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THE UPPER BRENT STRATIGRAPHY AND RESERVOIR ARCHITECTURE IN THE DEEP NORTHERN VIKING GRABEN

By Hilde Camilla Mari Sæther

Advisor: Rodmar Ravnås

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Abstract

This thesis describes the development of the regressive-to-transgressive shoreline prisms within the Middle Jurassic Tarbert Formation in the Martin Linge-Oseberg west flank and the Valemon-Kvitebjørn area in the Northern North Sea. Three correlations have been built, using 11 facies associations and 9 depositional elements, which comprises 14 facies. The Tarbert Formation has been interpreted to be deposited in a mixed tide and wave energy setting, and has subsequently been divided into the Lower, Middle and Upper Tarbert. The Lower and Upper Tarbert are dominantly wave-dominated, while the Middle Tarbert is tide-dominated. A transition from a more closed wave-dominated bay to a tide dominated estuary and back into a more open wave-dominated bay has been documented. Three lower order sequences have been inferred in the Martin Linge–Oseberg west flank correlation. Each sequence comprises a regressive and a transgressive segment. In the Valemon-Kvitebjørn area 6 higher order sequences are present. Due to the significant expansion of the Tarbert Formation in the southern part of the Rungne sub-basin, fault activity is identified as a major controlling mechanism for thickness variations and facies partitioning. Because the expansion can be noticed as early as in the Lower Tarbert Formation, the initial faulting most likely started before the Tarbert Formation was deposited. More faults became active later during the deposition of the Tarbert Formation, causing the variable thickness and facies shift in the Middle and Upper Tarbert.

Acknowledgment

First of all I would like to thank my supervisor Rodmar Ravnås. This thesis would not have been possible without his knowledge, excellent guidance, commitment and encouragement. I really appreciate the time, ideas and efforts given to make my thesis experience productive and fulfilling.

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Finally I would thank my mom for support and love.

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1. Introduction

The Brent group is the most productive reservoir unit in the Northern North Sea, only outnumbered in some fields by similar-type Triassic and Lower Jurassic reservoirs. The good reservoir properties of the Brent group have lead to considerable attention over the past few decades, and significant achievement in gross sedimentary structure and internal architecture of the unit has been made. As the focus on discovering new oil and gas fields continues, an increase in interest in the hydrocarbon potential in the deeper parts of the Northern North Sea rift system, i.e. the Central Viking Graben have appeared. Subsequently, the Brent group in this area is of interest due to its productivity in other parts of the Northern North Sea.

The Brent group has been proposed to represent two megasequences: the lower basal part of the unit consisting of the formations: Broom, Oseberg and Drake, and the upper part of the unit consisting of the formations: Rannoch, Etive, Ness and Tarbert (Steel, 1993; Ravnås et al., 2000).

This thesis will focus on the Tarbert Formation in the Central Viking Graben or the Rungne sub-basin. The Tarbert Formation is already the main reservoir in a number of fields in the Northern North Sea. The main focus will be to provide a detailed stratigraphic framework of the Tarbert Formation, and identify reservoir potential within the Tarbert Formation in the deeper parts of the Central Viking Graben.

1.1 Aim and rationale for the study

The Tarbert Formation is classified as estuarine based on its clearly transgressive trends. Most of the previous studies of the Tarbert Formation were conducted prior to public access to wells from the deeper parts of the Central Viking Graben. These wells encountered a significantly expanded Tarbert Formation with thick sandy packages. The limited access to wells in the Central Viking Graben has lead to less attention to the stratigraphic position of the sandy units and the overall control on their formation in the overall transgressive interval. In addition there has been recent developments in the understanding of mixed-energy dominated deltas and estuaries achieved via Joint Industry Projects (JIP's), such as FORCE tide, BITE and WAVE consortiums. This might lead to new interpretations of the transgressive unit.

The main objective with this study is two-folded:

1. Study the lateral along depositional strike and the proximal distal changes within the Tarbert Formation, with the intention to investigate the stratigraphic relationship within the formation. The main purpose will be to map out the overall stratigraphic structure and internal stratigraphic architecture of the thick transgressive unit.

2. Identify if changes in basin physiography was a response to changes in tectonic background activity or if there was a more complex control on the local shoreline bathymetry undulations induced by the interplay of tectonics, and spatially and temporarily variable sediment supply.

1.2 Study area

This study area comprises the Tarbert Formation in the Martin Linge area to the west, in the Valemon-Kvitebjørn area in the north and in the western flank of the Oseberg and Tune area to the east. The deposition of the Brent Group records the outbuilding of a major deltaic sequence from the south, and subsequently the retreat or back-stepping of the delta. The Brent Group is located within the North Sea rift basin. The North Sea rift basin represents a failed rift of Triassic-Jurassic age. The Tarbert Formation was deposited in the Bajocian to the Bathonian, and represents the back-stepping of the Brent delta (Ravnås et al., 1997).

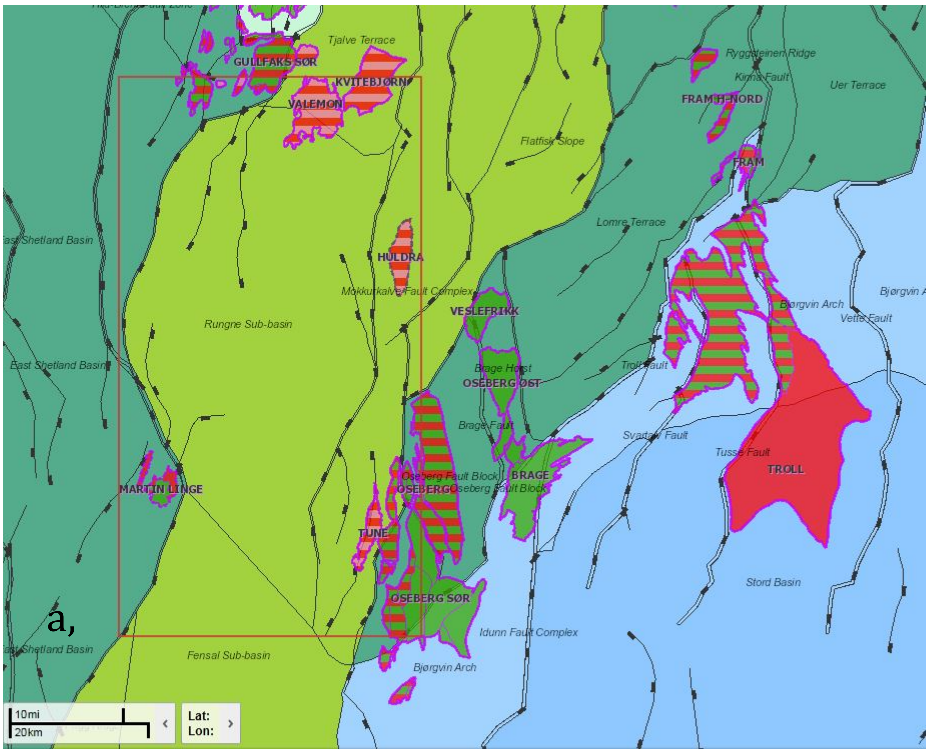


Figure 1-1. Location of the study area with the main structural elements and the fields located in the study area (NPD factpages).

1.3 Previous work on Brent

There is a considerable amount of published work on the Brent Group and the Tarbert Formation arguing different points of views regarding age, nature and paleographic evolution. Analyses of the depositional environments of the Brent Group are more or less similar, with some differences. The Brent Group is located in the central part of the Northern North Sea. In the Norwegian Sector of the North Sea the Brent Group is present in East Shetland Basin, on the Horda Platform and in the Viking Graben. The thickness of the group varies considerably through the area, due to differential subsidence and Middle Jurassic faulting and erosion (Vollset and Dorè, 1984). The Brent Group consists of the outbuilding and retreat of a major deltaic sequence from the south (Evans et al., 2003). A group of studies have documented a marked tectonic control on the Brent Groups thickness distribution. It has been argued that the thickness distribution is primary, as well as secondary due to subsequent erosion and facies tract portioning. Overall there is a significantly increased thickness in wells towards the deeper part of the Northern Viking Graben with expansion factors suggesting doubling or more of the primary thickness from bordering platform and terrace areas (Mitchener et al., 1992; Johannessen et al., 1995; Fjellanger et al., 1996; Ravnås et al., 1997; Folkestad et al., 2014). In a study by Wei et al. (2016) the sandy packages have been argued to be of estuarine origin. Other previous studies suggest that parts of the sandy units potentially had a deltaic origin, and that there was a change in overall deltaic style from one dominated by mixed fluvial-wave types in the regressive segments to one dominated by tide-influenced types in the transgressive segments of a megasequence (Ravnås et al., 1997, 2000). In parallel there has been a number of studies emphasizing the overall basinal physiography change from basin marginal to axial positions and stratigraphically positions through a single megasequence. One is argued to be more wave dominated in the basin marginal parts and in the regressive segments of the megasequence, while another one is argued to be tidally influenced to dominated in the axially parts and within the transgressive segments (Mitchener et al., 1992; Ravnås et al., 1997; Folkestad et al., 2014).

2. Geological Setting

2.1 Regional Setting

The Viking Graben rift basin is a part of the Northern North Sea continental shelf, which stretches from the East Shetland Platform to the Øygard Fault zone (Glennie and Underhill, 1998). The Northern North Sea rift basin formed across Lower Paleozoic Caledonian orogenic belt (Walter, 1972; Ziegler, 1990). During the Mesozoic the Northern North Sea rift basin experienced two episodes of lithospheric stretching, one in the Permian-Early Triassic and one in the Middle Jurassic- Early Cretaceous. These episodes were followed by periods of post-rift thermal relaxation and subsidence (Eynon, 1981; Badley et al, 1984, 1988; Giltner 1987; Gabrielsen et al. 1990; Stewart et al. 1992; Yielding et al. 1992; Steel 1993; Ravnås et al., 2000). The Permo-Triassic stretching episode generated fault movement that created major half grabens (Fisher 1986; Lervik et al., 1989; Yielding et al., 1992). The Central Viking Graben systems in the North Sea was likely established during the Triassic extensional period, but of a different structural configuration than the present (Ziegler, 1990). Moreover the Middle Jurassic sediments in the North Sea were deposited in an intraplate tectonic setting, during an intra-rift period (Ravnås et al., 2000). The middle Jurassic brought with it a period of thermal doming (Underhill and Partington, 1993, 1994; Glennie and Underhill, 1998). The second phase of rifting established the North Sea Central Graben system. During the Paleocene, uplift of the basin margins and rapid subsidence of the graben itself accompanied the last episode of the now Greenland-Sea rifting (Ziegler, 1990).

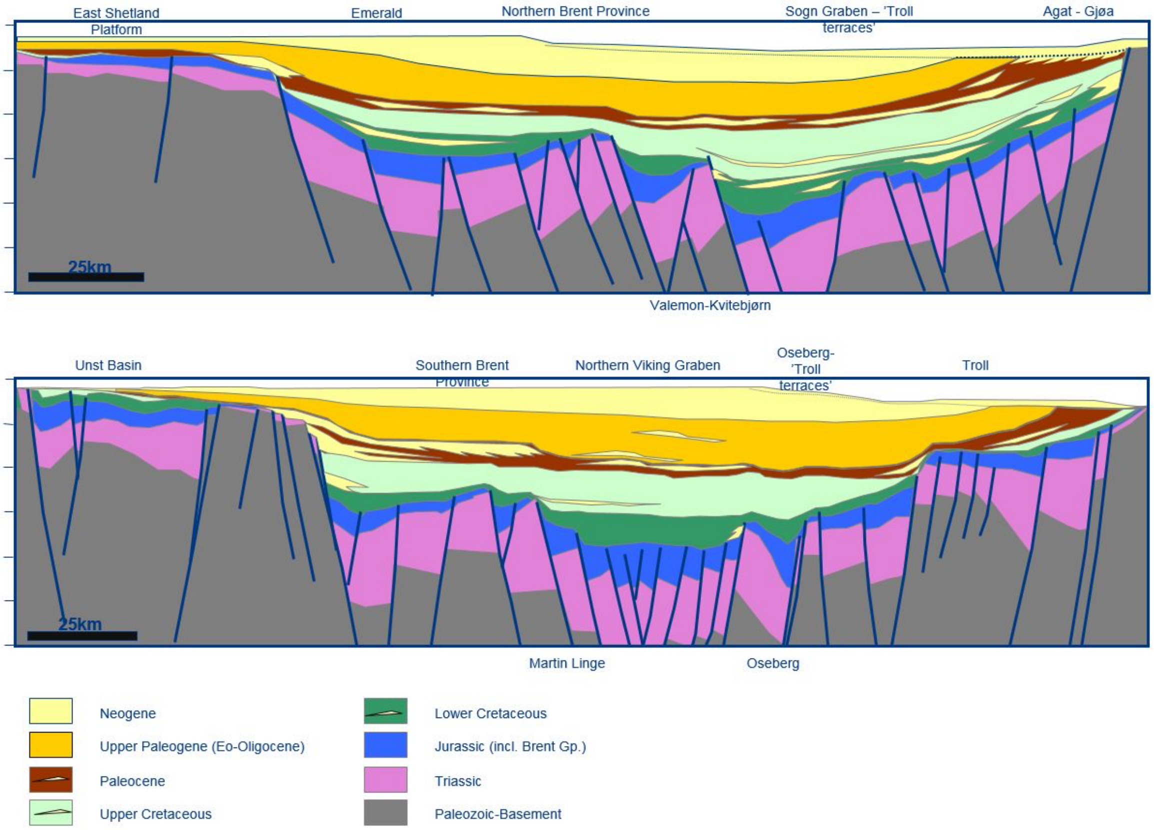


Figure 2-1. Transects showing the Permo-Triassic and Jurassic extension in the Northern North Sea (modified from Voorde et al., 2000).

2.2 Middle Jurassic doming and structuring

The evolution of the structuring caused by the Jurassic rifting episode can be divided into two stages; the first stage involves extension and rotational faulting where the response was either subsidence or uplift of half grabens. The second stage involves thermal subsidence driven by an isotactic response to the contraction of the mantle lithosphere as it cools and replaces the less dense asthenosphere (Jarvis 1984; Badley et al., 1988). The widespread Early-Middle Jurassic regional uplift or doming formed across what was going to become the North Sea triple junction. Stratigraphic evidence indicates that the dome itself was created by a thermal anomaly, which likely had a low-lying but irregular regional relief. The irregular regional relief allowed for an accumulation of non-marine to paralic sediments in areas that experienced some form of differential subsidence (Ziegler 1982; Glennie and Underhill 1998). Uplift of the eastern and western flanks of the basin occurred as a response to the doming. The doming related uplift was accompanied by a relative sea level fall (Ziegler 1982; Underhill and Partington, 1993; Fjellanger et al., 1996). Most of the faults active during the Jurassic period were reactivated basement-involved faults inherited from the Triassic rifting period. The faulting initially occurred along N-S trend, before shifting to a NE-SW trend (Færseth, 1995; Færseth & Ravnås, 1998).

2.3 Brent Group

The structural evolution of the Viking Graben has had a fundamental impact on the deposition of the Brent Group. The hydrocarbon discoveries in the Brent Group are mainly located in the northern part of the Viking Graben and its flanking terraces and platforms (Yielding et al., 1992). The middle Jurassic- Early Cretaceous stretching has been argued to pre-date the Late Bathonian. Accordingly parts of the Brent Group are argued to be included in the Middle Jurassic- Early Cretaceous syn-rift succession (Helland-Hansen et al., 1992; Mitchener et al., 1992; Johannessen et al. 1995; Fjellanger et al., 1996; Ravnås et al., 1997). The Brent Group is subdivided into five lithostratigraphic units: the Broom Formation, the Rannoch Formation, the Etive Formation, the Ness Formation and the Tarbert Formation. The depositional history of the Brent delta can be divided into phases of lowstand, progradation, aggradation, retrogradation and drowning. In the Aalenian the Brent lowstand was deposited as alluvial fan lobes shed off the basin margins and into the shallow sea of the North Viking Graben. The Brent delta prograded from south to north in the Late Aalenian to the Early Bajocian; filling the shallow sea with fluvio-deltaic sediments. During the Late Bajocian the delta remained overall stationary and aggraded vertically, before it started to retreat in the Early Bathonian. The retreat of the delta occurred in pulses, where the development of shoreline prisms represents intervals with more stable lagoonal and delta plain conditions. A series of successive floodings, producing a set of offset backstepping shoreline prisms eventually drowned the delta across the Northern Viking Graben (Helland-Hansen, 1991; Fjellanger et al., 1996). The Tarbert Formation represent marginal to shallow marine sandstones consist deposited in the overall retreat of the Brent Delta (Ronning and Steel, 1987; Grauè et al., 1987; Falt et al., 1987; Richards, 1992).

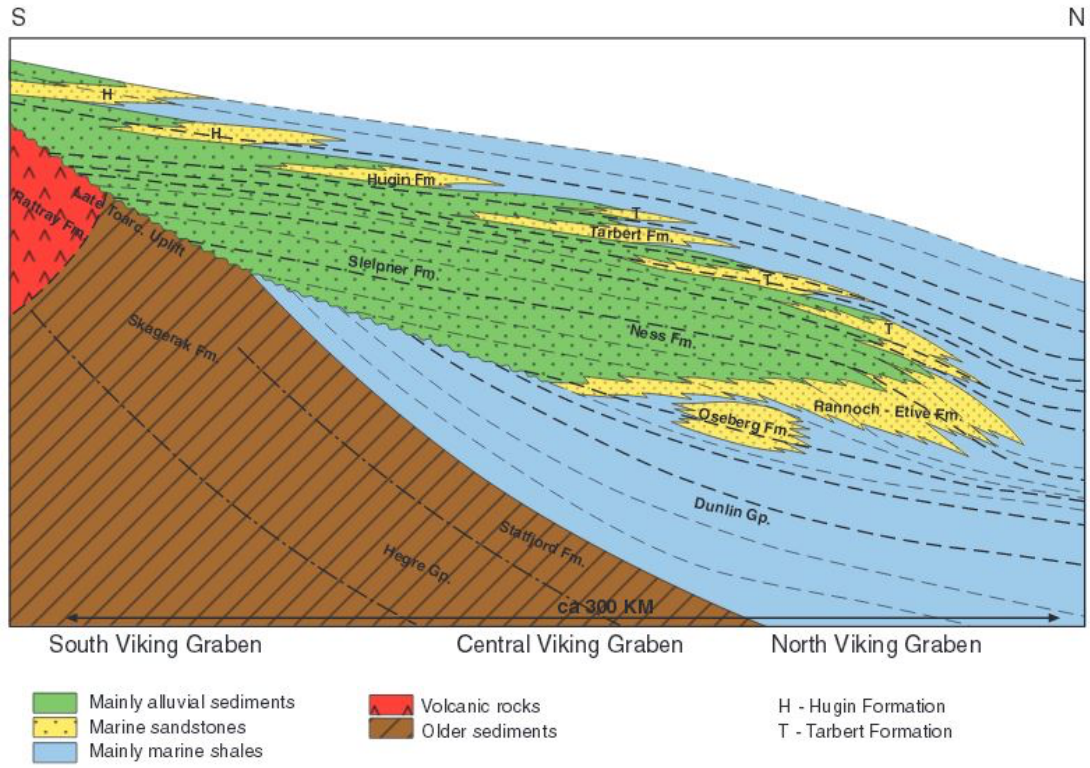


Figure 2-2: Schematic stratigraphic section of Brent-and Vesland groups, showing formations and timelines within the overall regressive-to transgressive megasequence (Helland-Hansen et al., 1992; Løseth et al.,2009).

2.4 Mechanisms to explain the Brent Group retreat

The retreat of the Brent delta started in the Early Bajocian and continued into the Oxfordian, with the drowning of the younger Vestland delta across the Southern Viking Graben. Graue et al. (1987) argues that the retreat of the Brent delta in the Norwegian sector started with the offset backstepping of progradational shoreline prisms. The evidence for this is the predominance of coarsening upward motifs and interfingering of marginal marine to shallow marine facies with continental deposits (Graue et al., 1987; Helland-Hansen et al., 1992). Studies in the UK sector of the North Sea shows less well-developed progradational trends in the Upper Ness and Tarbert Formation, but here as well most sediments have been deposited during regressive depositional phases with shoreface erosion during intervening transgressions (Brown et al., 1987; Helland-Hansen et al., 1992).

The back-stepping of the Tarbert Formation consists of both retrogradational and progradational elements. In platform areas the transgressive part is often thin because of rapid transgression over a low–gradient surface. The progradational phase consist of coarsening upwards sequences. Studies of the Upper Ness and the Tarbert Formation have indicated that there were already rotation and uplift of some fault blocks in the Early Bajocian and Middle-Late Bathonian (Helland-Hansen, 1992; Ravnås et al., 1997). The usually uniform development of the shoreline has a tendency to thicken structurally downflanks in half grabens, as a result of the effect of sedimentary expansion and differential erosion. The sands in structural low positions often show a vertical aggradational trend. These sediments can be products of upflank erosion or distal tongues of progradational prisms. The enhanced differential subsidence across faults indicates that during the retrogrodational part of the delta development there was an increase in tectonic activity (Helland-Hansen, 1992). When the Central North Sea, i.e the former up domed area started to subside along the rift and sediment supply from the south was consequently reduced, the Brent delta was forced to retreat southwards (Fjellanger et al., 1996). The delta retreat happened in retrogressive pulses while tectonically induced flooding events followed (Fjellanger et al., 1996). The delta gradually started to take form as an embayment opening to the north, before it became completely submerged (Helland-Hansen, 1992; Ravnås et al., 1997).

2.5 Advances in the understanding of paralic-deltaic-estuarine-shallow marine systems

To better understand the nature and significance of facies variability and significance of facies variability within and between tidal influenced and dominated systems, and especially the occurrence of tidal-bars, the BITE study was launched. The Bite study is built on the FORCE tide study, which had earlier developed sets of process based sequence stratigraphy models for tidally influenced deposits. These two studies have resulted in significant advances in the understanding of paralic-deltaic-estuarine-shallow marine systems.

Tidal bars are the fundamental building blocks of the deposits formed in almost all tidal environments. Through the fluvial-marine transition it is expected that the nature of the tidal bars change systematically because of the changes in channel characteristics (Dalrymple and Choi, 2003; Dalrymple et al., 2003). In the inland parts narrow channels and tidal bars consisting of tidally influenced or tidally dominated point bars or bank-attached bars will be abundant. In contrast the seaward part will display broader channels where the tidal bars are elongated and flow is parallel to the bars. The tidal bars will subdivide the larger channel into a series of sub-channels. Observations in modern systems have shown that bars with hybrid characteristics of point bars and elongated tidal bars can be found between areas with these two types of bars (Dalrymble et al., 2005).

Tidal bars can be described as elongated asymmetric features, which can reach several kilometers in width and tens of kilometers in length (Dalrymple and Rhodes, 1995; Wood, 2003; Dalrymple and Choi, 2007; Olariu et al. 2010). These bars are characterized by stacked sets of cross strata separated by later-accretion master bedding that in many cases would be interpreted as a channel or channel-bank deposits in ancient successions (Dalrymple, 2007; Dalrmple and Choi, 2007; Olariu et al. 2010). Tidal bars in offshore settings tend to form during transgressive conditions. For this to happen a widened shelf area has to be present together with sandy coastal deposits reworked on the shelf as the relative sea level rises (Dalrymple, 1992; Snedden and Dalrymple, 1998; Olariu et al., 2010). In wave-and-tide-dominated environments the geometry of the sandbodies created during the transgression is a function of the tidal ravinemenet processes, which characterizes the estuary inlet.

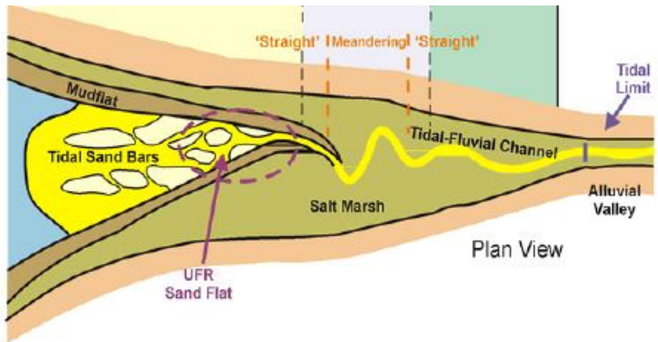


Figure 2-3. Tidal bars in an estuary (Dalrymple et al., 1992).

An estuary can be defined as both an incised valley filled with sediments deposited under mixed marine and fluvial processes (Dalrymple, 1992; Dalrymple et al., 1992; Yoshida et al., 2005) and a costal bay with a body of diluted sea water (Cameron and Pritchard, 1963; Pritchard, 1967; Yoshida et al., 2005). The reason for the two different definitions is that many modern costal depressions are referred to as just bay in literature without clarifying if it is assigned to an estuary or an embayment. In many cases the embayment and the estuary grade into each other. In many modern tide-dominated bays an estuary is occupying the inner bay, while a marine embayment constitutes the outer parts of the bay. The inner estuary part of the bay receives fluvial sediments, and the outer embayment part receives marine sediments (Yoshida et al., 2005). In a study by Yoshida et al. (2005) on the Woburn sands in England an embayment facies was interpreted in the transition between the estuary facies and shelf facies. Similar transitions from an estuary to embayment to shelf have been linked to hydrocarbon fields, such as the Middle Jurassic depositions in the Bruce field in the Northern North Sea (Dixon et al., 1997; Yoshida et al., 2002; Yoshida et al., 2005). Embayment facies can occur both in wave-dominated and tide-dominated settings (Yoshida et al., 2005).

In the study presented by Yoshida et al. (2005) two estuarine facies have been interpreted underneath a very fine to fine grained sandstone with tidal influence, such as double mud drapes, mud drapes, flaser bedding, ripples and different types of cross stratification. This sandstone have been interpreted as a large and thick in a tide-dominated sand banks in a marine embayment (Yoshida et al., 2005).

Tidal bars are as well present in tidal deltas. The Han River delta in South Korea is a structural controlled embayment that contains several enormous tidal bars. Several erosional ridges are present and may be source of sediments in addition to four distributary channels. The tidal bars are dissected by channels in the inner part, but are topographically smooth on its outer part. Seismic and core data indicate that the successions begin with fluvial deposits, overlain by thick tidal successions (Dalrymple et al., 2007).

Yoshida et al. (2004) have used two different sequence stratigraphic models of the Sego Sandstone in the Book Cliffs Utah, one that is transgressive (Van Wagoner, 1990, 1991; Yoshida et al., 2004) and a recent regressive model (Willis and Gabel, 2001, 2003; Yoshida et al., 2004) to interpret a mixed wave-tide dominated deltaic system. The Sego sandstone contains tidal point bars and tidal sand bank in a marine embayment. Three possible explanations for the change of dominant system are proposed, and subsequently three models were presented (Yoshida et al., 2004).

The first model contains a constant mixed-energy setting where the wave energy decreases toward the distributary mouths, and where tidal energy increases towards the distributary mouths in the regressive phase as can be seen in figure 2-4a. In the transgressive phase the tidal energy is increasing towards tidal bars or dunes, which are flanked by sand banks in a marine embayment. The wave energy is dispensed by sand banks in the marine embayment, as can be seen in figure 2-4b (Yoshida et al., 2004).

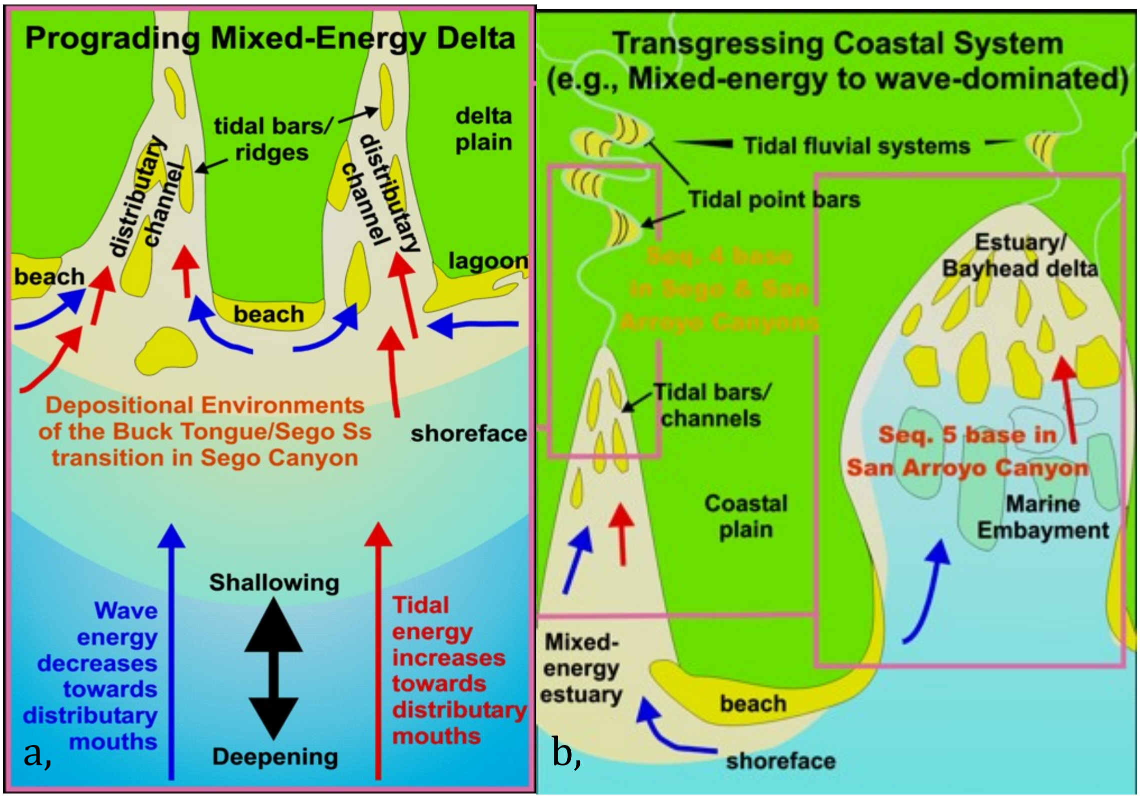


Figure 2-4. Tide and wave energy present in regressive deltas (figure 2-4a) and in transgressive estuaries (figure 2-4b) (Yoshida et al., 2004).

The second model proposes process change where geologically-instantaneous and drastic change in costal energy regime with tidal resonance switched on and off. This would imply a gradual change of regional coastal processes from wave-dominated (Highstand System Tract) to mixed energy (Forced Regression System Tract- Lowstand System Tract) and possible to tide domination in foreland basins that become smaller and narrower during the LST (Lowstand System Tract) (Yoshida et al., 2004).

The third model proposes product change because of change in available grain size (Yoshida et al., 2004).

The WAVE study explains wave energy on hybrid systems and changes in basinal energy regimes as a response to coastal physiography. Generally costal depositional models are over-simplified, and the real world mixed process systems are more complex. An increase in heterogeneity will be present as a system becomes more fluvial or tidal influenced, implying a decreased connectivity (Ainsworth et al., 2010).

3. Methodology

3.1 Dataset

This thesis is based on core data and well data, used to provide a frame for predicting the stratal architectures of the Upper Brent in the Rungne sub-basin, hence the deep part of Northern Viking Graben. The dataset provided includes core data from 7 wells, and additional well log data from 17 wells.

3.2 Core data

Core observations from 7 wells in the Martin Linge area-Oseberg area and Kvitebjørn-Valemon area is used. The core data comprise core data from the wells: 29/6-1, 30/4-2, 30/8-1 S, 30/9-19, 30/9-14, 34/10-23 and 34/11-3. A total of 720 meters of cores have been interpreted; 183 meters from Martin Linge, 221 meters from Oseberg west flank, 192 meters from Tune and 124 meters from Valemon-Kvitebjørn.

In addition the Tarbert Formation was studied on the Huldra field. However limited thickness over the Huldra area makes lateral correlation challenging.

3.3 Well logs

Gamma ray and density well logs were provided for the wells 17 wells located in the Martin Linge-Oseberg area, the Kvitebjørn-Valemoen area and the Nøkken-Visund area. The wells included are: 29/6-1, 30/4-2, 30/4-1, 30/7-8, 30/8-1 S, 30/8-3, 30/9-19, 30/9-14, 30/9-7, 30/9-8, 34/10-42 S, 34/10-23, 34/11-4 T2, 34/11-1, 34/11-3, 34/11-2 S and 34/8-5.

3.4 Internal reports

Documents featuring recent developments in the understanding of mixed-type reservoirs achieved via Joint Industry Projects (JIP's) were provided by A/S Norske Shell. Articles, presentations and reports from FORCE tide, BITE and WAVE consortiums were included.

3.5 Methodology

Core data in selected wells was studied lateral i.e along depositional strike transects over the study area. Facies, facies associations and depositional elements were interpreted, based on lithology, grain size, bed boundary, bed thickness, texture, sedimentary structures and degree of bioturbation. The interpretation of facies, facies associations and depositional elements were tied to gamma ray log and density log signature, which was used to identify similar facies, facies associations and depositional elements in the wells were core data was not available. Sedlog 3.1 was used to create graphic sediment logs of the interpreted cores. The sediment logs created in addition to the well logs were used to make three correlations across the area. Individual core shifts were preformed by matching the response of the specific log with the observed one from the core to correlate core and well data successfully. Sequence stratigraphic concepts were applied during the correlation to ensure a solid and confident correlation of depositional packages. Paleogeographic maps were made after integrating the different correlations with each other.

4. Facies, Facies Associations & Depositional Elements

The depositional environments in the Tarbert Formation has been illustrated by facies, facies associations and depositional elements from 7 wells: 29/6-1,30/4-2, 30/8-1 S, 30/9-19, 30/9-14, 34/10-23 and 34/11-3. The core coverage in the different wells varies, but together they provide a fairly complete core coverage. A total of 720 meters of cores have been interpreted; 183 meters from Martin Linge, 221 meters from Oseberg west flank, 192 meters from Tune and 124 meters from Valemon-Kvitebjørn. 14 different facies has been identified, grouped into 11 facies associations and used to characterize 9 depositional elements. The facies characterization was based on lithology, grain size, bed boundary, bed thickness, texture, sedimentary structures and degree of bioturbation.

4.1 Facies

Facies Type		Description	Bed Thickness	Processes
1	Hummocky cross stratified sandstone	Dark grey, fine to medium sandstone. Subangular to subrouded grains. Hummocky cross stratified. Moderately bioturbated. Mud drapes do occur. Low degree of bioturbation. Gradational to sharp bed boundaries	Centimeter to decimeter	High-energy processes have reworked sediments. Sedimentary structures were generated by storm and fair-weather wave processes.
2	Flaser-bedded sandstone.	Grey fine-grained sandstone. Subangular to subrounded grains. Flaser bedding and intervals with minor asymmetrical ripples can be seen. Intermediate degree of bioturbation. Gradational contacts.	Centimeter to decimeter	Sediments were deposited in a bidirectional tidal influenced environment.
3	Siltstone	Grey siltstone, with coal beds. Occasionally moderately bioturbated. No visible sedimentary structures, besides from some mud laminae. Sharp contact under and over the coals.	Centimeter to decimeter	Unidirectional currents, or ebb currents deposited the sediments.

4	Sandstone with mud drapes	Dark grey- grey very fine to fine sandstone with double mud drapes. Occasionally burrows, some of the burrows are filled with muddy sand. In some layers mud cracks can be seen. Subangular to subrounded grains. The degree of bioturbation is low to moderate. Gradational contact.	Centimeter to decimeter	Deposited in a low energy environment that was strongly influenced by tides.
5	Coarse massive sandstone	Grey medium to very coarse sandstone. Subangular to subrounded grains. Moderately sorted. Massive sandstone, with occasional pebbles. Low degree of bioturbation. Sharp contact at the base. Gradational contact at the top.	Centimeter to decimeter	Coarse sediments deposited by fluvial channels.
6	Angular cross-stratified sandstone.	Very fine to fine grey sandstone. Parallel lamination. Subangular grains. The beds are not graded to slightly graded. Moderately sorted. Low to moderate bioturbation. Gradational contacts.	Decimeter to meter	The parallel lamination in the sandstone is caused by cyclic changes in sediment supply.
7	Sandstone with symmetrical ripple cross lamination	Light grey very fine to fine sandstone, with symmetrical ripples. Subrounded grains. Well sorted. The degree of bioturbation is moderate. Gradational contacts.	Millimeter to centimeter	The symmetrical ripple cross lamination is a product from the migration of wave-generated ripples.
8	Highly bioturbated fine grained sandstone.	Grey very fine to fine structure less sandstone. Occasional layers with carbonate and sandstone with hummocky cross stratification. Well sorted. Subrounded grains. Highly bioturbated. Gradational contacts.	Centimeter to decimeter	Deposits were formed in an offshore setting, with a slow sedimentation rate.
9	Sandstone with asymmetrical ripple cross lamination	Fine grey sandstone. Subrounded grains. Moderately to well sorted. Ripples can be seen as well as unidirectional cross laminae with mud drapes. The degree of bioturbation is moderate.	Millimeter to centimeter	The cross-lamination is a product from the migration of a combination of wave-generated ripples and ripples made by unidirectional flows.
10	Mudstone	Dark grey/black mudstone. Very well sorted. No sedimentary structure. Coal or plant material is abundant. Low to moderate degree of bioturbation. Sharp to gradational contacts.	Centimeter to decimeter	Sediments are deposited by segment fall out, in a setting with low sediment supply.
11	Sandstone with wavy bedding	Very fine to fine grained grey sandstone, with wavy cross bedding. Well to moderately sorted. Subrounded grains. Parallel lamination and both	Centimeter to decimeter	The sediments have been reworked by both tidal and wave processes, most likely in the more distal part of

		asymmetrical ripple cross lamination and symmetrical ripple cross lamination can be seen. There is generally a low degree of bioturbation. Gradational contacts.		the delta or estuary.
12	Cross-stratified sandstone	Grey medium to coarse sandstone. Well sorted. Alternations between mudlayers and massive and normally graded strata. The degree of bioturbation is moderate. Sharp to gradational contacts.	Decimeter to meter	The cross stratification was formed due to avalanching down the side of the bedform. The mudlayers most likely formed when the tide changed: during still water.
13	Trough cross-stratified sandstone	Medium to coarse grey sandstone with through cross stratification. Well sorted. Subrounded to subangular. The layers are inclined at a low angle relative to the top and base of the bed. Moderately bioturbated. Gradational contacts.	Centimeters to decimeter	The through cross-stratification was caused by down flow migration of dunes.
14	Coal	Black coal. No sedimentary structures. Organic rich. No visible bioturbation. Rootlets underneath. Sharp contacts above and underneath.	Decimeter to meters	Plant materials brought by fluvial processes.

Table 4-1 Facies

4.2 Core pictures

Facies Type		Picture
1	Hummocky cross stratified sandstone	
2	Flaser-bedded sandstone with bioturbation	
3	Siltstone	

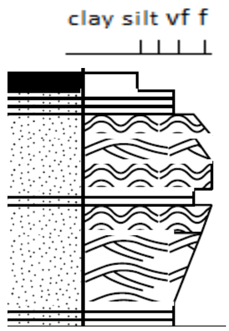
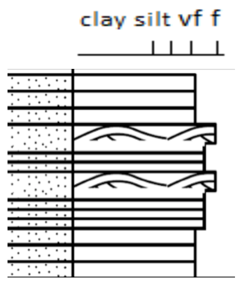
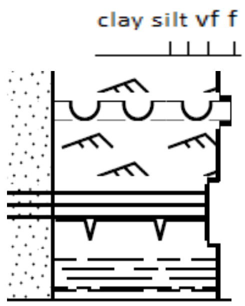
4	Sandstone with mud drapes	
5	Coarse massive sandstone	
6	Angular cross- stratified sandstone. (with mud drapes)	
7	Bioturbated sandstone with flaser bedding and some asymmetrical ripples.	

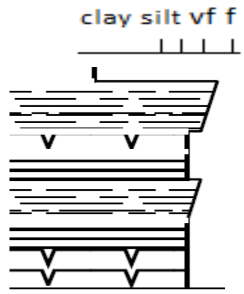
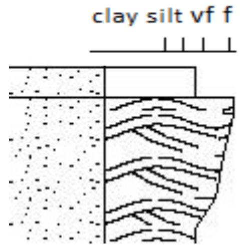
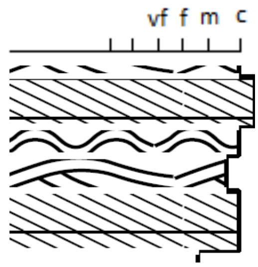
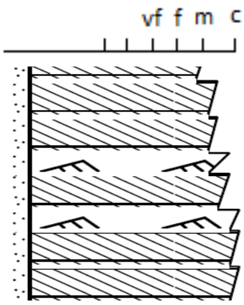
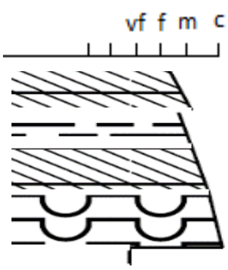
8	Highly bioturbated fine grained sandstone.	
9	Sandstone with symmetrical ripple cross lamination	
10	Mudstone	
11	Sandstone with wavy bedding	

12	Cross-stratified sandstone	
13	Trough cross-stratified sandstone	
14	Coal	

Table 4-2 Core pictures

4.3 Facies Associations

Facies Associations	Description	Log motif
FA1: Crevasse sub delta	Very fine to fine grained sandstone, with wavy-cross bedding (facies 11), asymmetrical ripples (facies 9) and flaser bedding (facies 2). Occasionally layers with hummocky cross stratification (facies 2) and some mud layers. The succession is usually coarsening upward into coal (14) or at occasions fining upward into tidal flats. Moderately to highly bioturbated. The bioturbation is represented by planolites and burrows.	
FA2: Bayhead delta	The bay-head delta mainly consists of very fine to fine sandstone with hummocky cross-stratification (facies 1), symmetrical ripples (facies 7) and some mud layers. At some occasions double mud drapes with burrows can be seen. (facies 4). The sequence is coarsening (shallowing) upwards into mudstone (facies 10) and coal (facies 14). There is a range in bioturbation from low to moderate. The bioturbation is represented by planolites, skolithos, diplocraterion and burrows. Plant material is abundant.	
FA3: Tidal Flat	Subtidal Mainly comprised by very fine to fine sandstone with mud drapes or double mud drapes (facies 4) and in some places a thin layer of hummocky cross stratified sandstone (facies 1). Low to moderate bioturbation can be observed, represented by diplocraterion and burrows. The successions are usually shallowing upward into intra tidal flat or deepening upward into shoreface deposits or estuarine channels.	
	Intratidal Very fine to fine grained sandstone with angular cross-stratification (facies 6), flaser bedding (facies 2), mud drapes (facies 4) and asymmetrical ripples (facies 9). Layers with calcite do occur. Occasional channels consisting of coarse massive sandstone (facies 5). Bioturbation is moderate and represented by diplocraterion and planolites. The succession is either coarsening upward into supratidal deposits or fining upward into subtidal deposits.	

	Supratidal Consists of very fine to fine grained sandstone with angular cross-stratification (facies 6), flaser bedding (facies 2) and occasionally mud drapes (facies 4). Siltstone (facies 3) with coal layers is abundant (facies 14). The unit is mainly coarsening upward into coal (facies 14), or fining upward into intratidal deposits. Occasional turbidities consisting of coarse massive sandstone (facies 5). There is a low degree of bioturbation. Roots and plant fragments can be seen under the coal.	
FA5: Delta-front	The lower-middle delta front consists mainly of very fine to fine grained hummocky cross-stratified sandstone. (facies 1) There is no visible bioturbation. The succession is coarsening upward into a sharp contact at the top.	
FA6: Shoreface	Medium to coarse sandstone with planar cross stratification (facies 6), cross-stratified sandstone (facies 12), occasional hummocky cross stratification (facies 1) and symmetrical ripples (facies 7). Low to moderate bioturbation. The biturbation is represented by burrows. Sharp contact at the base and at the top of the succession. Wave dominated deposits with some tidal influence.	
FA7: Estuarine	Mainly medium to coarse sandstone, with cross stratification (facies 12), trough cross-stratification (facies 13), angular cross-stratification (facies 6) and asymmetrical ripple cross lamination (facies 9). The dunes or tidal bars present in the estuary are overall fining upward, but with coarsening upward sequences. The tidal channels have fining upward packages, but are overall coarsening upward. Moderately to well sorted. Bioturbation is moderate and represented by diplocraterion, skolithos and chondrites.	
FA8: Fluvial and distributary channel	Fining upward sandstone with a sharp base. Consists mainly of medium to coarse sandstone with angular cross-stratification (facies 6), cross stratification (facies 12). In some parts the sandstone have flaser bedding (facies 2). The grains are very poorly to poorly sorted. There is no visible bioturbation.	

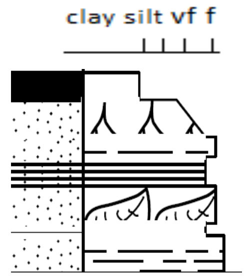
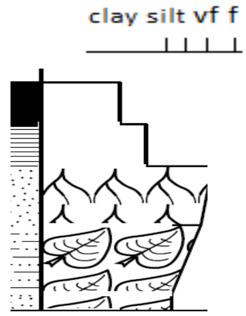
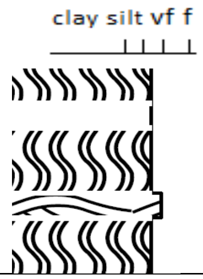
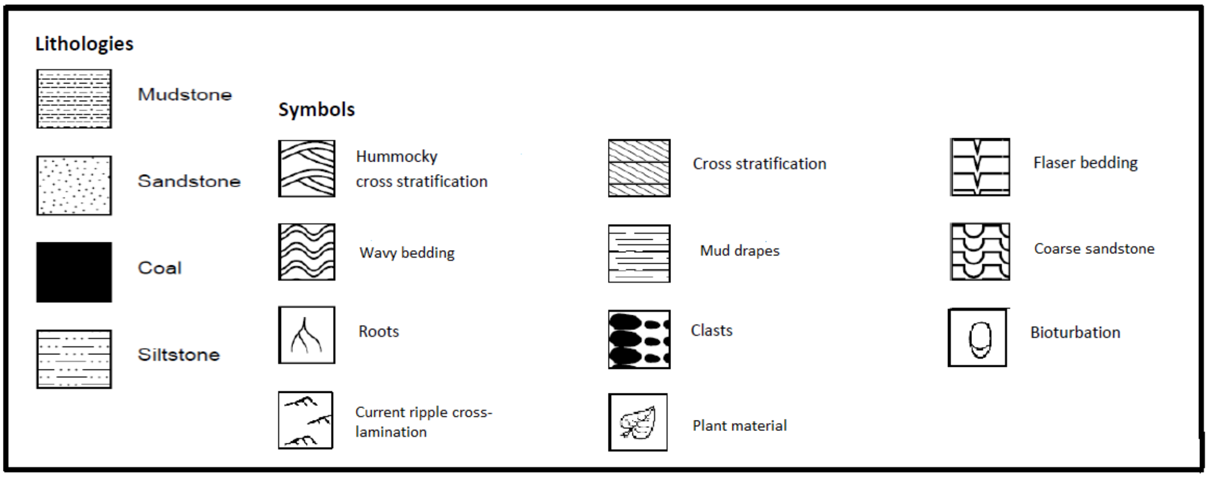
FA9: Lacustrine	Very fine grained sand and mudstone (facies 10) with some layers of parallel cross stratified coarser sediments (facies 6). Siltstone with mud lamina, coals and rootlets are abundant (facies 3). Very well sorted grains. Sediments are fining upward into coal. Low degree of bioturbation.	
FA10: Marsh or Swamp	Mainly very fine sandstone, mudstone (facies 10), siltstone (facies 3) and coal (facies 6). Sediments are coarsening upward into coal. Rootlets and plant fragments underneath.	
FA11: Shelfal	Bioturbated mudstone (facies 15) to very fine massive highly bioturbated sandstone (facies 12) deposited offshore and under open marine conditions. Highly bioturbated. Bioturbation is represented by burrows and belemnites. At occasions the unit is coarsening upward into carbonates and sandstone with hummocky cross stratification (facies 1).	

Table 4-3 Facies Associations



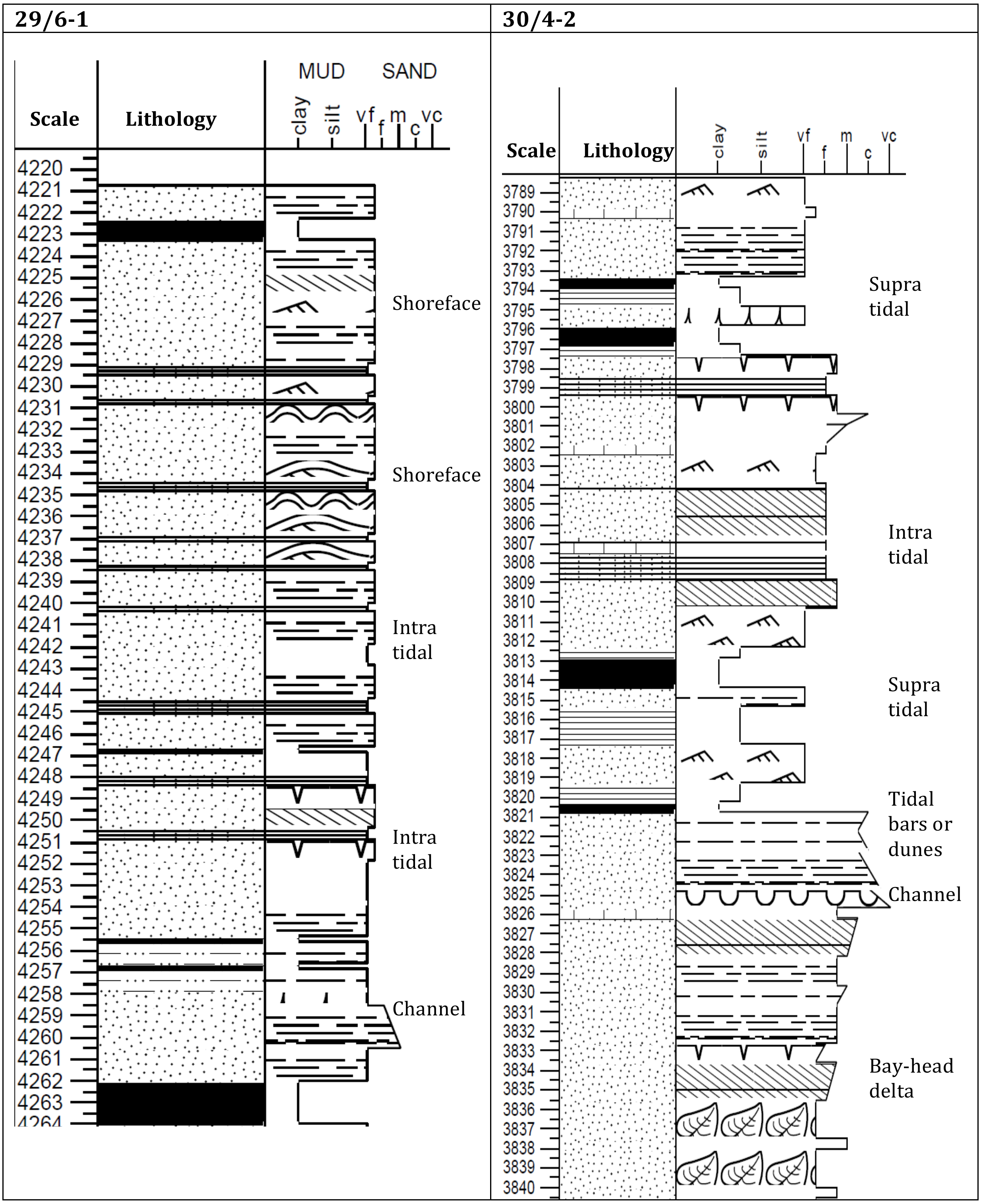
4.4 Depositional Elements

Depositional Element		Description	Facies Association
1	Tidal dunes or bars	Coarsening upward packages of medium to coarse sandstone with cross stratification (facies 12), trough cross-stratification (facies 13), angular cross-stratification (facies 6). Often present on top of a channel. Sediments are supplied by a fluvial system and marine sources, reworked by waves.	Estuarine
2	Embayment sandbank	Medium to coarse sandstone with a sharp base. Occasionally hummocky cross stratified (facies 1) and wavy bedding (facies 11) Slightly fining upward, into another sharp upper boundary. Underlying finer grained shoreface deposits. Deposited during the transgression as the embayment widens and the system becomes more mixed-energy dominated.	Shoreface
3	Mouth bar	Fine to medium sandstone, with abundant hummocky cross stratification (facies 1) and occasionally wavy-ripples (facies 11). Deposited in front of the delta, by wave processes.	Delta front
4	Barrier	Medium to coarse sandstone, with occasional hummocky cross stratification (facies 1), wavy bedding (facies 11) and asymmetrical ripples (facies 9). Sediments supplied by fluvial and marine sources have been reworked by waves.	Shoreface
5	Channel-fills	Mainly fine to coarse sandstone with angular cross stratification (facies 6) and cross-startification (facies 12). Occasional some layers with finer grained sandstone and flaser bedding at the top (facies 2). Fining upwards. Sharp contact at the base.	Estuarine, fluvial and distibutary channels and tidal flats
6	Tidal flat	Very fine to fine grained sandstone. Abundant structures are flaser bedding (facies 2), mud drapes (facies 4), asymmetrical ripples (facies 9) angular cross stratification (facies 6) and wavy bedding (facies 11). Occasional hummocky cross stratification (facies 1)	Estuarine
7	Sandy sheets	Sheets with fine grained sandstone. Sediments are reworked by tides.	Tidal flat
8	Hetrolitic sheet	Hetrolitic sheets containing very fine to fine grained sandstone. Sediments have been reworked by tides.	Tidal flat
9	Muddy hetrolitic sheet	Hetrolitic sheets containing very fine to fine grained sandstone with mudstone. Sediments have been reworked by tides.	Tidal flat

Table 4-4 Depositional elements

4.5 Sedimentary logs/core descriptions

4.5.1 Martin Linge



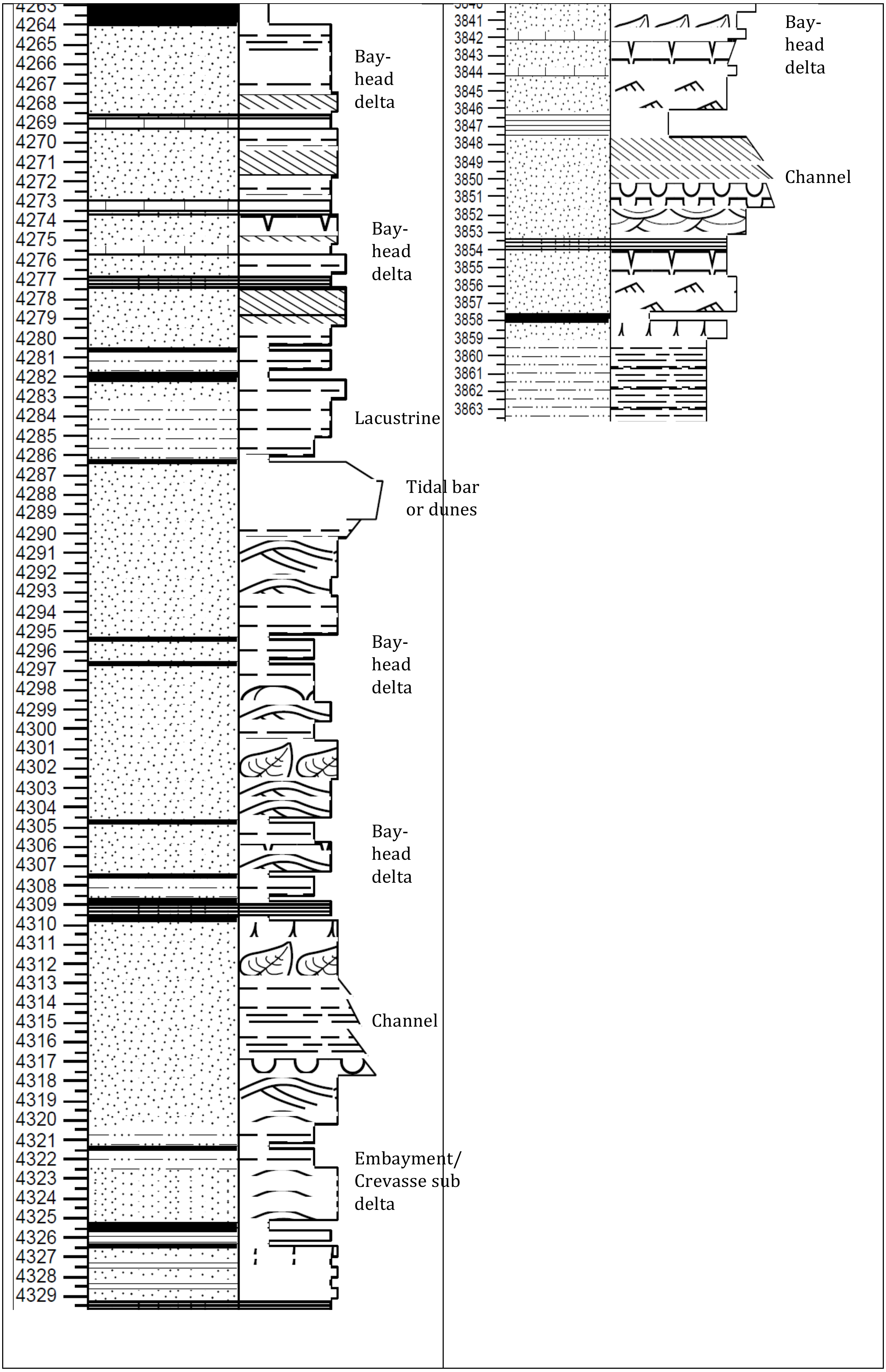
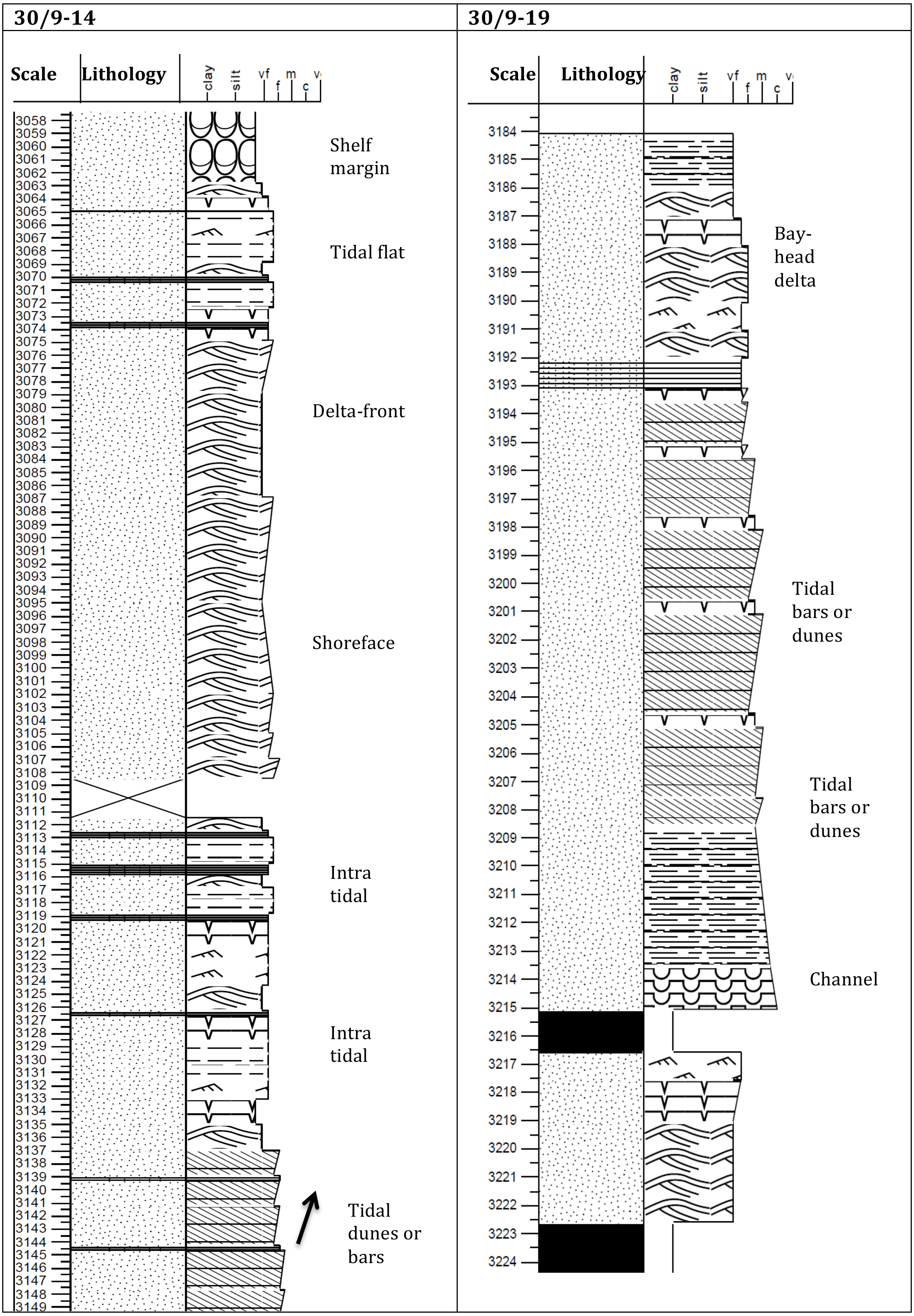


Table 4-5 Martin Linge

4.5.2 Oseberg


30/9-14
30/9-19
Scale
Lithology
clay
silt
vf
f
m
c
Shelf margin
Tidal flat
Delta-front
Shoreface
Intra tidal
Intra tidal
Tidal dunes or bars
Bay-head delta
Tidal bars or dunes
Tidal bars or dunes
Channel

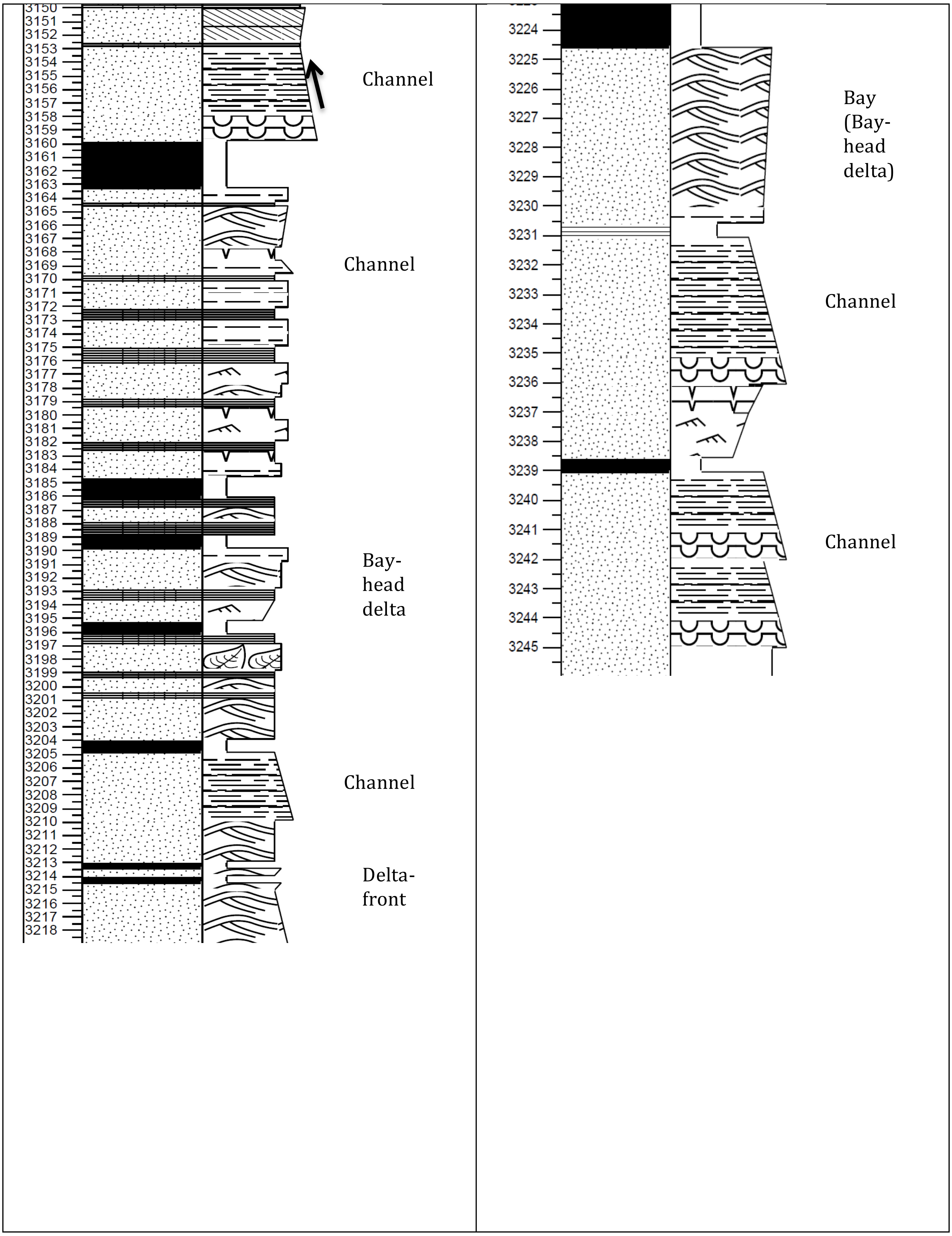
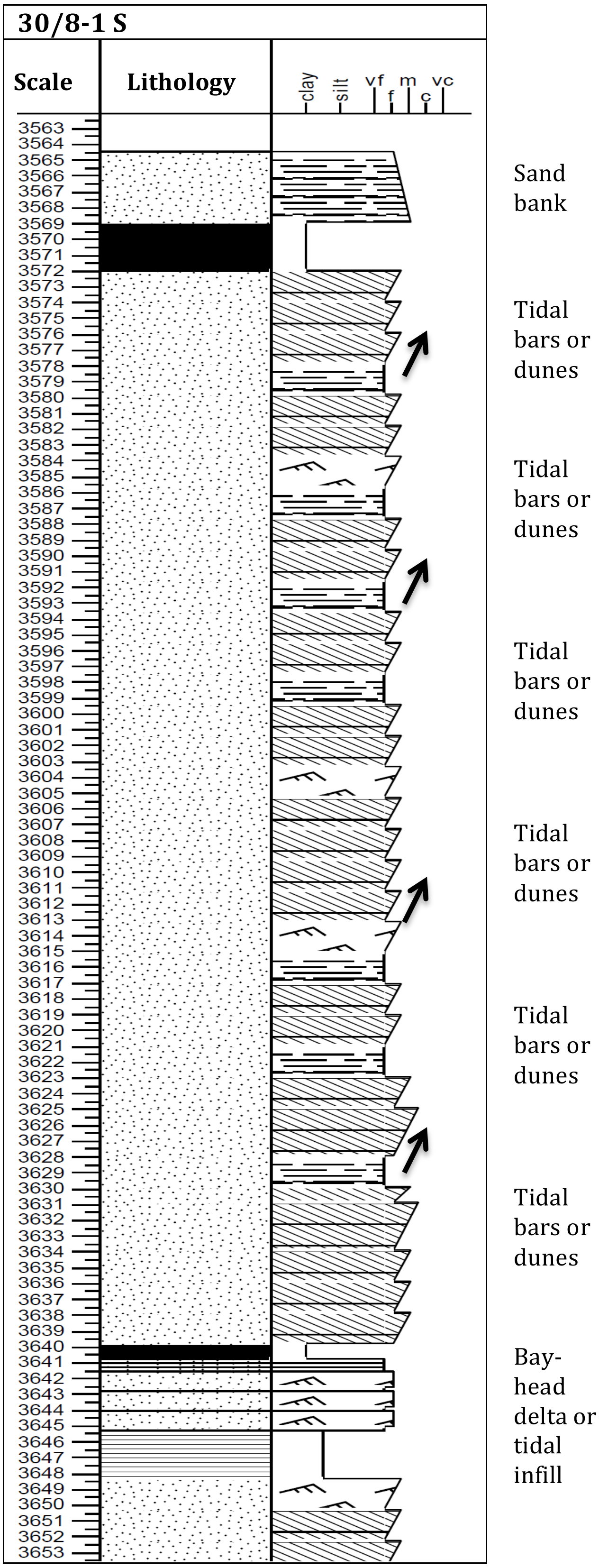


Table 4-6 Oseberg sediemntary logs

4.5.3 Tune


30/8-1 S
Scale
Lithology
clay
silt
vf
f
m
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3646
3647
3648
3649
3650
3651
3652
3653
Sand bank
Tidal bars or dunes
Tidal bars or dunes
Tidal bars or dunes
Tidal bars or dunes
Tidal bars or dunes
Tidal bars or dunes
Bay-head delta or tidal infill

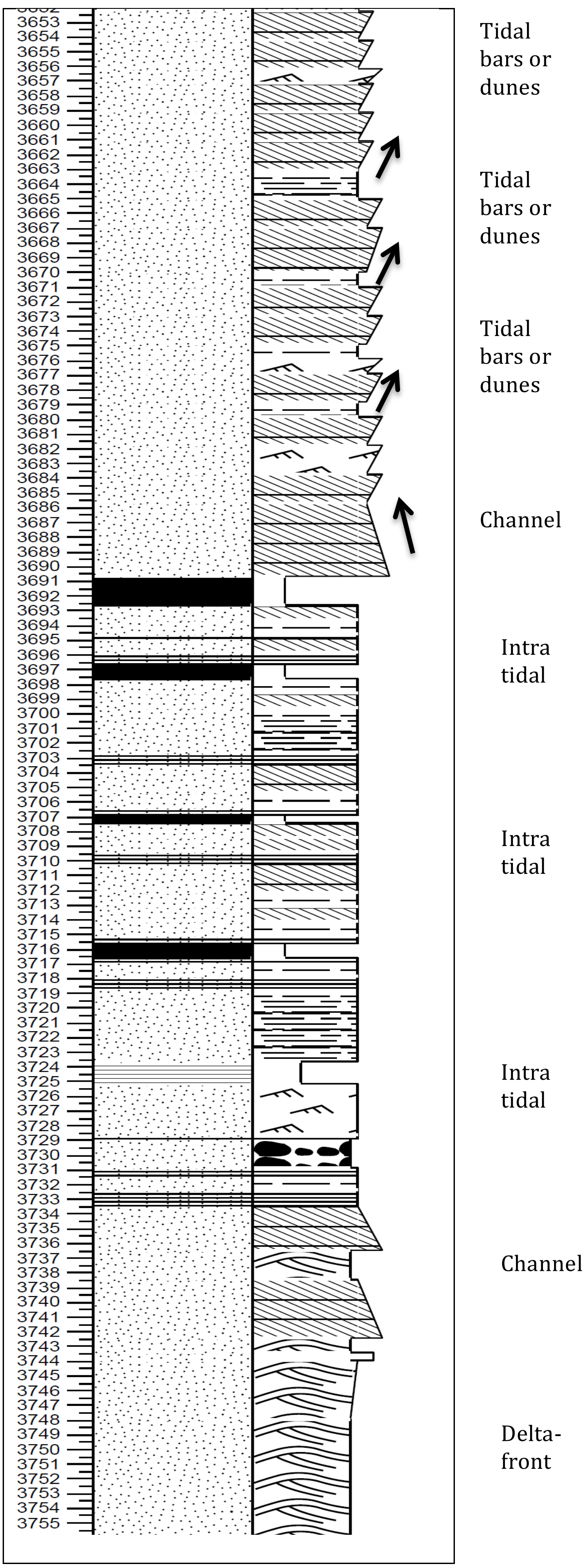


Table 4-7 Tune sediemntary log

4.5.4 Kvitebjørn-Valemon

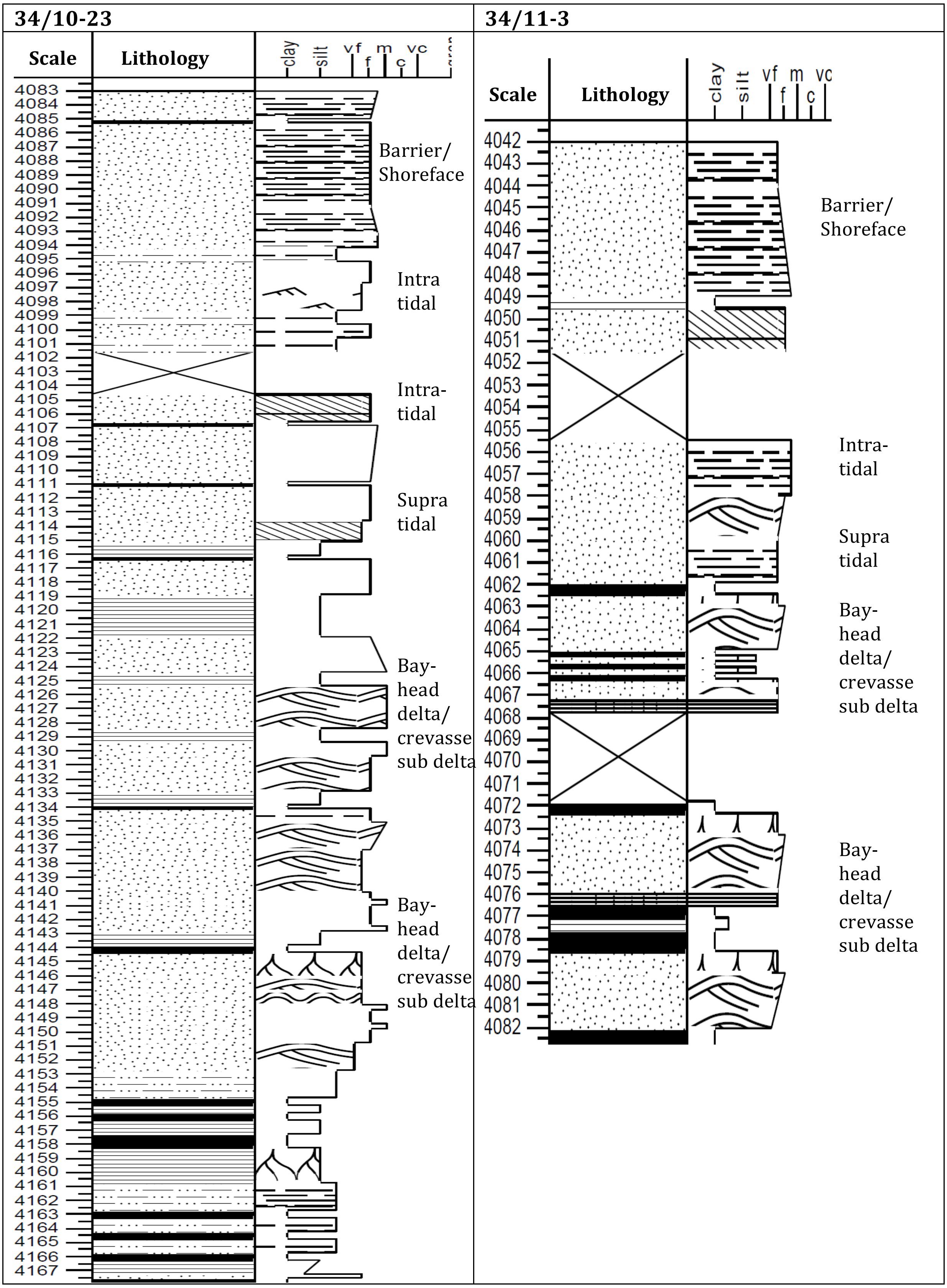
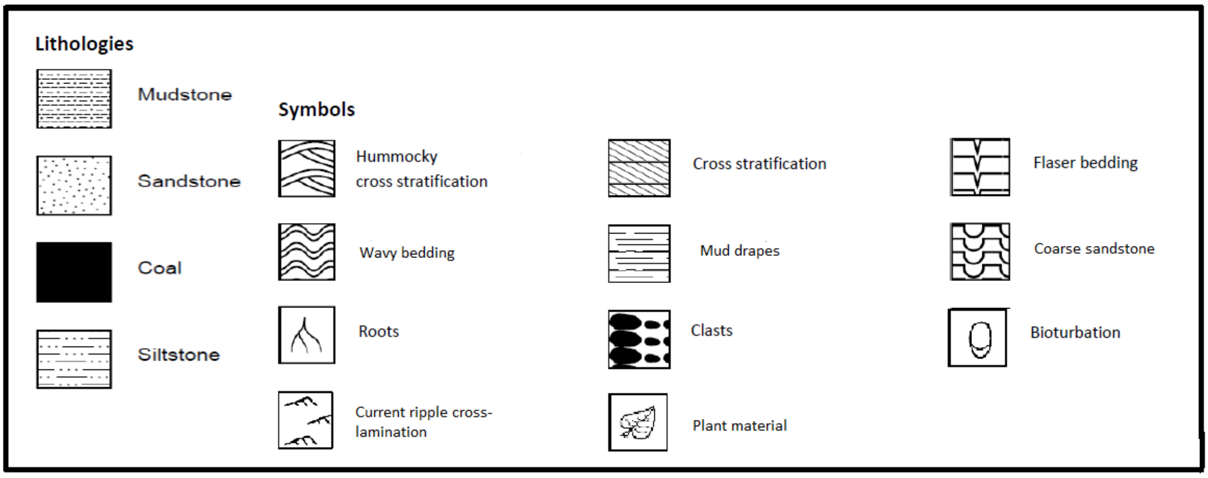


Table 4-8 Valemon-Kvitebjørn sedimentary logs



Lithologies
Mudstone
Sandstone
Coal
Siltstone
Symbols
Hummocky cross stratification
Wavy bedding
Roots
Current ripple cross-lamination
Cross stratification
Mud drapes
Clasts
Plant material
Flaser bedding
Coarse sandstone
Bioturbation

4.6 Lithofacies

The Lower Tarbert is wave dominated and form parts of the regressive segment in sequence as inferred in 5.1 sequence stratigraphy. The Lower Tarbert is defined by the presence of a thick and laterally extensive channel complex (FA8) in addition to bay-fill (FA2) deposits.

The Middle Tarbert is tide dominated. The transgressive segment in sequence I, in addition to sequence II and the regressive segment in sequence III (section 5.1) The Middle Tarbert is characterized by substantial amount of tide-influenced to -dominated facies associations; estuarine complexes with channel-fill (DE5) and tidal bars or dunes (DE1), bay-fills (FA2 or FA1) and tide-dominated delta deposits (FA8 , FA1, FA2 and FA10)

The Upper Tarbert is defined by the presence of a wave-dominated shoreline (FA6) as well as tidal flat (FA3) deposits and comprises the transgressive segment in sequence III (section 5.1).

4.7 Thickness Trends

4.7.1 Martin Linge- Oseberg

The overall thickness of the Tarbert formation is expanding when entering the central part of the Viking Graben or the Rungne sub-basin. To the east and the west the Tarbert Formation is thinning significantly.

The lower part of Tarbert comprises a channel complex that is considerably thicker in the Rungne sub-basin (well 30/4-1 and well 30/8-1) than on the western and eastern terraces, i.e the Hild and Oseberg west flank area. Respectively in the Oseberg west flank there is significant changes in thickening, i.e. after thinning out towards well 30/9-7 the channel complex thickens again in 30/9-8. The variation in the thickness in the channel complex is assumed to be related to tectonic activity, reflecting increased subsidence of the Northern Viking Graben.

Above the channel complex, a tidal flat succession is present in the Central Viking Graben (Well 30/4-1, 30/8-1 and 30/8-3). The tidal flat succession thins out towards the east and west. On the eastern (well 30/9-19, 30/9-14, 30/9-7 and 30/9-8) and western terraces (well 30/4-2 and 29/6-1) bay-head deltas successions are present. Together the tidal flat and the bay-head delta successions have a constant thickness, forming an evenly bedded unit or gross tabular package/architecture.

The Middle Tarbert comprises two separate units of estuarine complex separated by an interlayered succession of bay-head deltas. The estuarine complex consists of tidal dunes or bars and tidal channels. The basal part of the lower estuarine complex consists of a multilateral channel complex that may be fluvio-deltaic in origin. The lower estuarine complex has a constant thickness in the Central Viking Graben (well 30/4-1, 30/8-1, 30/8-3, 30/9-19 and 30/9-4). In the western Martin Linge area (well 30/4-2 and 29/6-1) the estuarine complex has thinned significantly. In the eastern Oseberg Area (well 30/9-7) the estuarine complex is again thinner, before it thickens towards well 30/9-8. The reason for the change is thickness both in the western Martin Linge area and the eastern Oseberg area is due to tectonic activity, reflecting syn-depositional rotational faulting (see Section 6.5).

The interlayered bay-head delta unit has a constant thickness in Rungne sub-basin and on the Oseberg west flank area. Towards western margin or the Martin Linge area the bay-head delta succession has thinned significantly.

The upper estuarine complex is considerable expanded in wells 30/4-1 and 30/8-1, relative to the Martin Linge and Oseberg west flank area. The upper estuarine complex in contrast has a variable thickness pattern with rapid lateral thickening and thinning between the wells. Across the Oseberg west flank area the estuarine complex is thin in wells 30/8-3 and 30/9-14, and thick in wells 30/8-1 S and 30/9-19. The variable thickness is possible due to tectonic activity or facies shift in areas between the wells. Tectonic activity is the preferred explanation, and as a result it has a highly variable thickens distribution within and between individual fault blocks.

The Upper Tarbert Formation comprises tidal flats successions in the Western Martin Linge area (well 29/6-1 and 30/4-2), and in parts of the Rungne sub-basin (well 30/4-1, 30/8-3 and 30/9-14.) The tidal flat has been interpreted to be present in well 30/8-3 because of the similar GR of the cored tidal flat succession in well 30/9-14. The tidal flat successions are thinning out towards well 30/8-1, 30/9-19 and 30/9-7, where tidal dunes and channels replace it. The combined thinning and facies change in wells located in structurally high positions on fault blocks is attributed to tectonic activity. An alternative interpretation is facies shift between the wells, which is less likely due to the locations of the wells with tidal flats successions, i.e on structural highs versus the locations of the wells without.

Above the tidal flat successions a variably thick succession of shoreface sediments is present. The succession is thickest in the Rungne sub-basin, and along the western Oseberg terraces. The variation in thickness in the western Oseberg flank (well 30/9-7 and well 30/9-8) is likely related to tectonic activity (Ravnås et al., 1997).

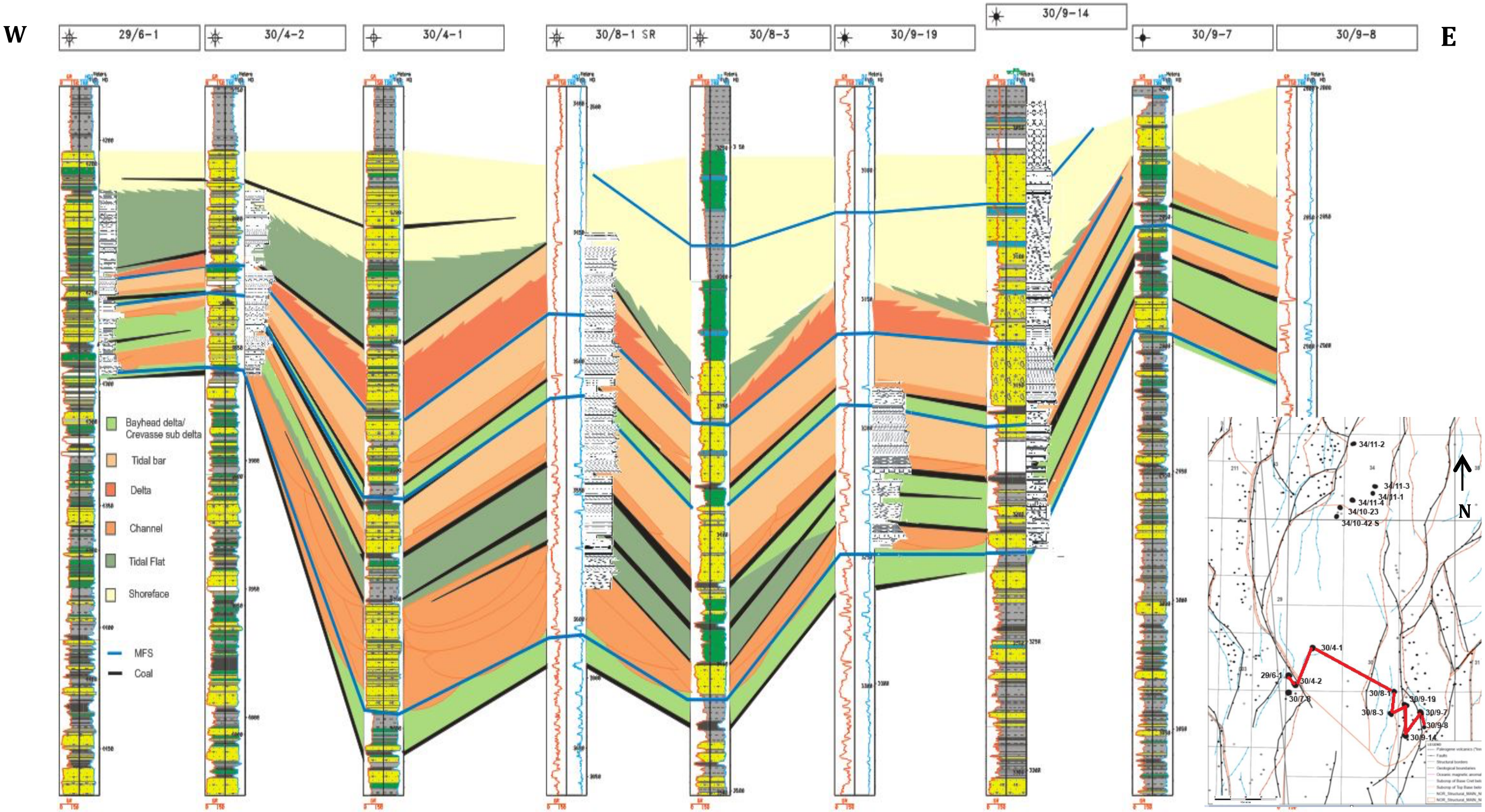


Figure 4-1: Correlation of the Tarbert Formation in the southern Rungne sub-basin,containing the Martin Linge area and the flanks of western Oseberg.

4.7.2 Valemon - Kvitebjørn

The successions in the Lower Tarbert in Valemoen- Kvitebjørn area consist of crevasse sub delta deposits or bay-head delta deposits, tidal flat succession and shoreface succession that can be divided into six higher order sequences. The higher order sequences are thinning upward, implying that the lowest one is thickest and upper one is thinnest.

The crevasse sub delta or bay-head delta succession has a constant thickness from west to east, with only minor local changes in thickness.

The tidal flat succession thins markedly from Valemon to Kvitebjørn towards the east (well 34/11-3). The thinning can be a result of facies shift, as the Tarbert formation becomes more trangsressive, representing a landward (westward) thickening.

Above the tidal flat, shoreface deposits with a relative constant thickness is present. Some variations in thickness can be seen due to interfingering with the tidal flat successions.

Overall the Tarbert Formation is thinning slightly from Valemon towards the Kvitebjørn (well 34/11-3), however there are clear variations between the various Tarbert units.

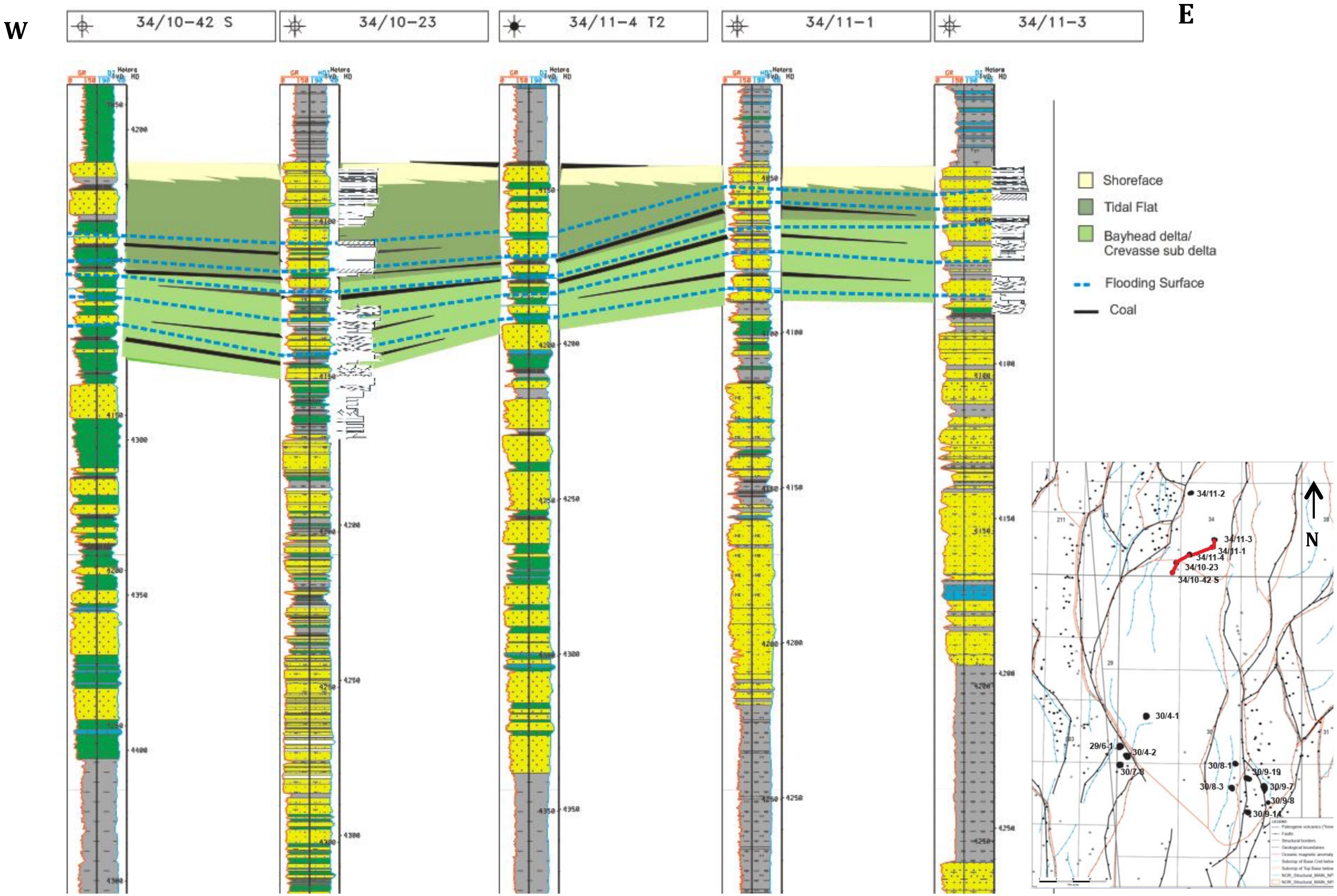


Figure 4-2: Correlation of the Tarbert Formation in the Valemon - Kvitebjørn area.

5. Stratigraphy, sequence stratigraphy and reservoir architecture

5.1 Sequence stratigraphy

Ravnås et al. (1997) argued in a study of the Tarbert Formation in the Oserberg-Brage area that the Tarbert Formation could be divided into three sequences, where each sequence comprises a regressive and a transgressive segment. This thesis focuses on the lower two of these sequences and their development within the deeper Northern Viking Graben. Ravnås et al. (1997) works included the lower part of the Heather Formation, and argued that this represents a distal part of a southerly-located Tarbert shoreline prism.

Ravnås & co-workers (1997) argued that the regressive segments were characterized by regressive shorelines deltas, which prograded axially in response to an increase in sediment supply. The southern and more landward areas included tidal shoreline deltas, especially in the lower part of the regressive segment. The fining-upward or the coarsening-to-fining upward sequences that characterize the transgressive segments showed stronger tidal influence in landward settings and more wave influence in seaward area. The transgressive-regressive turnaround-stacking pattern was recognized by an aggrading interval, which showed coal-bearing intervals or shoreline intervals (Ravnås et al., 1997). Subsequently Løseth & co-workers (2009) suggested that the Tarbert Formation should be divided into two wedges consisting of two regressive to transgressive successions of coastal and shallow marine deposits. These correlate to the lower two sequences of Ravnås et al. (1997).

The characteristics from the Oseberg-Brage area described above have been used as guidelines to recognize the transgressive and regressive segments. However, in the present study the Tarbert Formation has been subdivided into three higher order regressive and transgressive units or genetic sequences (Galloway, 1989). The fourth sequence seen in the Martin Linge-Oseberg correlation is present in the Heather Formation, and is subsequently not described. An even higher order subdivision of sequences is possible, and is advisable if a reservoir model is to be created.

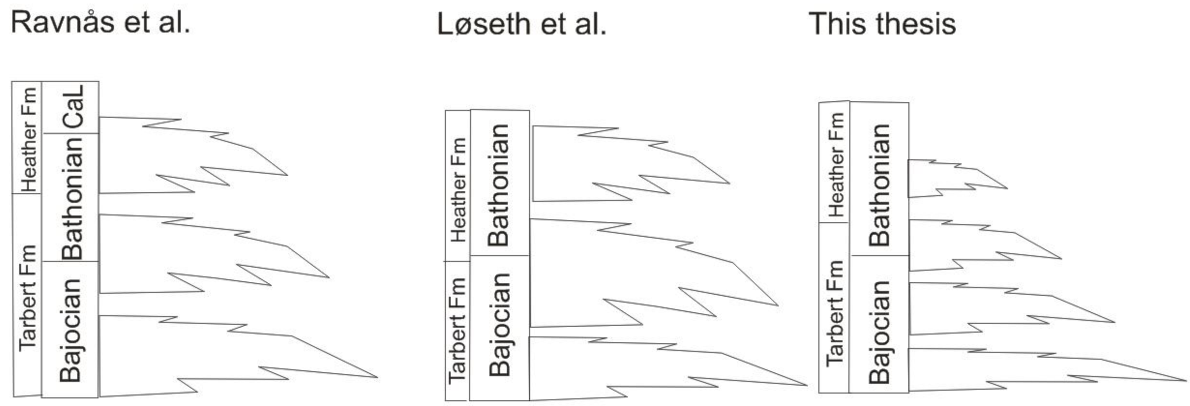


Figure 5-1. Sequences interpreted in this thesis compared by the sequences interpreted by Ravnås et al (1997) and Løset et al. (2009).

5.1.1 West-East Correlation (Martin Linge-Oseberg)

Sequence I

The first maximum flooding surface, which signify the base of sequence I is placed above transgressive bay strata and underneath a major channel complex. Løseth et al. (2009) argue that a ravinement surface is located underneath this flooding surface. The major channel complex is part of the regressive segment, and was formed during delta progradation. Above an aggradational unit is present, interpreted to be a tidal flat succession in well 30/8-1 S, 30/8-3, this tidal flat succession is likely extending into well 30/4-1. The aggradational unit is interpreted to consist of stacked bayhead delta units in the western Marting Linge area (wells 30/4-2 and 29/6-1) and the eastern Oseberg area (wells 30/9-19 and 30/9-14). The bayhead deltas and the tidal flat deposits mark the transition into the base of the transgressive segment. The delta complex occupied the central and axial part of the Northern Viking Graben where bays with bayhead delta deposits formed along interbasin margins. A candidate maximum regressive surface is inferred in the transition between the regressive segment and the transgressive segment.

The transgressive segment is composed of a thick sandy package comprised by massive sand with coarsening upwards and fining upwards units representing an estuary complex with stacked tidal dunes and tidal channel-fills. Løseth & co-workers (2009) interpret the estuarine package as channels. In their interpretation the estuarine unit contains both fining upward sequences and coarsening upward sequences, same as in this thesis with no differentiation on the origin between the two motifs. In this thesis tidal dunes or bars and channels have been distinguished by vertical facies motifs following Dalrymple and co-workers (2006). The coarsening upward sequences have been interpreted to be tidal dunes or bars, while the fining upward sequences to be channel-fill between the tidal dunes or bars. The estuarine character of the deposit indicates that the upper part of sequence I is overall transgressive. The genetic sequence and the transgressive segment are capped by a marginal marine mudstone, here interpreted to represent a candidate maximum flooding surface, defining the transition into sequence II.

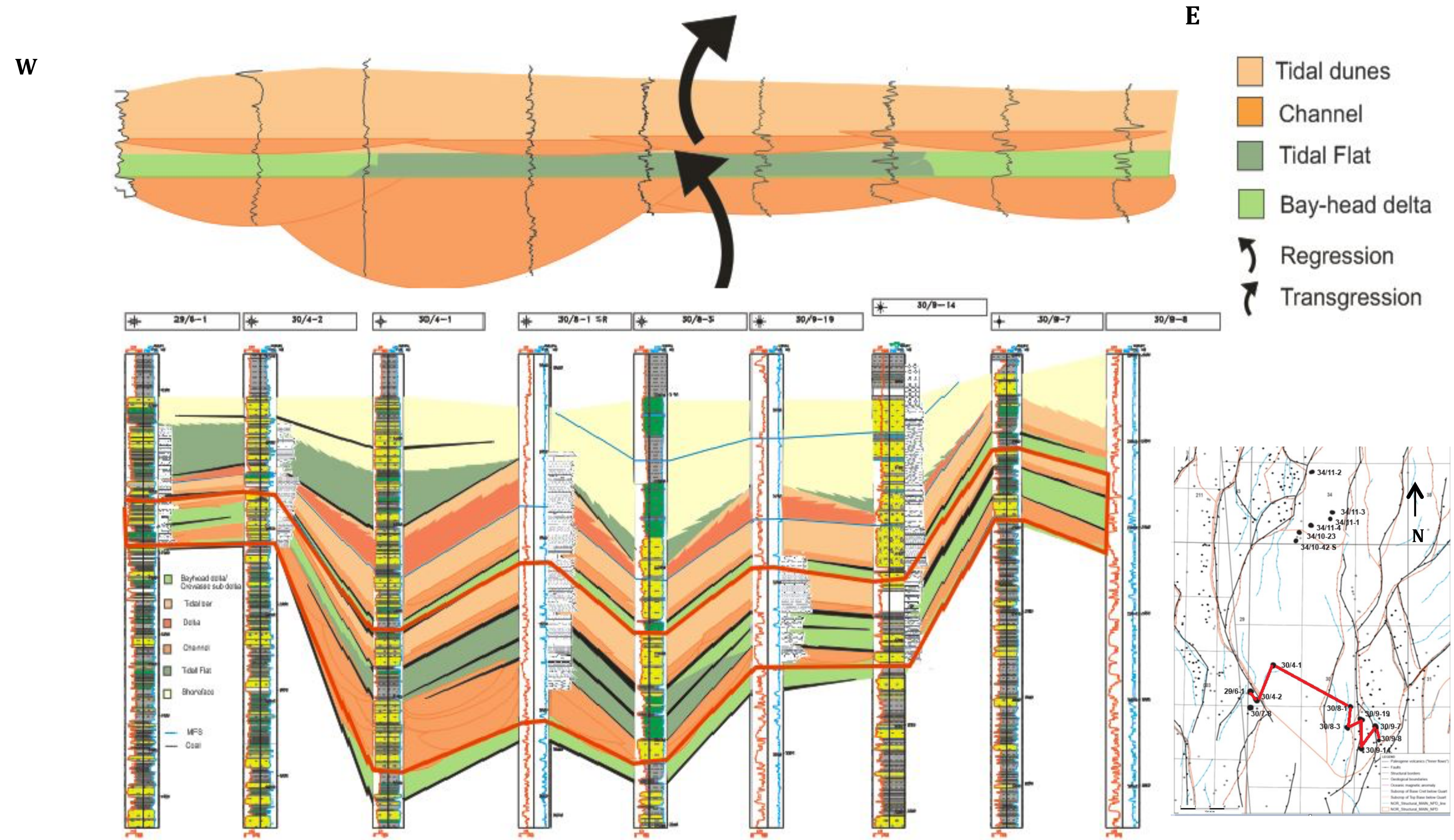


Figure 5-2. Sequence I stratal architecture with the sequence marked in red in the well correlation underneath.

Sequence II

A bay head delta unit capped by a coal layer at the top constitutes the bulk of the regressive segment in sequence II. Above the coal a channel complex of fluvial or deltaic origin is variably preserved, forming the uppermost part of the regressive segment. Where it is thin it appears to have been reworked into tidal dunes or bars. The regressive segment shows similarity to the bay-head delta deposits in the regressive segment in sequence I. In this thesis the coal at the top of the unit confirm that the position of the bay-head delta is more proximal than the marine bay-fill succession underneath, and that the unit is part of a regression. Løseth and co-workers (2009) included a similar aggradational package in their study. A candidate maximum regressive surface is inferred at the transition between the regressive and transgressive segment.

The transgressive segment is characterized by a thick succession. Again coarsening upward and fining upward motifs have been used to distinguish the tidal dunes and channels, respectively similar to the approach applied for sequence I. The transition into sequence III is defined by a maximum flooding surface capping the genetic sequence and the transgressive segment. Løseth & co-workers (2009) interpret the estuarine complex to be a channel complex, as they did with the similar tidal dunes in the transgressive segment in sequence I.

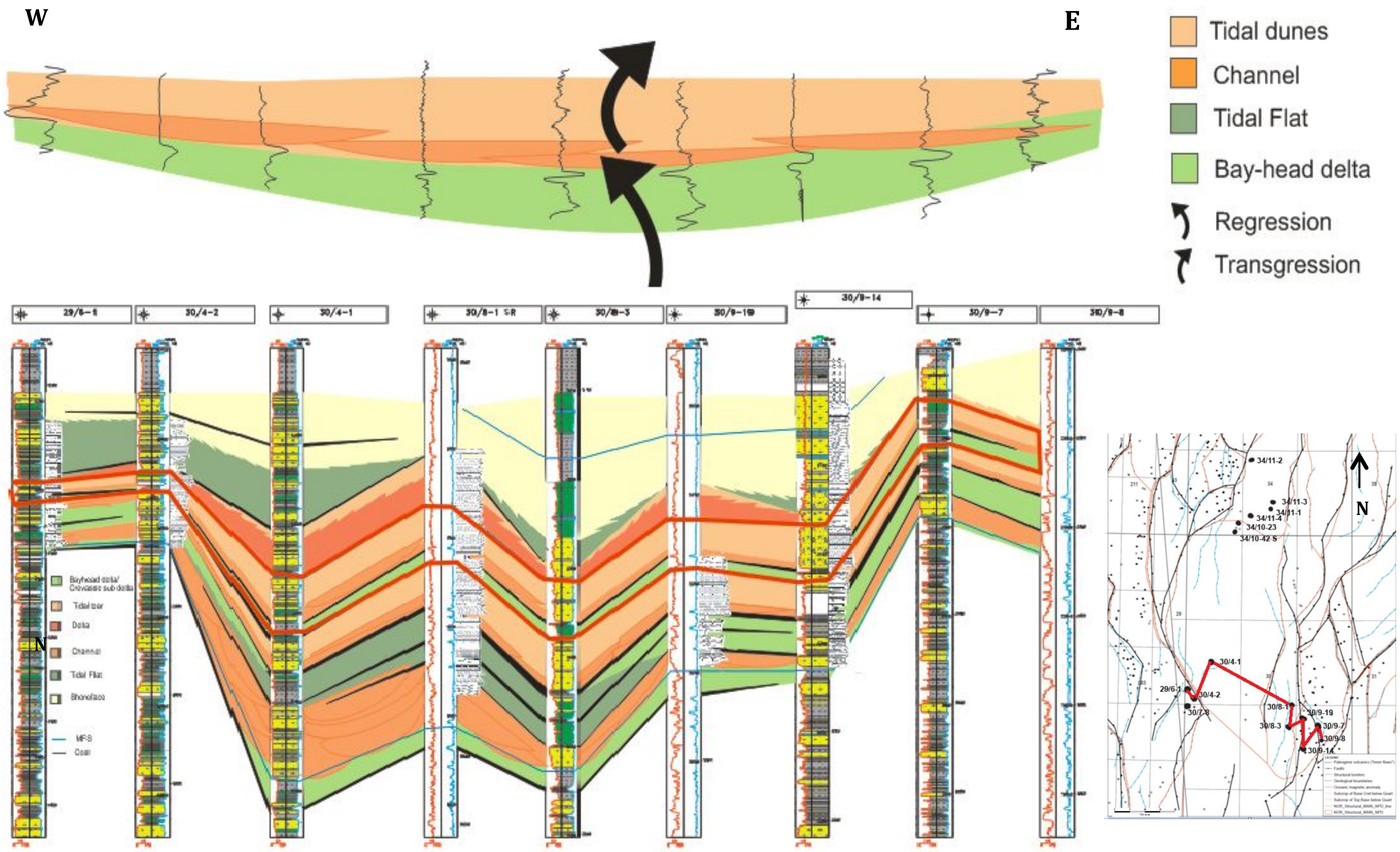


Figure 5-3. Sequence II stratal architecture with the sequence marked in red in the well correlation underneath.

Sequence III

Estuaries develop into deltas if there is sufficient direct river influence. (Dalrymple et al, 1992). The regressive segment in sequence III is composed of similar tidal dunes and channels as the transgressive segment in sequence II. The tidal dunes in this regressive segment has coarsening upward packages and is overall coarsening upward, here interpreted to represent a deltaic succession building out across the inherited estuary (Dalrymple and Choi, 2007), i.e. the transgressive segment of sequence II. The tidal dunes or bars and channels in the regressive segment are subsequently interpreted to be a tide-dominated delta. The tidal dunes or bars in the transgressive segments are composed of coarsening up packages that overall are slightly fining upward, and stands out from the regressive tidal dunes or bars. Slightly coarser sediments than the ones in the transgressive tidal dunes can as well recognize the regressive tidal dunes and bars in the tidal dominated delta.

The transition into the transgressive segment contains tidal dunes more similar to the ones described in the transgressive segments in the wells 30/8-1 SR and 30/9-19 as well as in the eastern Oseberg west flank. In the northern Martin Linge area and the wells 30/8-3 and 30/9-14 the transition is marked by tidal flats. The transgressive segment continues with sandbanks formed in an embayment setting as the transgression continues. Above the tidal dunes or bars and the tidal flat successions embayment sand banks and finer grained shoreface deposits representing a shoreline is present from the Martin Linge area to the Oseberg west-flank.

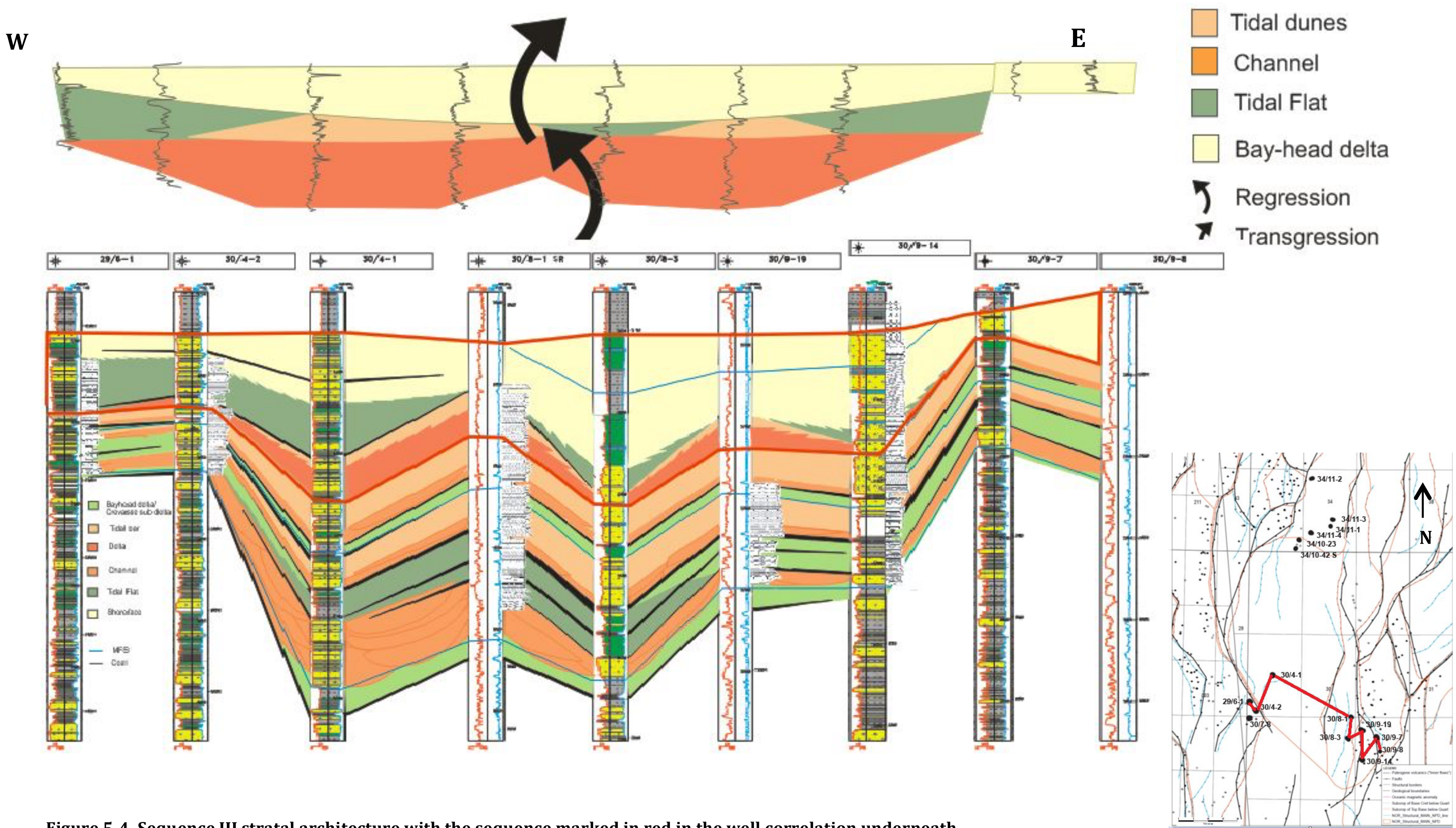


Figure 5-4. Sequence III stratal architecture with the sequence marked in red in the well correlation underneath.

5.1.2 Stacking pattern west-east correlation (Martin Linge-Oseberg)

Overall the Tarbert Formation is backstepping, and consists of four sequences in the Martin Linge-Oseberg area. Sequence I is thick and is wave and fluvial dominated. Sequence II is thinner and tide-dominated. Sequence III is thick, and the lower part is tide dominated, while the upper part is wave dominated.

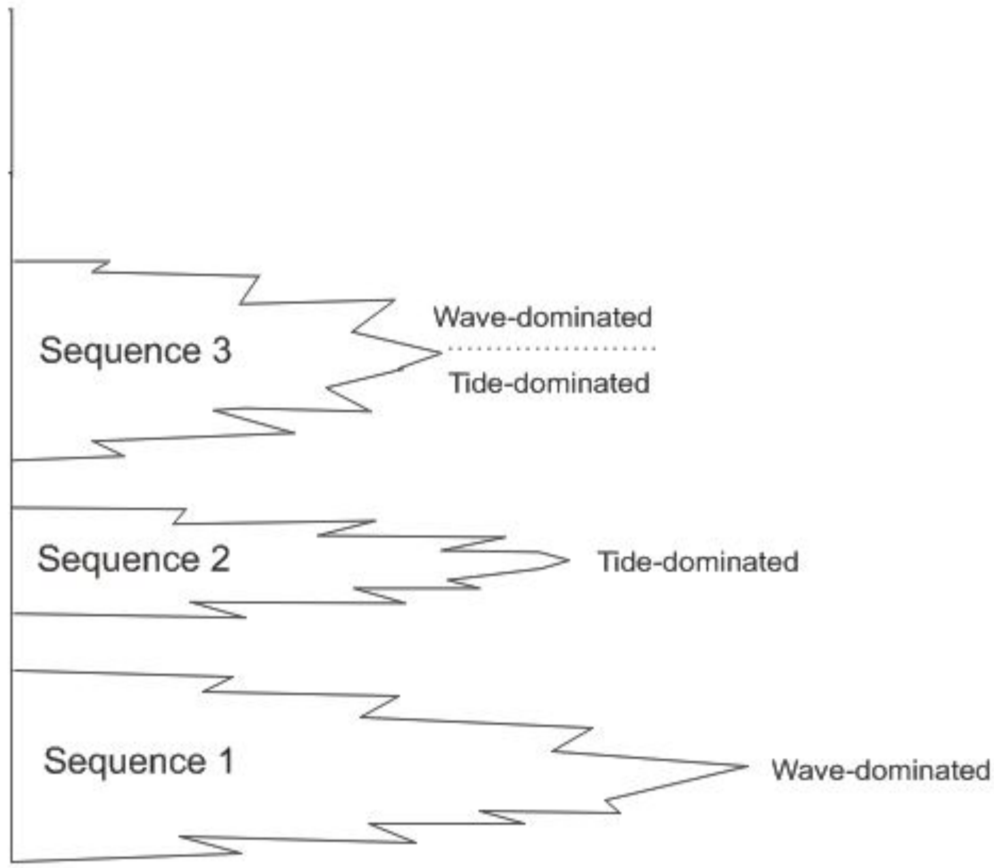


Figure 5-5. Stacking pattern of the three lower order sequences in the Martin Linge-Oseberg correlation.

5.1.3 West-East Correlation (Valemon- Kvitebjørn)

The Tarbert Formation in the West-East correlation in the Valemon- Kvitebjørn is composed of one low order package that can be divided into several higher order sequences.

A,

The regressive segment is composed of bay-head delta or crevasse sub delta deposits. This segment can be divided into four higher-order sequences, all capped by a flooding surface. The four higher-order sequences are typically coarsening upward into coal or mudstone with plant material, before being flooded.

B,

The transgressive segment characterizes a thick succession of tidal fills strata that is thinned from Valemon to Kvitebjørn. The initial tidal flat is composed of supra tidal deposits before it is flooded, and transitions into intra tidal flat. Some local variations exist in some of the wells.

C,

A shoreface succession represented by either a barrier or sandbanks and a finger-grained shoreline forms the uppermost part of the Tarbert Formation.

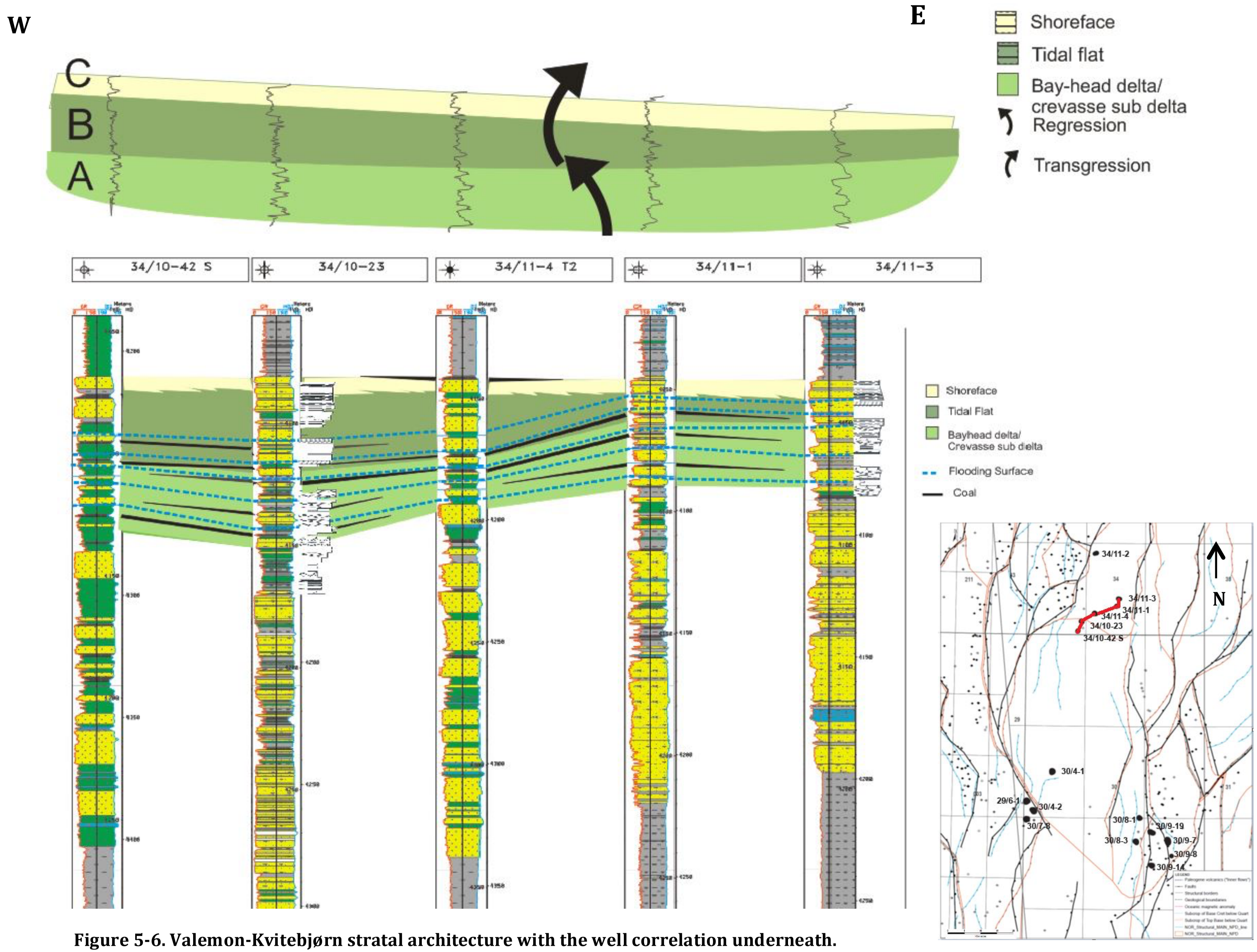


Figure 5-6. Valemon-Kvitebjørn stratal architecture with the well correlation underneath.

5.1.4 Stacking pattern west-east correlation (Valemon- Kvitebjørn)

Six higher order sequences are present in the Valemon-Kvitebjørn area. The four higher order sequences are in the bay-head delta or crevasse sub delta is thinning upward, implying that the lowest one is thickest and the upper one is thinnest. The upper higher order sequences in the tidal flat succession and shoreface succession is relative thick. Overall the Valemon-Kvitebjørn area is wave-dominated with some tidal influence in the tidal flat succession.

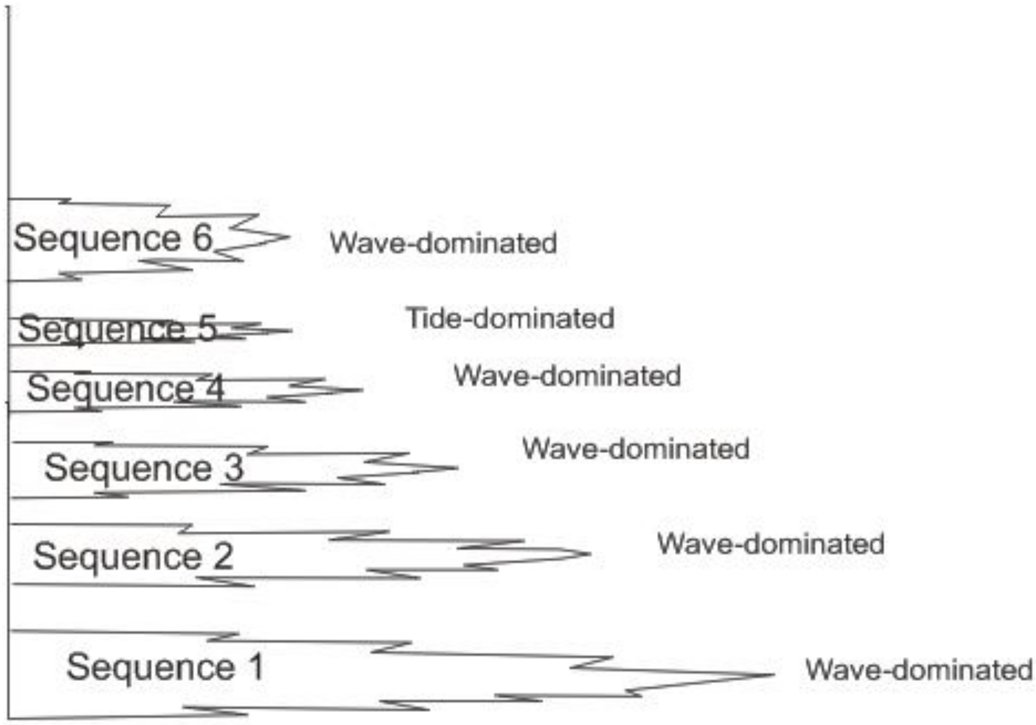


Figure 5-7. Stacking pattern of the lower order sequences in the Valemon- Kvitebjørn correlation.

5.2 Stratigraphic Evolution

The Tarbert Formation was deposited after the regressive maximum was reached in the end of the Early Bajocian, when the Brent delta started to back-step during the Late Bajocian-Early Bathonian (Helland-Hansen et al., 1992; Løseth et al., 2009). A ravinement surface marks the transition (Løseth et al., 2009) from the continental Ness to the marine Tarbert. The ravinement surface indicates that sediments were cut by wave action causing an erosional surface during the landward movement of the shoreline.

5.2.1 Martin Linge-Oseberg area

Sequence I

After the initial transgression the delta started to build outwards again. This renewed progradation is recognized by shallowing upward shoreface successions overlain by distributary and deltaic channel-fills. Above the deltaic channel-fills bay-head delta deposits are present along the western side and eastern side of the Central Viking Graben, i.e. the Rungne sub-basin. A significant amount of plant debris is present in the vertical stacked units of the bay-head delta. Plant debris and sediments were transported into the bay-head delta by nearby channels. Tidal flat can be recognized in the central part (between the western and eastern side) of the Rungne sub-basin, indicating that two different feeder systems are present, one on the eastern side and one on western side. Løseth et al. (2009) propose that the progradation was associated with a slow rise of relative-sea level, representing a normal regression. The interpretation of the normal regression is based on interfingering of facies, correlatable coal beds and coal-bearing embayment deposits (Løseth et al., 2009). In contrast Went et al. (2013) in their study on the Brent Group and Tarbert Formation in the British sector of the North Sea argue for a forced regression on the East Shetland Platform. If a normal regression took place the sediment supply had to exceed the sea level rise. The correlatable coal-layers and the vertical stacked packages in both the bay-head delta and tidal flat successions suggest an aggradational stacking, where the rate of sediment supply and sea-level rise is equally balanced.

Subsequently the relative sea level rise outpaced the sediment supply, in time resulting in a retrogradational phase. An estuarine complex comprised of tidal dunes and channel-fills represents the transgression. The clean, well sorted nature of the tidal dunes or bars suggest a marine sediment source and that they are likely a result of reworking. The tidal dunes appear widespread, forming a graben wide estuary or estuarine complex.

Sequence II

Another phase of progradation is marked by the transition from estuarine deposits to bay-head delta successions. The rate of sediment supply of the rivers increased and exceeded the sea level, causing another normal regression. Subsequently a smaller but similar fluvial system as in sequence I was present. The bay-head delta successions are vertical stacked and are similar to the ones in sequence I, suggesting an aggradation stacking. This indicated that after the initial increase in the rate of sediment supply, the sea level and the rate of sedimentation became equally balanced. This interpretation differs from Løseth & co-workers (2009), where bay-fill is interpreted to be part of the transgression.

The aggradational phase was followed by a retrogradation, caused by the sea level again outpacing the rate of sediment supply. Again a graben wide estuarine complex was deposited. Stacked tidal dunes or bars with channel-fills similar to the ones in sequence I are inferred.

Sequence III

However, after a period of retrogradation the system and this time the estuarine complex started to prograde and developed into a tide-dominated delta. Estuaries can develop into deltas if there is sufficient direct river influence (Dalrymple, 1992), implying that the rate of sediment carried by the river again increased and surpassed the relative sea level. Again this interpretation differs from Løseth & co-workers (2009), where transgressive channels were interpreted.

Subsequently the relative sea level again outpaced the rate of sediment supply, and another stage of retrogradation occurred. In the western Martin Linge area (29/6-1, 30/4-2 and 30/4-1) and wells 30/8-3 and 30/9-14 the transgression is marked by the transition into tidal flats. However, in the wells 30/8-1 and 30/9-19 the transition is signified by the transition from the regressive delta to transgressive estuarine tidal dunes. In the southern Oseberg area (30/9-7 and 30/9-8) shoreface deposits marks the transition into the retrogrdataion.

As the transgression continued, and the area became increasingly more distal, shoreface successions are deposited on top of the tidal flats and estuarine tidal dunes or bars. The coarser sediments above the tidal flats and estuarine tidal dunes represents sand banks were deposited in the outer part of an embayment. These sand banks are interpreted to represent a stage when the system becomes more mixed-energy to more wave-dominated. The shoreface deposits are fining upward and were establishing a shoreline before it eventually became overlain by marine mudstone representing the delta drowning stage.

5.2.2 Kvitebjørn- Valemon area

The Kvitebjørn-Valemon area is linked to another feeder system than the Martin Linge-Oseberg area.

Bay-head delta or crevasse sub delta deposits compose the progrdational phase. The successions are vertical stacked with correlatable coal-layers allowing a subdivision into 4 higher order sequences 4 progradational and 4 retrogradational phases can be recognized. In the progrdational phases the delta is building out due to an increase in the rate of the sediment supply. When the sea level outpaces the rate of the sediment supply a flooding occur, and the retrogrdational phase is present. This occurs for all the higher order sequences. The higher order sequences are becoming thinner upwards, suggesting a decreasing rate of relative sea level rise and sediment supply.

Tidal flat successions represent the transition into the retrogradational stage. The rise in relative sea level outpaced the rate of sediment supply. Subsequently the lower initial tidal flat succession is composed of supra tidal deposits, before the supra tidal flat strata are overlain by intra tidal facies supply.

As the back stepping of the delta continues and the area becomes more distal coarse shoreface sediments in form of a barrier is deposited. The barrier is a result from the reworking of fluvial and marine sediments done by waves. The sediments become more marine as the delta is being drowned.

5.3 Paleogeography

5.3.1 Progradation of sequence I

The progradation of the Lower Tarbert. A major axial fluvial system inferred present along the Northern Viking Graben with smaller deltas of lateral or transverse systems situated over the Hild, the Valemon-Kvitebjørn area and the Oseberg west-flank area.

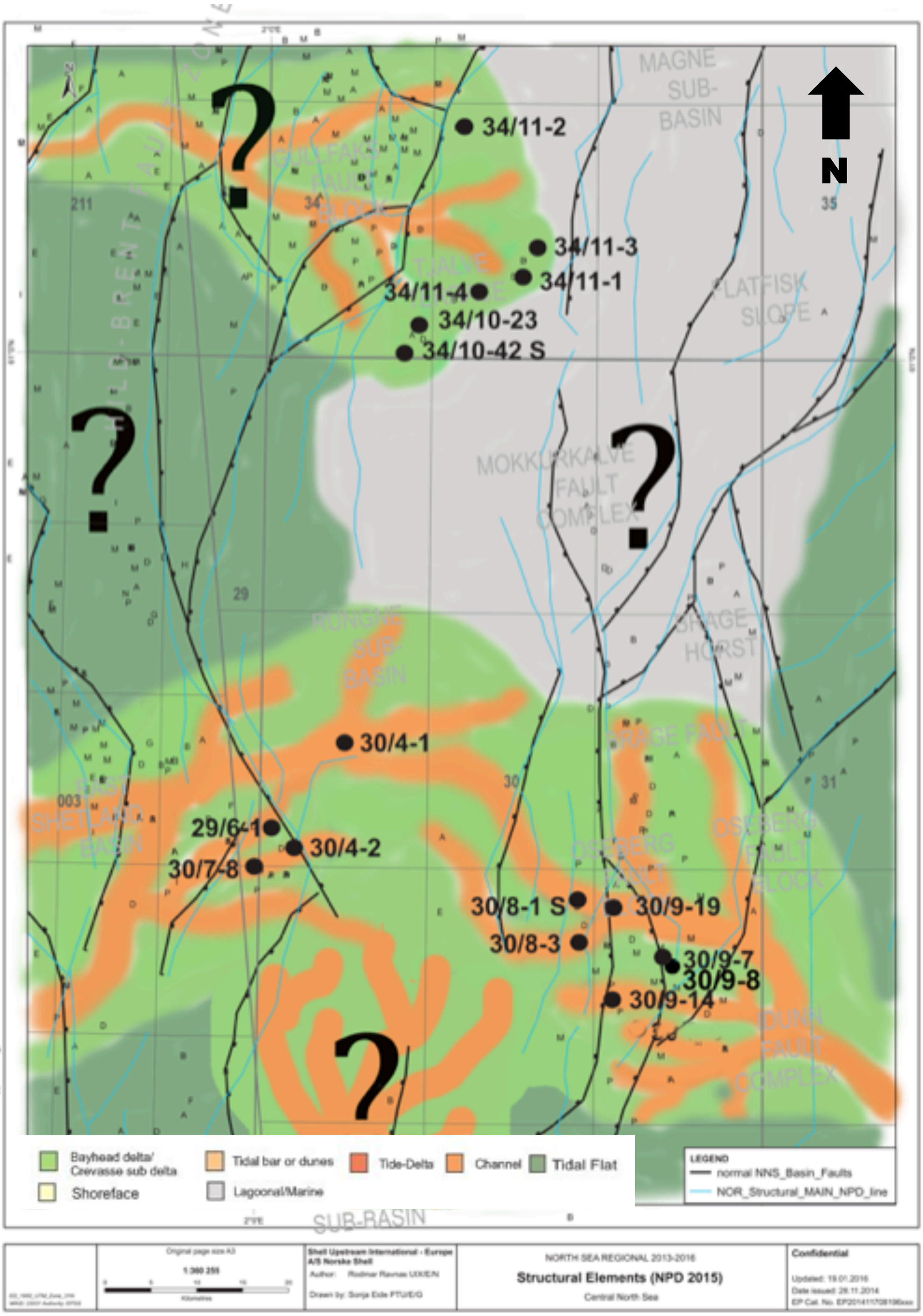


Figure 5-8: Progradation of the Lower Tarbert.

5.3.2 Aggradation of sequence I

The aggradation phase present in the Lower Tarbert. Tidal flats are inferred for Oseberg western wells 30/8-1 S and 30/8-3 in addition to well 30/4-1. Tidal flat infill has formed lateral to the major axial fluvio-deltaic systems. This in turn suggests that this axial system was more acing to a tide-dominated delta.

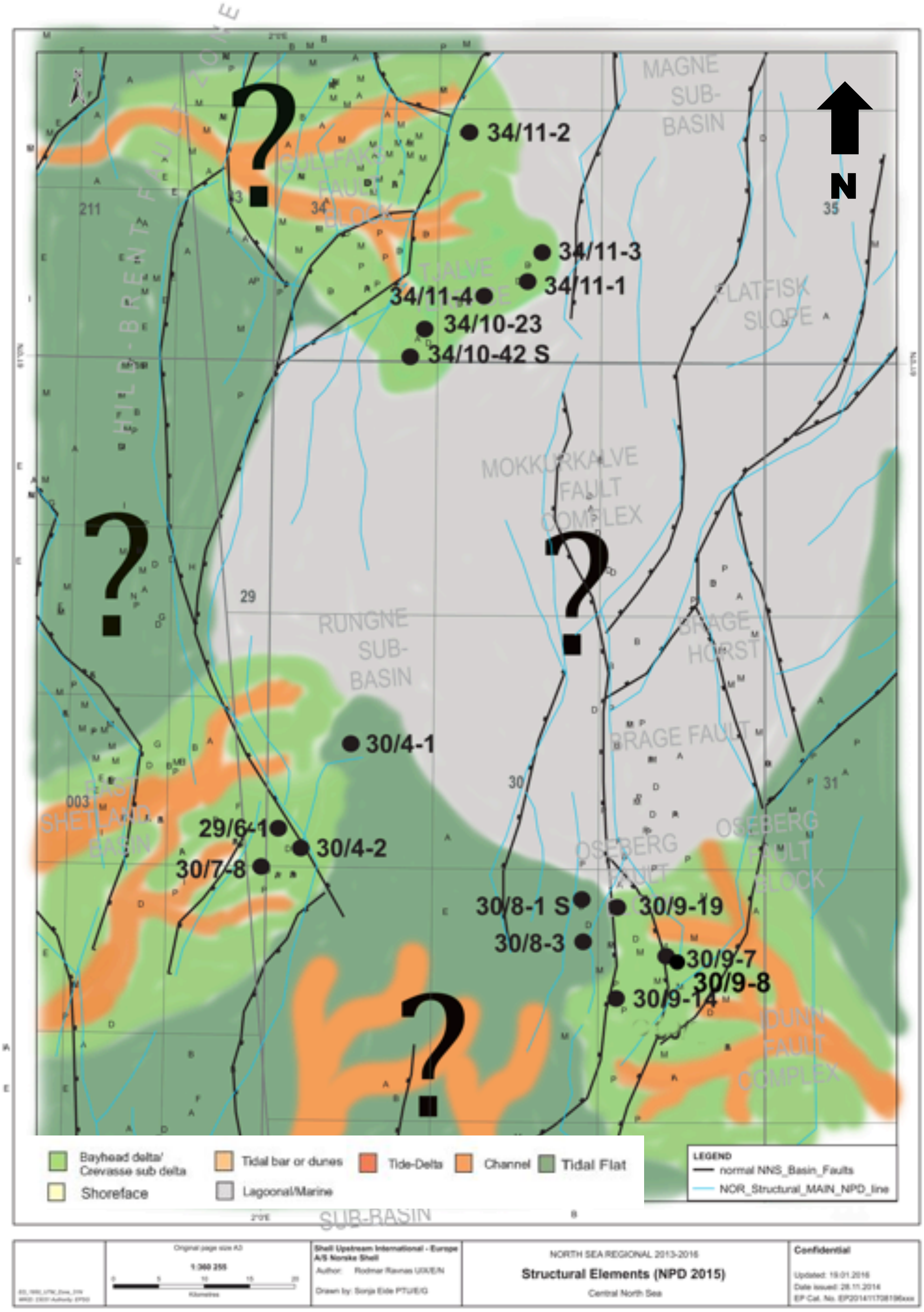


Figure 5-9: The aggrading part of the Lower Tarbert.

5.3.3 Retrogradation of sequence I

Retrogradation of the Middle Tarbert and the establishment of a tide dominated estuary. The tidal ridges are here drawn current parallel, implying a tidal dune origin. Such an interpretation would require dipmeter data to be validated. Sand banks are inferred present to outer part of the estuary by analogue by a similar interpretation in sequence III.

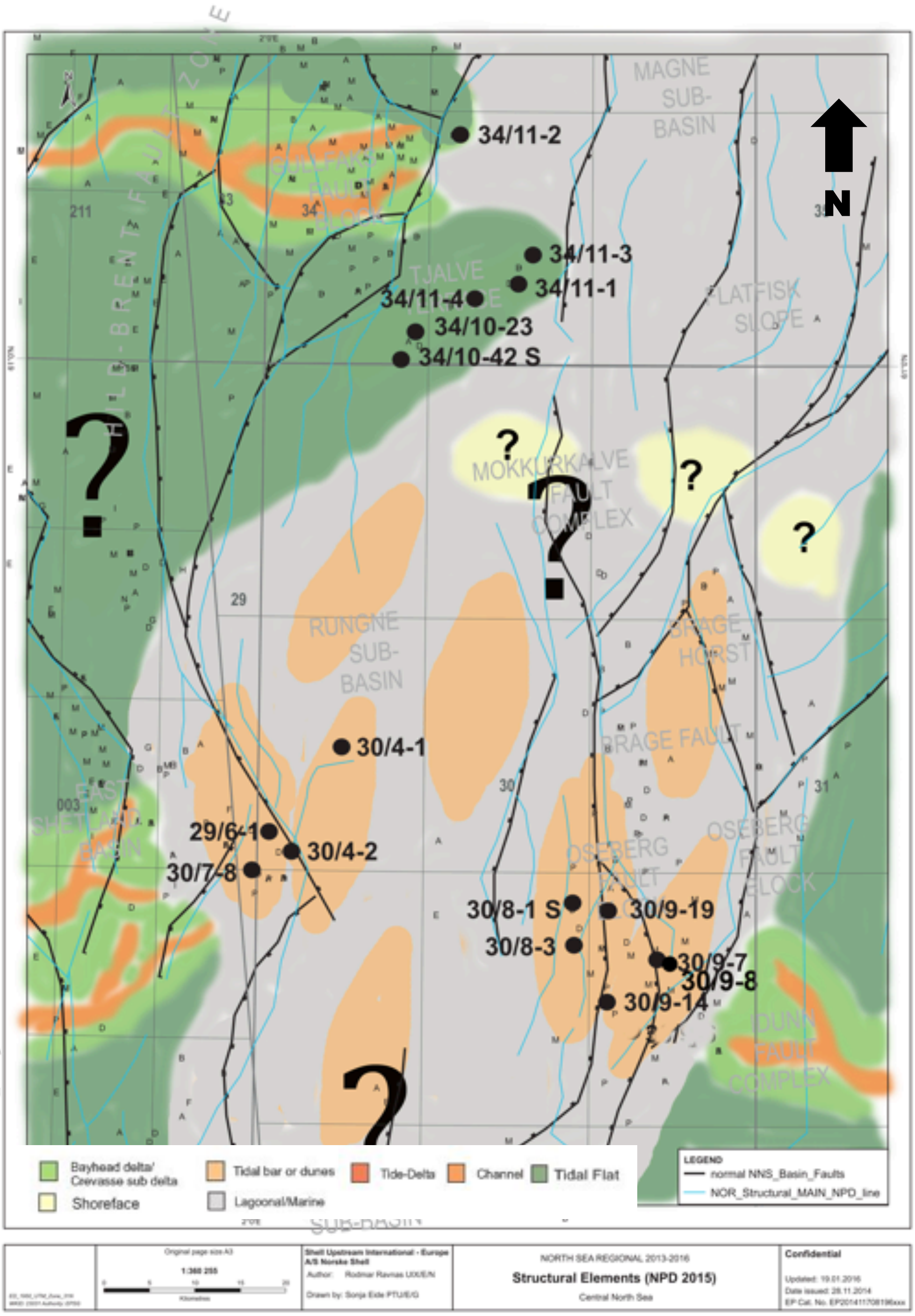


Figure 5-10. Retrogradation of the Tarbert Formation, and the establishment of an estuary.

5.3.4 Progradation of sequence II

Progradation of the Tarbert Formation. A smaller fluvial system started to prograde across the Martin Linge, Oseberg west flank and the Valemon-Kvitebjørn. Tidal flat successions are interpreted lateral to the smaller deltas or transverse systems situated over the Hild and Valemon-Kvitebjørn area. Subsequently the tidal flats turned into parts of the tidal flat flanks of the larger fluvial system situated along the Northern Viking Graben (not shown here).

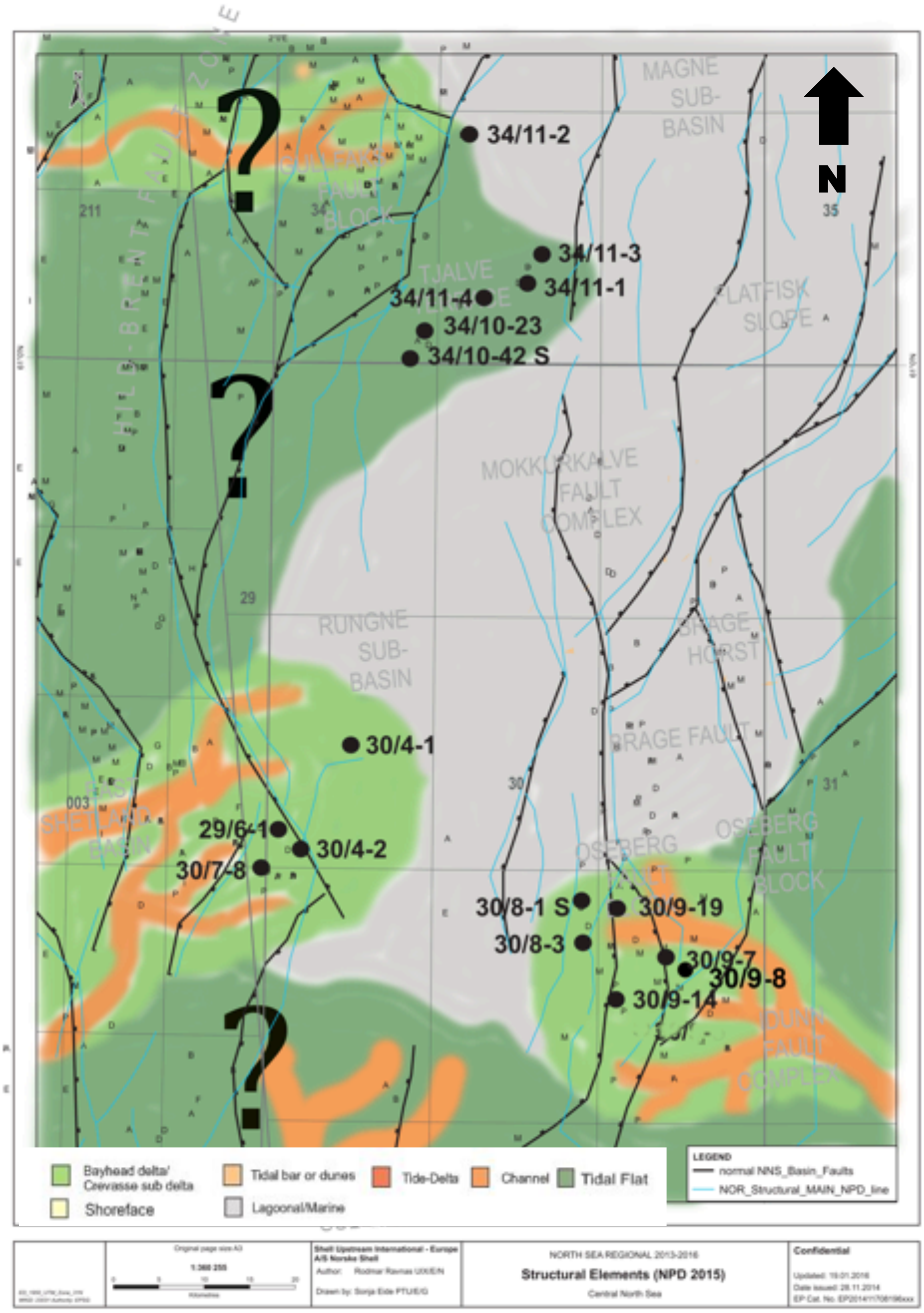


Figure 5-11. Progradation of the Tarbert Formation.

5.3.5 Retrogradation of sequence II

The upper estuary complex represent the transgressive segment of sequence II. The tidal ridges are again inferred to tidal dunes. Sand banks are interpreted present in the outer part of the estuary by analogue with a similar interpretation as in sequence III.

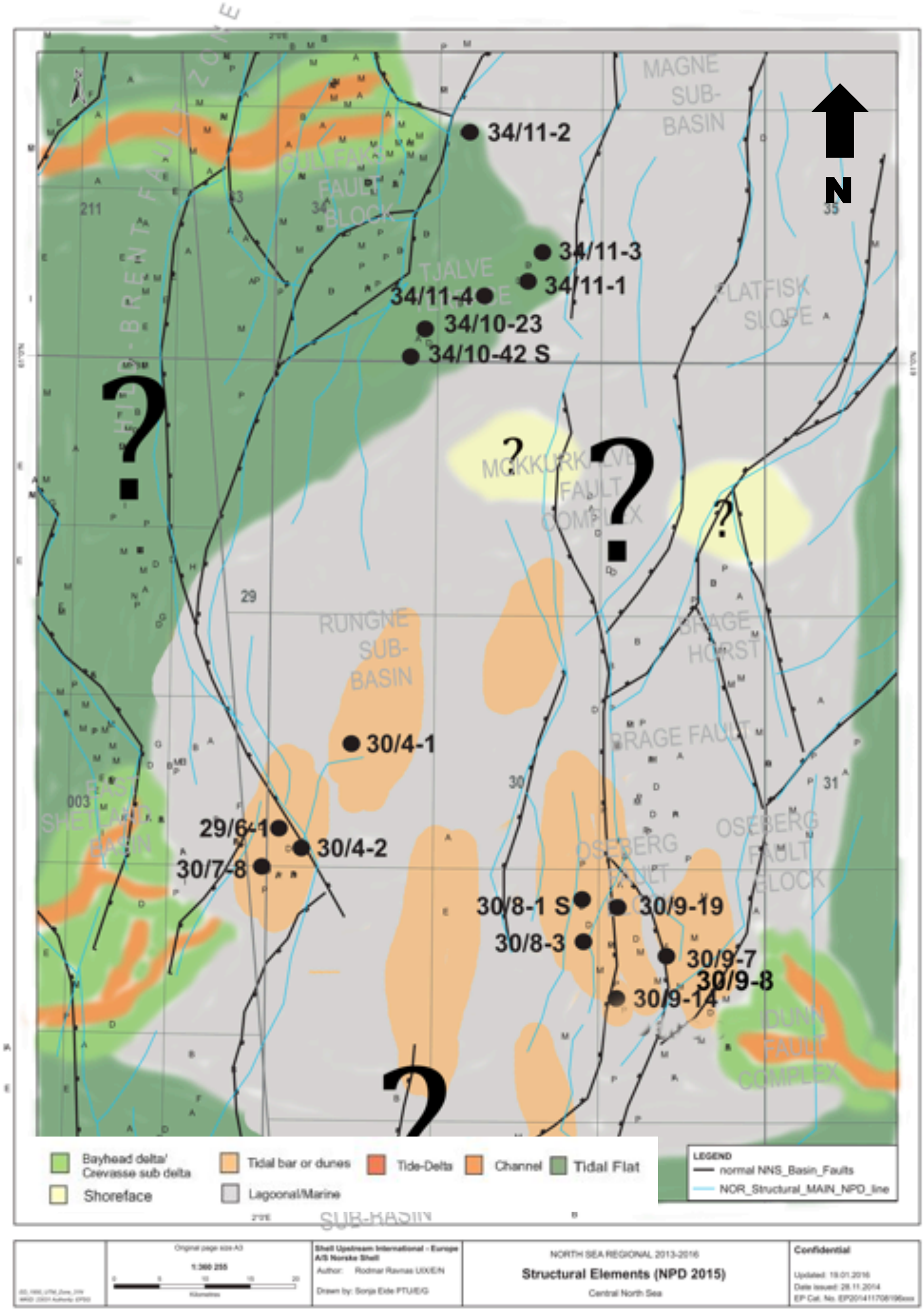


Figure 5-12. Retrogradation of the Tarbert Formation, and the establishment of the upper estuary complex.

5.3.6 Progradation of sequence III

Progradation of the Tarbert Formation and the establishment of a tide-dominated delta. An axial fluvial system is inferred along the Central Viking Graben. Tidal dunes are interpreted present in the seaward portion of the tide-dominated delta.

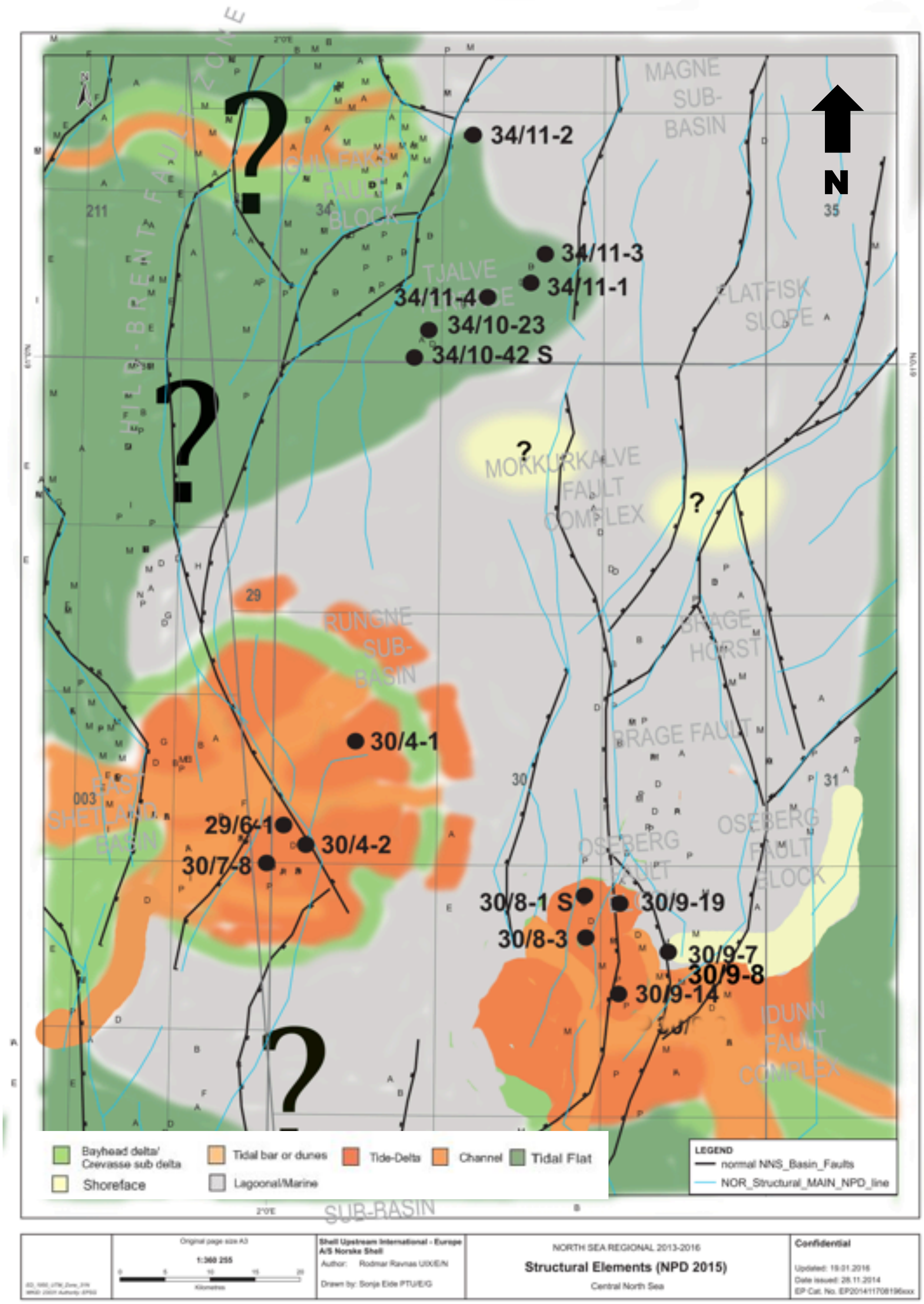


Figure 5-13 Progradation of the Tarbert Formation and the establishment of a tide-dominated delta.

5.3.7 Retrogradation of sequence III

Retrogradation of the Tarbert Formation, and the re-appearance of the estuary. Tidal bars are inferred in the structural lows in the Oseberg west flank, while tidal flat successions are inferred in the structural highs. A shoreline is established in the north of the Oseberg fluvial system. In the Martin-Linge terrace tidal flat successions are present. Sand banks are interpreted by analogue of the continued retrogradation in 5.3.8. A barrier is inferred in the Valemon-Kvitebjørn area.

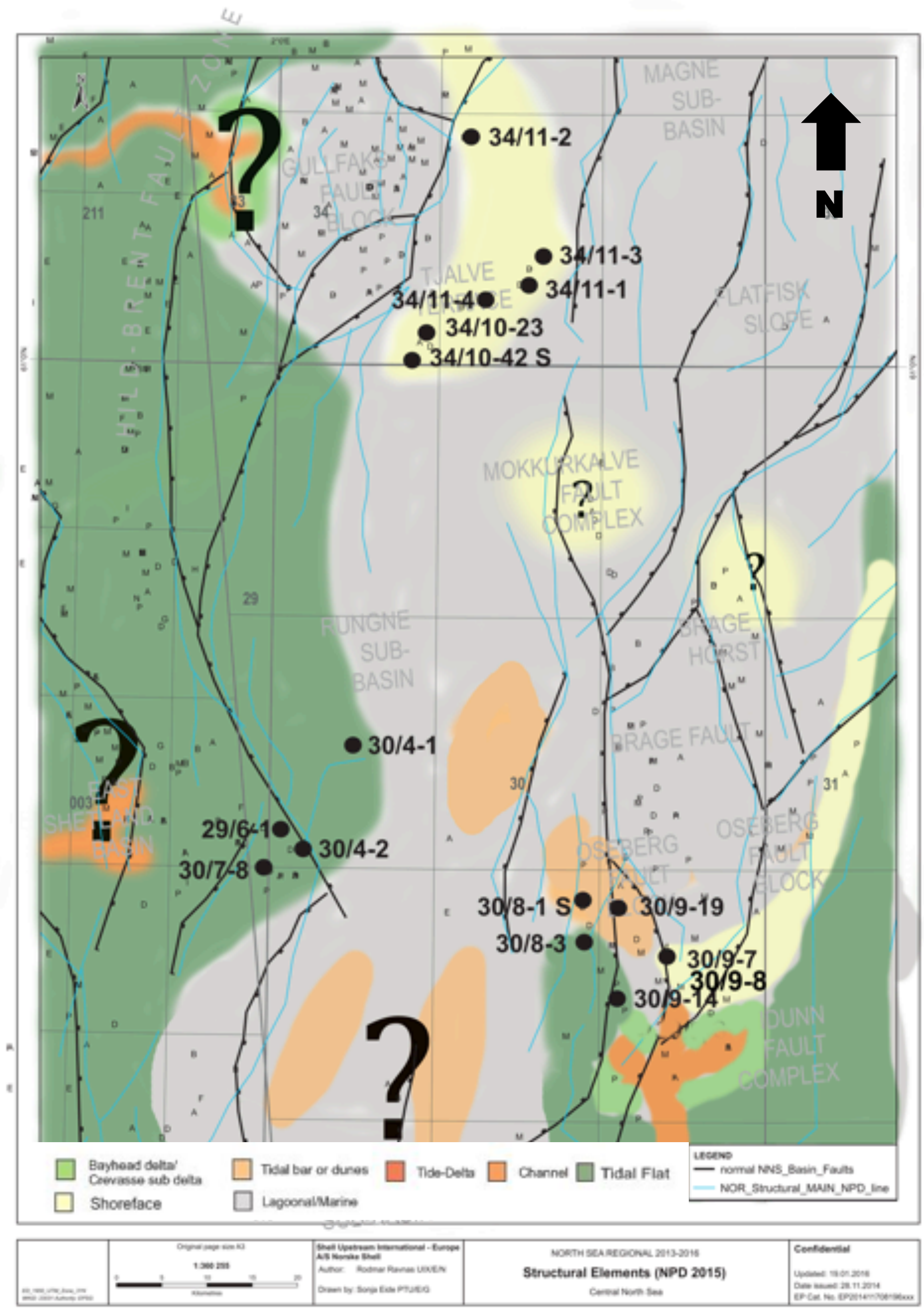
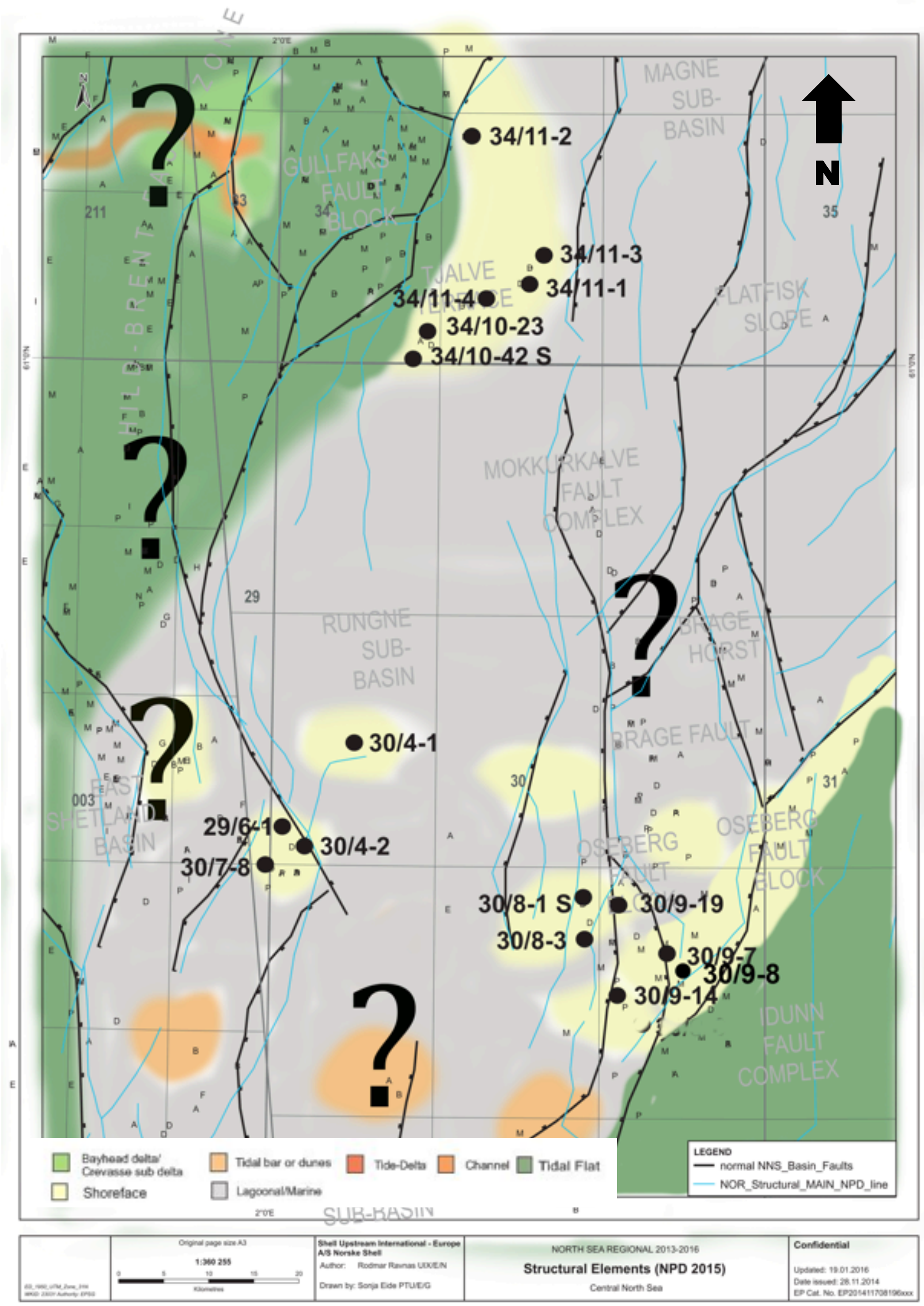


Figure 5-14. Retrogradation of the Tarbert Formation.

5.3.8 Retrogradation of sequence III

Continued retrogradation of the Tarbert Formation. Sand banks influenced by wave and tides are inferred present, representing the outer or seaward portion of the embayment.



Figur 5-15. Continued retrogradation of the Tarbert Formation, and the formation of sand banks.

5.3.9 Retrogradation of sequence III

The last stage of the retrogradation. A transgressive wave-dominated shoreline was established across the Rungne sub-basin before the sea eventually transgressed and submerged the Brent delta.

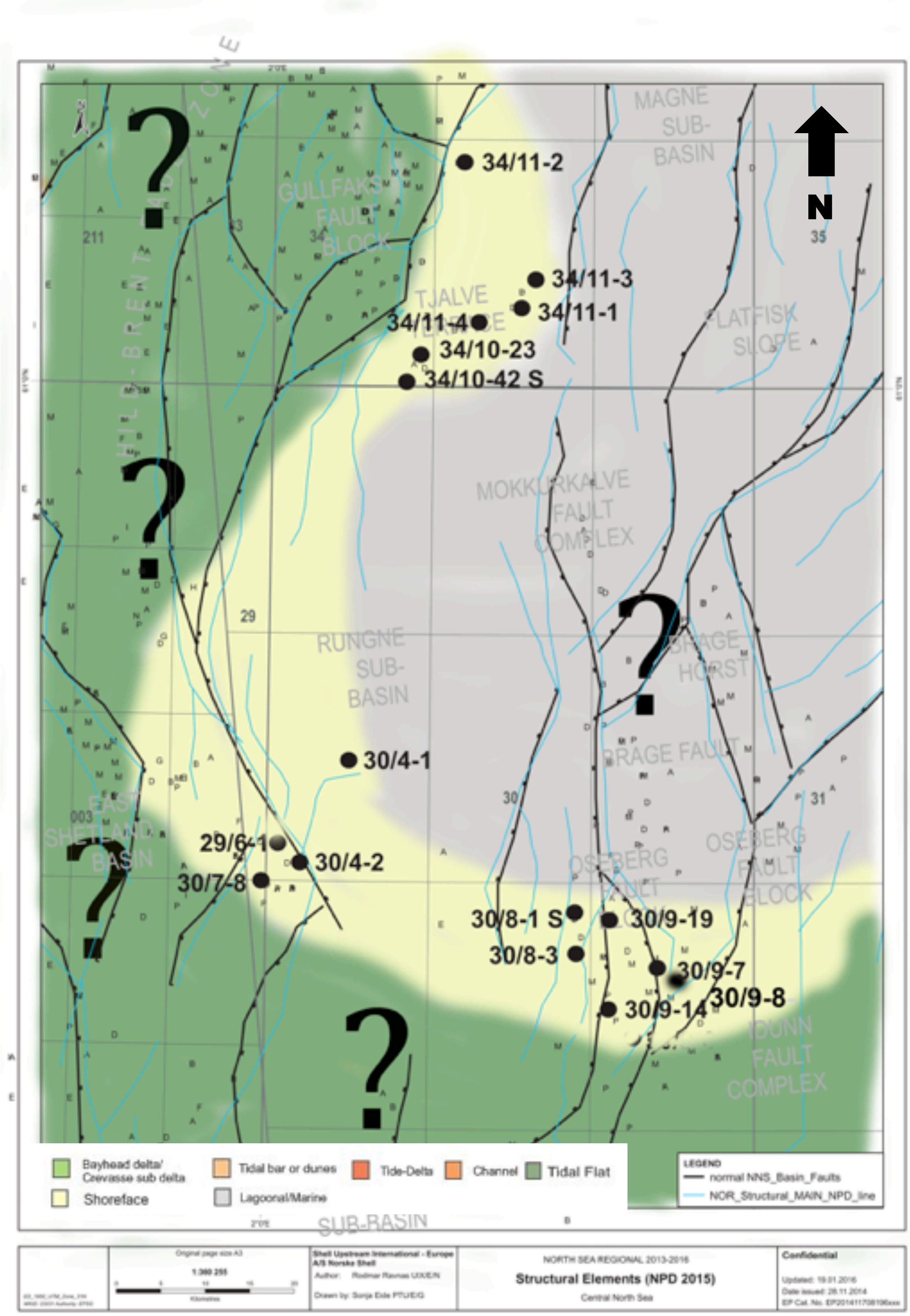


Figure 5-16. The establishment of a shoreline before the Tarbert Formation was submerged by the sea.

5.4 New observations and interpretations

The new observations and interpretations in this study are mostly related to well 30/4-1, and how well 30/4-1 can be linked to the Martin Linge area. Well 30/4-1 was drilled into a fault and dip controlled closure in the Viking Graben. Previously the Tarbert Formation has been interpreted to have a thickness of 29 meters, starting at depth 5182 meters according to NPD factpages. The formations below have been interpreted as Ness, Etive, Rannoch, Oseberg and Drake formations. The top Drake Formation was interpreted at 5400 meters. Subsequently Ravnås and co-workers (1997) assessed the succession to the Tarbert Formation by analogy with the Oseberg west-flank area. The succession below 5400 meters was assigned to the Ness Formation on the basis of its coal-bearing sediments. Subsequently, in well 30/10-6 in the south, the Tarbert Formation has been interpreted to be expanding and has a thickness of 423 meters (NPD factpages). In this thesis the Tarbert Formation in well 30/4-1 follows Ravnås et al. (1997) resulting in a thickness of 217 meters. This is in line with the Tarbert expansion in well 30/10-6 and on block 30/8 (30/8-1, 30/8-3 and 30/8-4).

The units interpreted as estuarine tidal dunes in Middle Tarbert have previously been interpreted as channels by Løseth and co-workers (2009). Tidal dunes in the Baronia sandstone in Spain show a similar facies succession as the motifs interpreted to represent tidal dunes in this thesis. In the Baronia sandstone tidal dunes are recognized by coarsening upward packages with a defined bottomset at the bottom and bar crest at the top (Dalrymple et al., 2006). The sand bodies that represent the compound dune can be 7-8 meters thick and extend laterally for hundreds of meters. The compound dunes can be amalgamated to form sand ridges that extend for kilometers(Olariu and Steel, 2006). This could be an explanation why there is a significant thinning to east and west of the tidal dunes inferred in the present study. A modern example of such compound dunes is present in the San Fransisco Bay (Olariu and Steel, 2006).

In wells 30/6-1 and 30/7-8 a medium coarse moderately to well-sorted sandstone is present on top of the tidal flat successions. In this thesis these sands have been interpreted as thick sandbanks in a mixed-energy marine embayment. In a study by Yoshida et al. (2005) on the Woburn sands in England an assemblage with similar structures was interpreted to be sandbanks in a tide dominated marine embayment. The Woburn sands have earlier been tied to Brent Group in the Northern North Sea because of its similar transgressive evolution (Dixon et al., 1997; Yoshida et al., 2002; Yoshida et al., 2005). Similar sandbanks have been proposed by Steel et al. (2004) in a mixed-energy to wave-dominated setting in a transgression coastal system. An alternative interpretation is a transgressive barrier beach system (Ravnås et al., 1997), however this is considered less likely because of the common occurrence of tidal generated structures and a gradual transition from the underlying deposits.

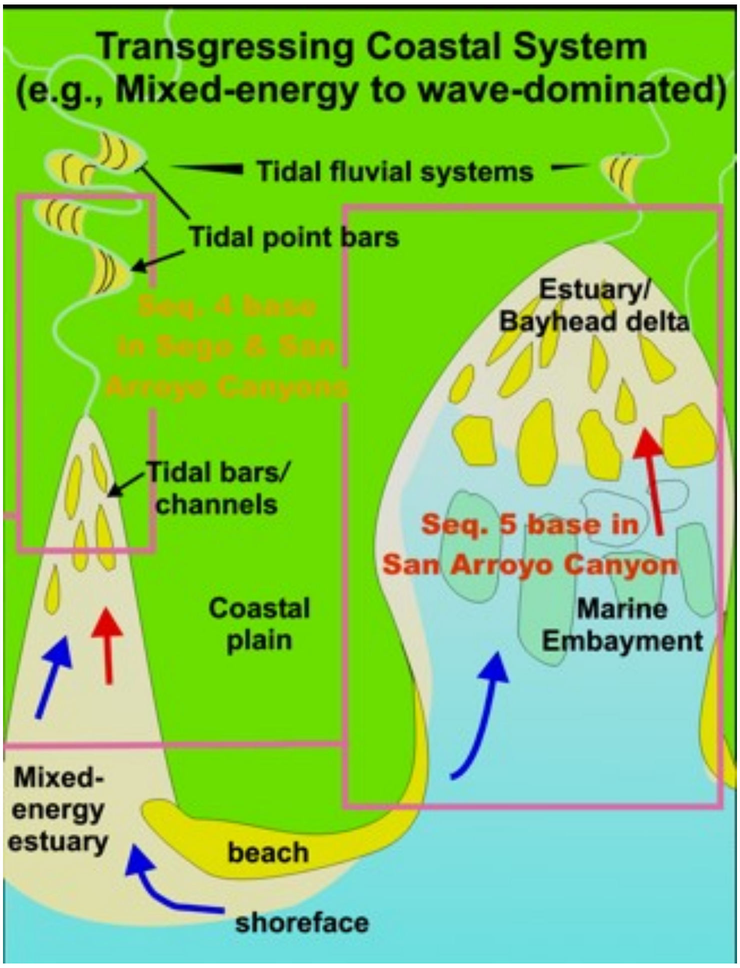


Figure 5-17: Early transgressive phase of a mixed energy system, showing the tidal bars (yellow) and sandbanks (blue) formed in a marine embayment (to the right) (Yoshida et al., 2004).

6. Discussion- Upper Brent in the Central Viking Graben

6.1 Lower Tarbert Deltas

6.1.1 Martin Linge- Oseberg area (regressive sequence I)

The lower Tarbert is recognized as a renewed progradation phase of the Brent, and accordingly represent a regressive phase. A wide channel complex signifies the base of the unit. The sequence itself is coarsening upward, even though the channel complex itself forms an overall fining upward succession. Løseth et al. (2009) interprets the channel complex as the initial regressive shoreline. Hummocky cross stratification and wave ripples are abundant in the overlying and underlying sediments. Similar structures were recognized by Løseth et al. (2009) and were interpreted as an indication of a wave-dominated environment with the basal contact representing a wave-generated ravinemnet surface underneath (Walker & Pint, 1992; Løseth et al., 2009). The channel complex itself consists of poorly cross-stratified sands, and has been interpreted to represent a series of the distributary channels. The overlying bay-head delta stacks to the east (Oseberg west-flank) and west (Martin Linge) have been interpreted as two separate systems with tide influenced delta plain in-between. Hence a more mixed wave-tide infill is preferred compared to the interpretation of Løseth and co-workers (2009). The bay-head deltas and the tidal delta plain are aggrading, based on the presence of a coal layer on top of vertical stacked packages of bay-head delta origin. This indicates that the fluvial system brought with it enough sediment to maintain the shorelines position during the relative sea level rise, as explained in the section 5.2. The bay-head delta sediments contain mainly wave-generated structures in the lower part, and both wave and tidal induced structures in the upper part. The wave-induced structures indicate that as the bay-head delta was formed, the system was dominated by waves. As the bay-head delta aggraded there was a gradual transition from wave-dominance to tide-dominance. The tidal flat or delta plain between the two bay-head deltas have more tide induced structures. The abundant wave-structures and tide structures can indicate that the barrier that is common in wave-dominated estuaries did not form. Usually the tide and wave influence in the inner part of a wave-dominated estuary is minor (Dalrymple et al. 1992). Løseth et al. (2009) interprets the bay-head delta and tidal flats as wave-agitated embayments with a persistent tidal influence. Mud drapes and flaser laminations were recognized. Løseth et al. (2009) suggest that such features can form under wave activity alone, despite being more common tide influenced settings. Bay-head deltas are found in the upstream section of most typical wave-dominated estuaries (Dalrymple, 1992). If a normal regression takes place the bay-head delta undergoes a “turn-around” from transgressive retrogradation to highstand aggradation (Plink-Bjorklund and Steel, 2006; Simms and Rodriguez, 2014). The highstand aggradation is similar to the aggradational bay-head successions in this thesis. A higher-order flooding surface should then be present in between the progradational delta channels and the bay-head delta. If the bay-head delta unit is in fact part of an estuary a barrier should be present seaward. Strata of barrier origin have not been encountered, and accordingly there is currently limited evidence of a wave-dominated estuary. The Gironde estuary is a modern example of a tide-dominated estuary with a tide-dominated bay-head delta fed by a river, without a sand-dominated seaward end member (Davies and Dalrymple, 2012). This explanation is not as likely in this case, as the sedimentary structures indicate that lower part of the environment is dominated by waves. A possible scenario could contain a wave-dominated embayment transition into a tide-dominated estuary like in the present day German Bight estuary and its laterally bordering tidal flats. The wave-dominated embayment would contain more transgressive bay-head delta succession, and this would concur with the transgressive tidal flats in-between them.

6.1.2 Middle Tarbert estuaries

(transgressive segment sequence 1, sequence 2 and regressive segment sequence 3)

The basal channel complex of this unit, along with the estuary complex with alternating tidal dunes or bars and tidal channel fill indicate a tidal-influenced environment. Tidal dominance can occur if wave action is limited or the tidal prism is large (Hayes, 1979; Davies and Hayes, 1984; Dalrymple et al., 1992). The tidal dunes or bars comprise coarsening upward units, while the channel at the base is fining upward. The basal channel is interpreted to be of fluvial or deltaic origin, and is interpreted to form a progradational succession and represent a renewed outbuilding of the Brent delta. Wei et al. (2016) argues for the presence of similar tidal dunes or bars as in this thesis in the Tarbert Formation in well 30/8-1 S. Their interpretation however does not include a fluvial deltaic channel complex at the base of the estuarine unit. In the present thesis the basal channel provide the sediments that was subsequently reworked by tides into the estuarine complex of tidal dunes and channel-fills. Since the estuary is dominantly influenced by tides, sediments brought in by waves are not considered a viable option.

Angular cross-stratification, mud drapes and occasional ripples can be seen in the tidal bars, all indicating tidal activity. The small fining-upward packages between the coarsening upward packages have been interpreted as channel-fills as mentioned in the sequence stratigraphy in section 5.1. Towards the top of the channel-fill bioturbation is often present.

The second upper estuarine complex has a progradational deltaic unit at its base, interpreted to represent the preserved parts of an originally thicker tide-dominated deltaic succession. The tide-dominated delta formed as the rate of sediment supply increased, and is recognized by coarser channel-infill and stacked tidal bars, arranged in an overall coarsening and shallowing upward succession, suggestive of regressive infilling a progradation of the overall system. In turn this suggest a deltaic origin. The coarse nature with occasional pebbly intervals further supports a fluvial delivery system. The shallowing upward and coarsening upward unit with tidal influence is seen in the majority of the wells.

Løseth et al. (2009) interprets the tidal dunes as estuarine channel complexes with intervals of bay-head deltas or tidally influenced mouth-bars. The rationale for the wave-dominated estuary interpretation (Løseth et al., 2009) was based on the fluvial dominated sandy portion in the inner estuary, and as an inferred sand-rich barrier system in the marine end and a central embayment of fine material in-between. As neither central basin finer barrier deposits have been referred for the Middle Tarbert, a tidal dominated estuary setting is proposed for the Middle Tarbert.

6.1.3 Upper Tarbert Shoreface (Transgressive segment in sequence III)

The Upper Tarbert shoreface represent the latest stage of the Brent delta transgression, and is overall back stepping. The tidal dominated estuary in the Lower and Middle Tarbert Formation became more open and hence influenced by waves, resulting in a thick succession of shoreface sediments. The coarser shoreface sediments present at the top of the tidal flats and estuarine deposits are interpreted to represent sand banks formed in the outer parts of an embayment. The sand banks were deposited as the delta changed from being tide to wave-dominated. The shoreface deposits overlying the sandbank are finer-grained overall more aggrading. Accordingly its interpreted to represent a wave-dominated coastline. Ravnås et al. (1997) and Løseth et al. (2009) interpret a candidate maximum flooding surface at the top of this unit, in the transition from the Tarbert Formation into the Heather Formation. In this thesis the progradation is interpreted to be minor and not associated with regional significance.

6. 2 Valemon – Kvitebjørn

The bay-head delta successions or the crevasse sub delta successions in the Valemon – Kvitebjørn area is more wave-dominated than the deposits in the Lower and Middle Tarbert in the Martin Linge- Oseberg area. Abundant hummocky cross-stratified strata imply the wave-dominance. The Valemon-Kvitebjørn area is located further north than the Martin Linge – Oseberg area. The Brent delta prograded from south to north (Fjellanger et al., 1996), implying that the location of the Valemon- Kvitebjørn is overall more seaward. In turn this suggest that the Valemon-Kvitebjørn represent a setting that is less protected from waves than the more landward Martin Linge-Oseberg area. The 4 higher order sequences identified in the bay-head delta or crevasse sub delta successions are all slightly coarsening and shallowing upward, representing delta-front to top environments. However the higher order sequence set is overall aggrading. The overall aggrading nature signifies that the sediment supply is overall balanced with the relative sea level rise. The coal layer placed at the top of each higher order sequence indicates that a large amount of plant material is present at different times.

Two different scenarios can explain the Valemon-Kvitebjørn areas relation to the Martin Linge – Oseberg area. The Valemon-Kvitebjørn area could have a different smaller feeder system than the Martin Linge – Oseberg area, present on the western side of a major bay, instead of representing the seaward part of the larger Brent-delta situated over the Rungne sub-basin. The smaller feeder system is illustrated in figure 6-1a.

Above the bay-head delta or crevasse sub delta higher order sequences, a succession of tidal flats are present. Interpretive of whether Valemon-Kvitebjørn area has a separate feeder system, the tidal flat can easily be explained as tidal flats present at the sides of either a minor wave-dominated estuary, minor wave-dominated bay or the sides of the larger Brent delta. The scenario where the tidal flat is present on the sides of a minor wave-dominated estuary is illustrated in figure 6-1b.

On top of the tidal flat medium to coarse shoreface sand is present. Overall the shoreface sand is well sorted, and is reworked by waves. In the scenario with the separate feeder system, a wave-dominated estuary is interpreted to have formed. The coarser shoreface sands represents the barrier system, illustrated in figure 6-1c. The barrier would have moved as the sea level rose, or represent the remains of a barrier system due to retrogradational reworking as seen on the Dutch and Danish wash.

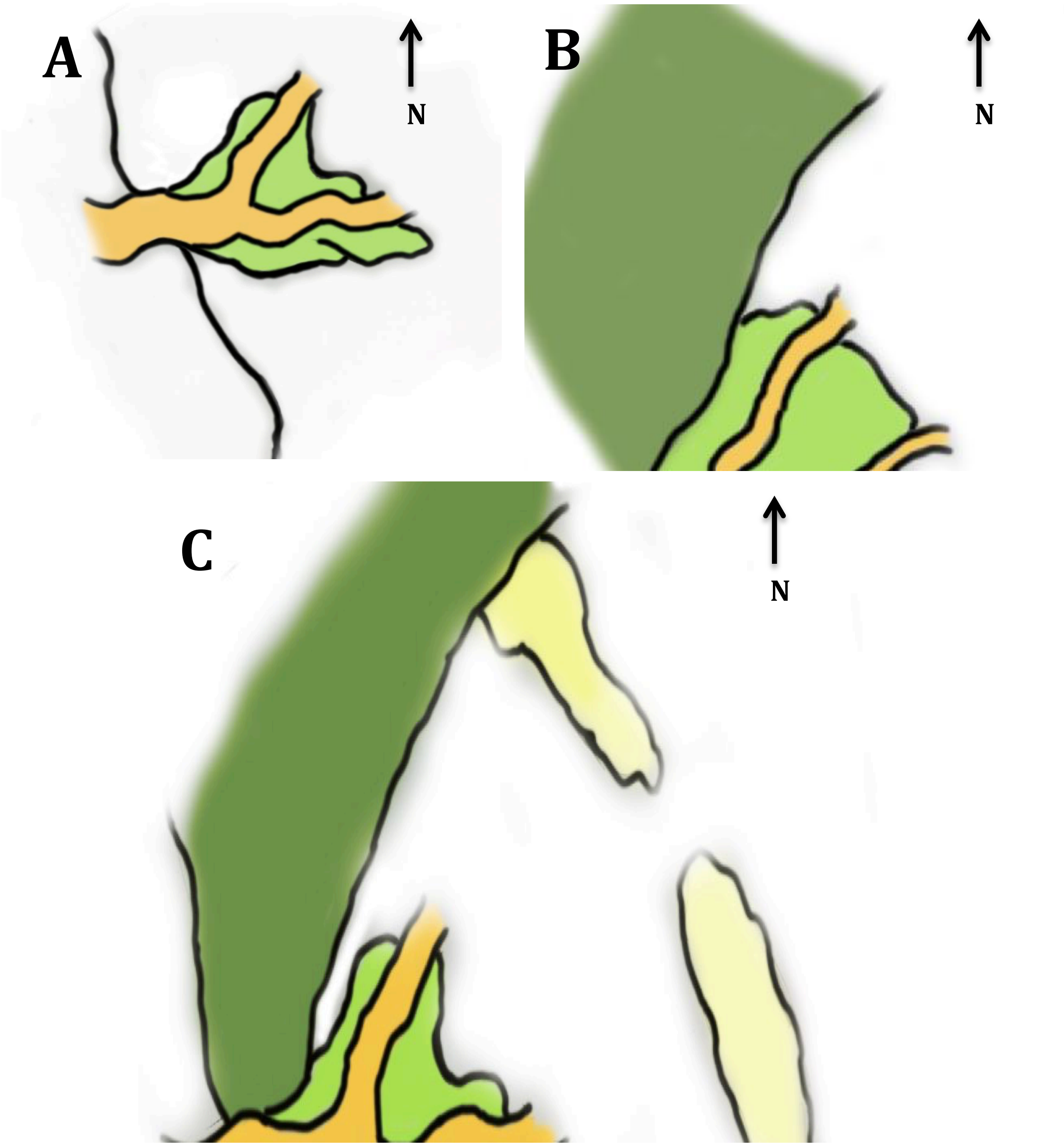


Figure 6-1. A seperate feeder system is inferred for the Valemon-Kvitebjørn area, including the three stage evolution of the system.

Another scenario could indicate that the Valemon-Kvitebjørn area is located behind a barrier, representing the bay or central part of a mixed-energy to wave-dominated estuary. A barrier or barrier lagoon would then be present seaward of the major Brent delta.

The scenario where the Valemon-Kvitebjørn area is located behind a barrier is considered less likely due to the wave-dominated nature of the bay-head delta or crevasse sub delta. The barrier would shield the area from wave processes if it were located behind the barrier.

6.3 From Martin Linge – Oseberg to Valemon- Kvitebjørn (south to north)

The Valemon- Kvitebjørn area is subdivided into a series of higher order sequences compared to the regressive and transgressive sequences in the Martin Linge-Oseberg area. The Martin Linge-Oseberg sequences can be divided into a higher order of sequences, however the number of sequences are not the same in the two areas. This poses as a challenge when correlating from south (Martin Linge-Oseberg) to north (Valemon-Kvitebjørn). To correlate the Valemon-Kvitebjørn and the Martin Linge-Oseberg areas, packages or strata with similar facies type or tracts have been correlated.

The aggrading bay-head delta successions in sequence I combined with the channel complexes present in the Martin Linge – Oseberg area (E-W southern correlation) have been correlated with similar aggrading units in the Valemon-Kvitebjørn area consisting of bay-head delta and crevasse sub delta successions, even though it lacks the channel-fills. Both the bay-head delta and crevasse sub delta successions and channel-fills in the Martin Linge-Oseberg west flanks are dominated by wave-generated structures, similar to the wave-dominated bay-head delta or crevasse sub delta present in the Valemon-Kvitebjørn area. The estuarine complex comprising the transgressive segment in sequence I is either not present (not deposited or eroded), or form parts of the estuary that is not present in the more seaward area part of the estuary.

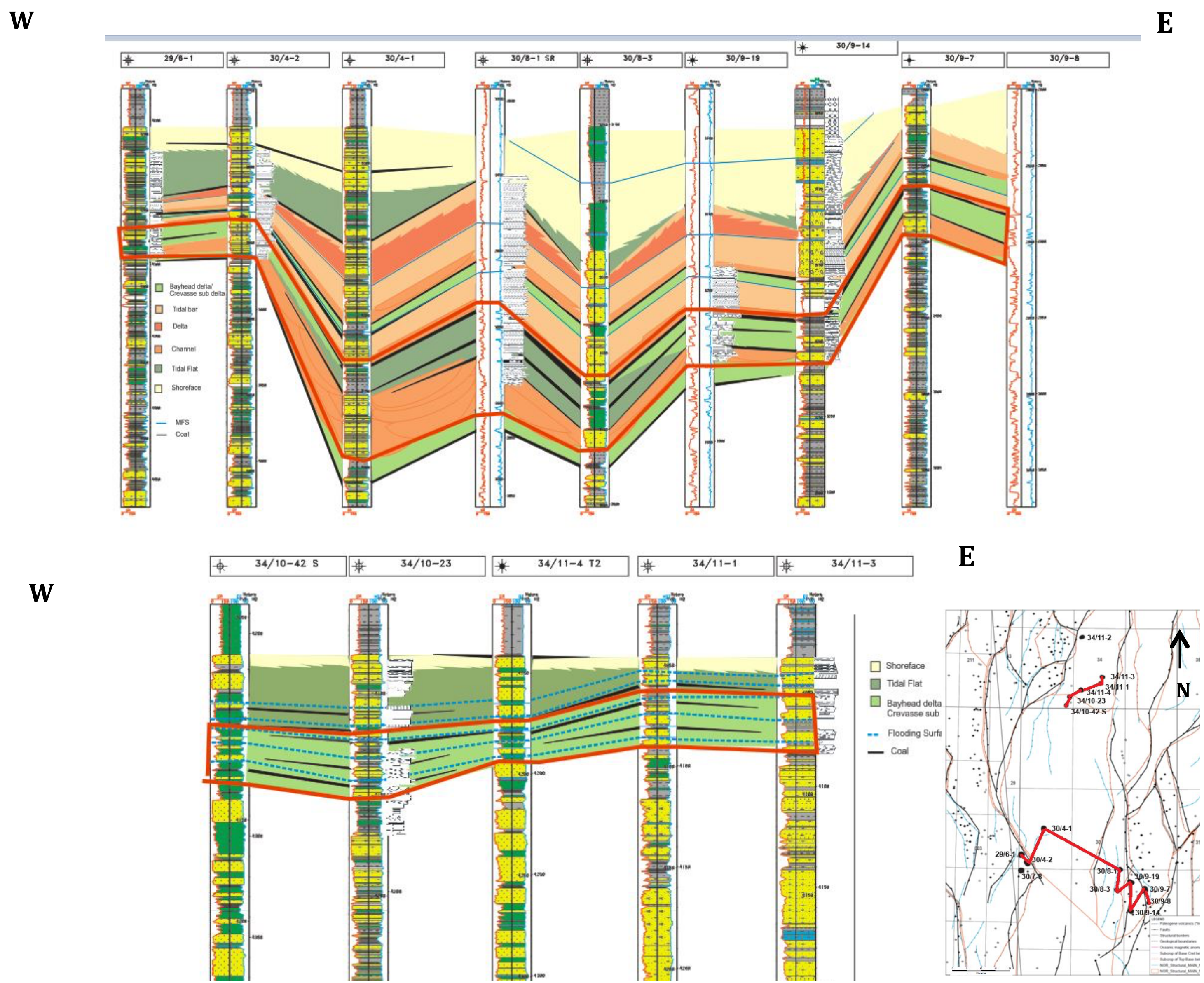


Figure 6-2. Approximately the same facies tracts (bay-head deltas) marked in red in the two correlations; subsequently they have been correlated together.

The tidal flat succession above the bay-head deltas or crevasse sub delta successions in the Valemoen- Kvitebjørn area is interpreted to correlate to similar tidal facies tracts in the Martin Linge – Oseberg area. Accordingly it is postulated to represent the lateral equivalents to the thick tide-dominated deltaic and estuarine succession in the Martin Linge - Oseberg west flank area. The upper estuarine complex is tide dominated, and is thinning out into tidal flats. It can be argued that the lower estuarine complex as well can be correlated towards the tidal flat succession in the Valemon-Kvitebjørn area due to the fact that both are tide dominated. The bay-head delta interlayed with the two estuarine complexes are similar to the bay-head delta or crevasse sub-deltas in the Valemon-Kvitebjørn, and subsequently the lower estuarine and the inter-layered bay-head deltas have been correlated against the lower bay-head deltas or crevasse sub deltas in the Valemon-Kvitebjørn area.

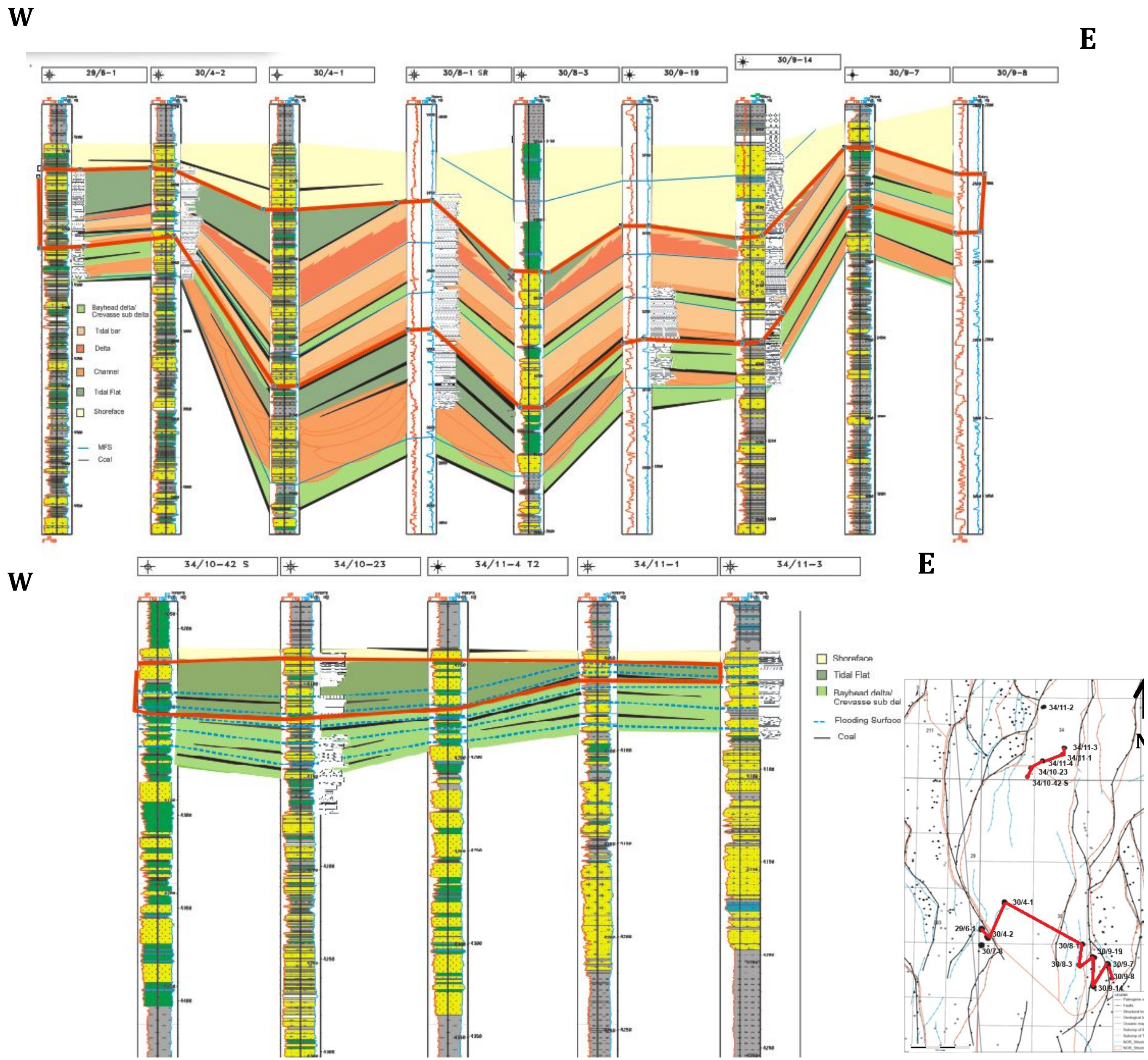


Figure 6-3. Approximately the same facies tracts (tidal flats) marked in red in the two correlations; subsequently they have been correlated together.

The shoreface deposits present above the tidal flat successions in the Martin Linge-Oseberg area is as well present above tidal flat successions in the Valemon-Kvitebjørn area. These shoreface deposits resemble each other as both are wave dominated. The lower coarse shoreface deposits in the Martin Linge-Oseberg area have been interpreted to be sand banks in an embayment due to some tidal influence. The coarser shoreface sediments in the Valemon-Kvitebjørn area has been interpreted to be part of a barrier system because of its reworked character. The finer shoreface sediments are similar in both the Martin Linge-Oseberg area and the Valemon-Kvitebjørn area and have been interpreted to be part of the same shoreline systems.

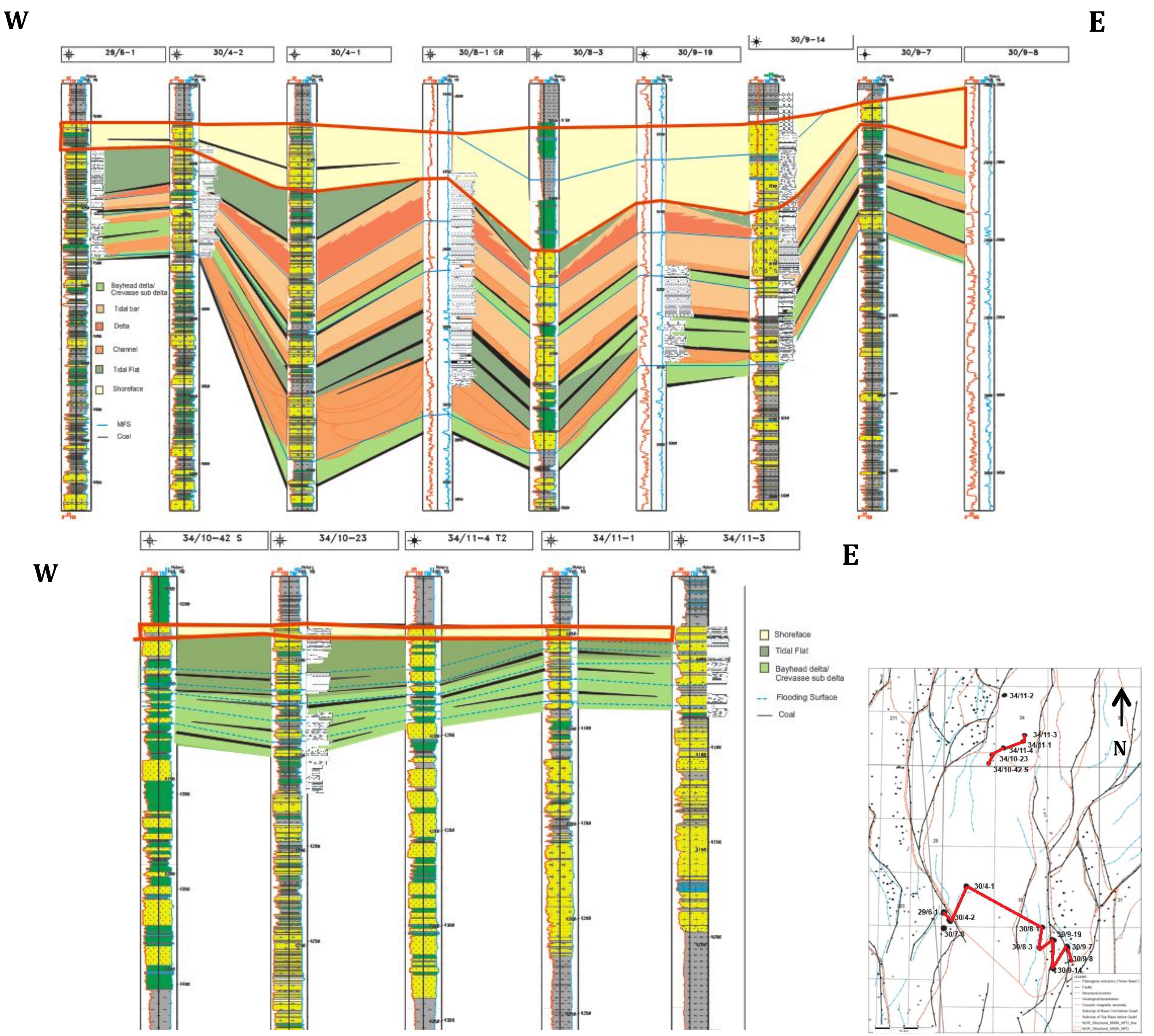


Figure 6-4. Approximately the same facies tracts (shoreface) marked in red in the two correlations; subsequently they have been correlated together.

Figure 6-5 illustrates the correlation between the Martin Linge – Oseberg western flanks in the south and the Valemon-Kvitebjørn area in the north. The bay-head deltas in the Martin Linge-Oseberg area is correlated with the bay-head deltas or crevasse sub deltas in the Valemon-Kvitebjørn area. The lower estuarine complex is thinning out and is not present in the Valemon-Kvitebjørn area. The upper estuarine complex as well as the tidal-delta successions is interpreted to thin out into tidal flats from south to north. The tidal flats are present on structural heights, implying that Valemon-Kvitebjørn is located further seawards at the sides of the larger estuary, and might be present on a terrace not as affected by faulting as the Martin Linge-Oseberg area. The shoreface deposits are similar in the Martin Linge-Oseberg area and the Valemon-Kvitebjørn area. In the Valemon-Kvitebjørn area the coarse shoreface sediments have been interpreted to be part of a barrier, which translates laterally into a shoreline system. This seems probable because of the location of the Valemon-Kvitebjørn, more seaward and subsequently more wave-dominated. In the Martin-Linge Oseberg area the coarser sediment is interpreted to be sand banks formed in an embayment, which are both tide and wave dominated. The sandbanks transitions into a shoreline similar to the one in the Valemon-Kvitebjørn area.

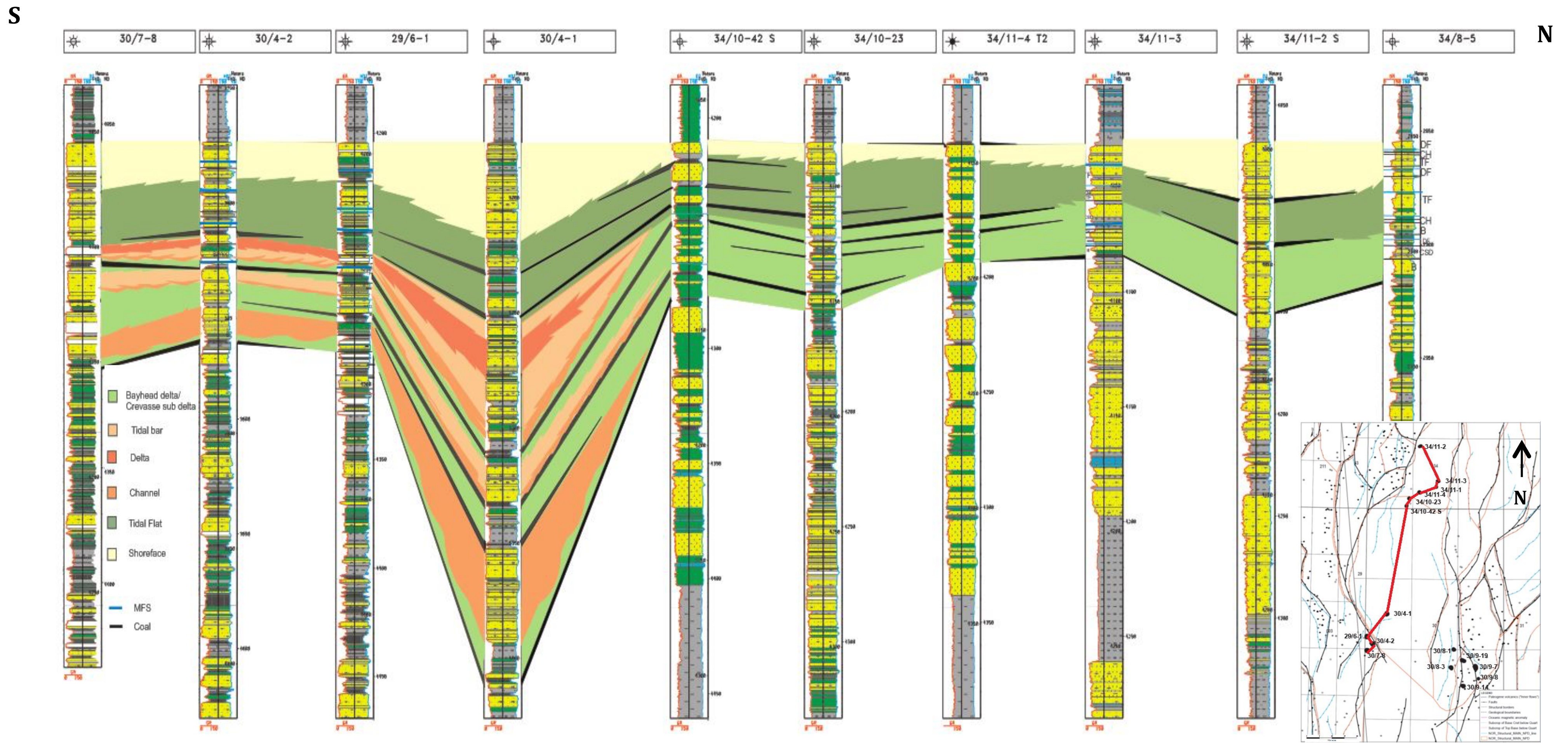


Figure 6-5. Correlation from the southern Martin Linge-Oseberg west flank to the Northern Valemon-Kvitebjørn area.

6.4 From wave-dominance to tide-dominance and back

Yoshida et al. (2004) proposes three different models to explain the transition from a wave influenced delta or estuary to a tide dominated delta or estuary, and for a tide dominated delta or estuary to transition into a wave-dominated delta or estuary. The Tarbert Formation has been interpreted to be a mixed energy-dominated system in the southern Martin Linge - Oseberg area, which transitions from being wave-dominated to being tide dominated and back to being wave-dominated.

Model 1

Model 1 contains a constant mixed-energy setting where wave energy decreases toward the distributary mouths, and where tidal energy increases towards the distributary mouths in the regressive phase as can be seen in figure 6-6a. In the transgressive phase the tidal energy is increasing towards the tidal bars or dunes in the inner part of the estuary bordered by sand banks in a marine estuary. The wave energy is caught by sand banks in the marine embayment, as can be seen in figure 6-6b (Yoshida et al. 2004).

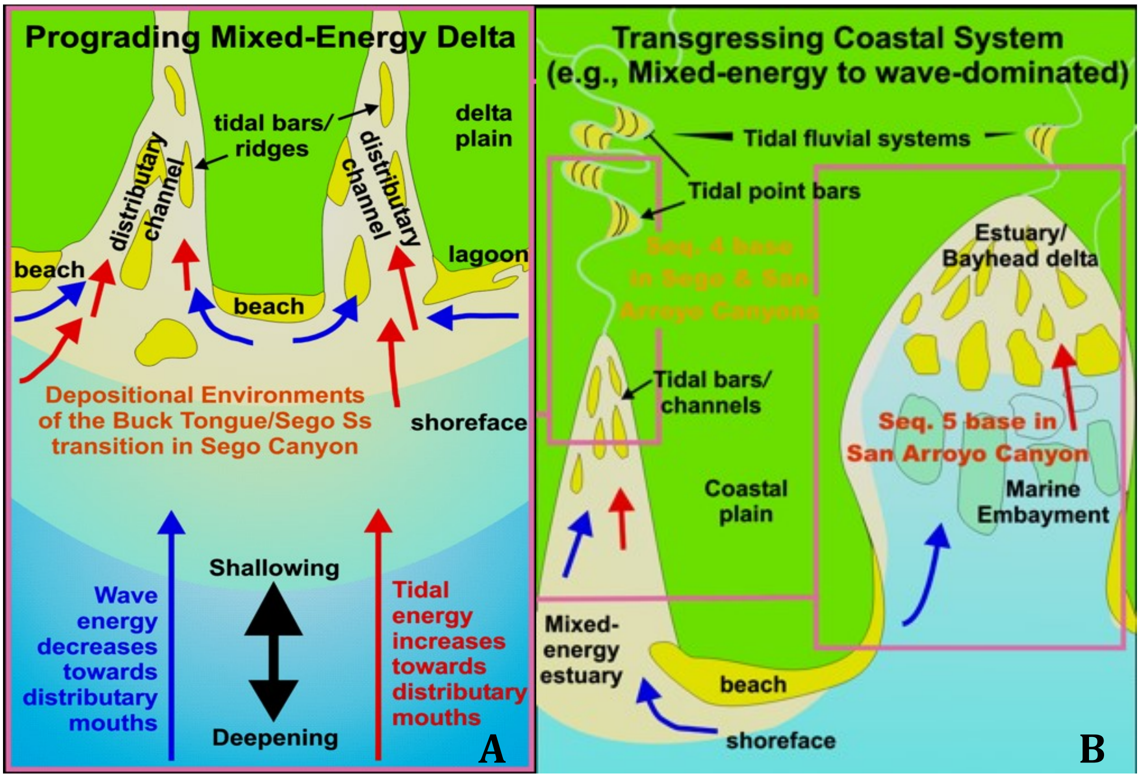


Figure 6-6: The tidal and wave energy present the regressive delta (A) and the transgressive estuary (B) (Yoshida, et al 2004)

If model I is applied on the Tarbert Formation, the regressive segment in sequence I, II and the aggrading segment in sequence I would coincide with the prograding mixed-energy delta which is both wave and tide influenced as seen in figure 6-6b. In such a scenario the transgressive estuarine parts in sequence I and II correspond to the inner tide dominated tidal bars or dunes seen in figure 6-6b. The regressive delta in sequence III correspond to the tide dominated delta in figure 6-6a. The shoreline deposits in the transgressive segment in sequence III correspond to the wave-dominated outer part of the estuary in figure 6-6b.

The Tarbert Formation is accordingly interpreted in form of a prograding wave and tide dominated delta (regressive segment, sequence I), which evolved stratigraphically into a tide-dominated estuary. During the subsequent regression in sequence II the delta built out and aggraded as a tide influenced bay-head delta. The subsequent transgression brought to a tide-dominated estuary. In sequence III a tide-dominated delta built out again, followed by a transgression with the return of a tide-influenced estuary or tidal flat successions. As the transgression continued sand banks in a marine embayment formed and shoreline sediments were deposited in a wave-dominated embayment.

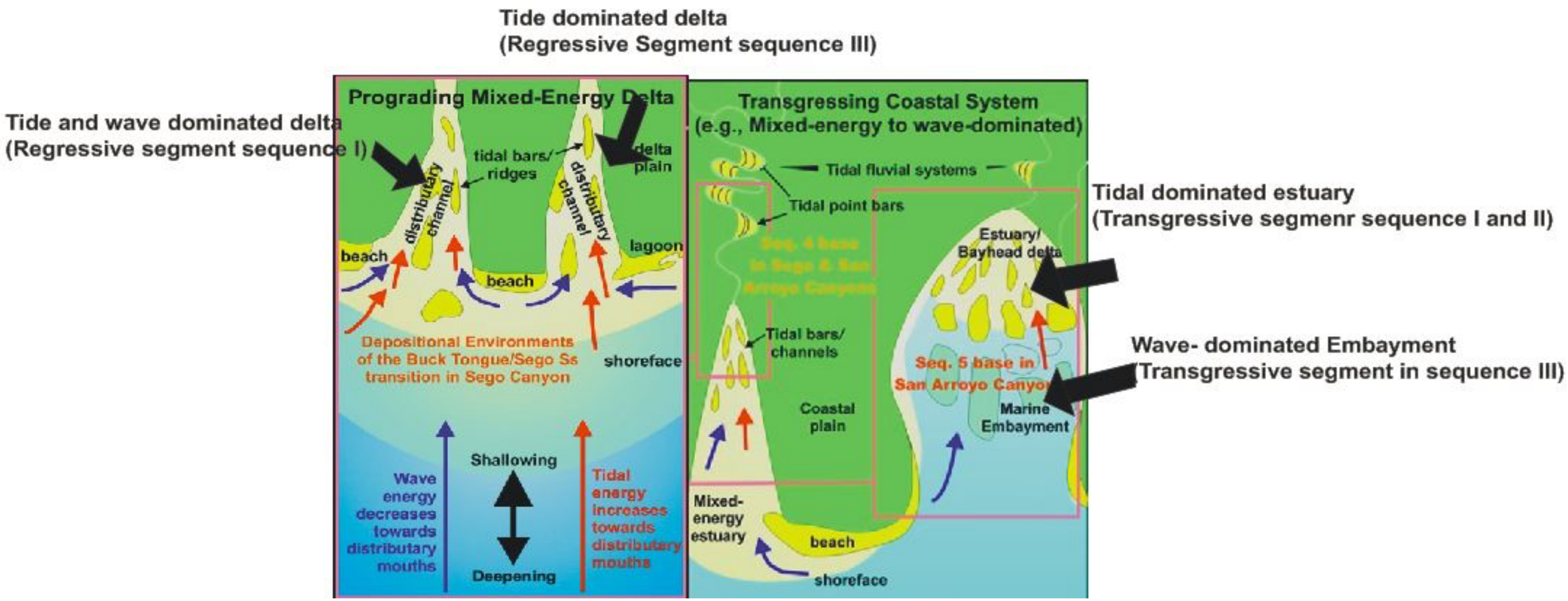


Figure 6-7. The Tarbert Formation interpreted in this thesis explained by model I (Yoshida et al. 2004).

Model 2

The second model by Yoshida and co-workers (2004) proposes a gradual change of regional costal processes from wave-domination to mixed energy to possibly tide-domination, with different basinal energy regimes partitioned by specific parts of the sequence development, i.e system tracts. The wave-dominated sediments will be deposited in the highstand system tract (HST), the mixed-energy dominated sediments will be deposited in forced regression system tract (FRST) to the lowstand system tract (LST) and possible tide dominated sediments will be deposited in the LST. The highstand system tract (HST) forms when the sediment accommodation exceeds the rate of relative sea-level rise (Vail, 1987). The LST includes deposits that accumulate from the onset of coastal transgression until the time of maximum transgression (Vail, 1987). The FRST or falling stage system tract (FSST) implies that a forced regression takes place due to the falling sea level (Plint and Nummedal, 2000).

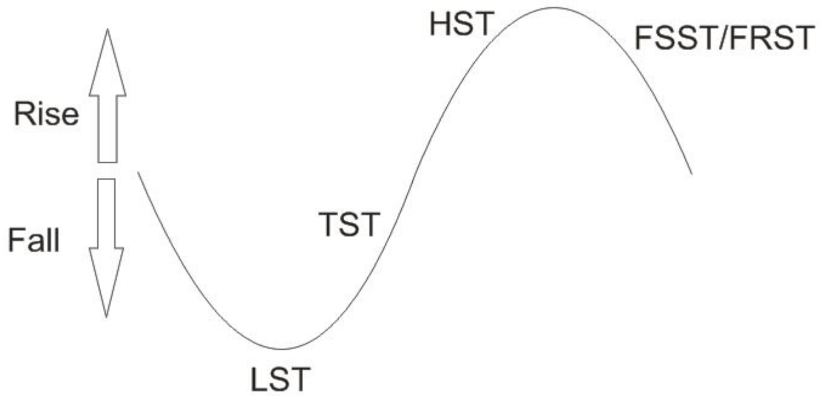


Figure 6-8. Sea level curve with the location of the LST, TST, HST and FSST/FRST.

The Tarbert Formation is developed in the alternating highstand systems (HST) tracts and in the transgressive system tract (TST). However, the Tarbert Formation is interpreted to have been deposited in a mixed-energy system, changing from wave-dominated, to a tide dominated system, and back to a wave-dominated system. Because waves and tides are present both in the HST and TST the model can partially correspond with the Tarbert Formation.

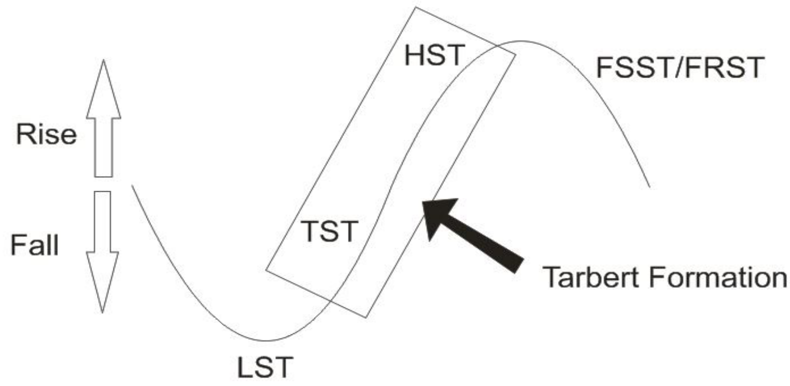


Figure 6-9. Sea level curve showing in which system tracts the Tarbert Formation is deposited in.

Model 3

One of the models proposes a product change because of change in availability in grain size (Yoshida et al., 2004). In the Tarbert Formation there is no fundament to argue this.

6.5 Controls on formation, location and implications.

Ravnås et al., 1997 argues that the uppermost Ness Formation, Tarbert Formation and Heather Formation represent the initiation of an early phase of Middle Jurassic rifting. During the deposition of the uppermost Ness Formation gentle rotational extension faulting, which resulted in basin floor subsidence and flooding across the Brent delta occurred. Progradation is interpreted to occur during repetitive tectonic dormant stages, while the successive transgressive segments interpreted are coupled against intervening periods with higher rates of rotational faulting and overall basinal subsidence (Ravnås et al., 1997). In contrary Løseth and co-workers (2009) argues that their wedge 1 or sequence I was deposited before the main phase of rift initiation and rotational faulting. Accordingly the main-rifting and fault-block rotation commenced in the deposition of their sequence II (Løseth et al., 2009). Løseth and co-workers (2009) suggest that the expansion of the estuarine channels is due to differential subsidence accommodated by non-rotational displacement of the main fault. Fault activity can be seen prior to the main phase of initial rifting due to thermally driven post-rift/pre-rift subsidence (Løseth et al., 2009).

Overall the Tarbert Formation in this thesis is significantly expanded in the Rungne sub-basin. The channel complex in sequence I is significantly thicker in wells 30/4-1 and 30/8-1. Between well 30/4-2 and 30/4-1 the western Viking Graben boundary fault is located, marking the boundary fault to the Central Viking Graben. The fault was most likely active during the deposition of the channel complex, due to the significant thickening. Helland-Hansen (1992) and Ravnås and co-workers (1997) demonstrated uplift of the Oseberg fault block at the same time as subsidence in the basin. Subsidence alone cannot explain the thinning out of the sediments towards the terraces, implying that some rotations of the fault blocks did occur.

In wells 30/4-1, 30/8-1 and 30/8-3 above the channel complex tidal flat successions or tidal-infill were deposited. Along the graben, i.e. the Martin Linge and the western flanks of the Oseberg area bay-head delta succession are present, implying a lateral facies shift. Both the tidal flat successions and the bay-head delta units are aggrading. The tidal flat successions or tidal in-fill are present along the Oseberg west flank inferred to occupy the portion between the deltaic systems.

The lower estuarine complex has a constant thickness in the Rungne sub-basin, and is thinning out on the Martin Linge terrace and on the flanks of the western Oseberg terrace, implying subsidence in the Rungne sub-basin, as well as some rotation of the western Viking Graben boundary fault and the Oseberg fault.

In addition there is a stratigraphic change from a wave-dominated deltaic setting to a more tide-dominated estuary. Active faulting can cause a change from straight to by a change from a open to more protected coast. In such a scenario the coast will change from wave to tide dominance.

The upper estuarine complex and tidal delta show variable thickness, implying that additional faults were active during the deposition. The active faulting resulted in rotational faulting and uplift of fault-blocks. Tidal flat strata appear more common in uplifted parts of fault, as seen in wells 30/8-3 and 30/9-14, in addition to the Martin Linge terrace. Tidal flat can as well have formed on the western Oseberg terrace, and then later been eroded.

Overall the thickness expansion into the Rungne-sub basin is overall constant, implying a constant rate of faulting. The variable thicknesses seen in Rungne sub-basin in the upper estuarine complex is most likely due to more active faults.

In this thesis the channel complex in sequence I demonstrate a similar expansion as the estuarine channels l in in Løseth and co-workers study (2009). The similar expansion could imply that a likewise non-rotational displacement occurred during deposition of the channel complex. If fault displacement is the controlling mechanism for the expansion of the channel the theory where Ravnås and co-workers propose that the rifting started in the uppermost Ness Formation is probable.

The delta and estuarine complex interpreted in sequence III in this thesis, which Løseth and co-workers (2009) interprets as estuarine channels has a similar thickness expansion as the estuarine channels interpreted by Løseth et al. (2009). The expansion in this thesis have minor differences with Løseth et al. (2009), mainly because more wells are taken into consideration in this thesis. In this thesis the estuarine complex of sequence III is thicker in structural lows, while tidal flat successions are present on structural highs and absent in structural lows. The structural lows are occupied by laterally estuarine tidal bar or dunes. This would accommodate a model where the basin at one stage was broad, and became narrower as the tectonic activity was present. Examples where lateral thickness variation is caused by fault induced differential subsidence includes the early syn-rift tidal embayment in the Hammam Faurn Fault block of the Miocene Suez rift (Carr et al., 2003; Jackson et al., 2005; Løseth et al., 2009) and in an Eocene estuarine system in the Seymour Island in Antarctica (Porebski, 2000; Løseth et al., 2009)

Fluctuations in relative sea level are not favorable as a valiable explanation for the thickness expansion due to the large variability in thicknesses and associated facies portioning. The main cause for the expanded Tarbert Formation is likely faulting and rotational faulting. Helland Hansen (1992) and Ravnås and co-workers (1997) argue that the limited faulting was initiated in the Upper Ness or the transition from Upper Ness to Tarbert Formation.

6.6 Reservoir architecture and predicted stratigraphy of the Upper Brent in the Central Viking Graben

Tidal dunes or tidal bars are interpreted to be present in the Upper Brent in the Central Viking Graben, in addition to sandbanks formed in a marine embayment. Sand that migrates under strong tidal regimes can stack together in two ways: through forward migration or through lateral migration. Forward migration form tidal dunes, while lateral migration form tidal bars (Dalrymple, 1984; Dalrymple and Rhodes, 1995; Snedden and Dalrymple, 1999; Berne et al., 2002; Dalrymple and Choi, 2007; Wei et al., 2016). Wei et al., (2016) argue that tidal bars are characterized by a channelized base and by a fining and thinning upward trend as described by Dalrymple and Rhodes (1995) in tidal bars in Cobequid Bay and Bay of Fundy. Furthermore, a tidal bar complex should show a significant increase in of tidal dunes scale in response to widen channels in the outer estuary. A decrease of fluvial influence and an increase in marine influence should follow. The tidal dunes or bars interpreted in this thesis have channelized bars and an overall fining and thinning upward trend, even though most of the smaller units have a coarsening upward trend. These characteristics correspond to Wei & co-workers (2016) description of tidal bars. However, fining upward units of fluvial origin are also interpreted in this thesis. This is more evident in the upper estuarine complex where a thicker delta succession is present at the base of sequence III. In this part the tide-dominated bars are attributed to the delta-front of a tide dominated delta. This would imply that tidal dunes with less fluvial influence, i.e influenced by marine processes are present further seaward/to the north of the deltaic tidal bar succession interpreted in this thesis. The tidal dunes present more seaward/to the north of the tidal bars would migrate forward. These tidal bars may be amalgamated and have formed sand ridges, which would be favorable for a reservoir in the Central Viking Graben.

Sand banks formed in an embayment have been interpreted above the estuarine complexes, in a transition between the estuary and an embayment. These sand banks can as well, be present further seaward/towards the north.

Towards the south distributary channels and fluvial channels delivering sediments to the deltaic and estuarine successions are expected. These would also form reservoir units, likely as broad, multilateral to multistory channel complexes, as well as isolated channel-fills. Channal complexs appear common within successions representing the main axial Brent-delta systems, where as single channel-fills become more common in the smaller transverse systems.

6.7 Reservoir properties/qualities of the Upper Brent in the Central Viking Graben

The sandstones in the Brent Group are primarily of sublithic-arentite composition, even though they have been modified during diagenesis. The principle cements present includes quartz, kaolinite, illinite and calcite (Daws, 1992). The Brent Groups prospectively in the deeper parts of the Northern Viking Graben is dependent on reservoir quality mechanism such as chlorite and illite mineral coats, or early charge to prevent cementation, which would obliterate the porosity and permeability. Norske Shell A/S studies on the Halten Terrace have shown that the formation of mineral coats as a means for reservoir property preservation is dependent on facies and a set of depositional conditions. The present re-evaluation of facies and depositional elements present in this thesis could form a base for a new look at facies control on reservoir properties within the Tarbert Formation in deeply buried settings.

6.8 Modern analogues

The Gironde estuary is a modern analogue of a mixed energy estuary containing tidal bars and channels (Yoshida et al., 2004).

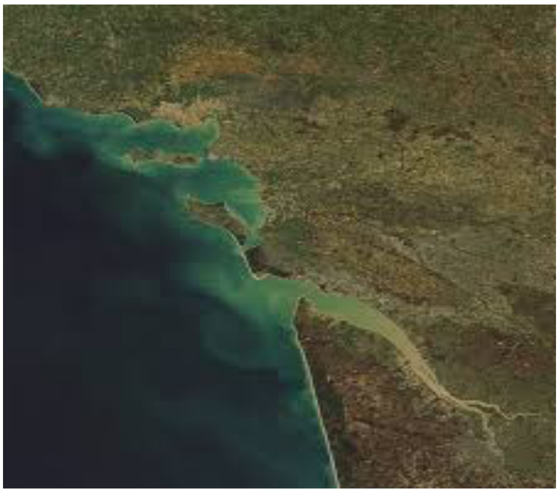


Figure 6-11. The Gironde estuary (Yoshida et al.)

The Wash estuary is a modern analogue of an estuary with a bay-head delta, tidal bars and a marine embayment (Yoshida et al., 2004).

Figure 6-12. The Wash estuary (Yoshida et al., 2004)

The German bight is a tide-dominated estuary with extensive tidal flats that displays lateral transitions into a wave-dominated barrier system along the western Danish and northern Dutch coasts. Mixed energy coastlines are present in-between. This area is inferred to represent a viable modern analog for the tide dominated Middle Tarbert Formation as interpreted in this thesis.

Figure 6-13. The German Bight (Hoogan, 2011)

The Bay of Fundy contains tidal bars (Dalrymple and Rhodes, 1995; Wei et al., 2016). that may be analogues to the tidal bars in the Brent delta, if it contains tidal bars and not tidal dunes.

Figur 6-14. The Bay of Fundy (Dalrymple et al., 2006)

The San Francisco bay contains tidal dunes that form san ridges (Olariu and Steel, 2006), which can be an analogue to eventual sand dunes in the Brent Delta.

Figure 6-15. The San Fransisco bay. (Sanger and Hart, 2003)

6.9 Further Work

Recommended further work would include using biostratigraphy to correlate the southern well 30/10-6, which contains an expanded Tarbert Formation with the wells 30/4-1, 34/10-42 S, 34/10-23, 34/11-4 T2, 34/11-3, 34/11-2 S, 34/8-5 for a north south correlation.

7. Conclusion

The Tarbert Formation has been studied in wells from the Martin Linge, Oseberg, Kvitebjørn and Valemon fields, i.e on terraces surrounding the Rungne sub-basin. A total of 720 meters of cores have been interpreted that form the basis for this thesis.

14 facies were identified in the Tarbert Formation in the northern Viking Graben based on lithology, grain size, character of bed boundaries, bed thickness, texture, sedimentary structures and degree of bioturbation. The 14 facies were combined to produce 11 facies associations with 9 depositional elements, covering the progradational deltaic and the retrogradational estuarine parts of the Tarbert shoreline prisms. Based on the facies associations, depositional elements, stacking patterns and sequence stratigraphic surfaces (maximum flooding surfaces, flooding surfaces and maximum regressive surfaces) three correlation profiles have been produced. One from west to east in the southern area (Martin Linge - Oseberg), another from east to west, but in the northern area (Valemon-Kvitebjørn) and one from south to north (Martin Linge –Oseberg to Valemon-Kvitebjørn)

Three genetic sequences were recognized in the Martin Linge-Oseberg area, each consisting of a regressive and transgressive segment. The genetic sequences are bounded at their base and top by maximum flooding surfaces. The maximum regressive surface is present at the transition from the regressive to the transgressive segment. In the Valemon-Kvitebjørn 6 higher-order sequences were recognized, where the 4 lower sequences define an overall aggrading to retrogradational stacking pattern. The upper two sequences are more transgressive. In the Martin Linge - Oseberg area the 3 genetic sequences can be divided into a series of higher order of sequences as well, but the number of sequences are different in the two areas. Subsequently packages or strata of approximately same facies type or tract was used to correlate from the southern Martin Linge-Oseberg area to the northern Valemon-Kvitebjørn area.

The study areas were interpreted to have different feeder systems. The Tarbert Formation is overall transgressive, with a high portion of estuarine and transgressive shoreline strata in all of the study areas.

Valemon-Kvitebjørn is identified as a wave dominated estuary located in the seaward part of a large embayment. The Martin Linge-Oseberg area was interpreted as a mixed energy-dominated delta and estuary, shifting back and forth from wave to tidal dominance, and from regressive to transgressive segments. The lower progradational delta in sequence I was identified as wave dominated. The estuary and delta successions in sequence II and III were all recognized as tide dominated. The transgressive shoreline successions in sequence III was identified as wave dominated. The Martin Linge-Oserberg is interpreted to have been located more landward in the same large embayment as the Valemon-Kvitebjørn area.

Due to the significant expansion of the Tarbert Formation in the southern part of the Rungne sub-basin, syn-depositional fault activity is argued to have exerted a major control on the stratigraphic architecture. Because the expansion can be noticed as early as in the Lower Tarbert Formation, the initial faulting most likely started before the Tarbert Formation was deposited. More faults became active later during the deposition of the Tarbert Formation, causing the variable thickness and facies shift in the Middle and Upper Tarbert.

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