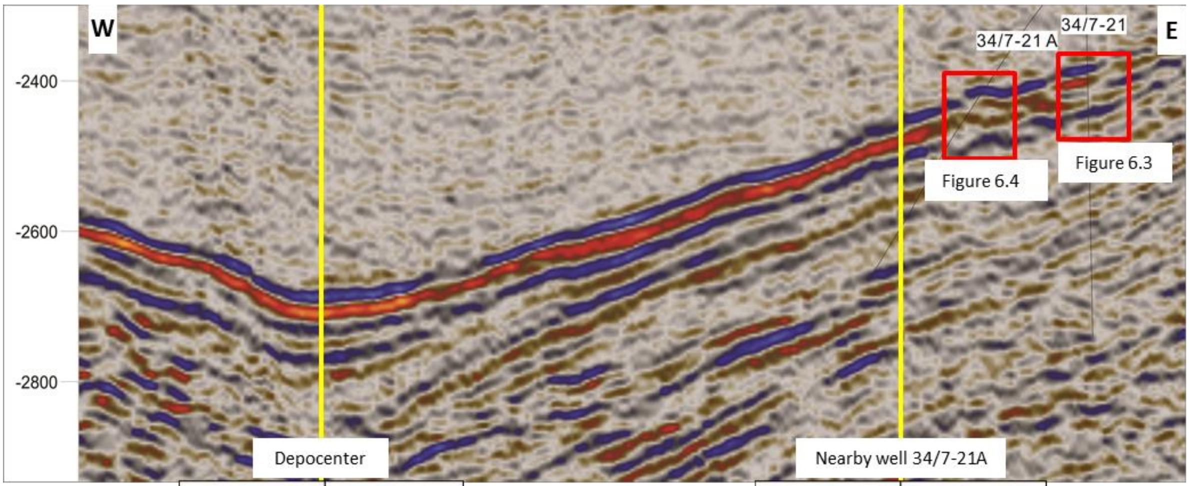
Furthermore, from the seismic data correlated to the well 34/7-21(Figure 6.3, middle), the duration of the whole seismic positive loop in the Upper Draupne Sandstone is 21ms. The range from BCU to Draupne shale peak is 42ms, which include three zero crossing and two positive loops. In well 34/7-21A (Figure 6.4, middle), the duration of the whole seismic positive loop of Upper Draupne Sandstone is 18ms. The range from BCU to the peak of Draupne shale is 40ms including three zero crossing. Particularly, in Figure 6.4, the seismic data shows a clear variance from two positive loops at east to one merged positive loop at west. At right, two positive loops in the 40ms range are called Double Loops in this study. At left, the positive loop has less number of zero crossing in the similar range.



BCU	-2416.62 ms
Zero crossing	-2423.42 ms
Sandstone	-2430.10 ms
Zero crossing	-2440.99 ms
Shale though	-2443.26 ms
Peak	-2456.41 ms
Heather	-2490.53 ms

Figure 6.4. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-21A, corresponding with the lithology log (left) and two-way time (right).

The seismic cross section with both wells 34/7-21 and 34/7-21A is shown in Figure 6.5, which is used to show seismic data in the deeper depositional area. The position of deeper BCU near well 34/7-21A is indicated by the yellow vertical line to the west, where the sandstone pinches out. The yellow vertical line to the west is located at the depocenter of western part of well 34/7-21A, and indicates the similar time pattern. Considering the sandstone hard to deposit in that deep depth, this position was regarded as deposited area of the shale (Figure 6.5).



Depocenter

BCU	-2688.85 ms
Zero crossing	-2699.12 ms
Shale	-2709.87 ms
Zero crossing	-2722.60 ms
Trough	-2733.32 ms
Peak	-2750.08 ms
Trough	-2771.88 ms

Nearby well 34/7-21A

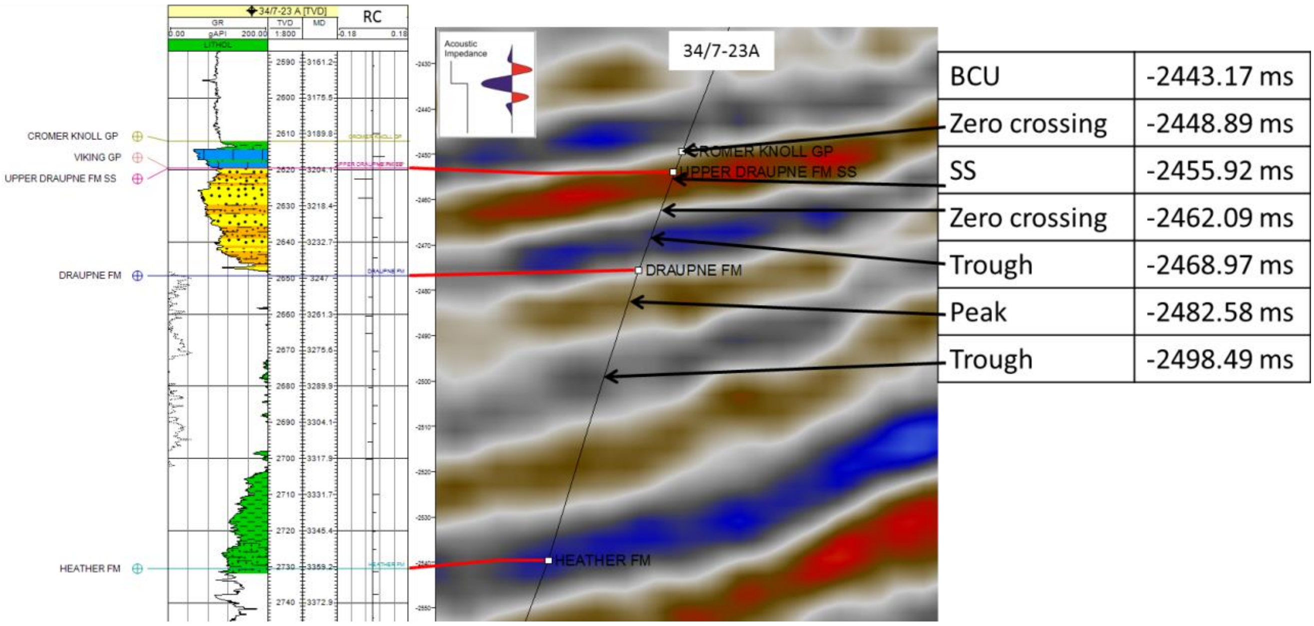
BCU	-2443.07 ms
Zero crossing	-2453.70 ms
Shale	-2467.36 ms
Zero crossing	-2482.93 ms
Trough	-2492.31 ms
Peak	-2507.32 ms
Trough	-2525.03 ms

Figure 6.5. Regional seismic data illustration the character of the sandstone, seismic cross section from A-A’ in Figure 4.4. Yellow lines indicated the two-way time distribution from BCU downwards in the table below.

In the seismic data near wells 34/7-21 and 34/7-21, it shows double positive loops in the sandstone area between BCU to 45ms below BCU. However, between BCU and 45ms, the seismic data near well 34/7-21A (Figure 6.5, yellow line to the east) and near the depocenter (Figure 6.5, yellow line to the west), shows only one positive loop with duration as 29ms and 23ms respectively. From the observation above, from BCU to 45ms below BCU, sandstone deposition includes more zero crossing number than that in the shale deposition area, they are also different at the duration of first positive loop below BCU.

Double positive loops (Figure 6.5) show in wells 34/7-21 and 34/7-21A because of presence of Upper Draupne sandstone, with a negative loop in the middle. However, in the area without sandstone deposition, there is no negative loop, negative duration and amplitude. More examples will be shows as below.

The Upper Draupne sandstone Formation from well 34/7-23A shows lithological property as negative RC value (Figure 6.6, left) below the formation well top and positive loop from the seismic data (Figure 6.6, middle). And from BCU to 45ms, the seismic data shows same double positive loops as that was mentioned above. And the duration Upper Draupne sandstone loop is 13ms.

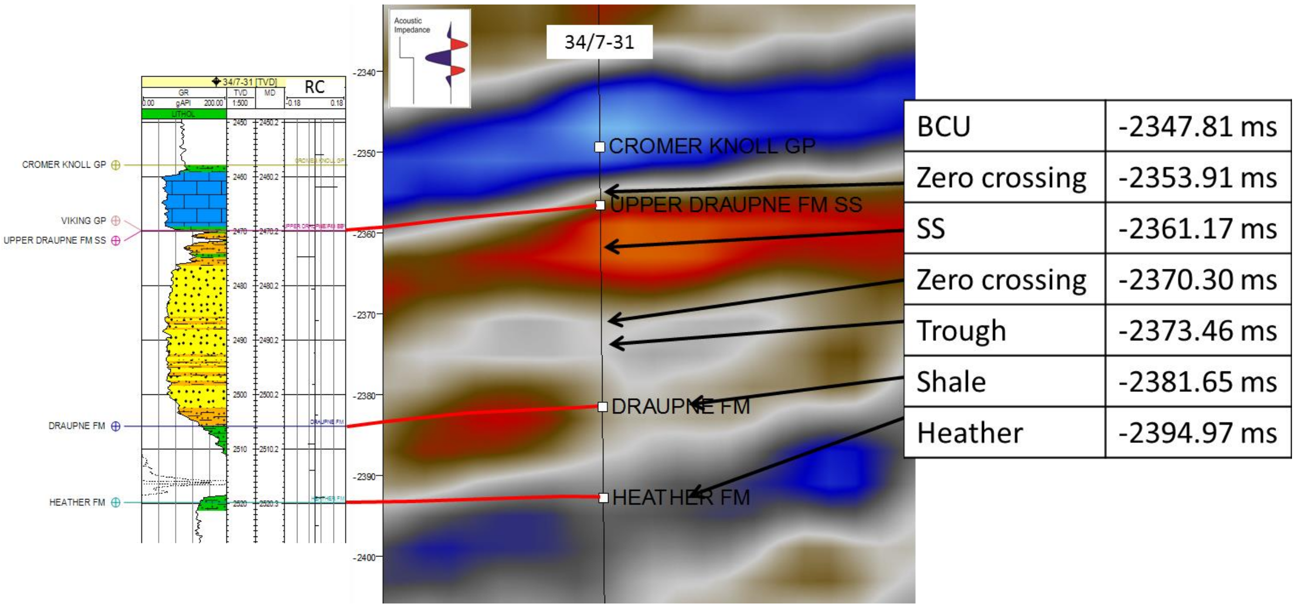


BCU	-2443.17 ms
Zero crossing	-2448.89 ms
SS	-2455.92 ms
Zero crossing	-2462.09 ms
Trough	-2468.97 ms
Peak	-2482.58 ms
Trough	-2498.49 ms

Figure 6.6. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-23A, corresponding with the lithology log (left) and two-way time (right).

In the well 34/7-31 (Figure 6.7), the Upper Draupne sandstone Formation shows lithological property as negative RC value (Figure 6.7, left) below the formation well top, and positive loop in seismic data (Figure 6.7, middle). The Draupne shale has the same shows as that of Upper Draupne sandstone. However, the Upper Draupne sandstone shows the double positive loops, as same as that in wells 34/7-21 and 34/7-21A, from BCU to 45ms below. And the duration of positive loop in the Upper is 16ms.

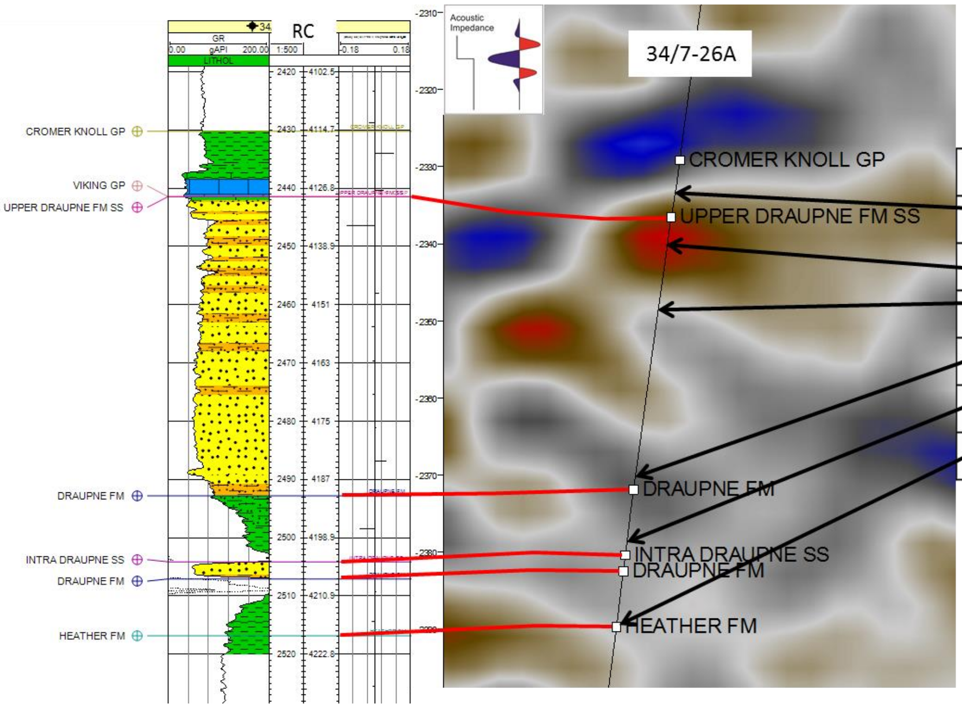
In the well 34/7-26A (Figure 6.8), the Upper Draupne sandstone Formation shows lithological property as negative RC value (Figure 6.8, left) below the formation well top and positive loop in seismic data (Figure 6.8, middle). The Draupne shale has the same display as Upper Draupne sandstone both in RC value and seismic loop polarity.



BCU	-2347.81 ms
Zero crossing	-2353.91 ms
SS	-2361.17 ms
Zero crossing	-2370.30 ms
Trough	-2373.46 ms
Shale	-2381.65 ms
Heather	-2394.97 ms

Figure 6.7. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-31, corresponding with the lithology log (left) and two-way time (right).

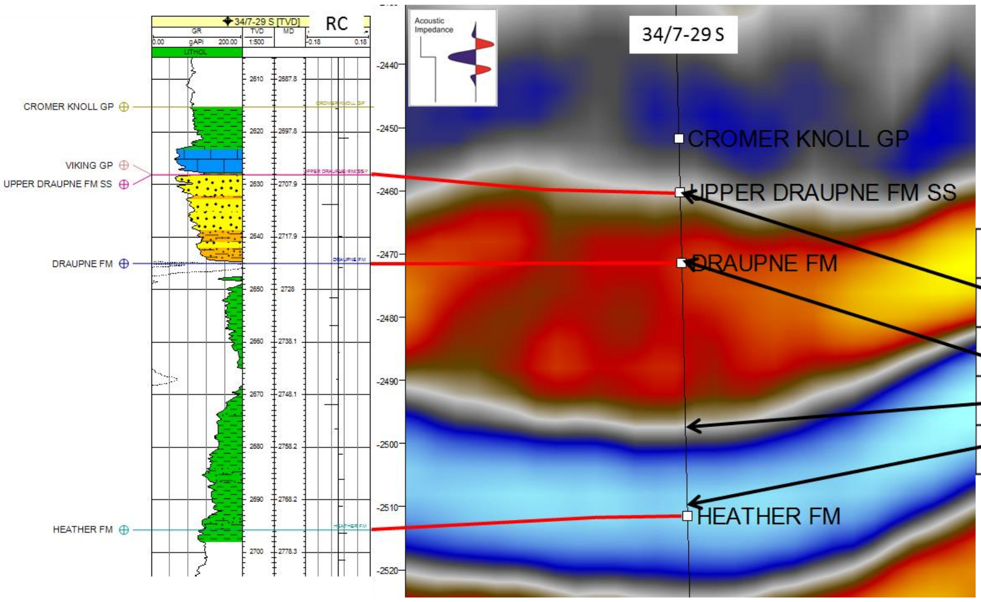
Specially, in the well 34/7-26A, it shows 54 meters Upper Draupne sandstone which is the thickest sandstone present in these wells. The double seismic positive loops are not clear in this well, which may be caused by the too high thickness of sandstone (Figure 6.8, middle). However, to the west nearby, the double positive loops have very clear shows, which have been seen from that near wells 34/7-21 and 34/7-21A (from BCU to 45ms below BCU). At this well, the positive loop duration of the Upper Draupne sandstone duration is 20ms.



BCU	-2331.69 ms
Zero crossing	-2338.38 ms
peak	-2347.69 ms
Zero crossing	-2358.15 ms
Trough	-2367.32 ms
Peak	-2379.42 ms
Trough	-2391.90 ms

Figure 6.8. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-26A, corresponding with the lithology log (left) and two-way time (right).

From the well 34/7-29S (Figure 6.9), the Upper Draupne sandstone shows negative RC value (Figure 6.9, left) below the FM well top and the Draupne Shale which underlying the Upper Draupne SS, shows positive RC value below the formation well top. However both of them show positive loop in the seismic data (Figure 6.9, middle).

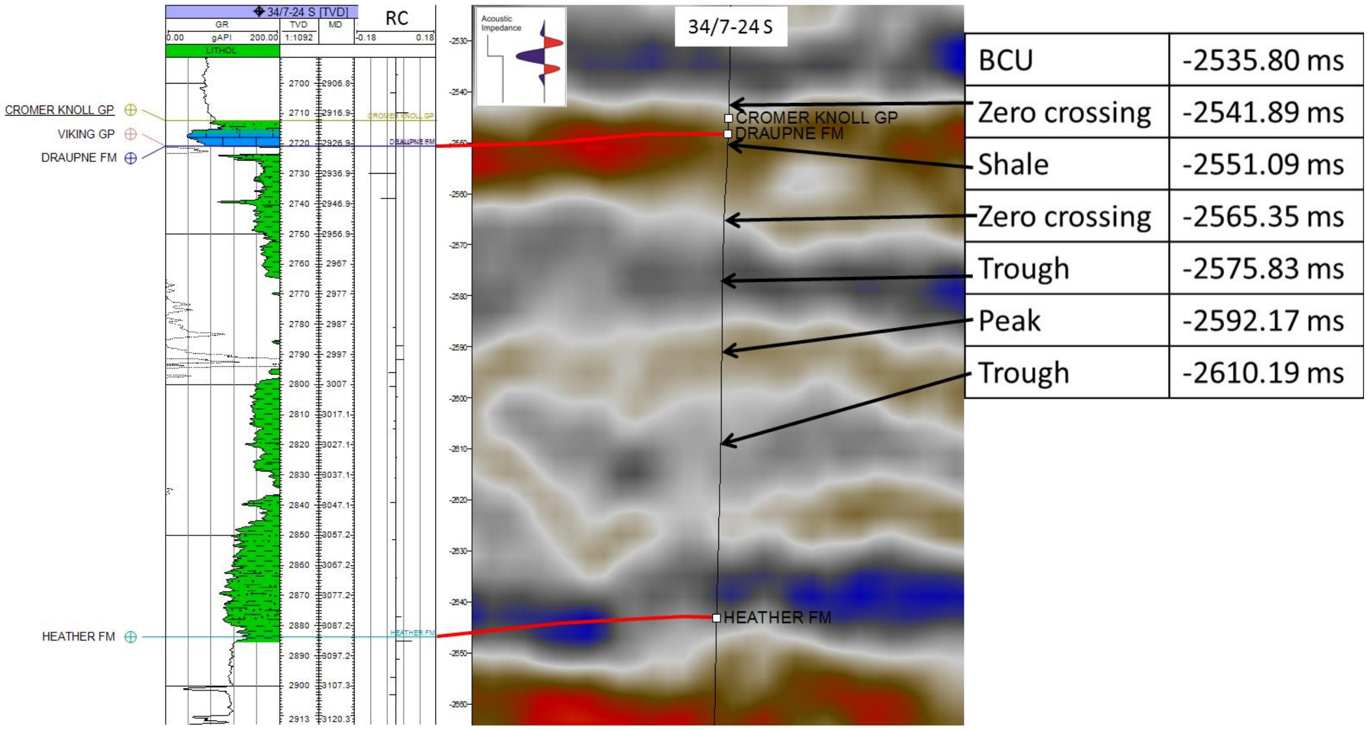


BCU	-2449.62 ms
Zero crossing	-2459.03 ms
Shale	-2479.15 ms
Zero crossing	-2497.19 ms
Heather	-2510.16 ms

Figure 6.9. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-29S, corresponding with the lithology log (left) and two-way time (right).

Differently, in the well 34/7-29S (Figure 6.9), the seismic loop of Upper Draupne sandstone merges with the seismic loop of Draupne shale below to a seismic positive loop with 38ms duration. This phenomenon may be caused by the low vertical resolution of the seismic data, which cannot separate the sandstone from the overlying shale.

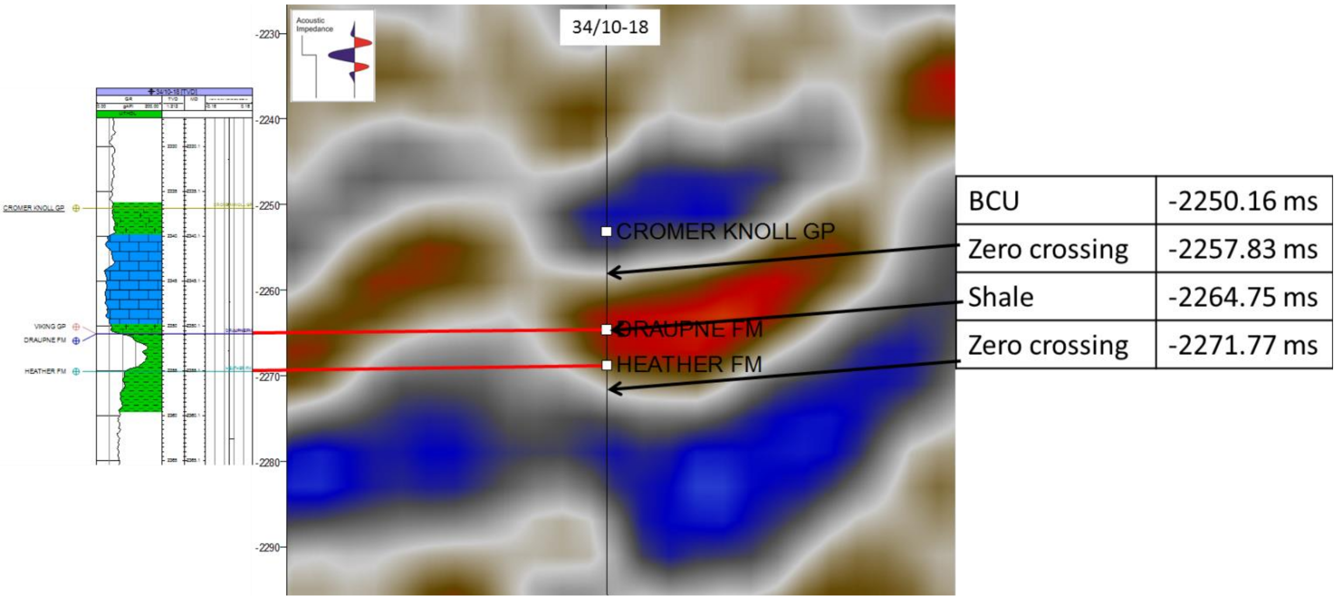
The Draupne Shale Formation shows negative RC value (Figure 6.10, left) below the formation well top in well 37/7-24S and positive loop in seismic data (Figure 6.10, middle) with 23ms loop duration. However, no Upper Draupne sandstone was found in this well, and there is only one positive loop from BCU to 45ms below BCU.



BCU	-2535.80 ms
Zero crossing	-2541.89 ms
Shale	-2551.09 ms
Zero crossing	-2565.35 ms
Trough	-2575.83 ms
Peak	-2592.17 ms
Trough	-2610.19 ms

Figure 6.10. Seismic Facies (middle) of Upper Draupne sandstone in well 34/7-24S, corresponding with the lithology log (left) and two-way time (right).

In the well 34/10-18 (Figure 6.11), only Draupne Shale shows up. The shale which includes both Draupne Shale and Heather Shale, shows positive loop in the seismic data (Figure 6.11, middle) with loop duration 14ms.



BCU	-2250.16 ms
Zero crossing	-2257.83 ms
Shale	-2264.75 ms
Zero crossing	-2271.77 ms

Figure 6.11. Seismic Facies of Upper Draupne sandstone in well 34/10-18, corresponding with the lithology log at left and two-way time depth at right.

Overall, in the Upper Draupne sandstone Formation wells, seismic double loops shows in the range from BCU to 45ms below, and no double loops in wells show Draupne shale only (Table 5). However, in well 34/7-29S shows no double loops with sandstone deposited, that may cause by the low vertical resolution of the 3D seismic data. In this time depth range, there are more zero crossing include positive and negative zero crossing. On the other side, at the time depth 45ms below BCU, the Upper Draupne sandstone area shows positive amplitude, but negative amplitude in the area only Draupne shale deposited. The duration of the sandstone shows unclear different, and then is hard to show in surface attribute.

Table 5. Summary of Double loops in seismic data from main wells

well name	Total thickness of Draupne FM (m)	Thickness of Upper Draupne SS (m)	Double loops in seismic data range 45ms below BCU	Duration of the first seismic reflector below BCU (ms)
34/7-21	79	39	Yes	21
34/7-21 A	95	17	Yes	18
34/7-23 A	111	30	Yes	13
34/7-31	45	31	Yes	16
34/7-26 A	75	54	Yes	20
34/7-29 S	68	17	No	38
34/7-24 S	168	0	No	23
34/10-18	5	0	No	18

6.4 Surface Attributes interpretation

From the observation of the seismic data, the remarkable differences between the Upper Draupne sandstone and the Draupne shale are the crossing number and the double loop character. The boundary for the surface attribute area is the same as that of Heather Formation.

To show the area of double loops, the amplitude value from the -45ms offset surface below BCU (Figure 6.12) should be extracted. It is assumed the surface attribute shows positive amplitude in the sandstone deposited area, and negative amplitude in the shale deposited area. However, the result is clear to see to the north that based on the seismic data of SG9701, but poor to value to the south that based on the seismic data of ST03M01, which is because of difference on the vertical resolution of the seismic data. Another reason of this difference of accuracy is because that, in the low gradient area, the thickness of Draupne Formations is thinner than 45ms and therefore the exacted amplitude comes from the layer below Heather surface is not accurate.

The other method of surface attribute to show the double loops area is called Number of positive zero crossing (Figure 6.13). In the sandstone deposited areas, it shows more positive zero crossing number than that in the areas only shale deposited. From application of this method (Figure 6.13), it shows this method good on differentiation and interpretation of sandstone.

Therefore, these two surface attributes can be used together for the sandstone interpretation guidance. Two seismic cross sections are shown for the sandstone interpretation based on both surface attributes in Figure 6.14 and 6.15.

The interpretation of sandstone (Figure 6.14) is based on the double loops area, and the deposition of the sandstone stopped at the deeper depositional environment in the middle area. This seismic cross section was extracted through the northwestern sub-basin (Figure 6.14). Considering the depositional environment as the shallow marine, the source of the sandstone sedimentary is from northwest, therefore sub-basin is very good for the potential deposition of the sandstone.

In Figure 6.15, the sandstone is interpreted at the slope area, and based on the double loops area in the seismic data.

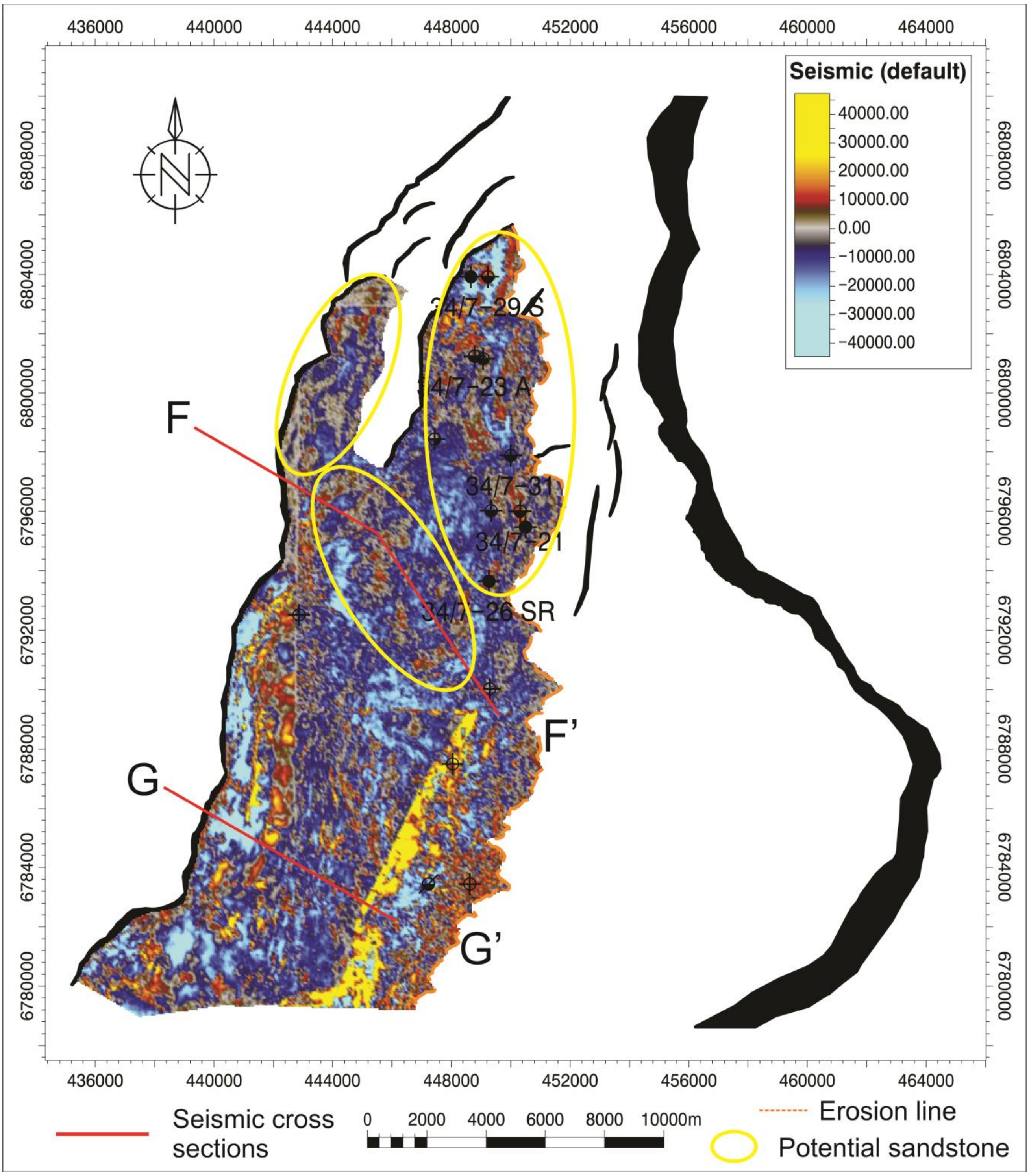


Figure 6.12. Attribute map of Extract amplitude value at -45ms below BCU.

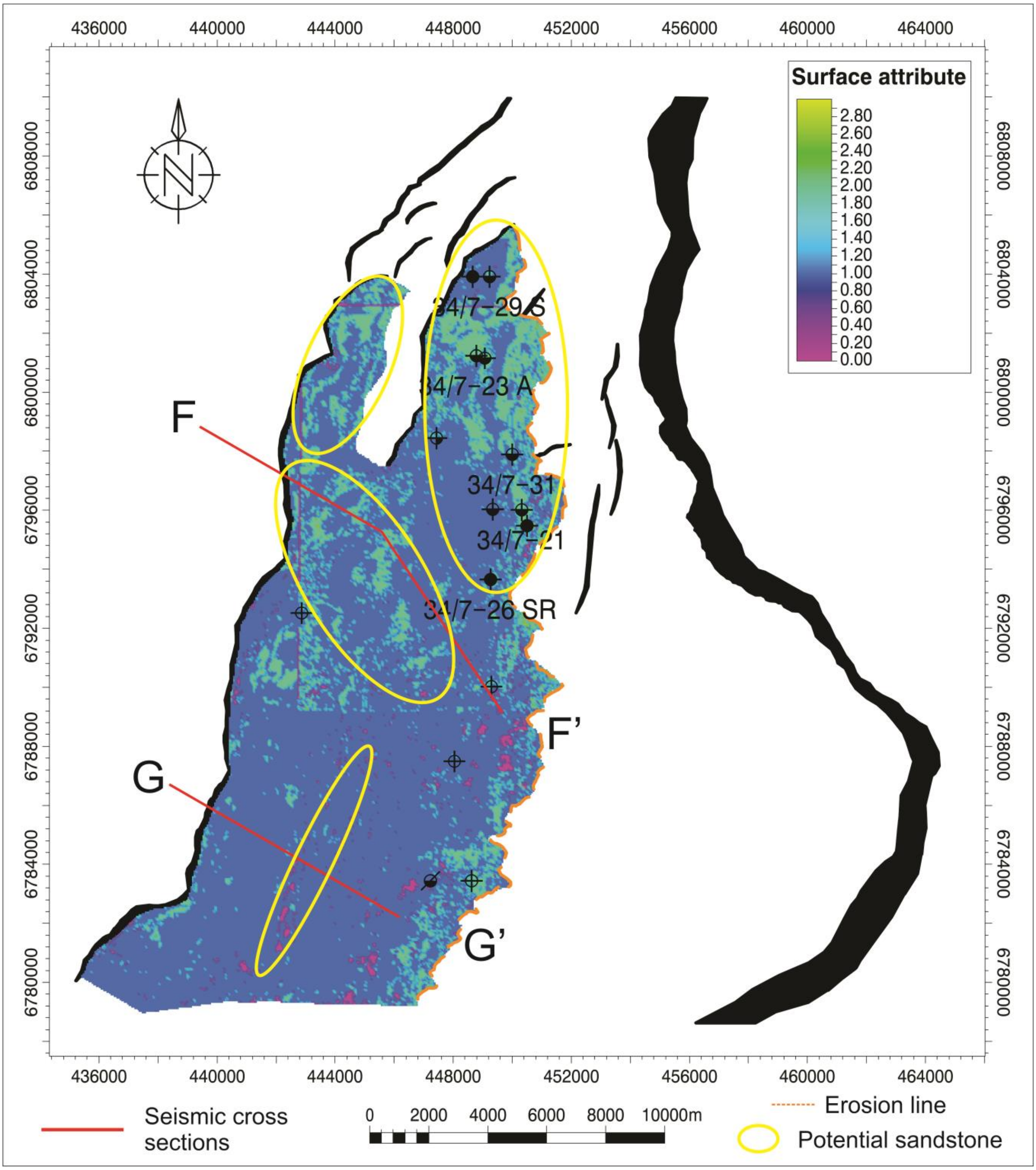


Figure 6.13. Attribute map of number of positive zero crossing between BCU to -45ms below.

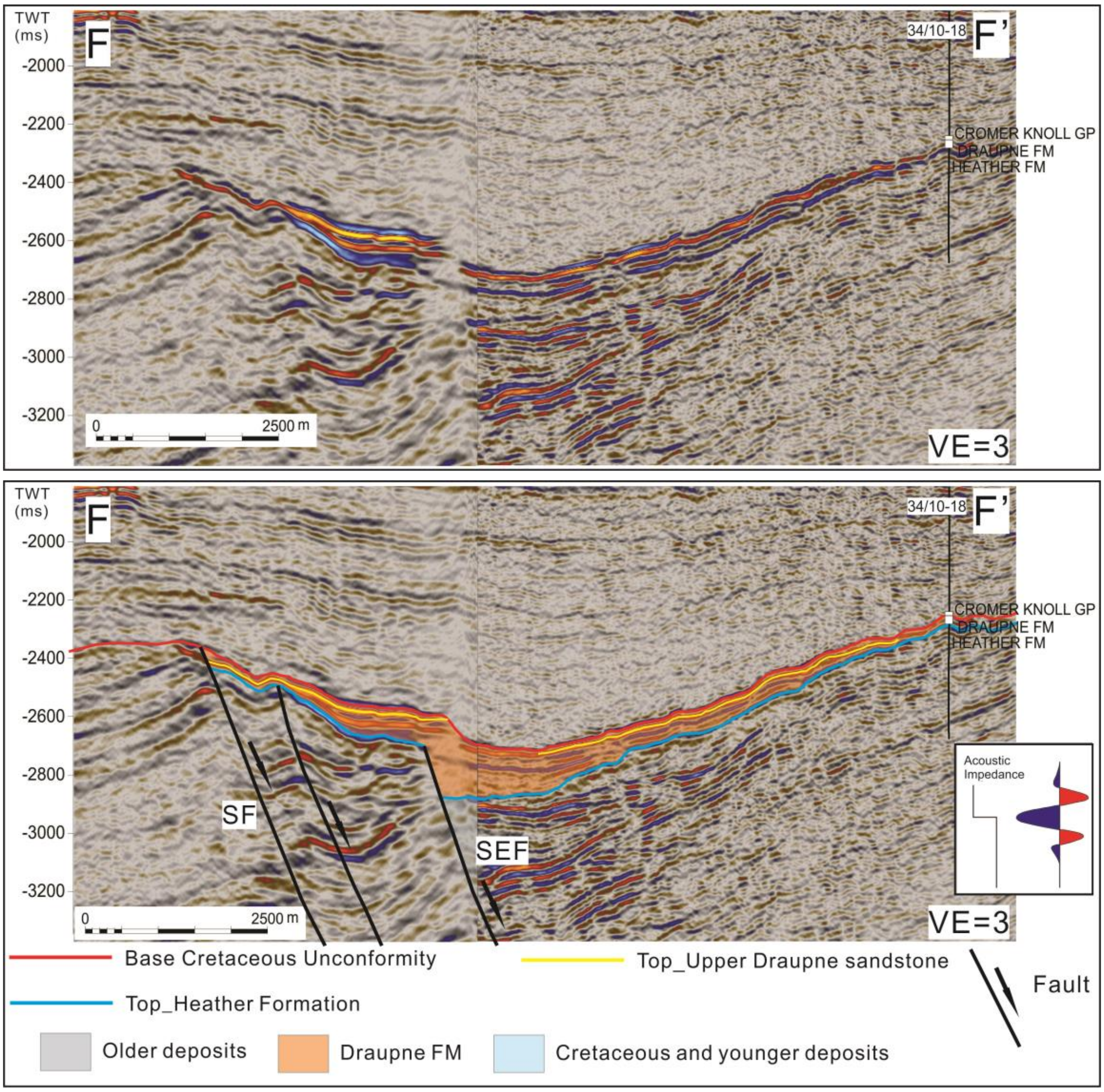


Figure 6.14. Seismic cross section F-F', original seismic data at up and interpreted cross section at low, the location is in Figure 6.12 and 6.13.

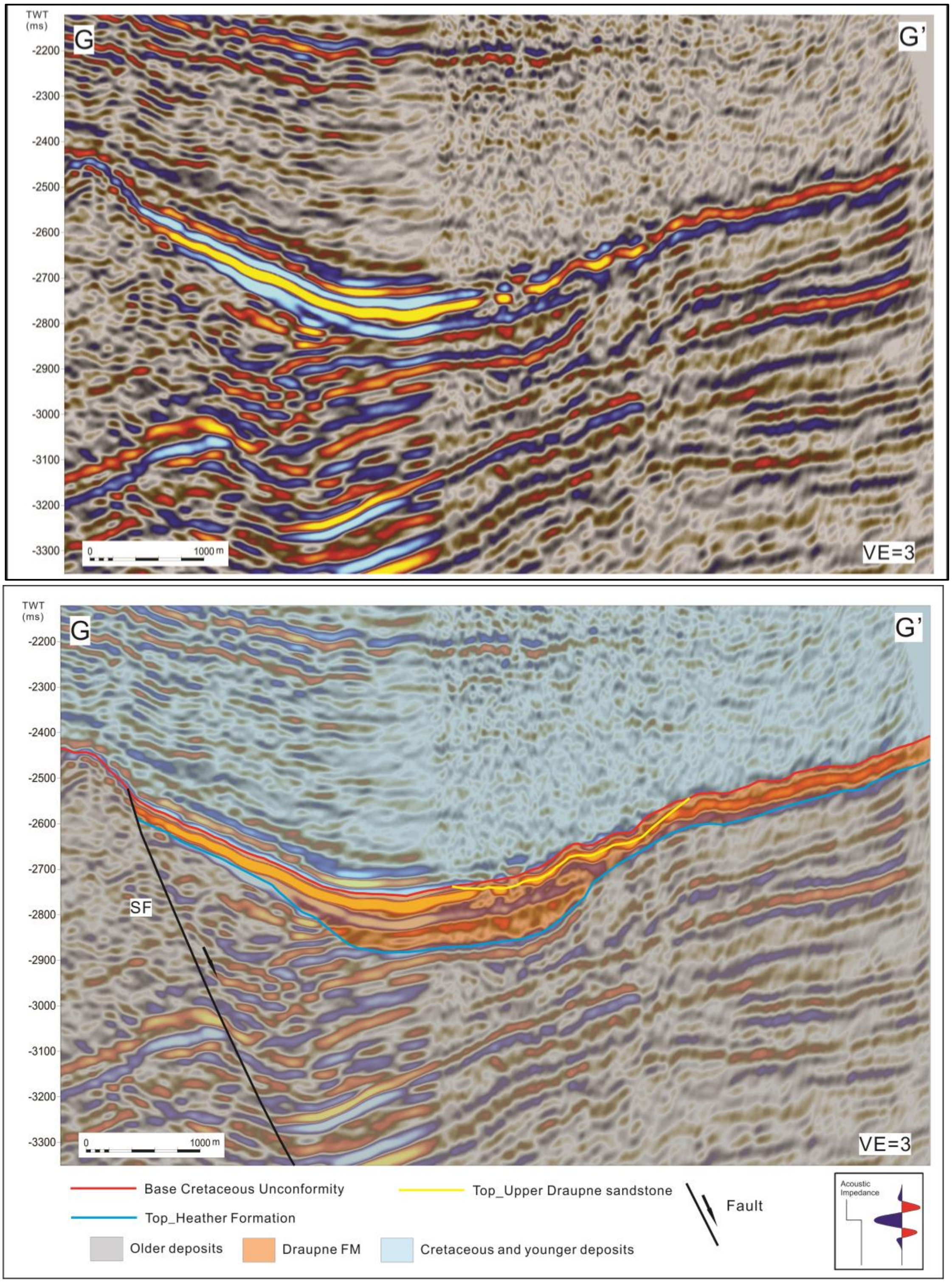


Figure 6.15. Seismic cross section G-G’, original seismic data at up and interpreted cross section at low, the location is in Figure 6.12 and 6.13.

7 DISCUSSION

1) Upper Draupne sandstones depositional map and estimation of paleowater depth.

Upper Draupne sandstones depositional map is shown in Figure 7.1, which is based on both well data and surface attribute results.

To analyse the depositional environment of these sandstones, Paleogeography of the Upper Draupne sandstone (Figure 7.2) will be needed which show the Paleowater depth during deposition. To build the Paleowater depth, the subaerial exposure area which locates between the erosion line and ISF, should be found out and interpreted. The paleowater depth indicates the time when the Upper Draupne sandstone deposition, which is only assumed as an approximate guidance. The analysis of paleowater depth is based on the erosion line of Heather Formation. The erosion positions on the uplift footwall block indicate the minimum depth of sea water during the Late Jurassic.

For this part of study, a horizon was made by interpolation from these erosional positions. The thickness of this horizon and BCU is the maximum value of paleowater depth, which is because this thickness was made without uncompaction and elimination of subsidence lately. To eliminate the influence of subsidence after Late Jurassic, a seismic layer is chosen which deposited far later after BCU, and show the clear subsidence and be interpreted. After that, the subsidence value will be calculated and will be removed from the calculation of thickness, although subsidence value is not an accurate value. However, the unit of the thickness value is still in two-way time. To convert the unit from two-way time to meters, the interval velocity of Draupne Formation of 2900 m/s from the wells data which was used, then can be transformed to meters by using formula "thickness*2900/2". Nevertheless, the uncompaction still has not been finished; even so the paleowater depth may still be able to be used for the analysis of depositional environment as a maximum standard.

Sandstones are described in the Figures 7.1 and 7.2. Sandstone 1 (S1) and S2 are interpreted based on both wells data and surface attributes data, which are respectively located at the northeastern sub-basin and the shoreface area. Compared with the paleowater depth map, the paleowater depth of S1 and S2 in the deposited area ranges from 0 to150 meters, which is the shoreface area.

S4 was interpreted only based on the surface attributes results, which is located to the northwest sub-basin. This basin was mentioned before as a good depositional environment for shallow marine sandstone, with the same source of the sandstone as S1. The paleowater depth for S4 is 0-150 meter, therefore the S4 has a good potential of shallow marine sandstone deposition.

S5 was interpreted out by the surface attributes results, which is located at the faults degraded area and at the hanging wall of SF. Compared with the paleowater depth ranging from 50 to 400 meters, the sandstone was identified as deep-marine fan systems.

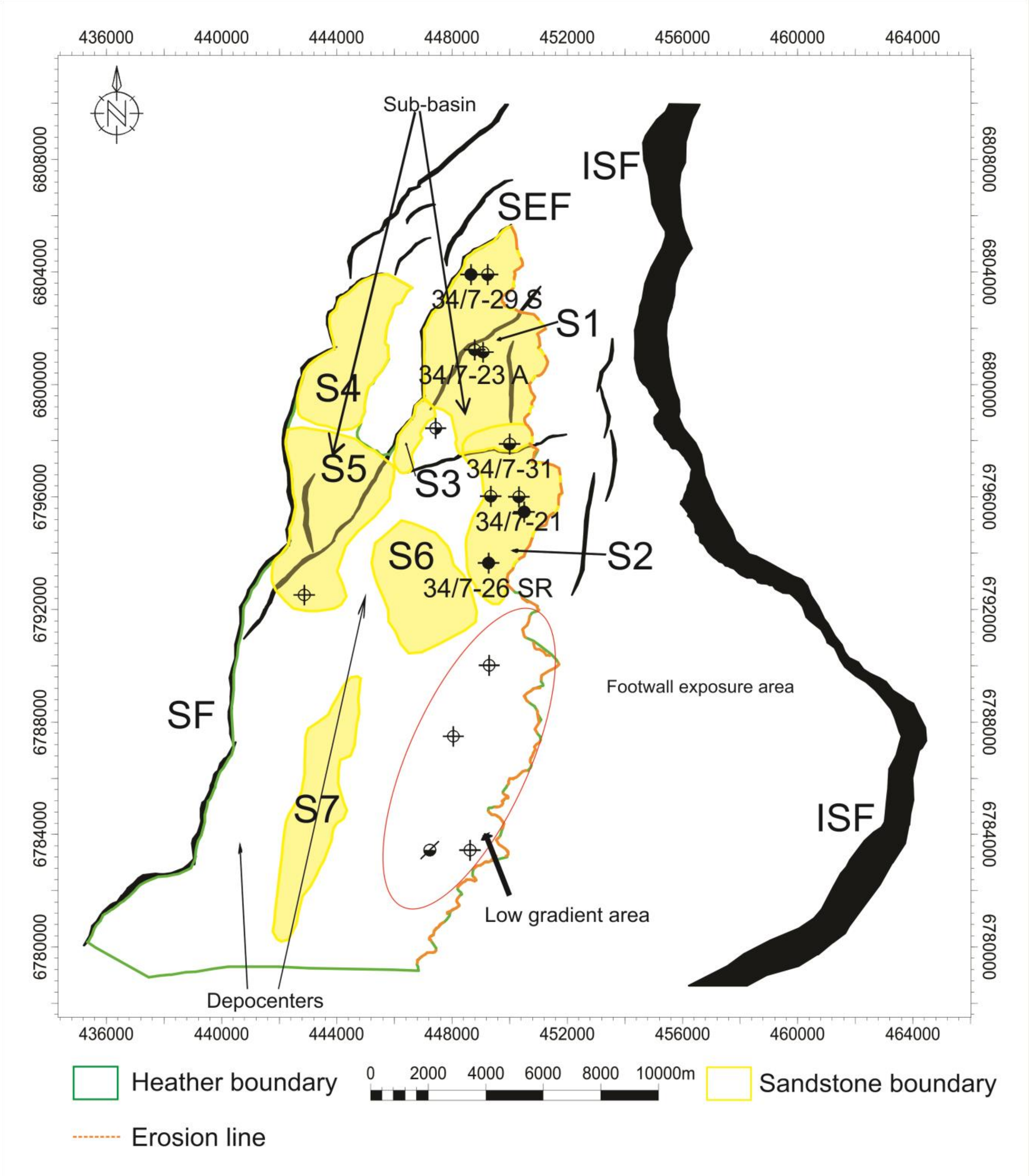


Figure 7.1. Depositional map of Upper Draupne sandstones.

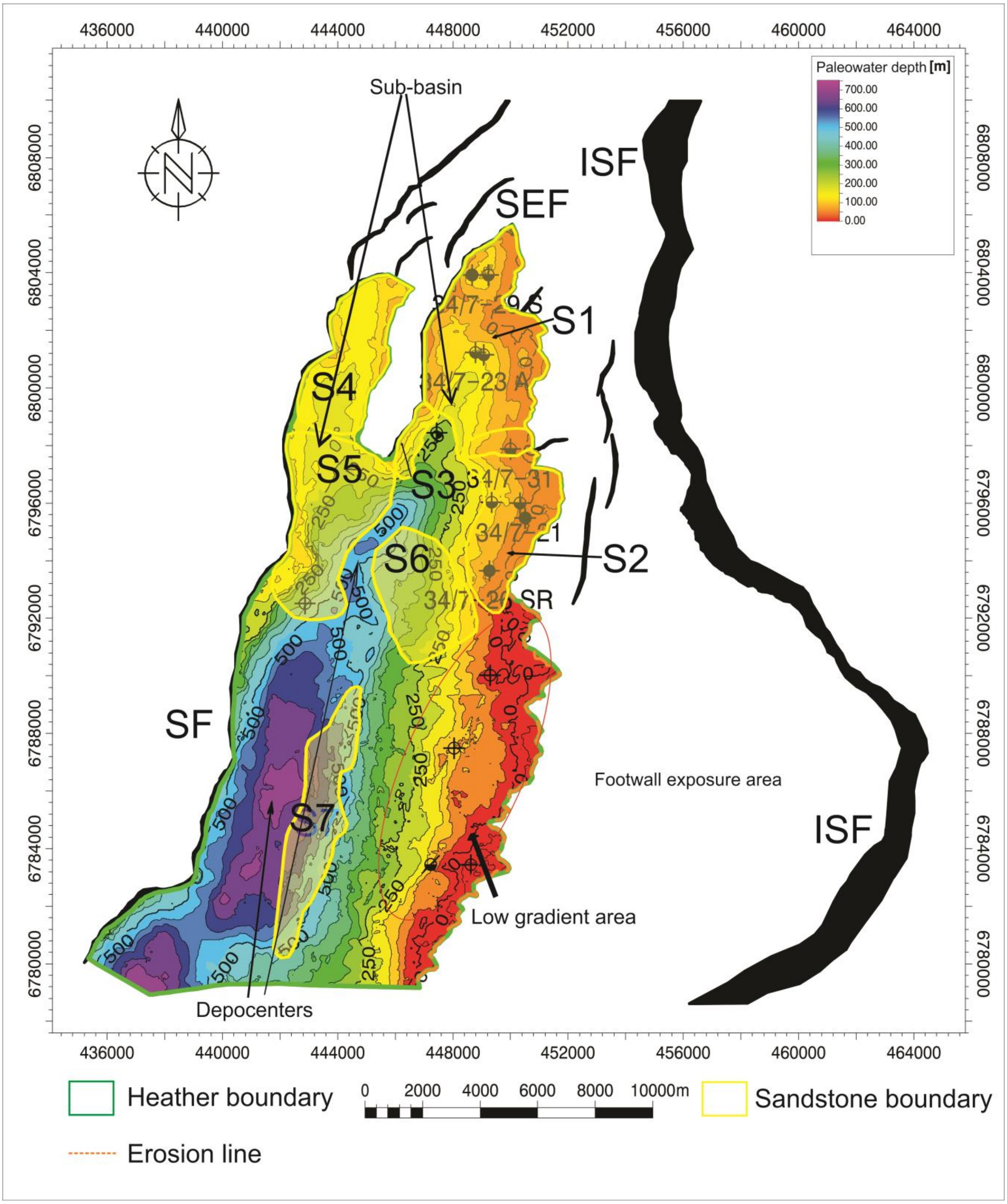


Figure 7.2. Rough paleowater depth map during the Upper Draupne sandstone deposition.

S6 and S7 were interpreted based on the clear double loops in the seismic data and the surface attributes results. S6 was deposited along the low gradient area to the margin of the depocenter in the paleowater ranging from 100 to 400 meters. Therefore, the depositional environment of S6 is the deep marine fan system. S7 was located at the narrow area of the shelf, ranging from 500 to 700 meters, and the depositional environment is identified as the sub-marine fan system.

2) The facies analysis is based on photographs of well cores. The observations of well cores lacks some details, therefore this result should only be regarded as a general analysis of sedimentary lithology.

3) The seismic datasets are of medium quality, which results in some difficulties in distinguishing between sandstone and shale. Therefore, the sandstones interpretation in this study is based on well data, seismic data and analysis of depositional environment.

4) Using these two methods of surface attribute, it shows good quality in the thick Draupne Formation area, while lower quality in the thin Draupne Formation area.

5) The result of Paleowater depth traced from Paleogeography of the Upper Draupne sandstone is only an approximate guidance for the depositional water depth, because the influence of compaction of the formations was not eliminated.

8. CONCLUSION

1) In addition to the Upper Draupne sandstones in the reservoirs of Borg and Borg Northwest fields (S1 and S2), more Upper Draupne sandstones (S3, S4, S5, S6 and S7) have been interpreted in the study area.

2) The Upper Draupne sandstones are deposited as shoreface sandstone in the shallow marine environment and as sub-marine fan system in the deep marine environment.

3) The Upper Draupne sandstones can be interpreted using seismic data. The surface attribute methods are very useful for the sandstone interpretation, however there is still some limits using these methods which depend on the quality of the seismic data.

4) In this study, Number of Positive Zero Crossing is a good way to identify the sandstones where double loops were shown in the seismic data, while the method of Exact Amplitude Value has some limits on doing this.

5) Among all available methods, studied two surface attribute methods, Number of Positive Zero Crossing and Exact Amplitude Value, were applied to guide the sandstone interpretation, while the others were considered not applicable.

6) There are no Upper Draupne sandstones deposited in the area of these two depocenters.

7) These major faults controlled the forming of the half graben in the study area, which is by the rotation of the fault block. These western faults defined the boundary of the half graben to the west.

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