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The Lower Brent Group Stratigraphy, Reservoir Architecture and Reservoirs Qualities in The Deep Northern Viking Graben

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Master Thesis:

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A special thanks to Hilde Camilla Mari Sæther, because without you I could not have done this! Finally I would thank my family and boyfriend for their support and love.

Abstract

This thesis will give a detailed description of the stratigraphy, reservoir architecture and reservoir qualities of the Lower Brent Group (Oseberg, Rannoch, Etive and Lower Ness formations) in the deep northern Viking Graben. Core descriptions and well logs from Valemon –Kvitebjørn, Huldra and Oseberg field are used to characterize 19 faceis, 10 facies association, 6 depositional systems, and 2 sequences of the Lower Brent Group in order to assess the factors that control their distribution within the Rungne sub-basin. The Brent delta is interpreted to be of mixed tide and wave influence, because of the abundance of double and single mud draps and tidal bundles in the Rannoch Formation and estuarine deposits in the Etive Formation. Transition form an exposed wave dominated shoreline into an embayed tide dominated shoreline is documented. The Oseberg formation is interpreted to be a part of the main Brent system, based on the lateral interfingering of the Rannoch Formation, indicating that the Oseberg delta was still active in the Oseberg field during deposition of Rannoch formation. Due to thickness change in the Lower Brent group and facies change; from wave influenced shoreline to wave and tide dominated shoreline in the Rannoch formation fault activity is identified.

Table of Content:

List of Figures:

List of tables:

The Lower Brent Group Stratigraphy, Reservoir Architecture and Reservoirs Qualities

in The Deep Northern Viking Graben

1.0 Introduction:

1.1 Background and problem

Since the discovery of the Brent Field by Shell in June 1971 (M. P. Coward et al., 2003), the Brent Group has been the most prolific reservoir unit in the Northern North Sea only in some fields outnumbered by similar-type Upper Triassic and Lower Jurassic reservoirs. The Brent Group has received considerable attention and more than 200 papers have been published on aspects of the stratigraphy, structure sedimentology and oil field geology (Husmo, et al., 2003, Mitchener, et al., 1992, Fjellanger, et al., 1996). There have been significant achievements made in the gross sedimentary structure and internal architecture of the Brent group (Husmo et al., 2003, Mitchener, et al., 1992, Underhill and Partington 1995, Olsen and Steel 95).

The Brent Group was argued to form parts of two megasequences (Steel, 1993) where the Broom and Oseberg Formations where defined as one megasequence while the Rannoch Formation to Tabert Formation comprices the other megasequece. The Oseberg and Broom Formations were argued to represent fan deltaic deposits stratigraphically underlying the regressive RENT-delta system.

The lower Brent Group is argued to be a regressive wave dominated delta. The wave dominated delta show indications of more tidally influenced to dominancy, with mud drapes and double mud drapes. The tide influenced intervals are also too thick to be part of a wave dominated delta. There is also an increasing number of estuarine strata which is somewhat problematic in this context, although it is congruent with the interpretation of the mid-Ness ‘shale’ as marine flooding within the central Ness Fm. There has also been published new articles with increased information about tide dominated delta. This interpretation and the new knowledge of tide dominated deltas makes it necessary with a new look at the Lower Brent Group.

Secondly, there are observations suggesting that the coarse-grained facies normally assigned to the Broom-Oseberg formations appear to interfinger laterally with Rannoch-Etive formations within the deeper parts of the northern North sea rift system. In the Oseberg Formation there are also indications of tidal influence. This indicates a much more complex Brent Group basin-fill architecture than recognized in previous studies focused on and along the bordering terraces and platform areas. This suggest the need for new look also at the basal part of the Brent Group. The data will then be used to further prediction and risk mitigation of reservoir potential of the deep targets of the central part of the Northern North Sea rift-system.

1.2 Aim of study

This thesis will focus on providing a detailed stratigraphic framework over the lower Brent Group in an around the central parts of the Northern Viking Graben, more specific the Rungne Sub-basin. The aim of the study will be to get a better understanding of the lower Brent group by interpreting and using different sets of data such as core and well log data. There are three main questions to be answered:

- Is the Oseberg Formation recording a transition from fan deltaic/braid-plain deltaic conditions into a braid-plain delivery system feeding the frontal Rannoch-Etive deltas and shorelines?
- Are the tidal reservoirs in the lower part of the Brent Group controlled by scale, i.e. can they be associated with similar deltaic (regressive) or estuarine (transgressive) conditions of higher-order cyclicity within the overall, lower-order regressive (lower Brent) setting, or is there a turnaround into overall lower-order transgressive conditions within the lower-to-mid Ness interval?
- Were changes in basin physiographies a response to local shoreline bathymetry undulations induced by the confluence of multiple feeder systems (e.g. westerly,

southerly and easterly derived deltas) instead of changes in tectonic background activity (e.g Folkestad et al., 2014)?

1.3Previous work

In the over 200 published papers on Brent Group there is described the advance of the Brent Group, sequence stratigraphy and tectonic influence on the Brent Group. Graue and coworkers (1986) and Helland-Hansen with coworkers (1995) gives a detailed description of the advance and retreat of the Brent delta. Sequence stratigraphy of the Brent Group is discussed by Michener and coworkers (1992) and Johannessen and coworkers (1995). Folkestad and coworkers (2014) and Olsen and Steel (1995) has discus the tectonic influence of the Brent Group. Most of the published papers on the Brent group is written over a short time period. Because of new articles with increased information and knowledge about tide dominated deltas it's time to take a new look at the Brent delta.

1.4 Deliverables

- A core description of the Lower Brent Group (Oseberg, Rannoch, Etiv and Lower Ness Formation) from 13 core samples.
- Detailed well interpretation, interpreted in facies and correlated.

2 Geological frame work

2.1 Study area

The Brent Province is located in the Northern North Sea, more specific the East Shetland Basin, the North Viking Graben and over parts of the Horda Platform. The province is named by the proses of the middle Jurassic Brent Group reservoirs which constitute the single most prolific reservoir unit in the Northern North Sea. In Horda platform, the Oseberg Formation forms the basal point coherence the bottom formation is the equivalent unit of the East Shetland basin/East Shetland platform of the Brent Group (NPD publications, 2014). The lithostratigraphy of the Brent group is divided into of six formations, which from the base upwards are Broom, Oseberg, Rannoch, Etive, Ness and Tarbert. (Graue et al., 1987, Helland Hansen et al., 1992). The Oseberg and Broom formations are interpret to represent lateral infill from the Norwegian and UK hinterlands, where the remaining units represent a widespread axial delta complex (Michener et al., 1992, Helland-Hansen et al., 1992). This study will focus on the lower Brent Group (Oseberg, Rannoch, Etive and lower Ness) in the Norwegian sector of the Northern North Sea, more specific the Gullfaks, Valemon, Kvitebjørn, Oseberg-Tune and in the Fram areas. The area encompasses Norwegian Block 34/10, 34/11, 30/3, 30/2, 30/6 and 30/9.

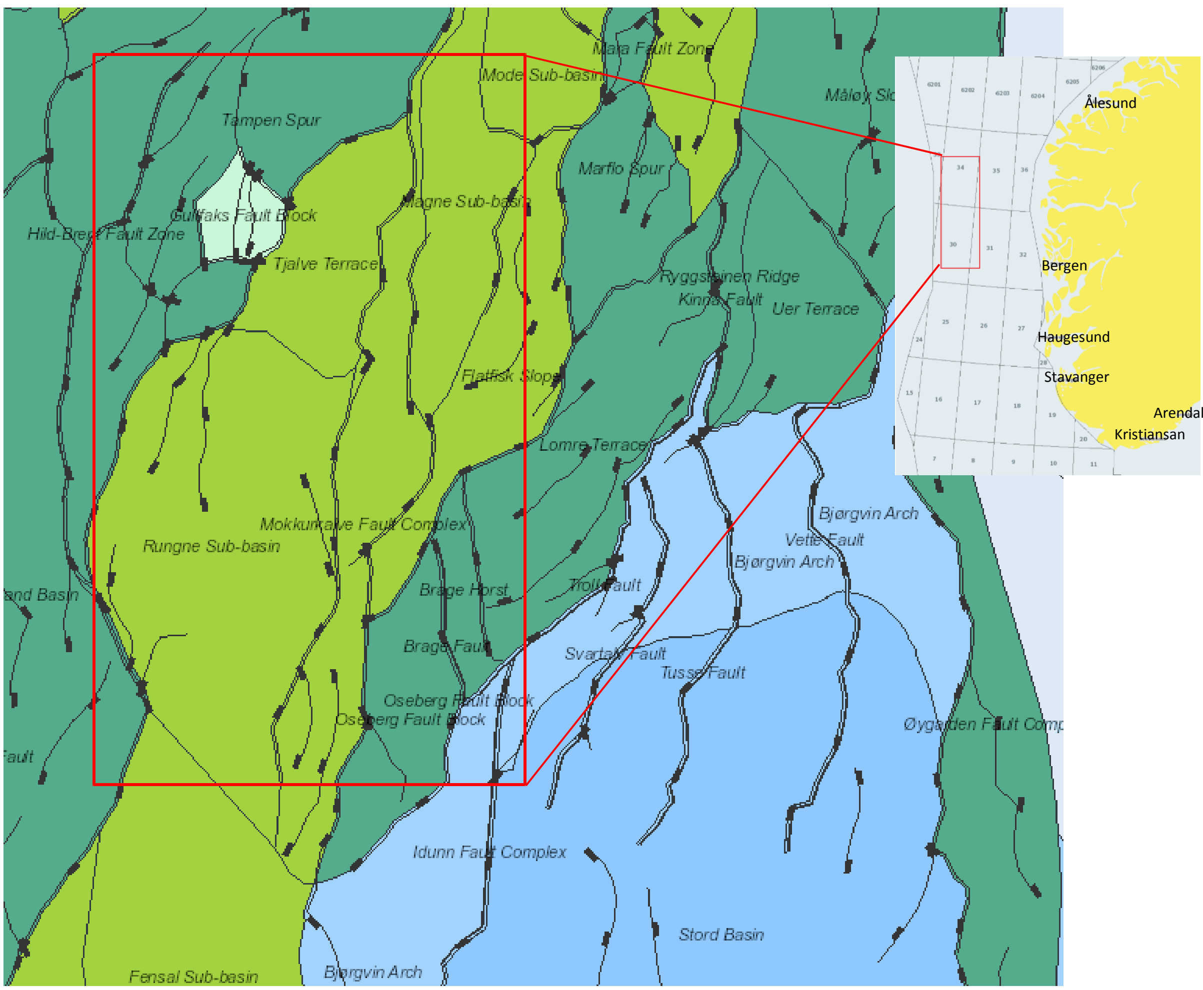


Figure 2.1: Location map, with structural elements, of the Northern North Sea, zoomed in on Rungne sub basin.

2.2 Tectonic settings

The basic structural framework of the North Sea is the result of several tectonic rifting events. There was two main rifting episodes the first occurred in the Permian to Early Triassic and the second was in Middle Jurassic to Early Cretaceous (NPD publications, 2014).

In the Paleozoic the tectonic framework developed in three main convergent tectonic episodes (McKerrow et al, 2000): The Ordovician Orogeny from about 460 to 450 Ma, the Devonian Orogeny around 400 Ma and the Variscan/Appalachian Orogeny from 400 to 300 Ma. This events can be divided into two accretionary events the Caledonian and Variscan Mountain building events (Coward et al., 2003).

The basement of the Northern Seas consist of an extensionally thinned continental crust representing the eroded and stretched Pre Cambrian to Caledonide basement (Coward et al., 2003, Badley et al., 1998). Mesozoic basin floor, eroded from the mountains formed in the Paleozoic (Olsen and Steel, 1995). The pre Triassic history s poorly known in the Northern North Sea, hence will not be further discussed.

The middle to late Jurassic was an interval dominated by post-rift subsidence continued post-rift subsidence after. Early Jurassic is marked by a widespread marine transgression from north and south that eventually flooded the Triassic basin (Coward, et al 2003). In the late-Early to early-Middle Jurassic volcanic doming caused uplift and erosion over the Central North Sea which followed by rifting. In the late-Middle to Late Jurassic large deltaic systems containing sand, shale and coal were developed in the northern North Sea and the Horda Platform (Brent Group) (NPD publications, 2014). The second rifting episode took place in the North Sea area during the Late Jurassic and lasted into the Early Cretaceous, forming the present-day fault-block structures (Løseth and Ryseth, 2003). During this tectonic episode, major block faulting caused uplift and tilting, creating considerable local topography with erosion and sediment supply. In the Cretaceous rifting ceased and was followed by fast thermal subsidence. This led to deep burial of the Jurassic rocks (NPD publications, 2014).

2.3 Middle Jurassic doming and structuring

The Lower Middle Jurassic unit is thin in the central North Sea but thickening substantially towards the Northern North Sea. This has been attributed as a broad regional uprating of the Central North Sea dividing the early to middle Jurassic. In the Aalenian there was a doming stretched over an area from the Scotland to Denmark (Coward et al., 2003). The doming caused uplift and erosion, and was followed by rifting with a triple junction formed centrally above the middle Jurassic thermal dome, between Viking Graben, the Central Graben and the Moray Firth Basin (NPD publications, 2014).

The Jurassic thermal dome rise and decay would have provided a zone of weakened lithosphere during later rifting, further enhancing the development of the tipple junction (Davies et al., 2001). The dome acted as a major source for the clastic material supplied during the Aalenian to Bathonian. During Aalenian to Bajocian the dome acted as a major source to the central North Sea providing sediments for the Brent delta. Coward and coworkers (2003) interpreted there to be no evidence of fault control, which will be discussed later in this thesis.

The Dome created a land barrier closing the marine sea ways that had linked the Arctic and Tethys seas during the early Jurassic, which resulting in separation of the Arctic and Tethys during late Aalenian to late Bathonian. Continental rifting have been argued resumed during the Bajocian to Bathonian time associated with enhanced subsidence and major marine transgression. The artic rift extended during Late Jurassic from the Barents Sea to the southern North Sea. Crustal thinning started in the Bathonian times in the northern Viking graben during deposition of the deltaic sandstone and mudstone of the upper Brent Group. The most important rifting phases, however took place during the Late Jurassic. In the Sothern Viking graben only minor amount of rifting is evident driving the Bajocian to Bathonian the main rifting started Callovian to early Kimmeridgian. The rifting created normal fault blocks which trending North to north-east with north-west trending tear and transfer faults in the Viking graben. The rifting continued during the Oxfordian (Coward, et al., 2003).

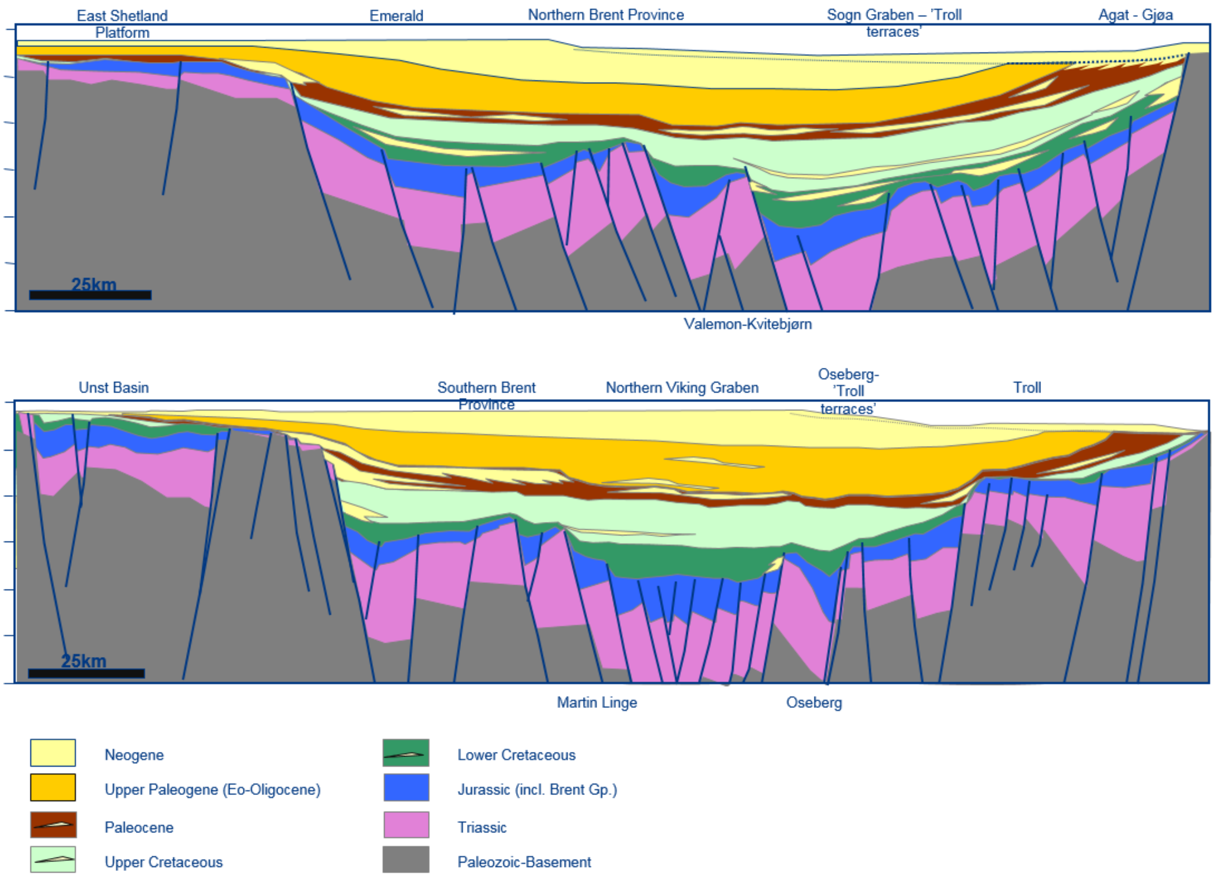


Figure 2.2: A regional east-west cross section of the geological structures in the Northern North Sea modified from Ter Voorde et al (2000). The section shows fault and horizons, displaying the Triassic –Jurassic rifting event

2.4 Brent Group

The Brent field was discovered by Shell in June 1971 (Coward et al., 2003) which was the first discovery in the Brent Group reservoir. Deposition of the Brent group started in Alenianand lasted until early Bathonian age. The Brent Group consist of sandstones, siltstones, mudstone and coals that can reach thicknesses up to 600 m in the deepest part of the North Sea. On the platform areas the Brent group it is considerably thinner (Helland-Hansen et al., 1992).The Brent Group stratigraphy represent three main phases of infill; lateral infill of the basin (Oseberg and Broom formations), advance of the axial Brent delta (Rannoch, Etive and lower part of Ness formations) and backstepping in response to drowning of the group (Tarbert and upper Ness formations) (Helland-Hansen et al., 1992).

The lower part of the Brent Group interfingers distally with the claystone and mudstone of the Dunling Group (Drake Formation) whereas the upper Tabert Formation with means claystone and mudstone of the Heather Formation. The unit is thin on structural high due to syn-deposited sediments and subsequently eroded (Helland-Hansen et al., 1992)..

The late Aalenian transgression produced an extensive marine shelf, onto which Brent delta then prograde northward, accumulating Rannoch, Etive and Lower Ness formations. The establishment of the Brent delta are generally believed to be related to late Jurassic dome uplift in the southern region as well as uplift on the eastern and western flanks of the basin, which in turn caused a relative fall of sea level (Olsen and Steel, 1995). In the Northern North Sea, the general structural control on the deposition of the Brent Group was thermal subsidence related to Early Triassic crustal stretching, although evidence for extensional block-rotation is found in the late Bajocian and Bathonian in some areas. The Rannoch, Etive and Lower Ness formations are accordingly argued pre-rift deposits, opposed to the Upper Ness and Tabert formations which is interpreted as early syn-rift deposits (Olsen and Steel, 1995).

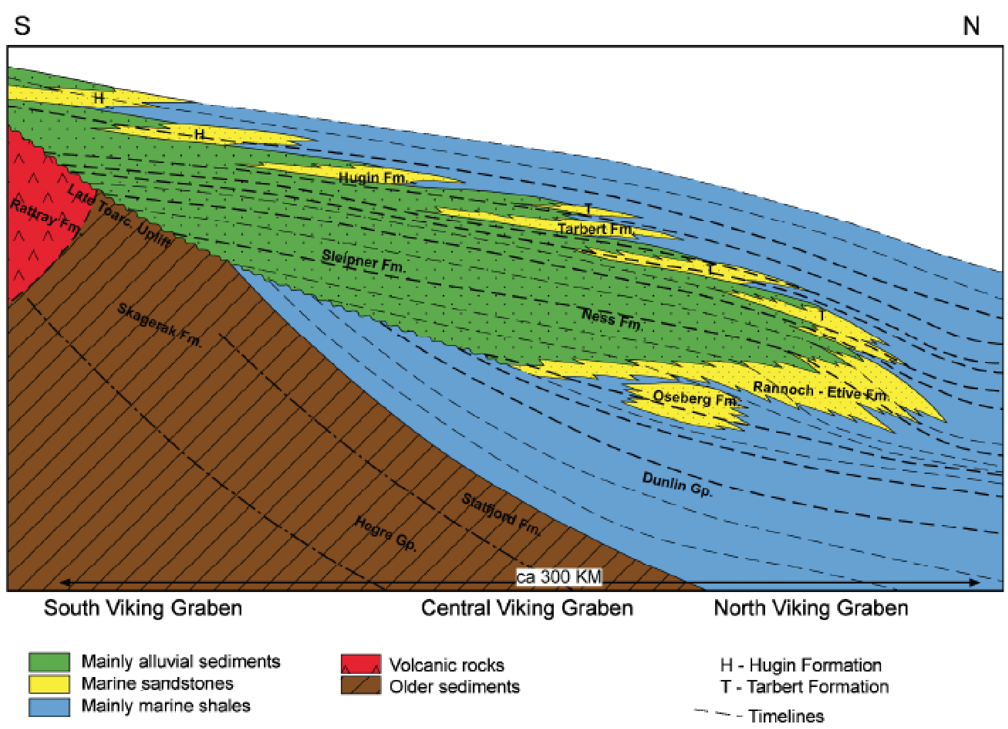


Figure 2.3: Schematic section through south-north of the Brent and Vestland groups showing formations and timelines within the overall regressive-to-transgressive megasequence (Helland-Hansen et al., 1992, Løseth and Ryseth, 1992)

2.5 Mechanisms to explain Lower Brent delta advance

The Lower Brent Group is generally subdivided into two main phases; first is related to the early lateral infill of the basin (Oseberg and Broom Formations) and the second phase records the advance of the delta (Rannoch, Etive and Lower Ness formations)(Helleland-Hansen, 1992).

The Outbuilding of the Brent Delta into the Viking Graben and East Shetland Basin was a response to a Late Torcian uplift centered in the North Sea (Graue et al., 1987, Ziegler, 1981). The elevated areas were subjected to erosion, as a result sediments began building out toward the west northwest and backfilled the previously emerged areas during the subsequent relative sea-level rise (Folkestad et al., 1995, Helland-Hansen et al., 1992).

In addition to major outbuilding of the Brent delta there were smaller depositional system building out (Graue et al., 1987). The Oseberg Formation were building out along the eastern flank, while the Broom Formation were building out in the western flank of the late Viking Graben and Sogn Graben (Graue et al., 1987, Helland Hansen et al., 1992, Steel et al., 1993). The Broom and time equivalent Oseberg Formation is interpreted as a fan delta which rapidly progrades towards west northwest across the Horda Platform and aggrade near the main fault scarps. It is suggested that these systems are indictative of early tectonic movement along the basin margin (Graue et al., 1987). During the Deposition of the Oseberg fan delta the Rannoch Formation shoreline was building out further in the south towards north (Graue et al., 1987). Graue and coworkers (1987) interpreted that the Oseberg Formation drowned in the Aalenian-Early Bajocian before the Brent delta system had reached this far north, this is going to be discussed later in the thesis. After the outbuilding of Oseberg and Broom formations the main progradation of the Brent Group followed.

The marine flooding in the Bajocian time across the Oseberg and Broom formations produced an extensive marine basin opening to the north (Helland-Hansen et al., 1995). The progradtaion of the Brent delta (Rannoch, Etive and Lower Ness formations) proceeded with a northward outbuilding across the foundation of the drowned Oseberg and Broom Formations (Graue et al., 1987). In the North the Brent delta reached deeper water, making the progradation slow down, generated an increased rate of subsidence relative to sediment supply. This is reflected by the increasing thickness of the Rannoch and Etiv formations towards north (Graue et al., 1987).

3.0 Data set and methodology

3.1 Dataset

The dataset was provided by A/S Norske Shell and comprises core data from 13 wells and additional well logs data from 17 wells.

3.2 Core data

This thesis is based on core observation from 13 wells located within the Gullfaks-Valemon-Kvitebjørn, the Oseberg-Tune and in the Fram areas. The core data consisted of well 34/10-23, 34/11-3, 34/11-1, 30/2-1, 30/2-2, 30/2-3, 30/3-1, 30/6-7, 30/6-9, 30/6-11, 30/9-2, 30/9-14 and 30/9-19.

3.3 Well logs

The gamma ray and density well log data comprise 19 wells located in the Gullfaks-Valemon-Kvitebjørn, the Oseberg-Tune, in the Fram areas and Martin Linge area. The well logs comprises well 30/2-1, 30/2-2, 30/2-3, 30/3-1, 30/6-9, 30/9-1, 30/9-2, 30/9-3 A, 30/9-19, 34/8-5, 34/10-23, 34/10-42 S, 34/11-1, 34/11-2 S, 34/11-3 and 34/11-4 T2. Jointly this well data set provides a frame for prediction of Brent Group stratal architectures on the Rungne sub-basin, hence deep parts of the Northern North Viking Graben.

3.4 Methodology

As the first step well log and core interpretation was conducted. The cores were studied lateral, i.e. along depositional strike, and proximal-distal changes within the basal Brent Group to investigate stratigraphic relationships between the Oseberg Formation, the Rannoch-Etive formations and Lower Ness Formation. Then the cores were interpreted to identify facies, facies associations, depositional/architectural elements and sub environment in the Lower Brent Group. The core interpretation was based on lithology, grain size, internal sedimentary structures, well log interpretation and degree of bioturbation. The second step was therefore too detailed interpret well logs signature correlate constant well correlation across the study area. The well logs where interpret with respect to facies, sequences, stratigraphy and depositional environments. Sequence Stratigraphy principle applied during correlation on the Lower Brent Group to ensure a more solid and confident correlation of depositional packages to developed a more detailed framework for the depositional environment. The last step was to integrate the different data sets from the different study areas, and create paleographic maps.

2.0Facies, Depositional Elements & Facies Associations

Core Data Analysis was preformed to record the occurrence of the facies architecture, depositional element and facies association. The facie characterization was based on lithology, internal structure, degree of bioturbation, grain size and log motif. A total of 19 facies were recognized and grouped into 12 facies associations and 4 depositional systems.

4.1Facies

Facies	Description	Core Appearance	motif	Interpretation
1 Massive sands	The lithology consist of light gray to brown, well to medium sorted, medium to coarse grained sandstone with some background mudstone from the shelf edge. The boundary is mostly gradational and occasional sharp. The internal structure consist of vague sand structure, low degree of bioturbation.		Ungraded centimeters to meters thick beds.	The sediments are deposited by gravity flow processes like high density sandy debris flow transitional to more turbulent flow.

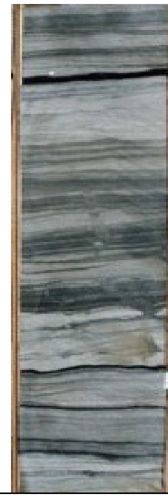
2 Cross stratified sandstone	The lithology consist of light gray to brown, well to medium sorted, medium to coarse grained sandstone. The boundary is gradational. The internal structure consist of massive trough and planar-tabular cross stratification in large scale. Low degree of bioturbation.		Meters thick beds, occasional upwards-coarsening	Migrateing 2D or 3D bedforms unidirectional flows with rives or large scale foresets
3 Bioturbaited Cross stratified sandstone	The lithology consist of light gray, porly to medium sorted, coarse grained sandstone. The boundary is gradational. The internal structure consist of massive trough and planar-tabular cross stratification in large scale. High degree of bioturbation.		Meters thick beds, occasional upwards-coarsening	Migrateing 2D or 3D bedforms unidirectional flows with rives or large scale foresets
4 Medium grained matrix with clast supported conglomerat e	The lithology consist of brown, medium to poorly sorted coarse sandstone, with clasts present. The boundaries are mostly gradational and occasional sharp. The internal structure consist of cross stratified to horizontal lamina, sorted with no bioturbation.		Centimeter to meters thick beds. Occasional upwards-coarsening	The sediments are deposited with high energy gravity flows of fluctuating energy

5 Horizontal laminated sandstone	The lithology consist of gray to brown, medium to poorly sorted, medium to coarse grained sandstone. The boundaries are mostly gradational and occasional sharp. The internal structure consist of horizontal laminated sandstone with mud drapes or double mud drapes and asymetrical ripple x-lamina. Low degree of bioturbation.		Centimeters to meters thick beds. Occasional upwards-coarsening	Sediments are deposited in fluvial and/or tide dominated environment, with lower flow regime on exterior flats
6 Fine to medium grained matrix with clast supported conglomerat e	The lithology consist of light gray to brown, well sorted, fine to medium grained sandstone with clasts. The boundaries are sharp. The internal structure consist of humockey cross stratification and horizontal lamination with clast supported rounded granules and pebbles. Low degree of bioturbation.	 	Centimeter to decimeters	The sediments are high energy event deposits most likely gravity flows aching towards sandy debris flow or more turbulent flows.
7 Hummockey and swaley cross stratified Sandstone	The Lithology consist of light gray, well sorted, fine to very fine grained sandstone with alternating siltstone. The boundaries are gradational. The internal structure consist of hummocky and swaley cross stratification as the dominant stratification, with single or double mud drapes.	 	Centimeter to meter thick beds Occationaly upwards fining	Mainly wave storm stratification, with some tide influence.

8 Organic rich sandstone with hummockey cross stratification	The Lithology consist of light to dark gray, well sorted, very fine grained organic rich sandstone. The boundaries are sharp. The internal structure consist of hummockey cross stratification, parallel lamination and single or double mud drapes.		Centimeter to decimeter thick upward coarsening beds.	Wave processes are dominating with some tidal influence, limited bioturation
9 Planar lamina sandstone	The lithology consist of light gray, well sorted, very fine grained sandstone. The boundaries are gradational. Low-angle, sub-horizontal, parallel laminated sandstone, with indistinct wispy lamina, and single or double mud drapes. Low degree of bioturbation.		Centimeter to meter thick beds	Mainly wave dominated, some tidal influence

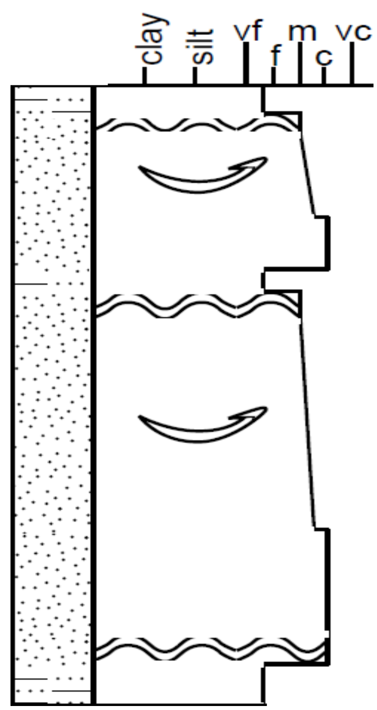
10 Sandstone with mud drapes	The lithology consist of light gray to brown, well sorted, fine grained sandstone. The boundaries are gradational. The internal structure consist of single or double mud drapes, Current ripples, which is tangential and sigmoidal. Low degree of bioturbation.		Centimeters to meter thick beds	Migrating 2D and 3D sigmoidal to tangential bedforms.
11 Sandstone with mud clasts	The lithology consist of light gray to brown, well to medium sorted, medium to coarse grained sandstone with mud clasts. The boundaries are gradational to sharp. The internal structure consist of cross-stratified sandstone with mud clasts and low degree of bioturbation.		Millimeters to centimeters thick fining upward beds	Migrateing 2D or 3D bedforms
12 Mud clast	The lithology consist of dark gray, very fine grained mudstone. The boundary is sharp. The internal structure are ungraded.		Ungraded centimeter thick beds	The sediments are deposited in lags

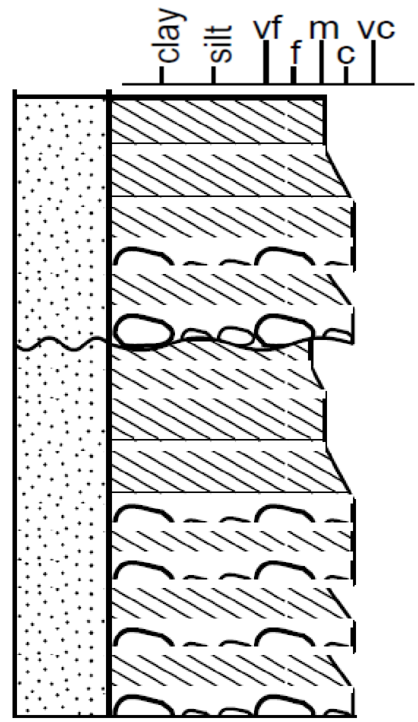
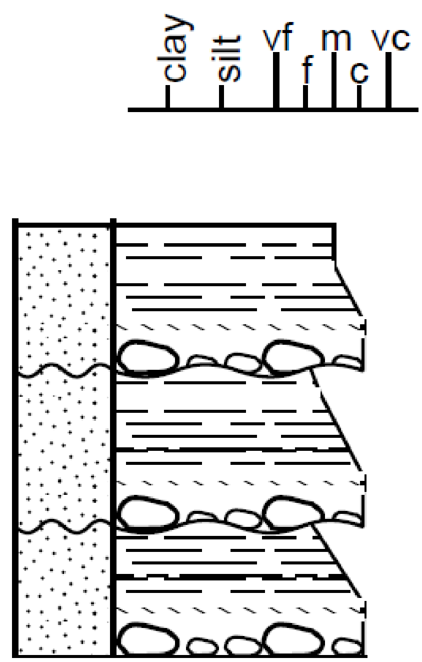
13 Sandstone with large scale cross stratification	The lithology consist of light gray, well to medium sorted, coarse to medium grained sandstone. The boundaries are gradational. The internal structure consist of planar and through cross strata. Low degree of bioturbation.		Centimeters to meter thick fining upward beds	Migrating 2D or 3D dunes deposited in relatively strong energy regime,
14 Small scale cross stratified sandstone, ripple x-lamina	The lithology consist of light gray, well to medium sorted, medium to fine grained Sandston, with some mud clasts. The boundaries are gradational. The internal structure consist of low angle cross stratification. Low degree of bioturbation.		Centimeters to meter thick beds	The cross stratification indicates tidal influence while the mud clast indicates fluvial influence
15 Flaser bedded sanstone	The lithology consist of light to dark gray, well to medium sorted, very fine sandstone. The boundaries are gradational. The internal structure consist of flaser beddeding. Low degree of bioturbation.		Centimeters to decimeter thick beds	Flaser beds are formed in a high energy environment with mainly tidal influenced and some fluvial influence

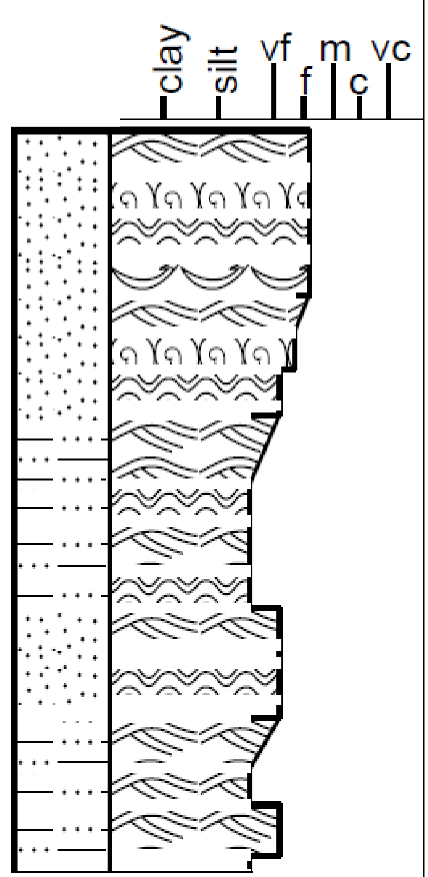
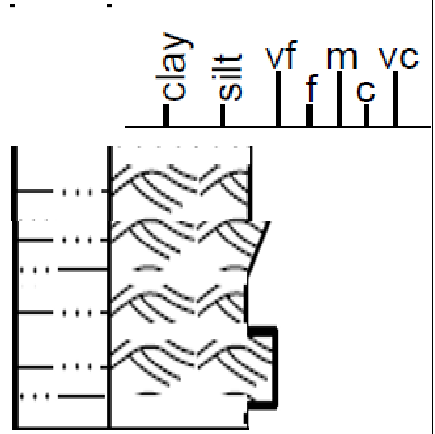
16 Wavy bedded sandstone	The lithology consist of light and dark gray, well sorted, fine grained Sandston, mud and coal. The boundaries are gradational. The internal structure consist of flaser lamination. Low degree to moderate degree of bioturbation.		Centimeter to decimeter thick beds	Flaser beds are formed in a high energy environment with mainly tidal influenced and some fluvial influence
17 Lenticular bedded sandstone and mud	The lithology consist of dark gray, very fine alternating layers of mud and sandstone. The boundaries are sharp to gradational. The internal structure consist of lenticular bedding with some bioturbation present. Low to moderate degree of bioturbation.		Centimeters thick beds	Lenticular beds are formed in a high energy environment, intertidal, with mainly tidal influence
18 Bioturbated mudstone	The lithology consist of dark gray, very fine grained organic rich mudstone with moderate degree of bioturbation. The boundaries are sharp to gradational. The internal structur is ungraded.		Ungraded centimeters thick beds	Low energiy enviornment

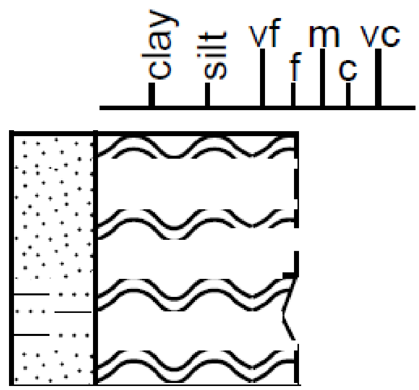
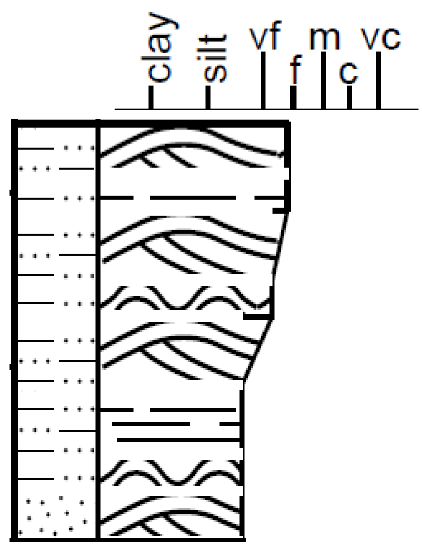
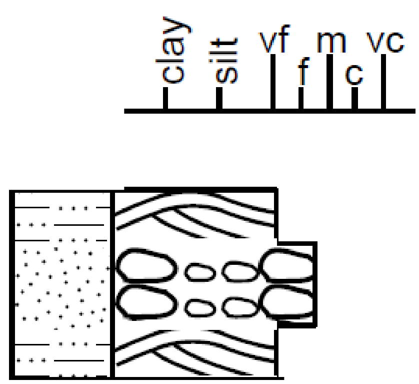
19 Coal and roots	The lithology consist of dark to light gray, very fine grained sandstone with, of coal and rots. The boundaries are mostly gradual and occasionally sharp. No bioturbation.		Ungraded Centimeters to meters thick beds	Low energy enviornment

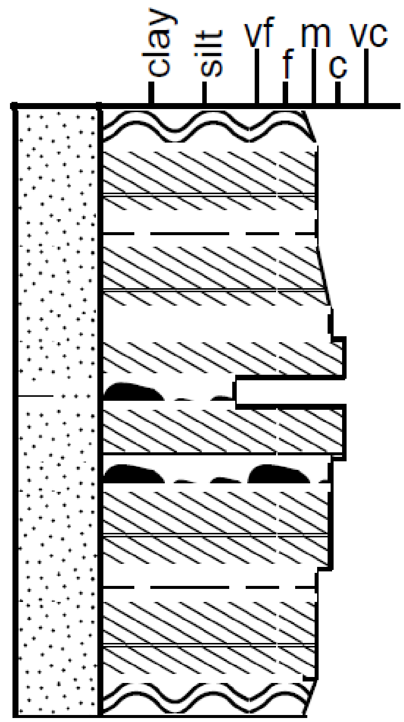
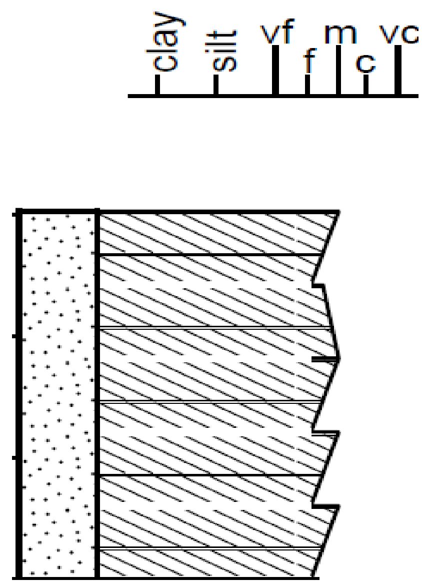
4.2Facies Associations

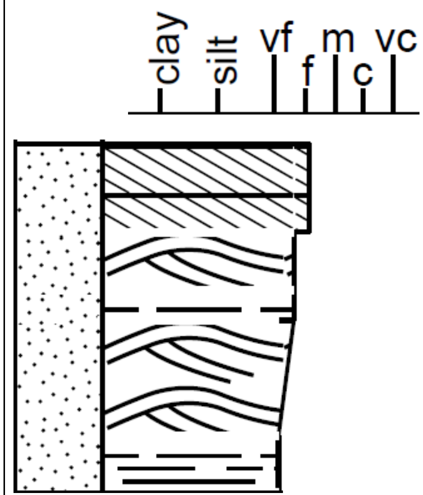
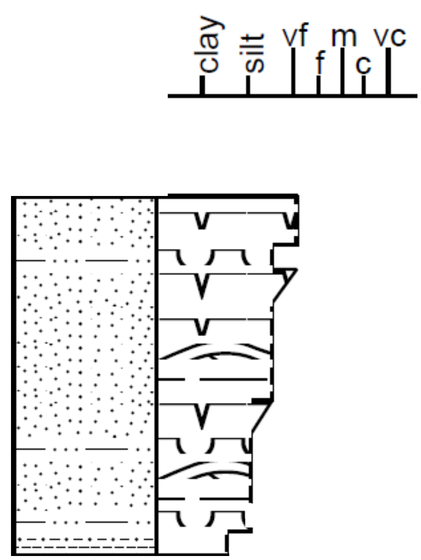
Facies association	Description	Interpretation	**Log motif lithology**	Sub environment
FA 1. Gravity flow dominated pro delta	The sandsontes of facie 1 interbeded with mudstone, in fining upward sequences	Thick gravity flows/turbidit beds and mud partings indicate inner shelf to prodelta		Inner shelf to Prodelta, gravity flows

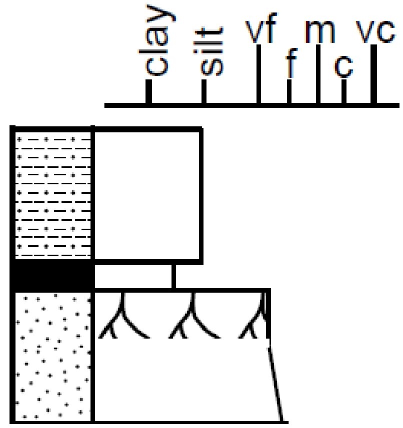
FA 2. Delta foreset	The internal structure consist of trough and planar-tabular cross stratification mud drapes and ripples (facies 2). There are fining upward sequences with erosive base. In the base there are "floating" granules and small pebbles poorly sorted (Facie 4). Including bedding surface and some places with bioturbation (facies 3)	The sedimentation are occurring along slope where the sediments were influenced by gravity flow or/and coarse material debris flow. The mud drapes indicate tide influence		Delta-front, channelized, gravity flow dominated foresets part of delta
FA 3. Delta topset	The internal structure consist low angle to horizontal laminated sandstone (facie 5), with occasional clast (facie 4), in fining upward sequences.	The topset are formed when river gradient are reduced causing bedload load to settle which lead to clast deposits in almost horizontal beds over the delta top. There are some mud drapes indicating tidal influence.		Delta-top to uppermost part of delta-front, outer distributary channels transitional to channelized part of upper delta-front with gravity flow dominated channels

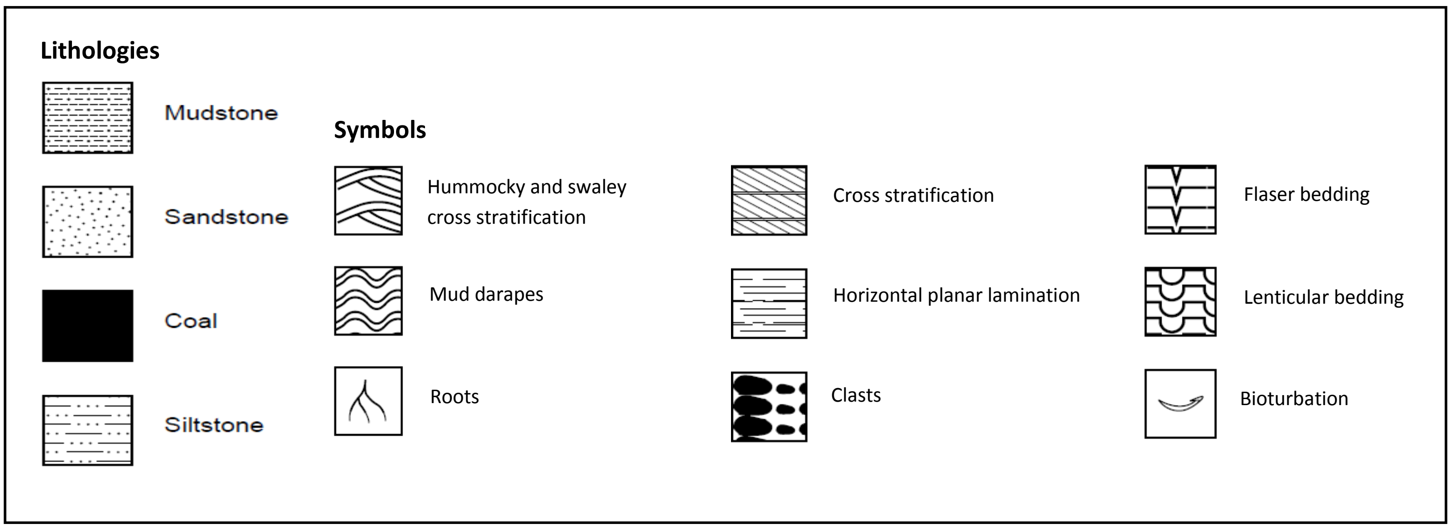
FA 4. A,B and C Lower shoreface to middle shoreface	The the bottom interval (FA 4. A) Consist of wave dominated facie, the middle interval (FA 4. B) consist of a mix between wave and tide dominated facies, the upper intervals consist of wave and fluvial dominated facies (FA. 4 C)	The lower shore face is where the waves start to feel the bottom. This is an area of low energy consisting of alternating fine grained sandstone and mud. There are limited bioturbation. The middle shoreface is subjected to higher wave energy. The storm wave are in events, which indicates that the mud drapes can be deposited when the storm calmed down.		Shallow marine (offshore transition zone to shoreface) Lower to middle shoreface, wave dominated influence with some tide influence
FA 4 A Lower shoreface	The internal structure consist of swaley and hummocky cross stratification (facie 7) and planar lamination (facie 9)	In the lower shoreface wave and storms currents are dominating and mud is brought up form offshore marine		Shallow marine (offshore transition zone to shoreface)

FA 4 B. Upper shore face	The internal structure consist of mud drapes and double mud drapes (Facie 10). The grain size is fine with Alternating silt/sand layers with various thicknesses.	Upper shoreface wave process is limited and a mix of wave and tide currents dominates.		Upper shoreface deposits influenced by tides
FA 4 c. Distributary Mouth bars	The internal structure consist of hummocky cross stratification (facie 7 with tide impact (facie 10) and some planar-lamination (facie 9). The grain size consisted of fine to very fine sands interfingering with mud/silt, coarsning upward. There are a lot of organic matter present.	Distributary mouth bars are developed by a river and reworked by waves and tides. Deposition occur during a flooding and then the sediments are reworked by waves and tide currents. The fining upward sequence indicates deposition by unidirectional river current.		Mouth bars deposits, wave dominated influence with some tide influence
FA 5. Shoreline with gravity flows	The internal structure consist of hummocky cross stratification(facie 7) with tide impact (facie 10) and medium grained matrix with clast supported conglomerate (Facie 6), in fining upward sequences	Gravity Flow are pouring into a shoreline environment.		gravity flow dominated delta

FA 6 Estuarine distributary channels	The internal structure consist of three-dimensional subaqueous sand dunes, cross stratification (facies 11), in some wells there were lags of mud clast (facie 12). The grain size was medium to coarse, and the sequences was fining upward and occasionally coarsening upward.	Distributary channels are developed on top of delta plains where a primary fluvial channel flows. The Channels are alternating between fluvial and tidal processes that form the deposits, which can make mud drapes. Channelized tidal flows has slack water periods that result in mud drapes. The floor of the Distributary channel is erosional and often littered with lags of mud clasts.		Central estuarine, dominated by river system and tide processes
FA 7 Estuarine	The internal structure consist of large scale cross stratification (Facie 13), mostly fining upward but occasionally coarsening upwards	The estuarine is found on top of the channels.		Central estuarine, dominated by river system and tide processes

FA 8 Estuarine Tidal bars	The internal structure consist of massive sands, parallel lamina, humockey cross stratification (facie 7) and cross stratification (facie 13). The grain size varies between fine to medium in coarsening upward sequences.	The bars are distributed in the outer part of the estuarine, which is the most tidal dominated zone. The transportation of sedimentary material is influenced by the fluvial channels and the tide currents. The tidal bars migrates within the channel cause of tidal currents generating cross-bedded sandstone beds.		Outer estuarine
FA 9 Tidal flats	The internal structure consist of falser bedded layers (facie 15), wavey bedded sandstone (facie 16), lenticular (facies 17) and organic rich mudstone (facie 18). Coarsening upward sequences of alteration of fine grained sand and mud into coal.	Muddy tidal flat deposits rich in organic material may contain sandy sediment deposited within tidal creeks, at the highest tides and during storms.		Tidal flat deposits

FA 10 Marsh	The internal structure consist of coal roots (facie 18) and organic rich mud rock. The grain size is fine to very fine.	Organic rich mudstone, coal and roots are located in the uppermost supertidal part, in the wetland indicating a marsh.		Marsh deposits



4.3 Depositional systems

Depositional systems	Description	Processes
braid-delta depositional systems	Medium to coarse grained sandstone. Characterized by pro delta and gravity flow with mudstones (FA 1), delta forests (FA 2) and delta topsets (FA 3)	The braid delta system are mainly dominated by gravity flow regime
shoreline depositional system	Very fine to medium coars sandstone. Characterized by lower to middle shoreline (FA 4) , middle to upper shoreline (FA 5)and distributary mouth bars (FA 6)	The shoreline depositional system is dominated by wave and tide regime
estuarine depositional system	Fine to coarse sanstone. Characterized by estuarine distributary channels (FA 7), tidal flats (FA 8) and estuarine tidal bars (FA 9)	The estuarine depositional system are dominated by fluvial and tide regime
delta plain depositional system	Very fine to fine grained sanstone. Characterized by tidal flats (FA 10), bays (FA 10) and marsh (FA 11).	The delta plain depositional system are mainly dominated by tide regime.

The Oseberg Formation is characterized by 6 facies (facies 1-6 table 1). Facies 1 consist of massive ungraded sands, indicating a sediments deposited by gravity flows deposition and unidirectional channels. Facies 2, 3 and 4 shows cross stratified strata indicating migrating 2D or 3D bedforms. Facies 5 consist of horizontal laminated sandstone indicating sediments deposited in fluvial or tide dominated environment. Facies 6 of (humockey cross stratification and horizontal laminated sandstone) with clast supported rounded granules and pebbles indicating a gravity flows. The facies are divided into 3 facies association (FA 1-3 table 2) which comprise elements of braid-delta depositional systems; FA 1 pro delta and gravity flow with mudstones (facies 1), FA 2 delta forests (facies 2,3 and 4) and FA 3 delta topsets(facies 5).

The Rannoch Formation is characterized by 4 facies (facies 7-10 table 1). Facies 7 and 9 consist of hummocey cross stratification, swaley cross stratification and planar laminated sandstone, indicating a wave storm dominated deposits. Facies 10 consist of hummockey cross stratification with abundant single and double mud drapes, indicating a tide dominated deposits. Facies 8 is similar to facie 7 and 9 but there is a high abundance of organic material indicating a wave dominated delta with fluvial supply. The facies are divided into into 3 facies associations (FA 4 A, B and C and 5 table 2) which comprise elements of shoreline depositional system; FA 4 lower to middle shoreface(facies 7 and 9), FA 5middle to upper shoreface(facies 10) and FA 6 distributary mouth bars (facies 8).

The Etive Formation was characterized by 4 facies (Facies 11-14 table 1). Facies 11 and 12 comprises cross stratified sandstone with mud clast indicating migrating 2D and 3D bedforms with lag deposits. Facies 13 comprises cross stratified sandstone indicating migrating 2D and 3D bedforms. Facies 14 comprises low angle cross stratification indicating fluvial influence. The facies are divided into 3 facies associations (FA 6, 7 and 8 table 2) which comprise elements of estuarine depositional system; FA 7 estuarine distributary channels (facies 9 and 10), FA 8 tidal flats (facies 13) and FA 9 estuarine tidal bars (facies 14).

The Lower Ness was characterized by 5 (Facies 15-19). Facies 15, 16, 17 and 18 consist of flaser bedding, lenticular bedding and organic rich sandstone, indicating tidal influenced deposits. Facie 19 consist of sandstone with roots and coal, indicating a landward deposition. The facies are divided into 2 facies associations (FA 10-11 table 2) which comprise elements of delta plain depositional system; FA 10 tidal flats (facies 15 and 16), FA 10 bays (17 and 18) and FA 11 marsh (facies 19).

5.0Sedimentary logs /core descriptions

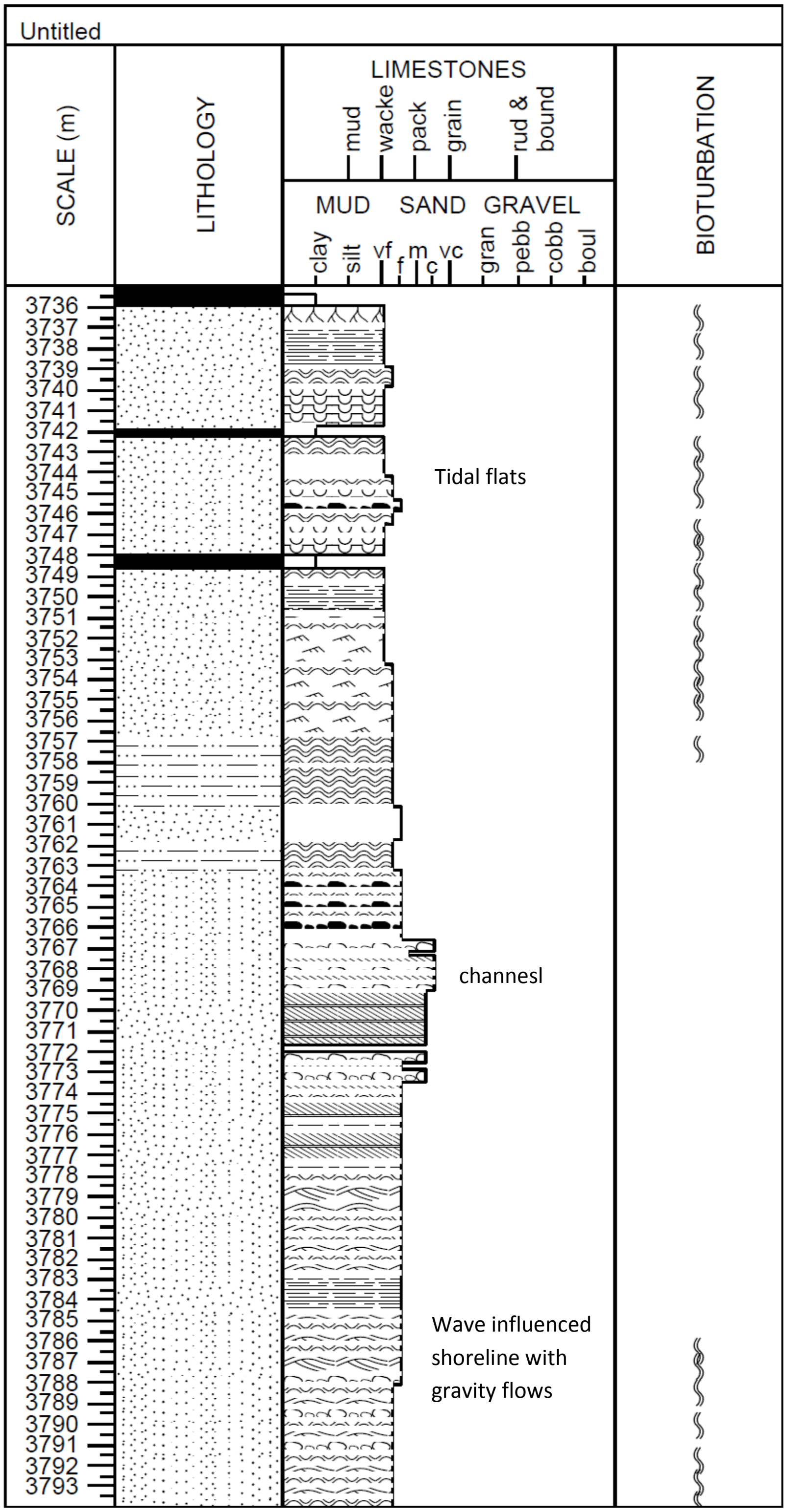
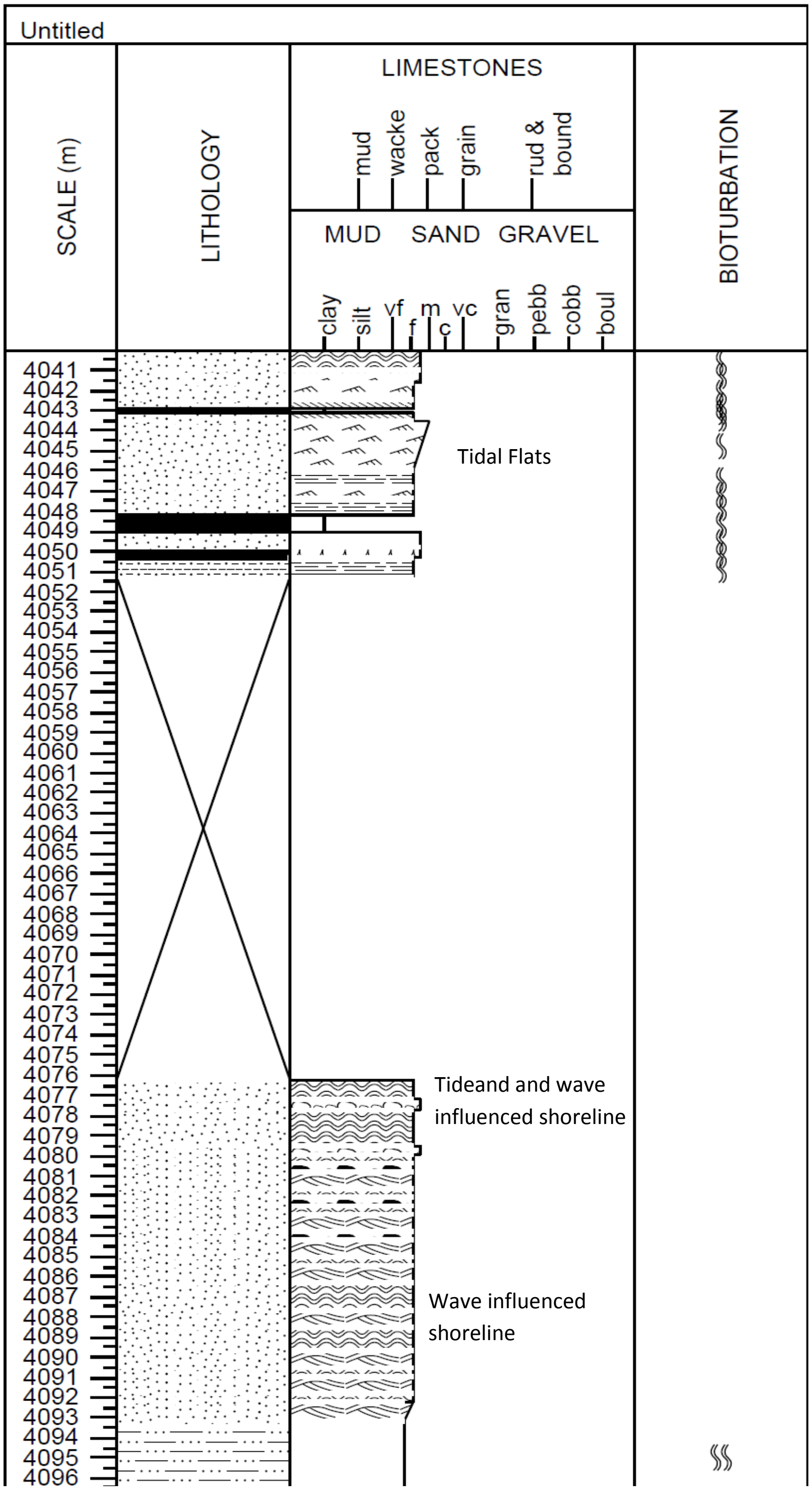


Figure 5.1: Core description of well 30/2-1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Tidal Flats
Tideand and wave influenced shoreline
Wave influenced shoreline

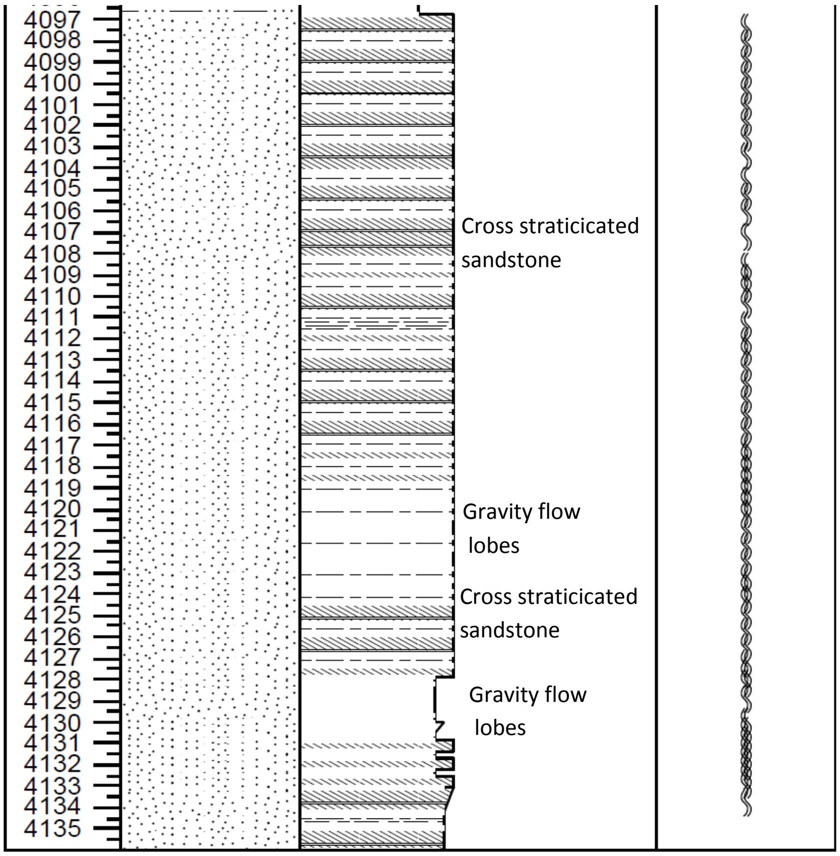


Figure 5.2: Core description of well 30/2-2

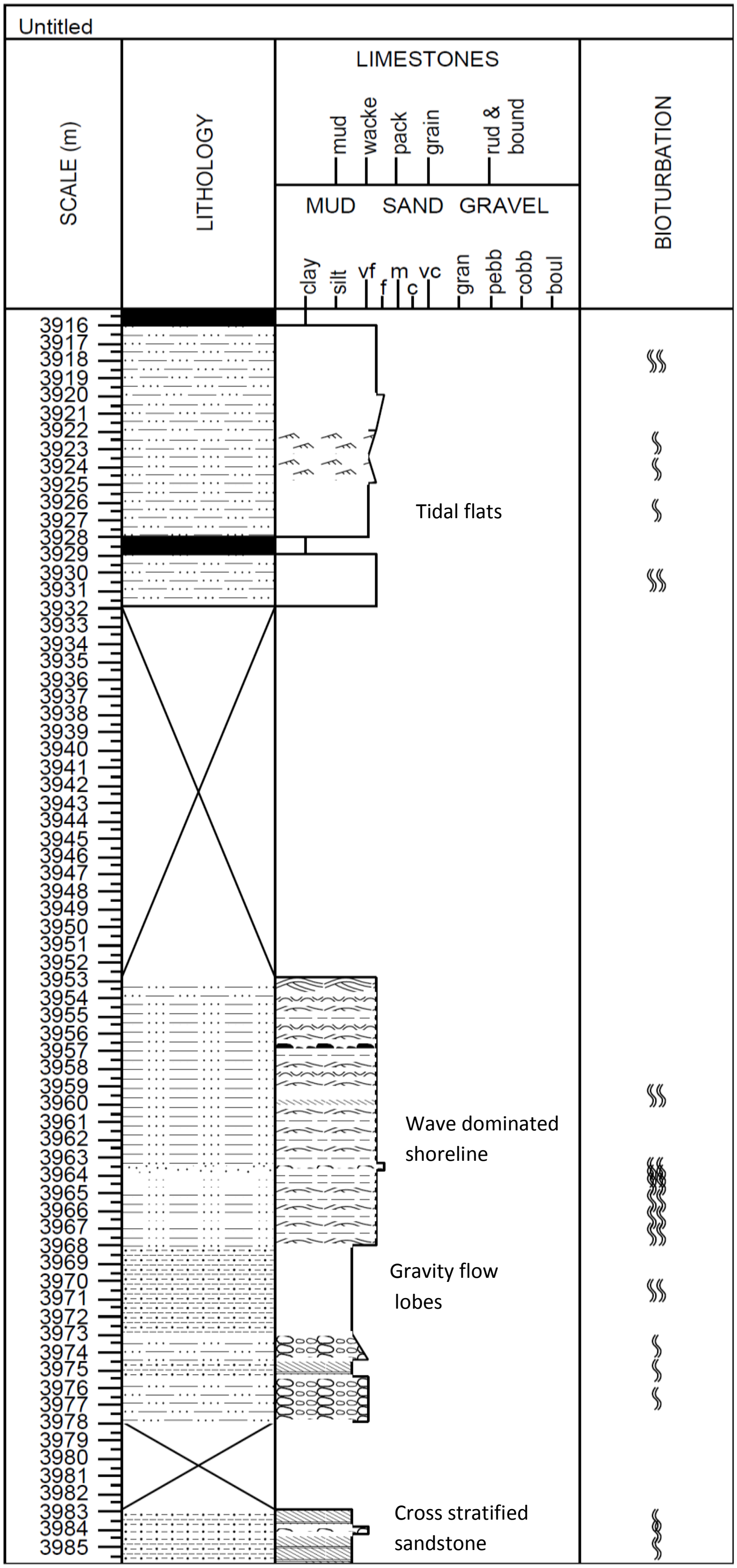
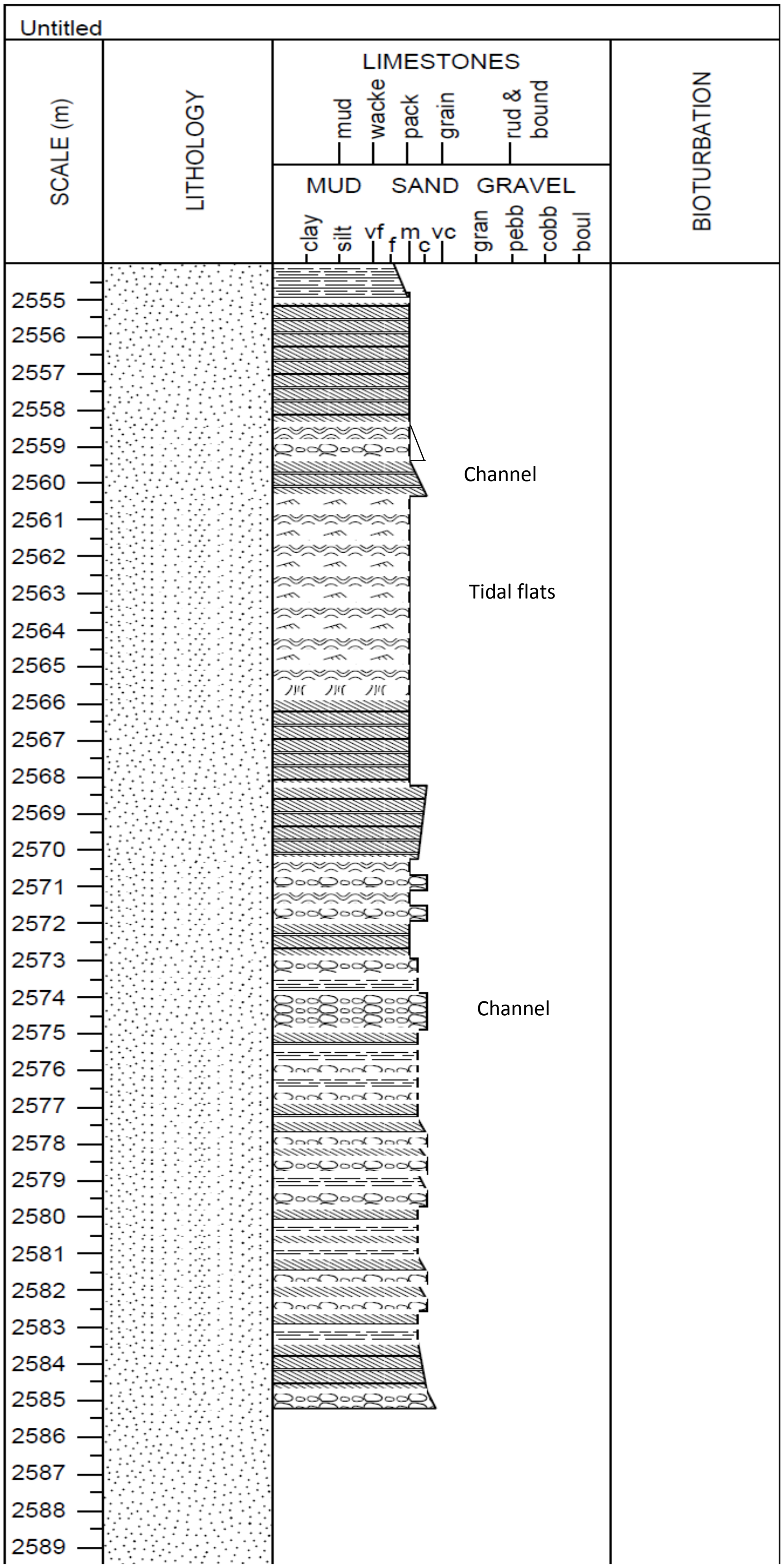


Figure 5.3: Core description of well 30/2-3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Channel
Tidal flats
Channel

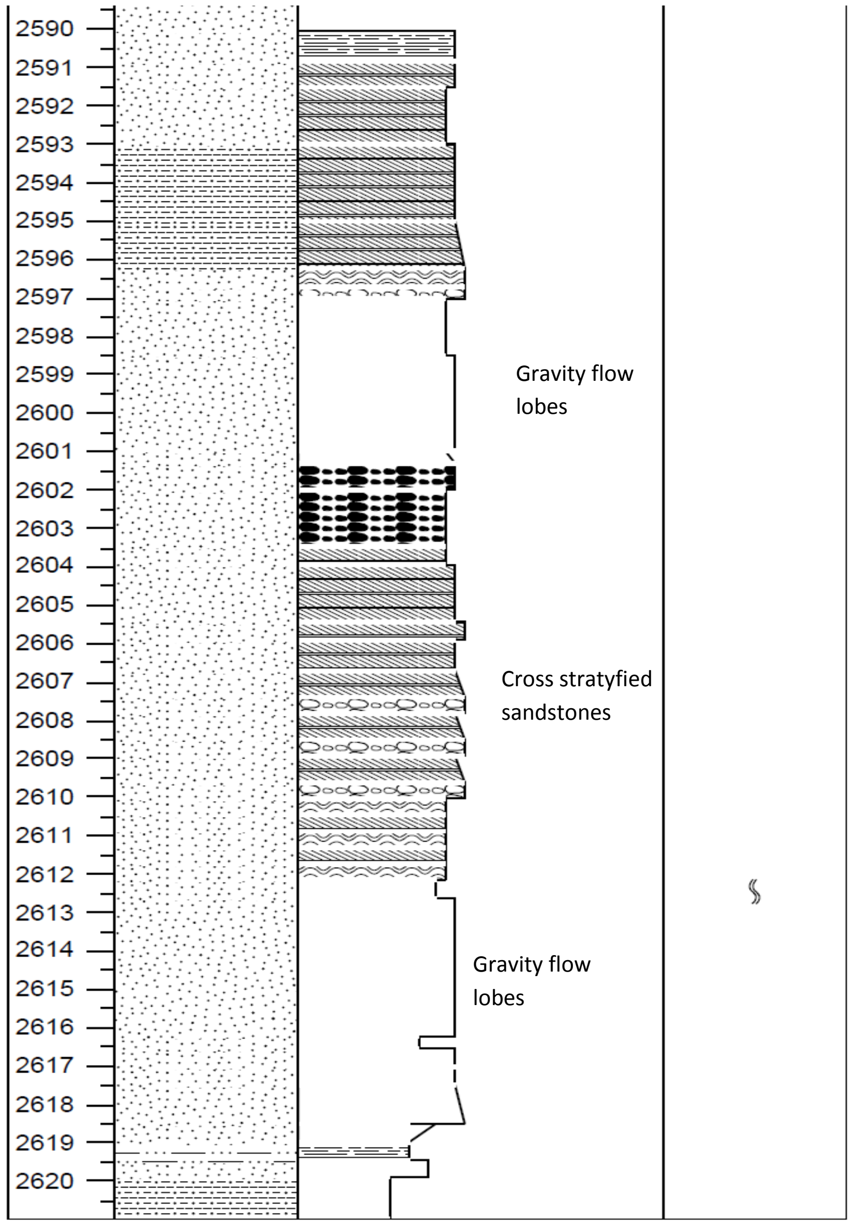


Figure 5.4: Core description of well 30/6-9

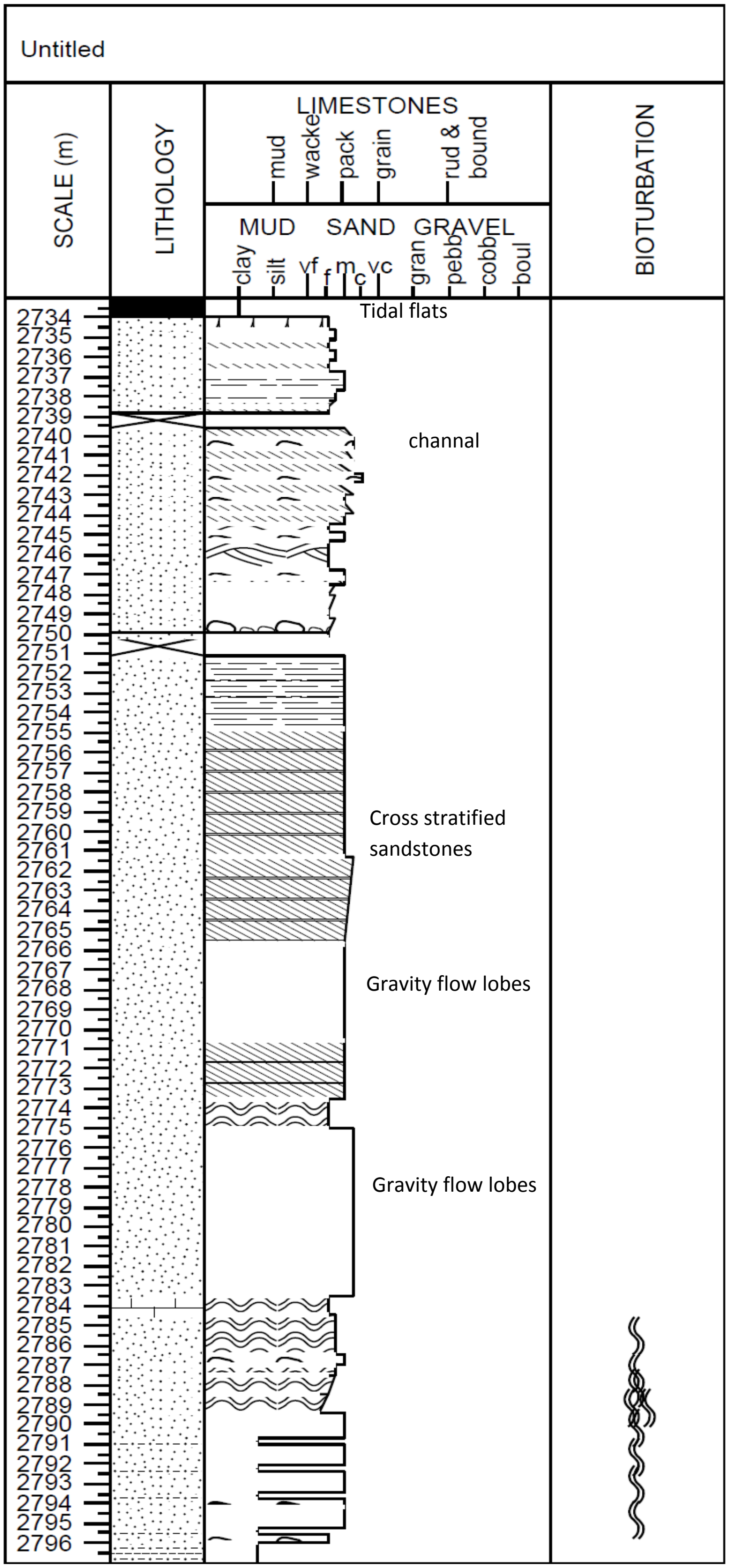


Figure 5.5: Core description of well 30/6-7

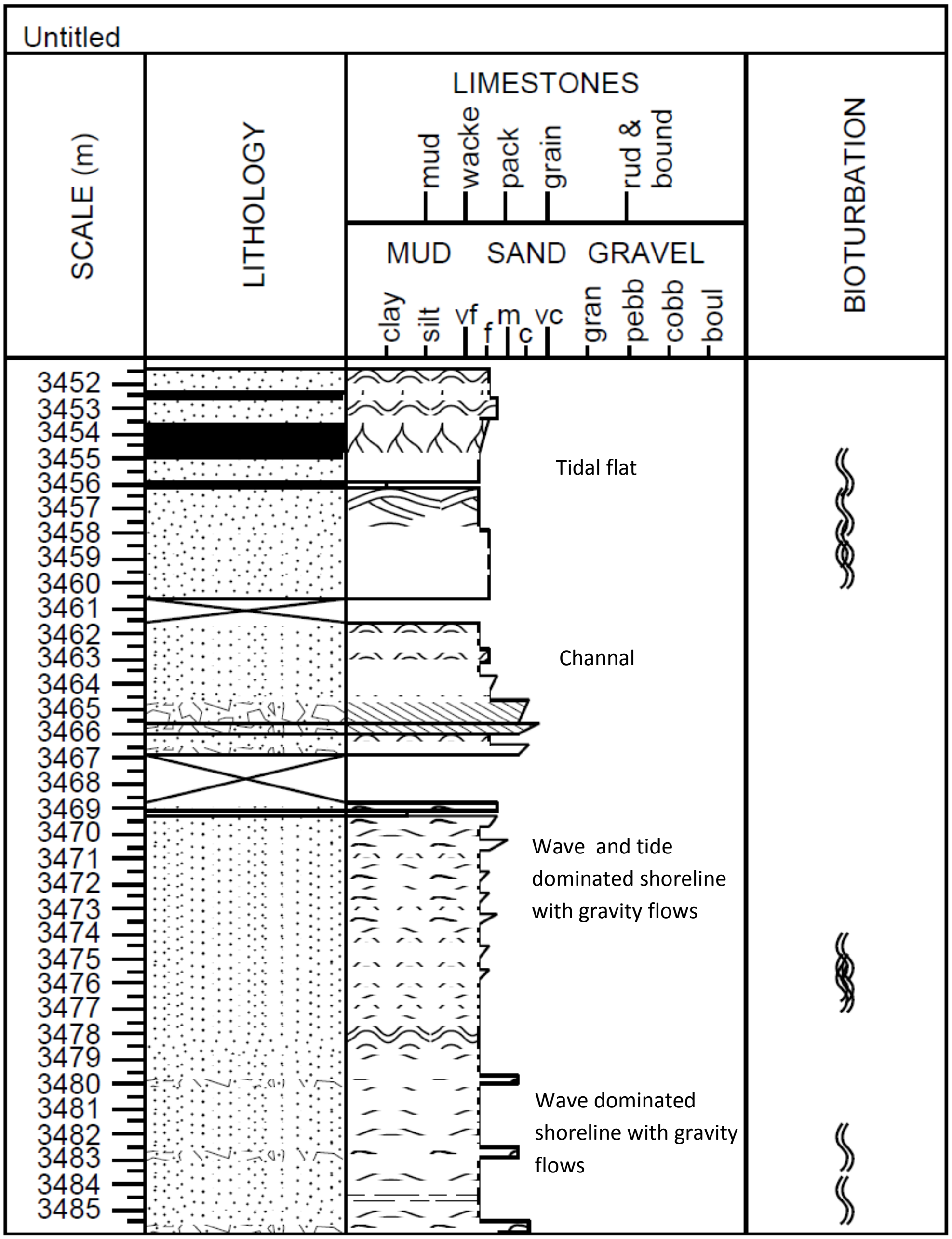


Figure 5.7: Core description of well 30/6-11

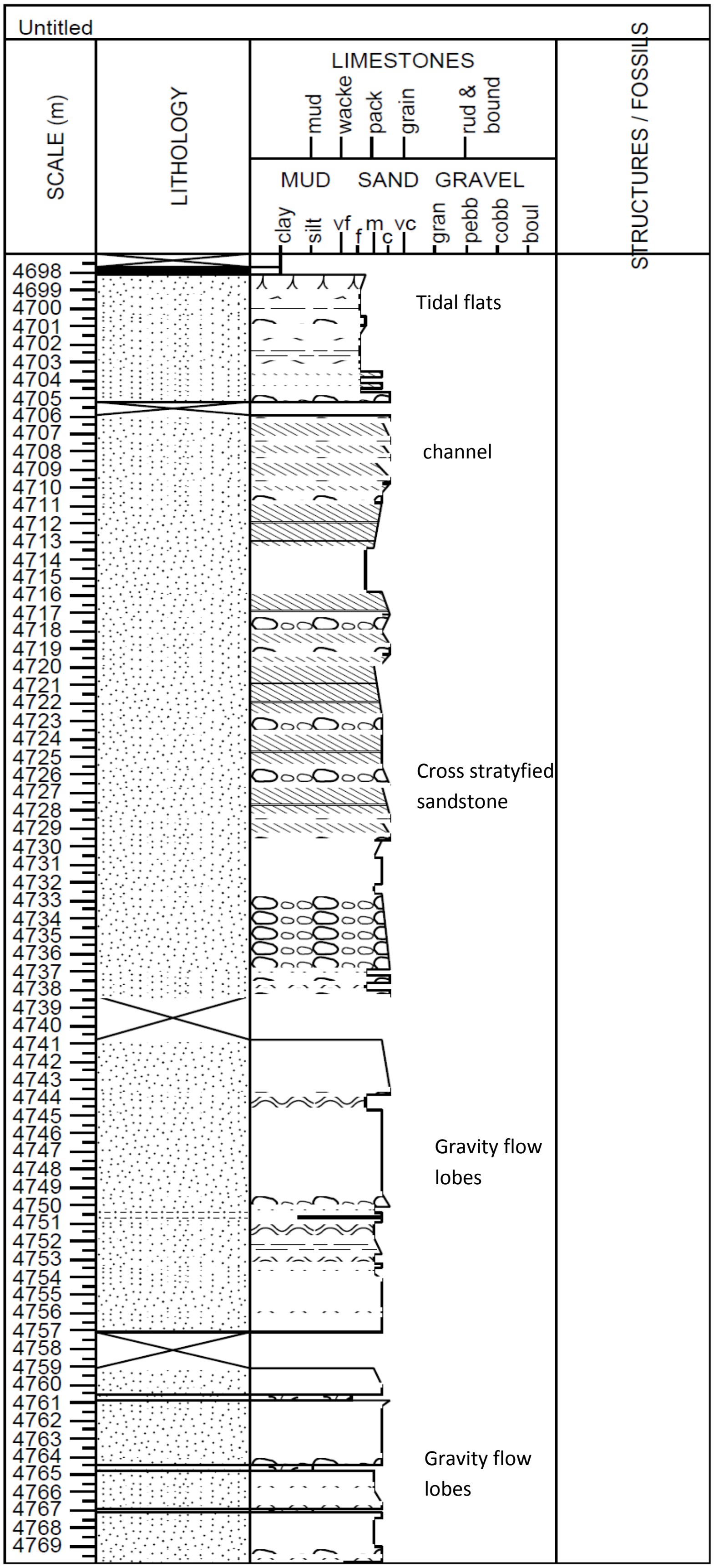


Figure 5.8: Core description of well 30/9-2

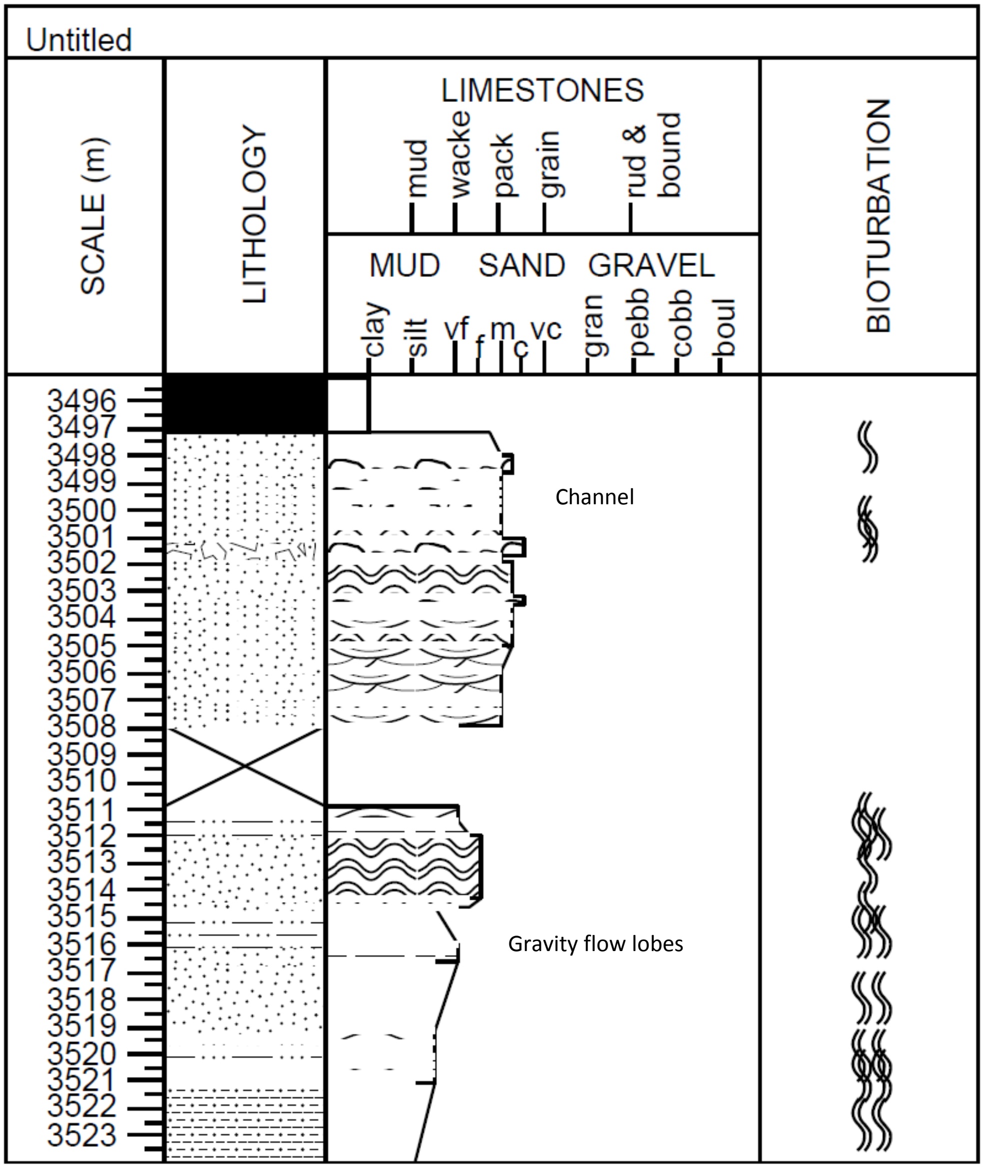


Figure 5.9: Core description of well 30/9-14

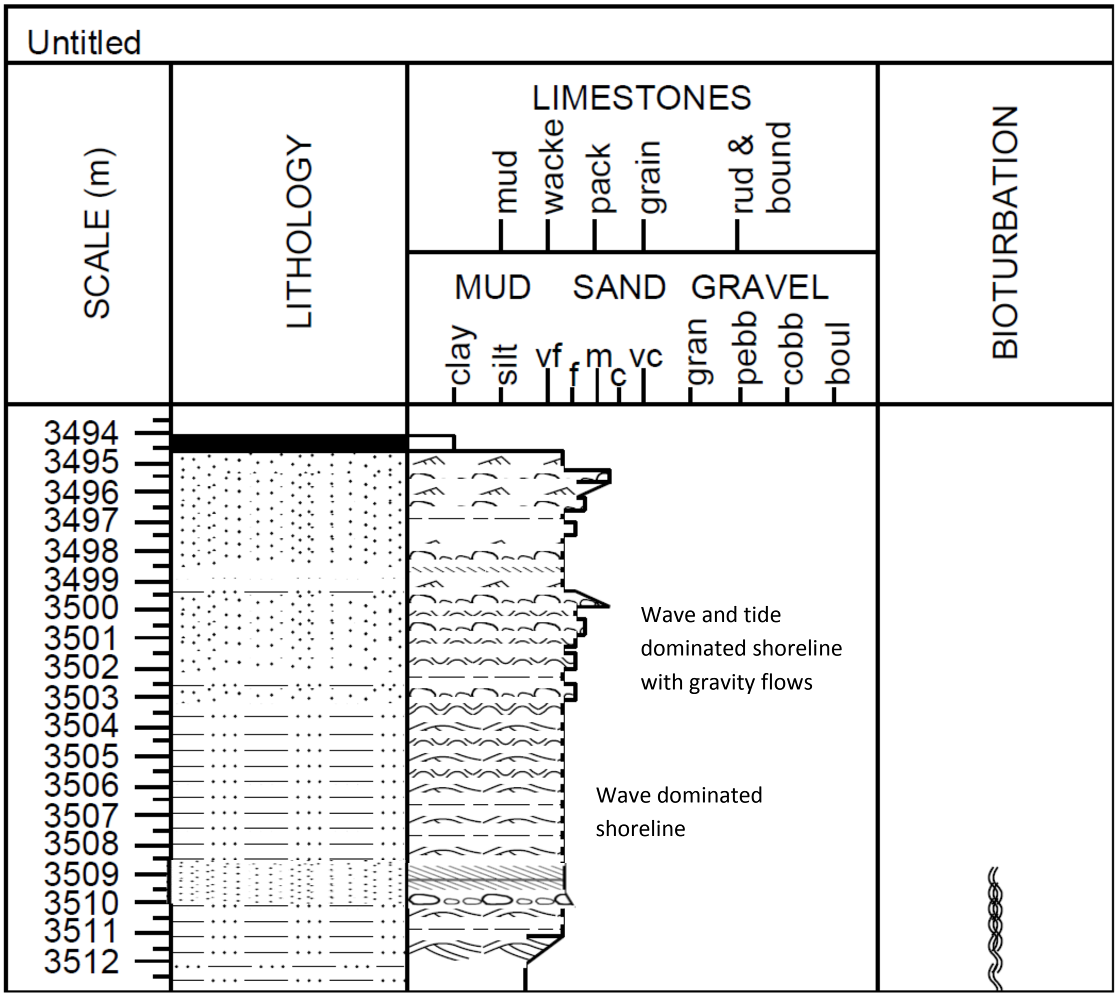


Figure 5.10: Core description of well 30/9-19

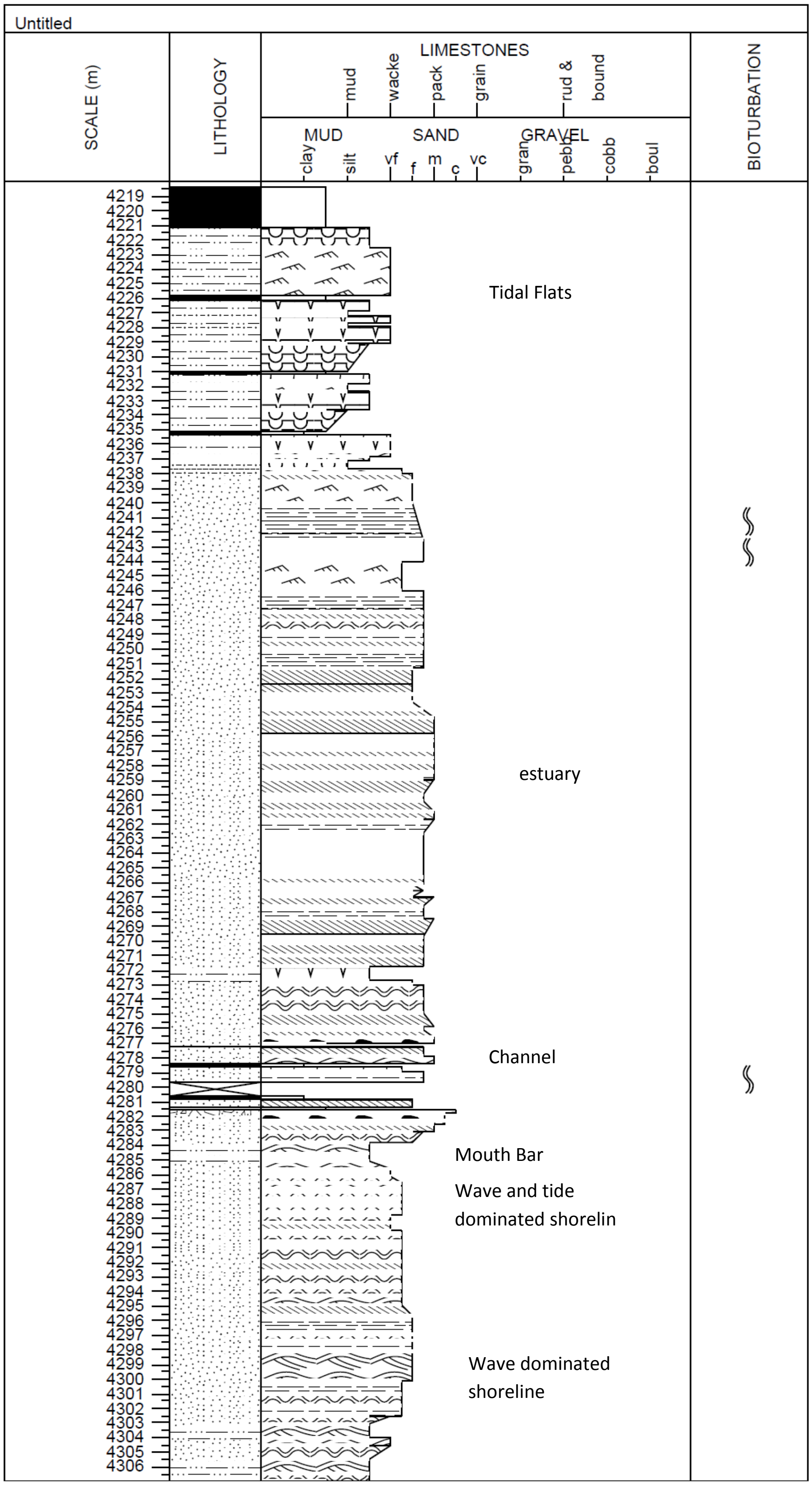


Figure 5.11. Core description of well 34/10-23

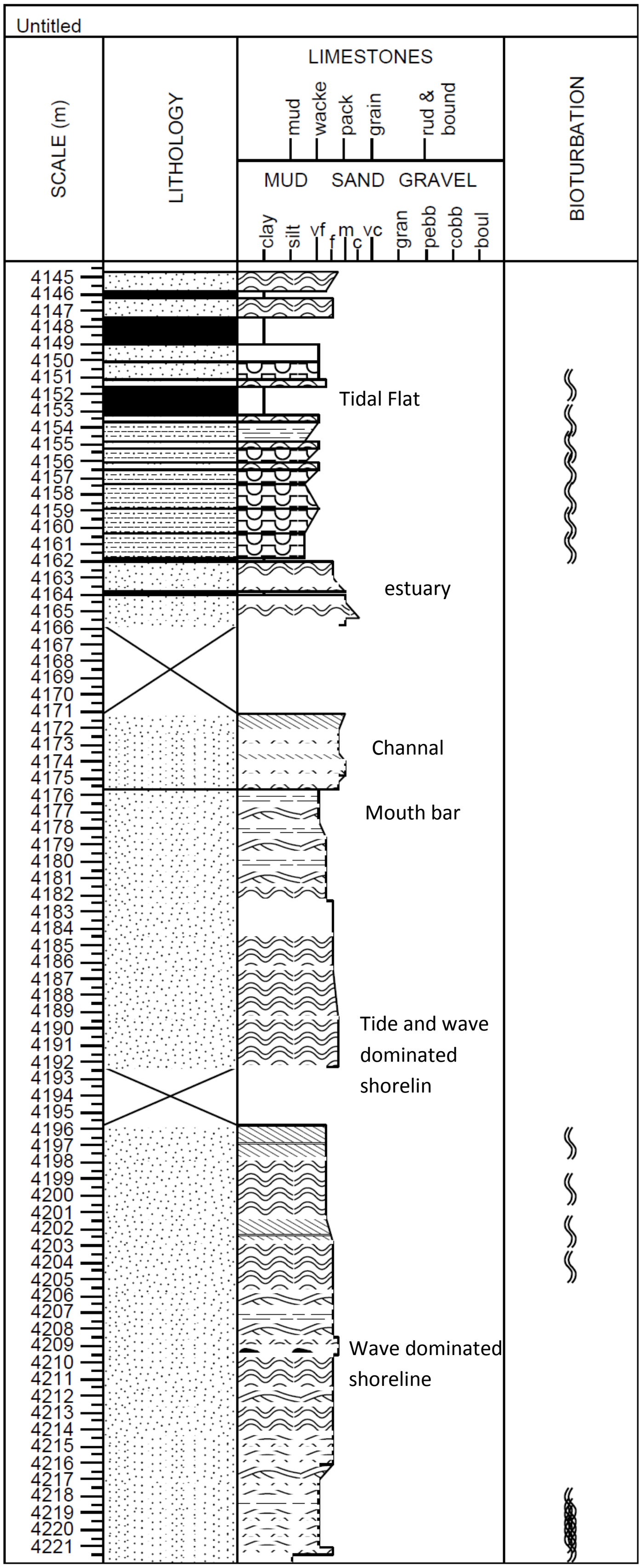


Figure 5.12: Core description of well 34/11-1

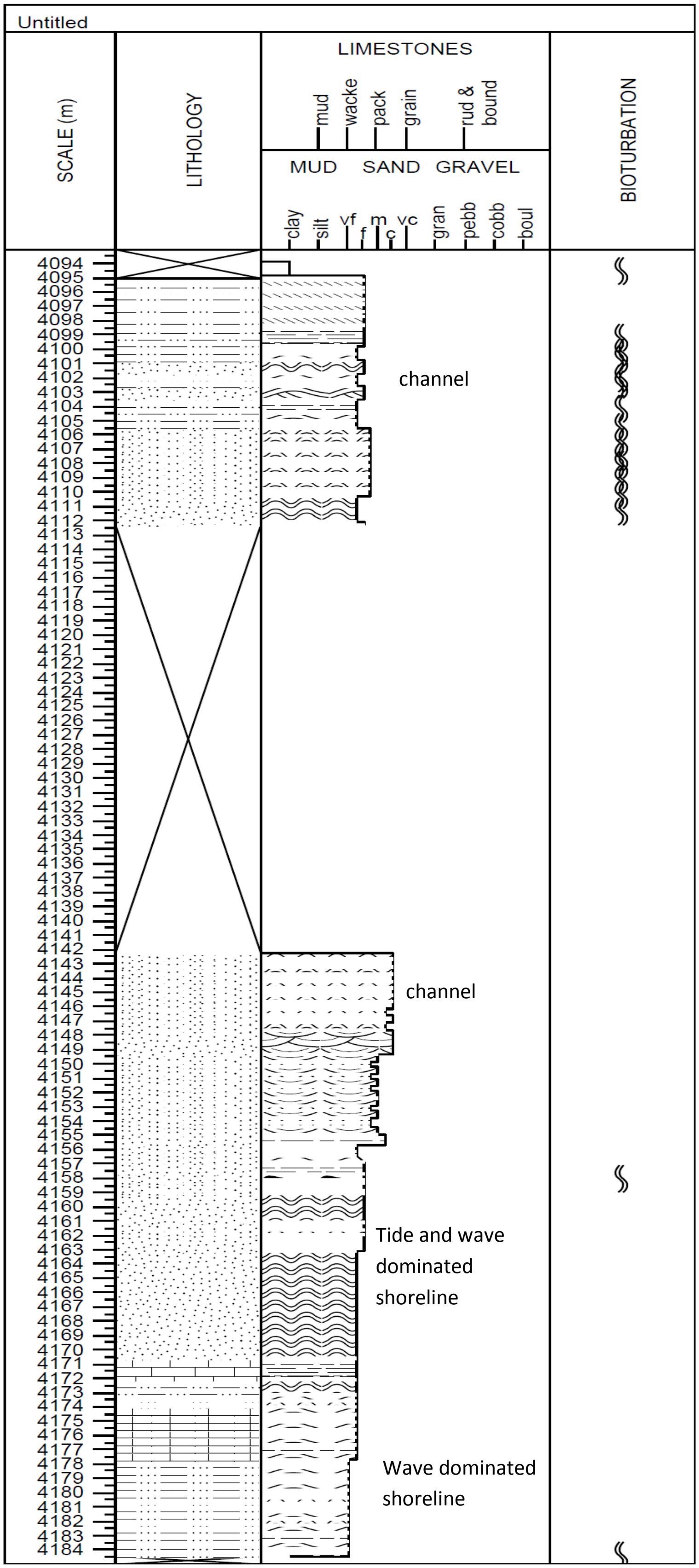
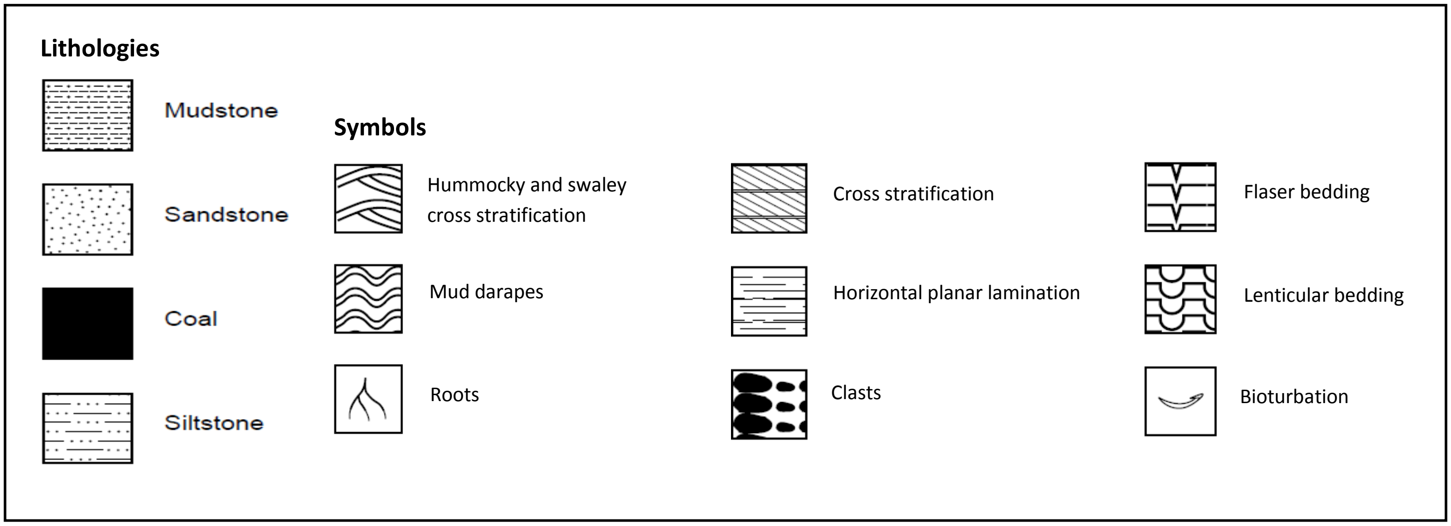


Figure 5.13: Core description of well 34/11-3


Lithologies
Mudstone
Sandstone
Coal
Siltstone
Symbols
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Mud darapes
Roots
Cross stratification
Horizontal planar lamination
Clasts
Flaser bedding
Lenticular bedding
Bioturbation

6.0 Lower Brent Stratigraphy, GDE's & Infill style

Sequence stratigraphic analysis of the Lower Brent Group (Oseberg, Rannoch, Etive and lower Ness Formations) was preformed to ensure robust correlation of depositional packages to develop more detailed framework for the depositional environment within the formations/units. Interpretation is based on sequences, stratigraphic cycles, different orders of magnitudes with in terms of thickness and paleography. The Lower Brent group is divided into two sequences; each consisting of a regressive segment and one transgressive segment which and. Both sequences were capped by a flooding surface. Thickness variation is interpreted in lateral variation and changes in basin topography/physiography and on influence of syn-depositional structuring

6.1 Well Log correlations

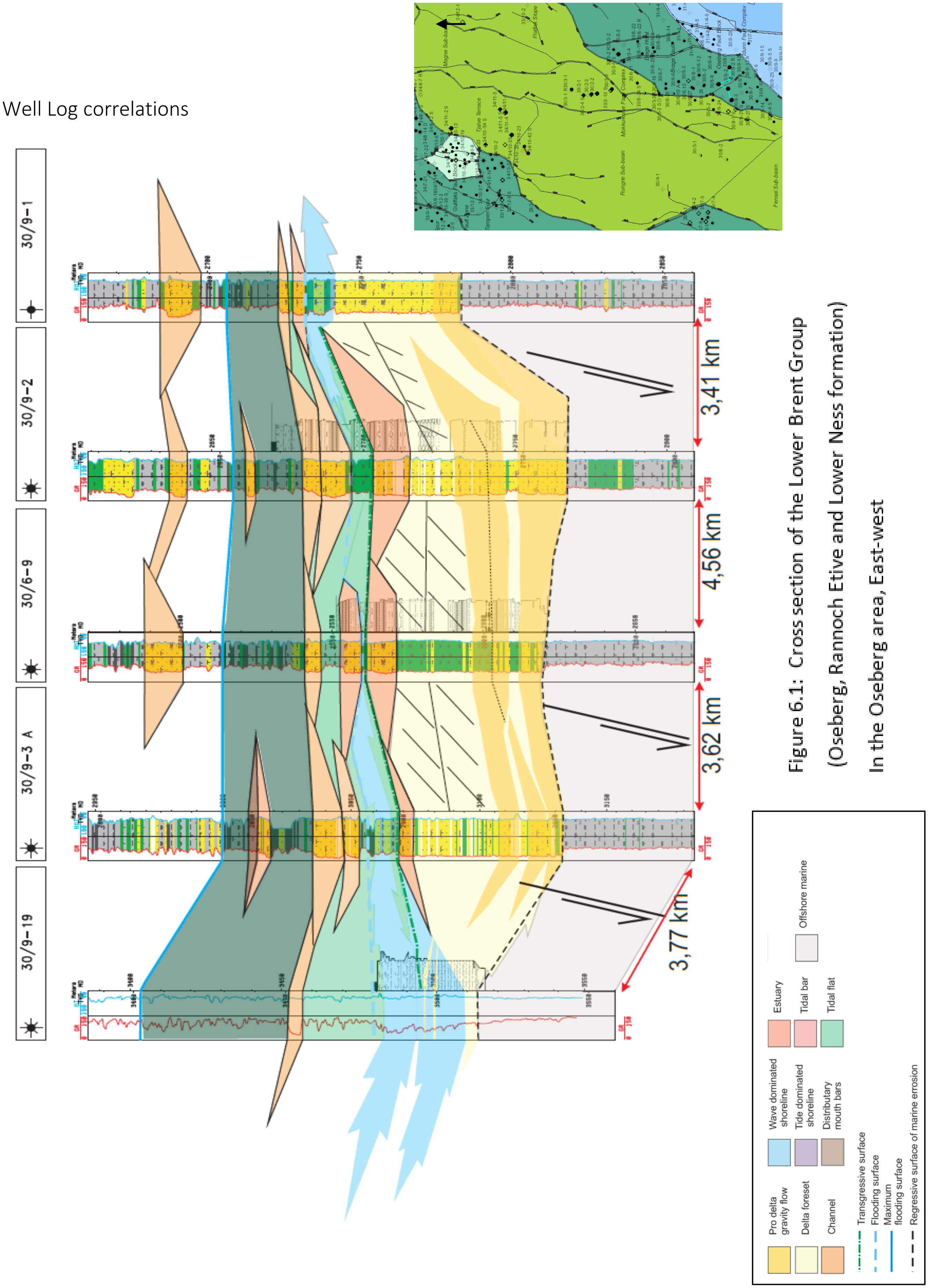
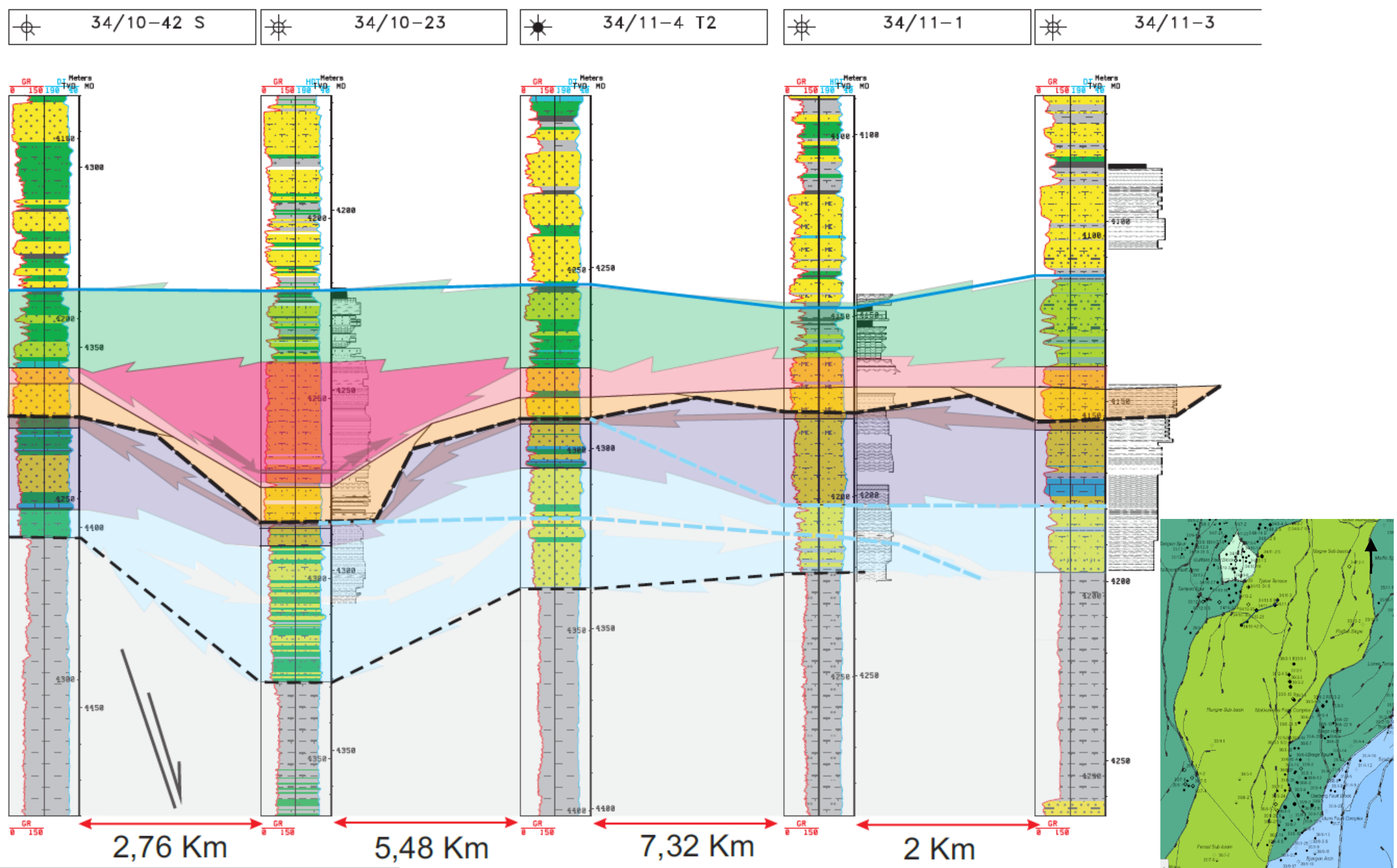


Figure 6.1: Cross section of the Lower Brent Group (Oseberg, Rannoch Etive and Lower Ness formation) In the Oseberg area, East-west



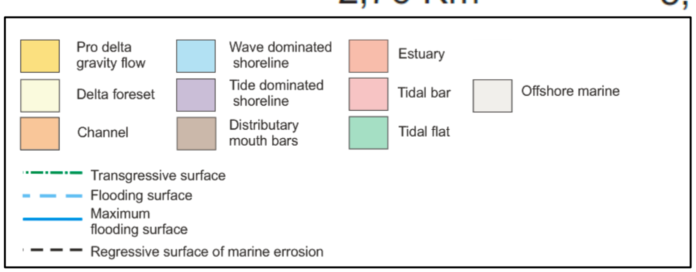
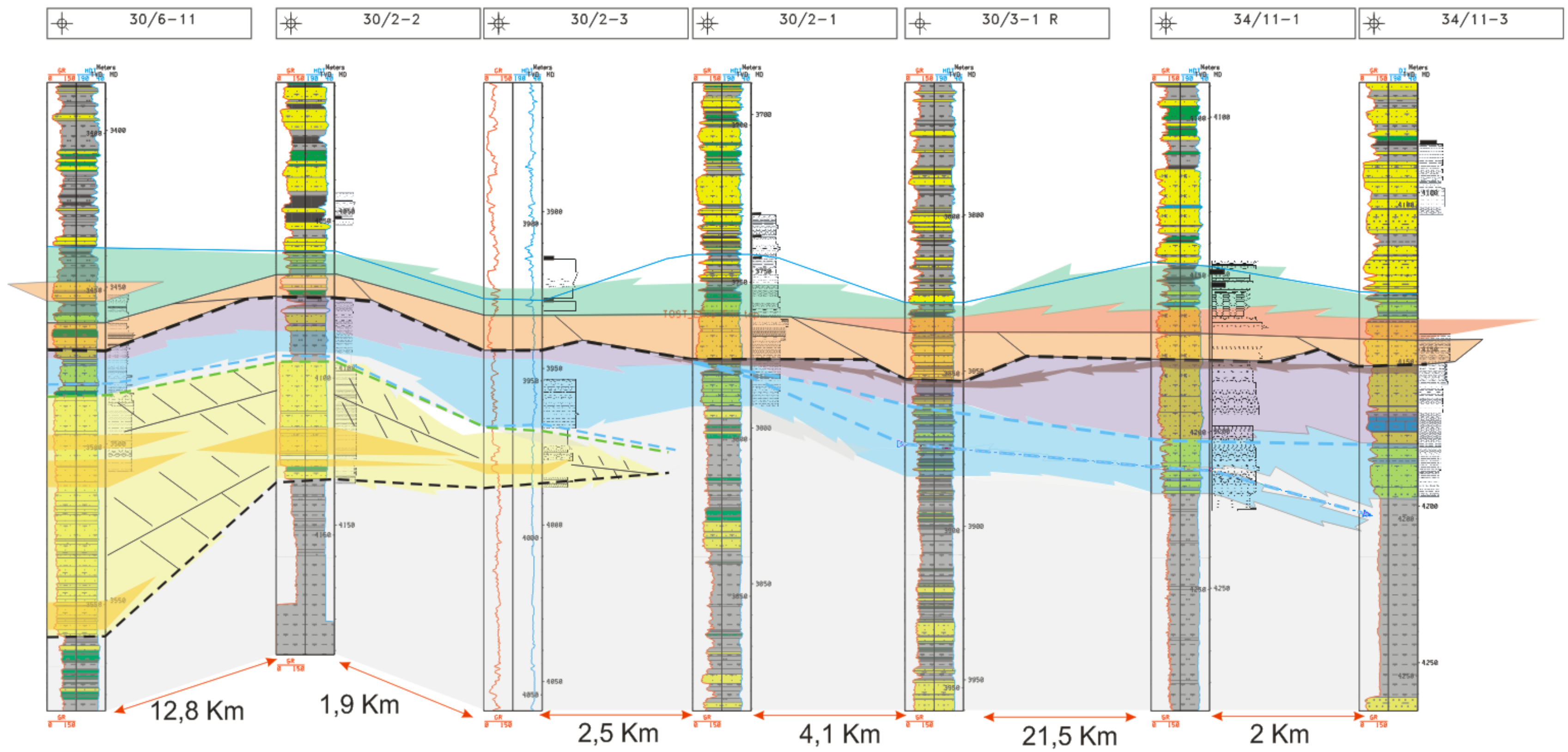
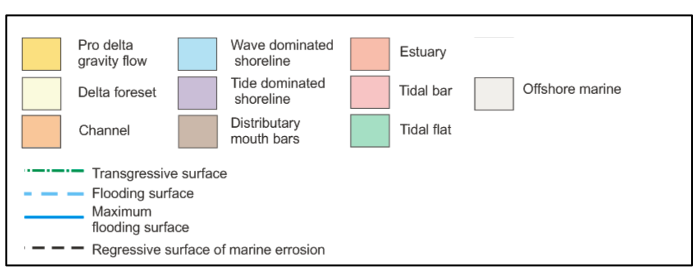


Figure 6.2: Cross section of the Lower Brent Group (Rannoch Etive

And Lower Ness formation) in the Kvitebjørn - Valemon area, East-west





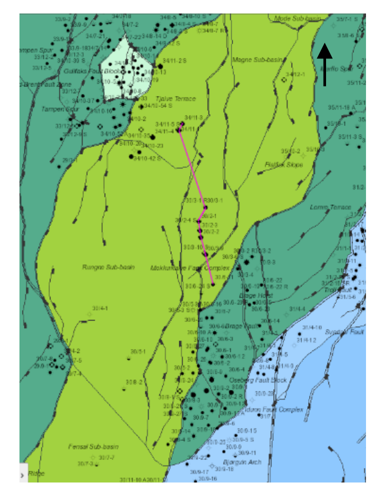
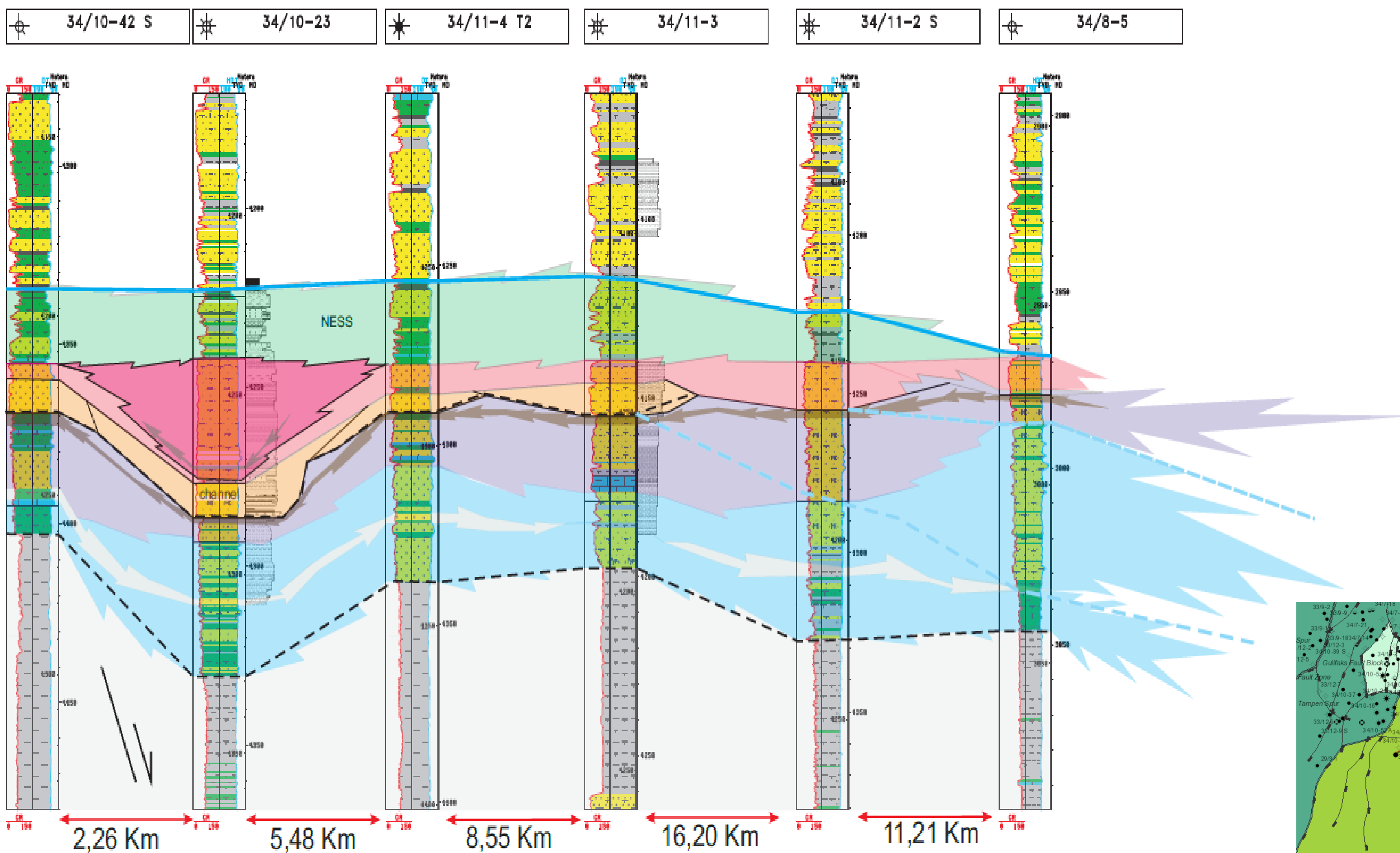
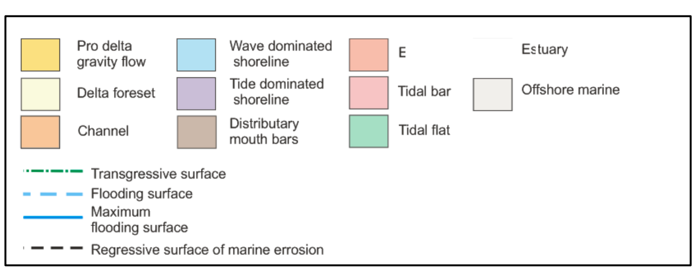


Figure 6.3. Cross section of the Lower Brent Group (Oseberg, Rannoch, Etive and Lower Ness formations) in the Huldra and Kvitebjørn Valemon area, south- north.





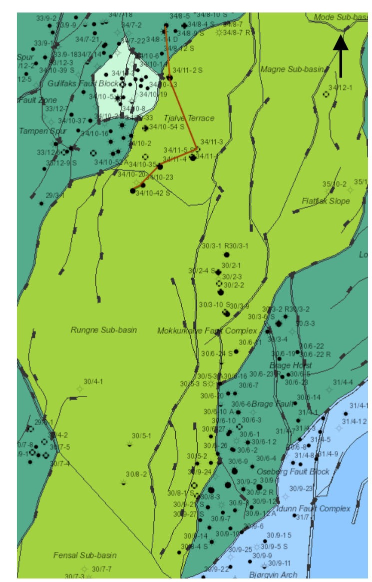


Figure 6.4 Cross section of the Lower Brent Group (Rannoch, Etive and Lower Ness formations) in the Kvitebjørn –Valemon area, south -north

6.2 Stratigraphy – (Oseberg, Rannoch, Etive and Lower Ness Formation) definition composite facies

6.2.1 Oseberg Formation

In The Oseberg Field (figure 6.1) the base of the Oseberg Formation is defined by a sharp contact between the shallow marine and deltaic sandstone/siltstones of the Oseberg Formation and offshore claystone/mudstone of the Drake Formation. However in The Huldra Field (figure 6.3) the Oseberg Formation is interfingering with the Drake Formation, indicating a gradual boundary. The abrupt relationship across the Oseberg Field suggests that the Oseberg Formation was deposited during a relative sea level fall, and that the boundary between Drake Formation and Oseberg Formation is a regressive surface (e.g Graue et al., 1987).

The lower part of the Oseberg Formation consist of gravity flow lobes which forms the delta front to prodelta, which is the more distal part of the delta. The lobes are thinning out toward the distal part of the delta, and disappears completely in well 30/9-19 (figure 6.1) and well 30/2-1 (Figure 6.3). Above the lobes, large scale cross-stratified sandstone facies are building out, the cross-stratified sandstone represent the delta foresets. The cross stratified sandstone are thickest toward the east in well 30/9-1 (figure 6.1) and towards north in well 30/6-11 (figure 6.3). The cross stratified sandstone is thinning out towards the west and north; where only a thin layer of cross stratified sandstone is present in well 30/9-19 (figure 6.1) in the west, and is completely gone in well 30/2-1 Figure (figure 6.3) in the North. This indicates that the delta was supplied form east and were prograding toward northwest. The delta forests are overlain by fluvial units of cross stratified strata that represent channels system that extends from well 30/6-9, 30/9-2 to well 30/9-3 A (figure 6.1). The channel-fill are overlain by marine units, on both the western side, the eastern side (figure 6.1) and in the north (figure 6.3) shoreline units are present with wave reworked sand units, which represent transgression and relative sea level rise. The drowning of the Oseberg Formation lead to deposits of the younger tidla flat deposits (Oseberg field) and lower shoreline inner shelf (offshore transition zone) deposits. This suggest that the marine flooding across the Osberg delta only readied the northwestern part of the Oseberg fault belt.

The upper boundary of the Oseberg Formation is normally defined by the transition into the Rannoch shoreline (see below). In the Huldra Field the Oseberg Formation represent a delta front while the overlying unit represent lower to middle shoreline deposits, which has been interpreted as a distinct flooding of the Oseberg Formation and the presence of a flooding surface (e.g Graue et al 1987). These observations have been used to argue for placing a maximum transgression at the boundary between the Oseberg Formation and the overlaying units, representing a transgressive surface followed by a pronounced flooding surface (e.g Løseth and Ryseth et al., 2003). However along the Oseberg west flank there appear to be intercalations of Oseberg type mass-flow deposit with Rannoch Formation shoreline deposits. The Oseberg Formation is overlain by fan -/braided plain deltaic deposits when time-equivalent with Rannoch Formation shoreline sandstones. The Oseberg west-flank area (Rugne sub-basin) in turn this suggest a more complex facies transition between the Osberg and Rannoch formations.

6.2.2 Rannoch Formation

The base of the Rannoch Formation is separated from the Oseberg and Broom formations by a transgressive surface, or by the Drake Formation by a regressive surface. The boundary between Rannoch Formation and Oseberg and Broom formations normally represent changes from fluvial dominated delta deposits to lower/middle wave dominated shoreline deposits which indicates a transgression (se section 6.1.1). The boundary between Rannoch and the Drake Formations is a gradual transition from offshore mudstone of the Drake Formation into shallow marine sandstone/siltstone of the Rannoch Formation representing a gradual shallowing upward section and a regression.

The Rannoch Formation comprises several high order flooding surfaces which is defining the Rannoch Formation shoreline clinoforms (shingles) and a high-order sequence set. These high order sequences shows a forstepping stacking pattern toward North in the Kvitebjørn-Valemon Field. This indicates that the supply of the Rannoch Formation overall was from the south and that the Rannoch Formation prograded northward. The gradually coarsening upwards trend of the Rannoch Formation, with rare fining-upward trends and interbedded mudstone is argumenta by Tore M. Løseth and Alf Ryseth (2003) to favor a prograding shoreline.

In the Kvitebjørn-Valemon area the Rannoch Formation transitions from Wave influenced shoreline into tide and wave dominated shoreline. This indicated changes from a exposed shoreline to a more protected embayed shoreline.

The marine units in the Oseberg Field interpreted as Rannoch time-equivalen equivalent consist of tidal flats and channels, interpreted as a braid plain. In well 30/6-9 and 30/9-1 (Figure 6.1) there are two thin channels present, while in well 30/9-3 A and well 30-9-2 (Figure 6.1) there are only one thick channel present. Hence the channels are better developed in well 30/9-3 A and well 30-9-2. On top of the channel-fill coal and bay deposits are is present, which indicates continued relative sea level fall.

The upper boundary of the Rannoch Formation is separated by a sharp and well defined contact from the Etive Formation in the East (figure 6.1). This observation indicates that the Rannoch Formation is a regressive fore-stepping shoreline. The regressive shoreline has been developed by competition between basinal processes (wave and tides) and fluvial outflow and supply (e.g R. Ravnås, et al 1997). The Rannoch has been interpreted as a low stand system tract of the Brent mega-cycle (Helland-Hansen, et al 1992). In the Oseberg Field the time equivalent Rannoch Formation consist fan-/braided plain deltaic deposits, the Huldra field the Rannoch Formation is represented by shoreline deposits.

Moreover the Rannoch Formation tidal strata over the Oseberg Field appear time-equivalent with typical Rannoch Formaition shoreline deposits over the Osberg west-flank area (well 30/9-19 figure 6.1) Hence the lower of the two Rannoch Formation shoreline units are correlated with and argue to interfingering with time equivalent Oseberg Formation from the Oseberg fault block to the east (figure 6.1).

6.2.3 Etive Formation

The lower channel complex of the Etive Formation is separated from the Rannoch Formation shoreline deposits by a regressive surface of marine errosion.

The basal surface that separates the Etive Formation from the Rannoch Formation representing the base of channel fill succession, is erosive, and there appears to be no interfingering of the two formations. However, in the western Oseberg flank the boundary between the two formations are gradual and there is some possibly interfingering (figure 6.2). The boundary between Etive and Rannoch formations is subsequently changing character laterally from being erosive on the structural highs such as in the Kvitebjørn-valemon and Huldra Fields to a conformable surface with interfingering character in the Oseberg western flank. Interpreted as the Etive channels are feeding the Rannoch system, indicating a prograding stacking pattern.

In the Kvitebjørn- Valemon arean the Etive Formation represented by distributary channel, mouth bar depositsoverlain by estuary and tidal flat deposits, which represent upper shore face to foreshore delta front and outer delta plain, as well as estuarine deposits. To the north Nøkken area well 34/11-2S the Etive deltaic estuarine deposits are replaced by upper shoreface foreshore strata, likely representing reworked mouth bars and active estuary (tide and wave reworked) tidal bar units. Both the Rannoch and Etive Formations has been interpreted as regressive (Grauer et al., 1987). However, the estuarine strata presented in the upper part of the Etive Formation in the Kvitebjørn -Valemon Field implies a sea level rise, which suggests a transgression. In turns the transgression was followed by a normal regression into the Ness Formation.

6.2.4 Lower Ness formation

The lower Ness is separated by sediments recognized as middle Ness. The lower Ness consist of marginal marine to bay fill mudstones and siltstones is interpreted to represent tidal flats and bay-fill units, deposed in a delta plain environment (Ryseth 1989, Ryseth & Fjellbirkeland 1995, Ryseth et al. 1998). This marginal paralic strata are overlain by middle Ness shallow marine strata, which implies a relative rise in sea level. This observation indicates that the middle Ness strata represents a candidate maximum flooding surface. In contrast to the Flooding surface across the Oseberg Formation the middle Ness marine flooding reclined beyond the Oseberg west flank area as indicated by the fluvial marginal marine to shelf mudstones in well 30/1-19 whereas thick coal bearing strata represent the equal maximum flooding interval in the paralic succession on the Oseberg and Broom area.

6.3 Area differences in ORELN (Oseberg, Rannoch, Etive and Lower Ness)- Central Viking Graben

6.3.1 Oseberg and Rannoch formations – Western flank

The Oseberg Formation in the Huldra Field consist of fining upward units of mass flow facies (Facies 1-5 table 1). The lower part the Oseberg Formation consist of prodelta to lower delta front debris flow/turbidite lobes (FA 1 table 2), overlain by and high scale cross stratified sandstone interpreted to be delta forests (FA 2 table 2) inturn overlain by uppward fining cross stratified sands interpreted as channels of delta topsets (FA 3 table 2). This indicates that the Oseberg Formation consist of prodelta, delta forests and delta topsets normally is interpreted as a fan delta sucsesson (Graue et al., 1987). However, the laterally extensive base Ness (lower Brent group) channel complexes present across the Horda platform (e.g Graue et al., 1987, Helland-Hansen 1992, Steel, 1993) would rather suggest a braid plain setting origin in turns suggesting that the Oseberg Formation should be interpret as a braid plain delta (Nemec et al., 1988, postma et al., 1984) This could correspondingly fit in as a delta located at a braided delta plain. The Rannoch formation marginal marine (tidal flat) deposits (FA 6 table 2), developed across these (well 30/9-19 and 30/9-1 figure 6.1) shoreline deposits (FA 4 table 2) gradually replaced towards the west.

Figure 6.1 shows a cross section of the Oseberg to lower Ness formation delta in the Oseberg Field, in a west- east direction. The Oseberg Formation is shaleing out towards the distal part of the delta. The Rannoch Formation is very thin in the Oseberg Field (figure 1). In well 30/6-9 there is a normal Rannoch Formation with lower to middle shoreline deposits is not present, while in well 30/9-3 30/6-9 and 30/9-2 the Oseberg Formation is overlain by tidal flat facie. The Rannoch formation is thickening toward west, where is an aggradational facies change from tidal flats to lower/middle shoreline.

The Rannoch formation is mainly wave dominated with some tide influence. In the Oseberg west-flank area there are isolated coarse sands units present in the Rannoch formation, interpreted as gravity flows from the Oseberg Formation. This observations indicate that the

Oseberg Formation is interfingering laterally into Rannoch Formation, while it has a sharp contact with the Drake Formation. The Rannoch formation is overlain by a distributary channel system that is building out across the Oseberg west flank area (Etive and Lower Ness formations). The Lower Ness is very thick and thickens toward west.

The thickening and facie changes attributed to syn-depositional faulting during deposition of the Oseberg and Rannoch formations. The units across structural/syn-deposited positional topography thicken in the downthrown areas indicating syn-depositional rotation of the fault blocks.

6.3.2 RELN – Kvitebjørn -Valemon Field

In the Kvitebjørn -Valemon Field the Rannoch formation consist of upwards coarsening units of storm wave and tide influenced facies. The lower part of the Rannoch formation consists of hummocky and swaley cross stratification and parallel lamination interpreted as lower to middle shoreline deposits (FA 4A table 2), while the upper part consist of hummocky cross stratification, swaley cross stratification and single and double mud drapes interpret as middle to upper shoreline deposits (FA 4B table 2). The degree of tidal influence increases upwards. The Etive Formation in the Kvitebjørn -Valemon Field consist of upwards fining fluvial and tide dominated units. The lower part consist of upwards fining three dimensional subaqueous sand dunes and cross stratification interpreted as distributary channels (FA 6 table 2) overlain by upwards fining cross stratified layers interpreted as tide influenced estuary (FA 7 table 2), well 30/10-23 bordered laterally by extensive tidal flats. The lower Ness consist of tidal flats (FA 9 table 2) and marsh (FA 10 table 2) deposits.

Along the west-east transact of the Kvitebjørn –Valemon Field (Figure 6.2) the Rannoch Formation shows a more or less similar thickness while the Etive Formation shows a significant thickening in well 34/10-23 associated with the processes of thick estuary fill sandstone. The Ness Formation shows relative constant thickness.

The Rannoch Formation has earlier been interpreted as a part of a wave-dominated delta (Richards and Brown, 1986 and Graue et al., 1987). Observation done in this thesis shows abundant tidal influence suggesting a mixed tide-wave influenced setting. In the lower part of the Rannoch Formation were wave storm beds are abundant there is less influence of tidal-current reworking. The upper part of the Rannoch formation is increasingly tide dominated unit. The amount of tidal influence suggest a more tide dominated shoreline setting, however the coocurrency with hummockey crossstratification and swaley cross stratification suggest that waves were still abundant. In turns shoreline suggest that there was a tidal-wave mixed settings but of increased tide dominance.

The wave dominated units thin out towards the western and eastern flanks of the Kvitebjørn-Valemon Field while the tide dominated units is thicker. Hence, the shoreline is interpreted to evolve from open to more protected embayed settings. Subsequently represent a channel complex built out on top of the Rannoch Formation, interpreted to the Etive Formation. The distributary channel complex is present in all the wells. The upper part of the Etive Formation contain tide dominated deltaic cross-bedding with mud drapes here interpreted as tidal dunes.

The succession with basal channel fills overlain by tidal dunes in turns capped by subtidal flats and outer embayment marginal marine strata is indicatively supportive of an estuary margin for the tidal dune succession. Hence it is argued that the distributary channels were transitioned into estuarine during the subsequently transgression.

The high amount of estuarine strata is problematic considering a wave dominated delta origin. The Etive Formation has a thick isolated sandstone unit in well 34/10-23 which is not present in any other well. The several tens of meters thick sandstone unit in well 34/10-23 is interpreted by Folkestad and coworkers (2014) as a fluvial complex in the Lower Ness. From observations done in this thesis the sand unit has been interpreted as a part of the Etive Formation (e.g Wei et al., 2016).

The thickness trends indicates the presence of an syn-depositional normal fault located between well 34/10-42 s and 34/10-23, influencing the deposition of the Etive Formation. The thick isolated sandstone unit in well 34/10-23 suggest presence of a local depocenter formed during active rifting. The deposits close to the footwall is thicker and thinning out towards north, indicating a rotation of the fault block. The thickening trend indicates that mainly the Etive Formation is affected by the faulting, while Rannoch and Ness formations are less effected. However, the change of facies in the Rannoch Formation; from wave dominated shoreline to tide dominated shoreline indicates a physiographic change. Hence, the transitions from open to protected shoreline may suggest fault influence as well. Another alternative for the facies changes is that the delta created an embayed coastline drowning progradation (Ainsworth et al., 2008). The thickness change in the Etive Formation, emphasizes physiographic changes. The syn-deposit also supports Helland- Hansen and coworkers (1992) observations, with a thickening of Osbeberg Formation. It is therefore postulated that the syn-depositional faulting in the Oseberg Formation continue during deposition of the Rannoch, Etive and lower Ness formations (in the Oseberg west-flank area).

6.3.3 Oseberg formation S-N

The Oseberg Formation in the Huldra Field consists of fining upward units of mass flow facies. In the lower part prodelta gravity flow lobes are present (FA 1 table 2), overlain by large scale cross stratified sandstone interpreted to be delta forests (FA 2 table 2). This indicates that the Oseberg Formation in the Huldra Field represent a pro-delta to delta front setting. The Rannoch Formation in The Huldra Field consist of wave and storm dominated shoreline (FA 4A table 2) replaced up-section by mixed-tide wave dominated shoreline deposits (FA 4B table 2).

There are two possible ways of interpreting the Oseberg Formation; as a part of the main Brent system or as an isolated detached system (Graue et al., 1987). The lower part of the Rannoch Formation in the Huldra Field is dominated by wave and storms dominated shoreline deposits. In the Oseberg Field the time equivalent Rannoch Formation consist of fan-/braided plain deltaic deposits. The fan delta of the Oseberg Formation in the Oseberg Field is located at the flanks of the uplifted basin, which is the source of the sedimentary supply. The Oseberg Formation is couple hundred km which implies that the uplifted basin alone could not be the only sedimentary source to the Oseberg fan delta. There are observations of channels in the Oseberg Field which indicates a braid plain as the second source. High amount of sedimentary supply and accommodation space created by the dome and distributary channels caused rapid outbuilding of the coarse sediments. When sedimentary supply and accommodation space were in equilibrium a transgressive system tract were created. As sedimentary supply diminished, the sequence were drowned in the Huldra Field. Sea level fall caused progradation of the fan delta, and branched fluvial channals build out on top of the Oseberg delta. During sea level fall the shoreline will move rapidly seaward by the process of forced regression. The Huldra Field will be located in the distal end of the fluvial succession causing the Rannoch Formation to be more marine, and a wave storm dominated shoreline was deposited. In the lower part of the Rannoch Formation (well 30/2-3, 30/2-1 and 30/3-1) there are isolated coarse sands units, interpreted as gravity flows from the Oseberg Formation. This observations indicate that the Oseberg Formation is interfingering into Rannoch Formation. Subsequently this indicates that the Oseberg Formation is Sourcing the Rannoch Formation from south west, but there will also be a source form the south.

In the Huldra area the Oseberg Formation is shaleing out towards the north (figure 6.3), in well 34/2-1 the Oseberg Formation is absent. The Oseberg formation is a lot thicker to the south (well 30/6-11). The thickening change is because well 30/6-11 is located more proximal delta whereas well 30/2-2 and well 30/2-3 is located more distal. The thickness variation containing thicker and additional pro-delta and delta front units as well as delta top channel fills probably also reflect an element of syn-depositional faulting as well 30/6-11 located on the middle part of the Huldra Field block, whereas well 30/2-2 and 30/2-3 are located updip on the Huldra Field Block. In the Huldra area the Brent shoreline was inferred to have faced deeper water, which had the effect of slowing down the northward progradation of the Oseberg delta (Graue et al., 1987).

The Rannoch and Etive Formation is thickening towards North (figure 6.3). This gradual thickening towards the north is explained in terms of a combination of accommodation from already existing space is front basinward of Oseberg delta deposition and increased subsidence rates northwards (Graue, et al 1987). In the North distal part of the delta (well 30/2-1 to well 34/11-3 figure 6.3) the Rannoch Formation has a sharp contact with the Drake Formation. The lower part of the Rannoch Formation is interfingering with the Oseberg Formation. The upper part of the Rannoch Formation consist of mixed tide-wave influenced sandstone. The tide dominated sandstone units are very thin proximal areas were the Oseberg Formation is present present (well 30/2-2, 30/2-3, 30/2-1 and 30/3-1), and thickens toward North in well 34/11-1 and 34/11-3. In well 30/2-1 a mouth bar is present in the upper part of the Rannoch formation and it continues all the way to well 34/11-1. Suggesting that the Huldra –Kvitebjørn -Valemon area represent dominantly delta front area during late Rannoch deposition. These Observation indicate that the Brent delta shoreline was more open during the initial stage of Brent delta progradation, and became increasingly embayed or protected, during establishment of the delta lateral delta-front. The Rannoch Formation is overlain by Etive channel complex, which is present in all the wells (figure 4). In well 30/3-1 R there are estuarine unit on top of the channel which is going toward south. The area where Oseberg Formation is present there are more storm and wave dominated deposits, while the areas where Oseberg Formation is absent there are more tide dominated deposits. The pinching out of the Rannoch Formation shoreline clinoforms towards north indicates that the Rannoch Formation in Kvitebjøn -Valemon is a younger than in the Oseberg Field.

6.3.4 RELN - Valemon- kvitebjørn- Visund SW-NE

In the Kvitebjørn Valemon field the Rannoch Formation consist of upwards coarsening units, where the lower part consist of wave and storm dominated lower to middle shoreline deposits (FA 4A table 2), while the upper part consist of tide dominated middle to upper shoreline deposits (FA 4B table 2). The Etive Formation in the Kvitebjørn Valemon Field consist of upwards fining distributary channels (FA 6 table 2) deposits overlain by upwards fining estuarine (FA 7 table 2) deposits in the upper part. The lower Ness formation consist of tidal flats (FA 9 table 2) and marsh (FA 10 table 2) deposits. (Detailed description in 6.3.2).

Figure 5.1 shows a cross-section from of the Rannoch, Etive and Lower Ness ormations in the Kvitebjørn –Valemon area across the Northern discovery of Visund field, west-east north-south direction. The Rannoch Formation has a more or less uniform thickness moreover a little bit of thickening towards the north and the pinches out. Etive Formations shows the same thickening trend towards north as for the Rannoch Formation, but has a significant thickening in well 34/10-23, which is not present in the Rannoch formation. The Lower Ness shows a thinning towards the North. The left we part of the profile is similar to that of figure 6.2 and the discharge present in section 6.3.2 also appears here.

The thickening of the Rannoch Formation towards north indicates that there was a deepening of water and hence inversed accommodation space. Northward in the Valemon-Kvitebjørn area the Rannoch Formation is overlain by distributary channel complex, ascribed to the Etive Formation. The Etive distributary channel complex is present in all wells except the two well 34/11-2 and 34/8-5, where the distributary channels are replaced by estuarine strata. Subsequently the channels are overlain by estuarine strata, which is present in al wells. Well 34/11-2 has not been interpreted in detail but core pictures from NPD has been investigated.

This well the Etive Formation contains coarse marine sandstones alternating with horizontally to slightly inclined parallel-stratified sandstone that contains bidirectional cross stratification indicating mixed or alternately wave and tide influence respectively.

These observation indicates that the well is located at the outer part of on estuary, likely the inferred upper Etive estuary tidal flats argued present across the Valemon-Kvitebjørn area.

6.4 Sequences

Based on the stratigraphy and component facies (5.1) the Lower Brent Group is divided into two sequences in accordance with Johannessen and coworkers (1995) and Helland-Hansen and coworkers (1992).

Sequence I

The first sequence comprises the Oseberg Formation which is bounded at its top by a flooding surface (e.g Graue et al., 1987). Underneath this flooding surface transgressive shoreline strata of Rannoch formation is separated from a major channel complex of the Oseberg Formation by a transgressive surface (e.g Løseth and Ryseth 2003). The transgressive surface is placed close to the flooding surface. Uplift and erosion of the Central North Sea as well as basin-marginal hinterland, caused fluvial systems to prograde westwards, which was the Oseberg delta building out on top of the Drake Formation. A regressive surface of marine erosion is placed between the offshore mudstone from the Drake Formation and fan delta sandstone from the Oseberg formation. The delta complex occupies the southeastern part of the Northern Viking Graben and prograde towards northwest.

The transgressive segment is characterised by upward fining sequences of shoreline deposits. The Oseberg formation is interpret to interfinger with the Rannoch formation which indicates that the genetic sequence and the transgressive segment are capped by a higher order flooding surface, defining the transition into sequence II.

Sequence II

The Second sequence is bounded at tits top by a candidate maximum flooding surface separating lower Ness tidal flat strata from middle Ness marine strata. Underneath the flooding surface a transgressive succession is represented by estuarine, i.e. estuary tidal bars and tidal, strata. A regressive surface of marine erosion is present between the shoreline strata of the Rannoch formation and the channel complex of the Etive Formation(figure 6.2). The Rannoch Formation comprises a succession of regressive shoreline deposits. These define a series of coarsening upwards motifs capped by high-order flooding surfaces. The coarsening upwards motifs representing a progradational sequence set, with the flooding surfaces defining a series of shoreface clinoforms. The high-order nature imply with parasequences thinning and tapering out between closely spaced wells (e.g. Figure 6.3 and 6.4), suggest that these likely can be correlated over short distances only. The delta complex occupied the central (and axial) part of the Northern Viking Graben and prograded towards north.

The transgressive segment is characterised by thick sandy packages comprised by massive coarsening and fining upward units representing an estuary complex with stacked tidal dunes and tidal channel fills. The estuary complex translates laterally into broad tidal flat successions to the west and east (e.g Figure 6.2). The genetic sequence and the transgressive segment are capped by marginal marginal marine mudstone and coal, here interpreted to represent a candidate maximum flooding surface.

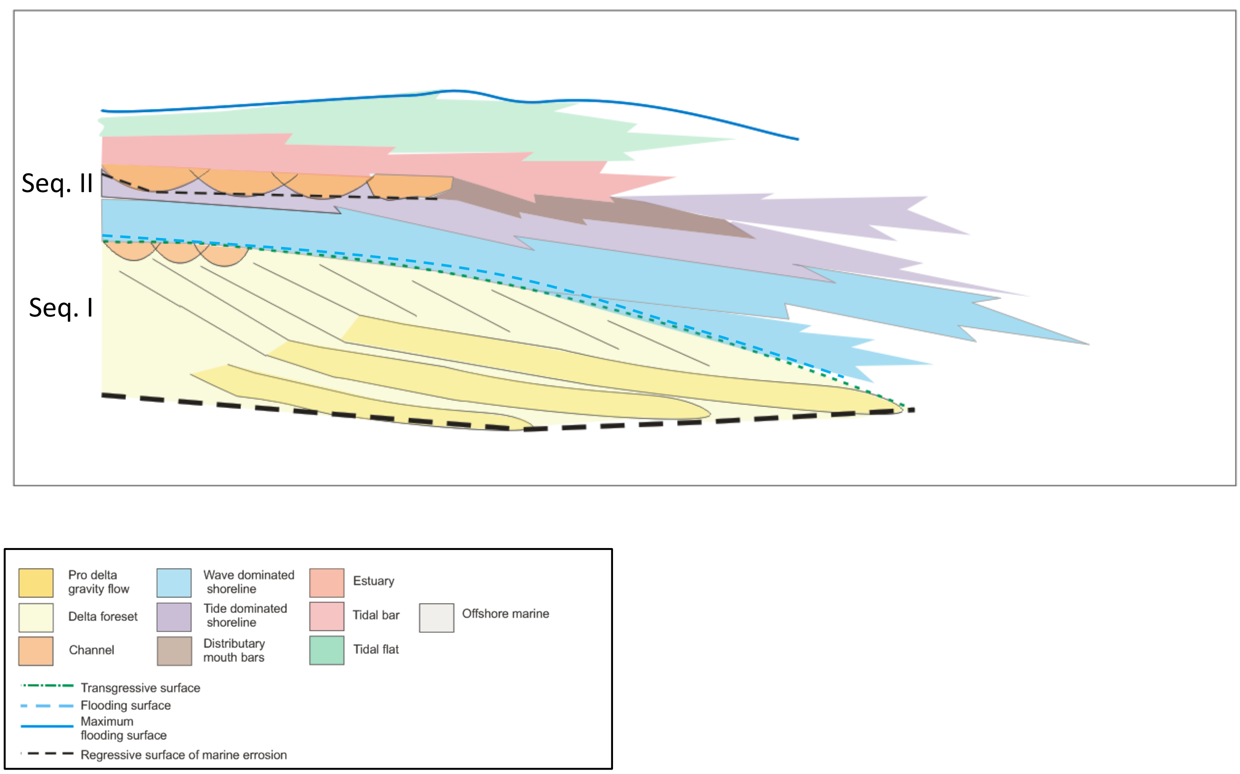


Figure 6.5. Cross strata architecture of Lower Brent (Oseberg, Rannoch, Etive and Lower Ness formations) and Lower Brent Key architecture.

6.5 Palaeogeographie of the Lower Brent Group

Two depositional sequences of the middle Jurassic lower Brent group has been identified. The sequences represent the geological development of the Brent deltaic system through the main phases of progradation, retrogradation and drowning (sequences 6.3). These observations are used to build a series of palaeographic maps to illustrate the evolution of the Lower Brent Group.

6.5.1 Stage I Aalenina –Oseberg and Broom and basal Rannoch formations

The Oseberg fan delta is located along the Oseberg and Huldra area, while the Broom fan delta is located at the Martin-Linge-Brent-Statfjord area, i.e. at the eastern and western flansk of the Northern Viking Graben, respectivley (figure 6.6). The Oseberg delta top is located in the central and southern parts of the Oseberg Field. The delta front is located over the Huldra field with possible shoreline deposits in the northern flanks. Distributary channel are suggested to be located in the lower parts of the half graben/fault block. The delta is earlier interpreted to be deposited as a response to uplift in the east area (Graue et al., 1987) with the size of the delta, i.e. the landward fluvial/alluvial area, rather favouring a braid-plain as the delivery system. There is an analogue system along the western flank of the Northern Viking Graben, the Broom delta, whereas an axial delta, the initial Brent delta had already reached the Rungne sub-basin and started to interfinger with the two transverse deltaic systems.

6.5.2 Stage II, III and IV late Aalenian - Rannoch Formaiton

In Late Aalenian the sea level started to rise resulting in the Brent delta to build out towards north across the Oseberg field (figure 6.7). The Rannoch shoreline sandstones was sourced form a fluviodeltaic system likely located in the south east (Oseberg Field) and from the south, i.e. located within the Northern Viking Graben / Rungne sub-basin. The Brent delta continued to prograde across the Kvitebjørn-Valemon field (figure 6.8) with broad and deep distriutary channels now forming parts of the lower delta plain (e.g Ryseth and Løseth 2003). The Rannoch shoreline transitioned from open wave dominated shoreline into a protected tide dominated embayed shoreline (figure 6.9) as the delta filled in the gently structured fronting shelfal area. During peak regression The axial fluvial system was positioned across the Kvitebjørn-Valemon area (figure 6.10).

6.5.3 Stage VI Late Aalenian to early Bajocian - Etive formation

In the Late Aalenian to Early Bajocian the sea level started to rise, which led to retreat of the Brent delta, indicating that a maximum regression should be positioned between stage IV and stage VI. The retreat of the delta resulted in the formation of extensive estuary systems (Figure 6.11), which was fed by fluvial channels from the south (Ravnås et al., 1997). By analogy, another candidate estuary system was likely located to the east of the Kvitebjørn field in the Magne sub-basin (not studied in this thesis).

6.5.4 Stage VII Early Bajocian late Bathonian - Ness Formation

In The Early Bajocian to Late Bathonian the Brent delta was gradually drowned over the northern parts of the Viking Graben, causing the delta to retreat southwards (Figure 13). As a result, shorelines with a broad embayment was established within the Rungne sub-basin, with the fluvio-deltaic system now positioned to the south of the study area.

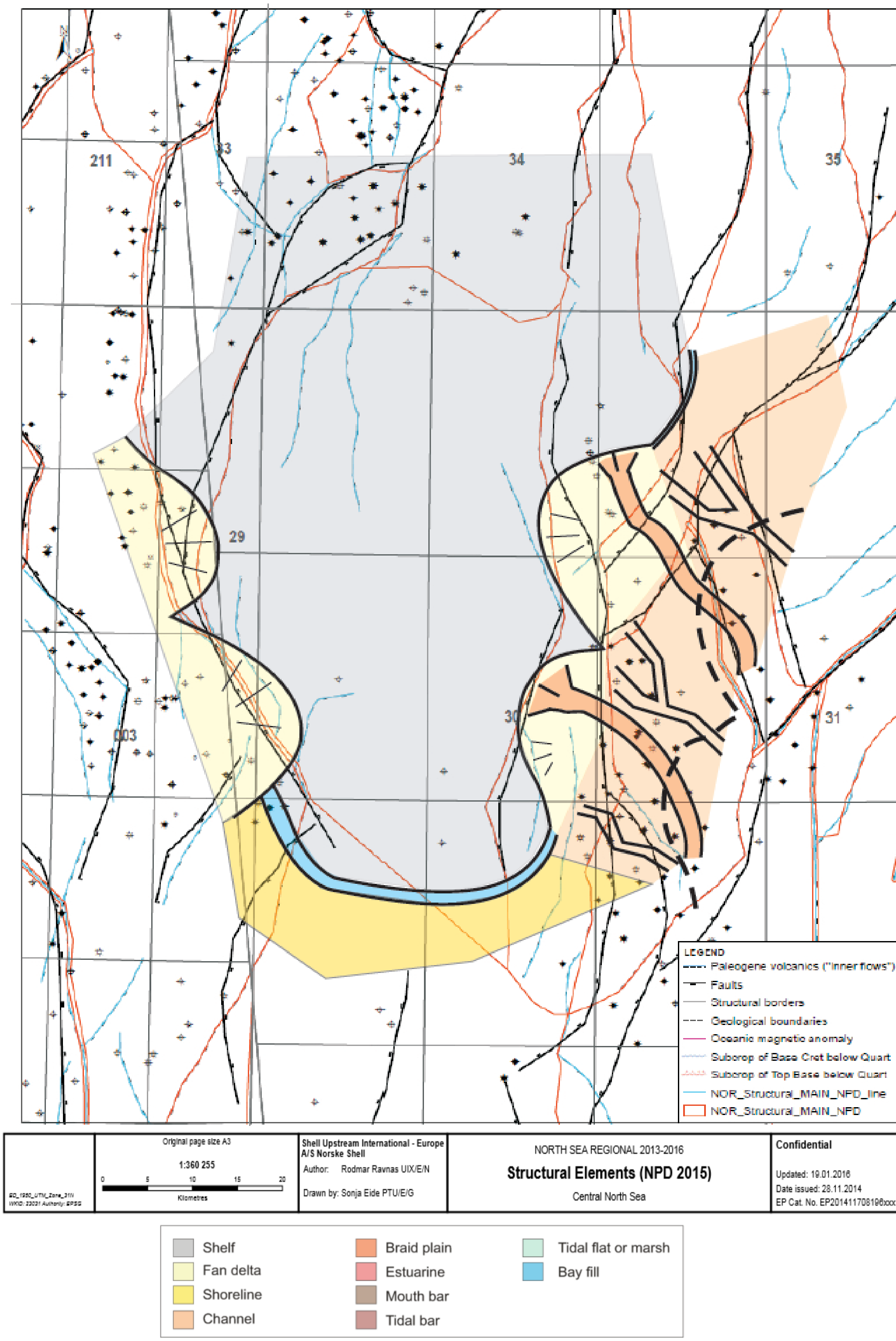


Figure 6.6: Schematic models for palaeogeographical setting during stage I deposition of prograding Oseberg Formation

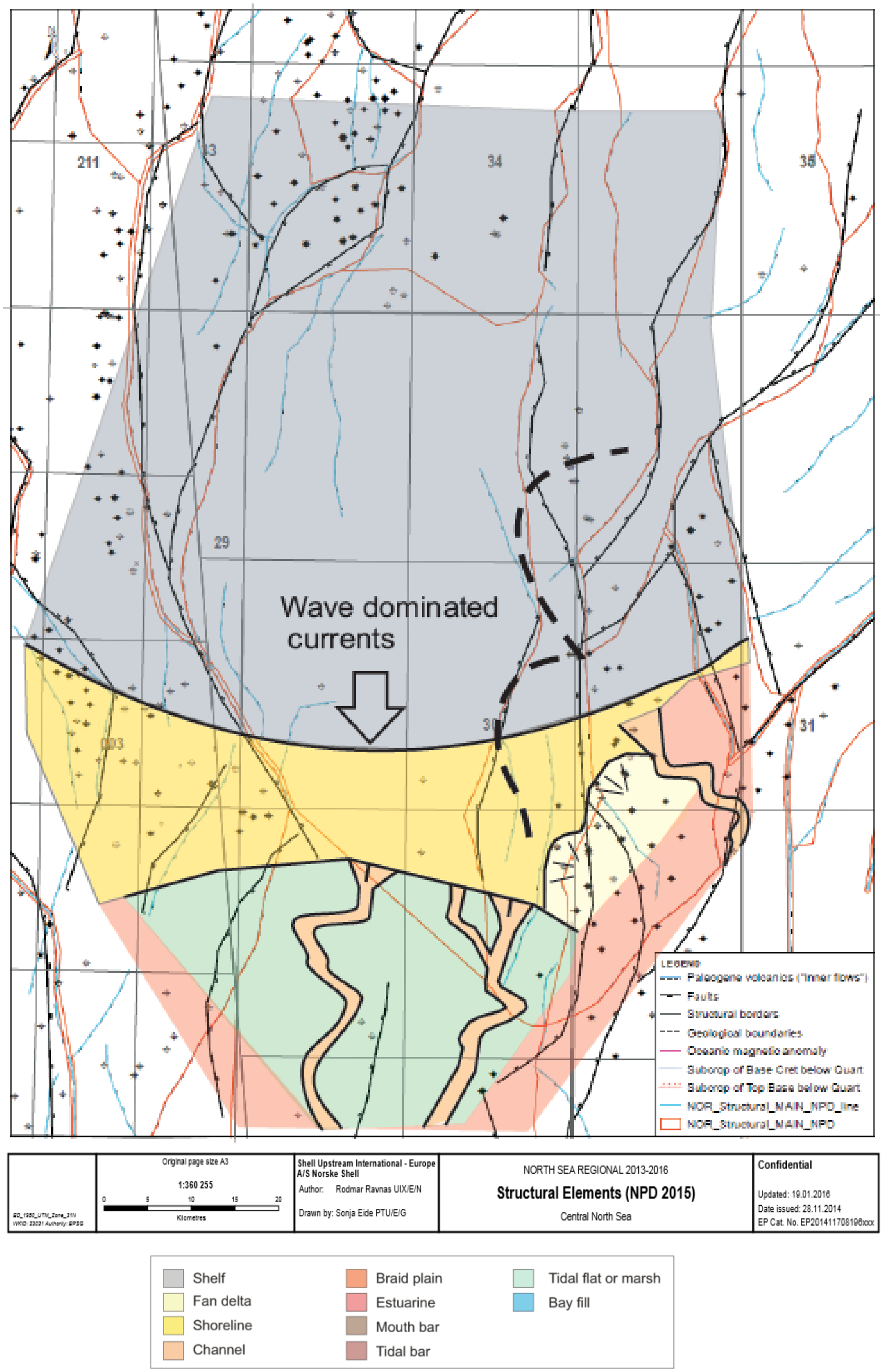


Figure 6.7: Schematic models for palaeogeographical during stage II and deposition of Rannoch formation. Shows the Progradation towards north

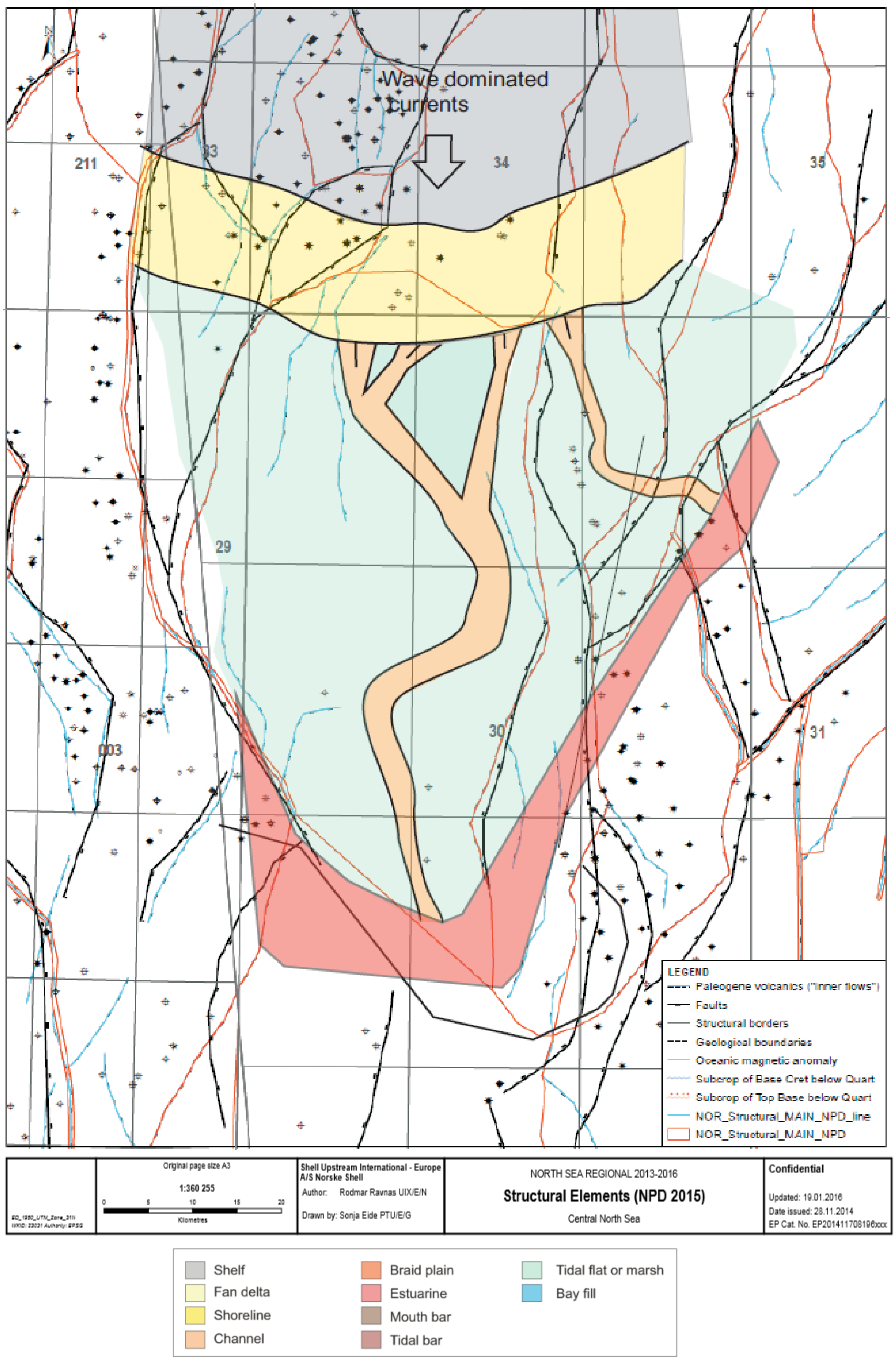


Figure 6.8: Schematic models for palaeogeograpy during stage III and progradation of the Rannoch formation across Kvitebjørn-Valemon field.

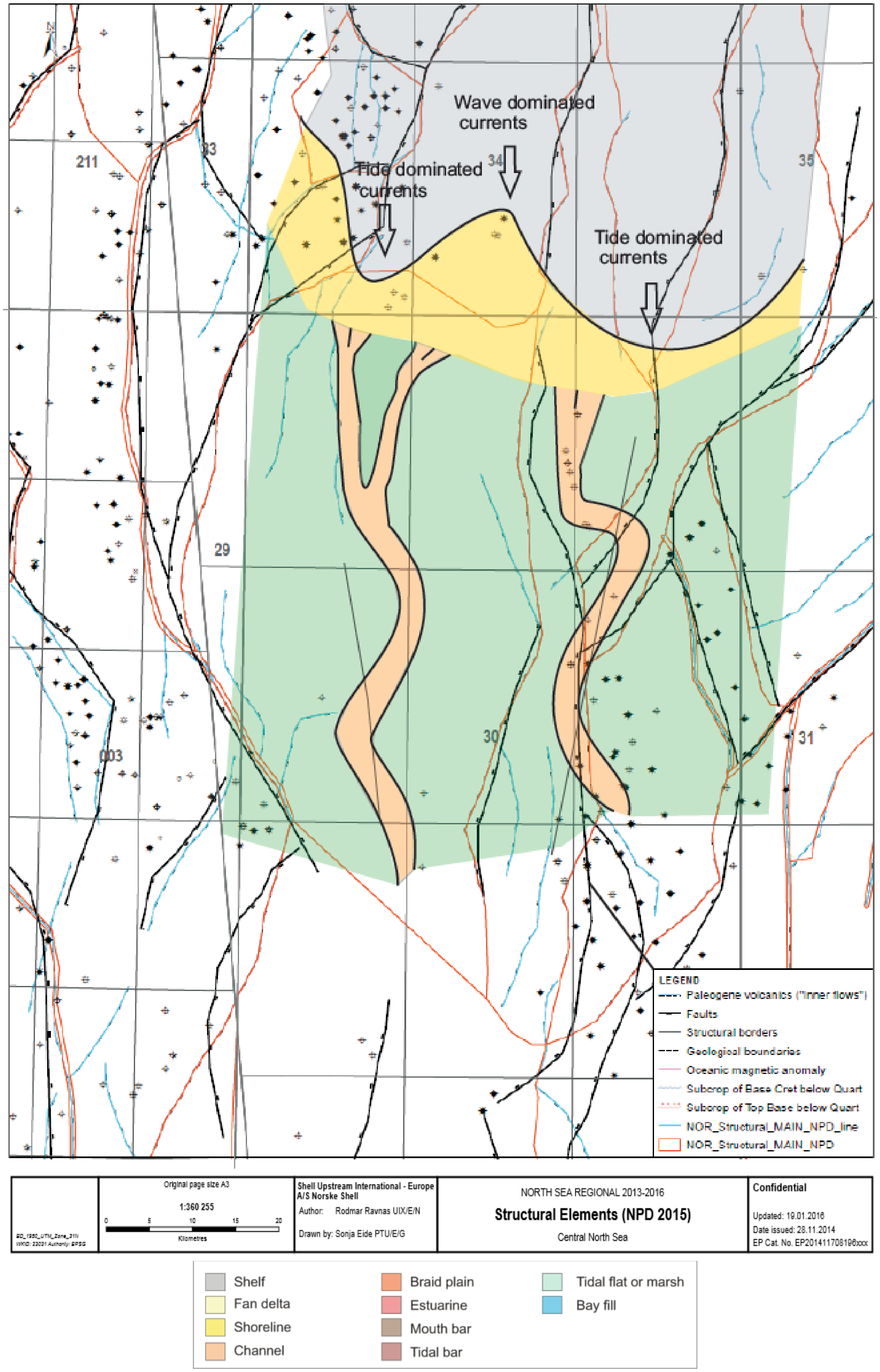


Figure 6.9: Schematic models for palaeogeography during stage IV and transition of a exposed shoreline to a protected embayed shoreline.

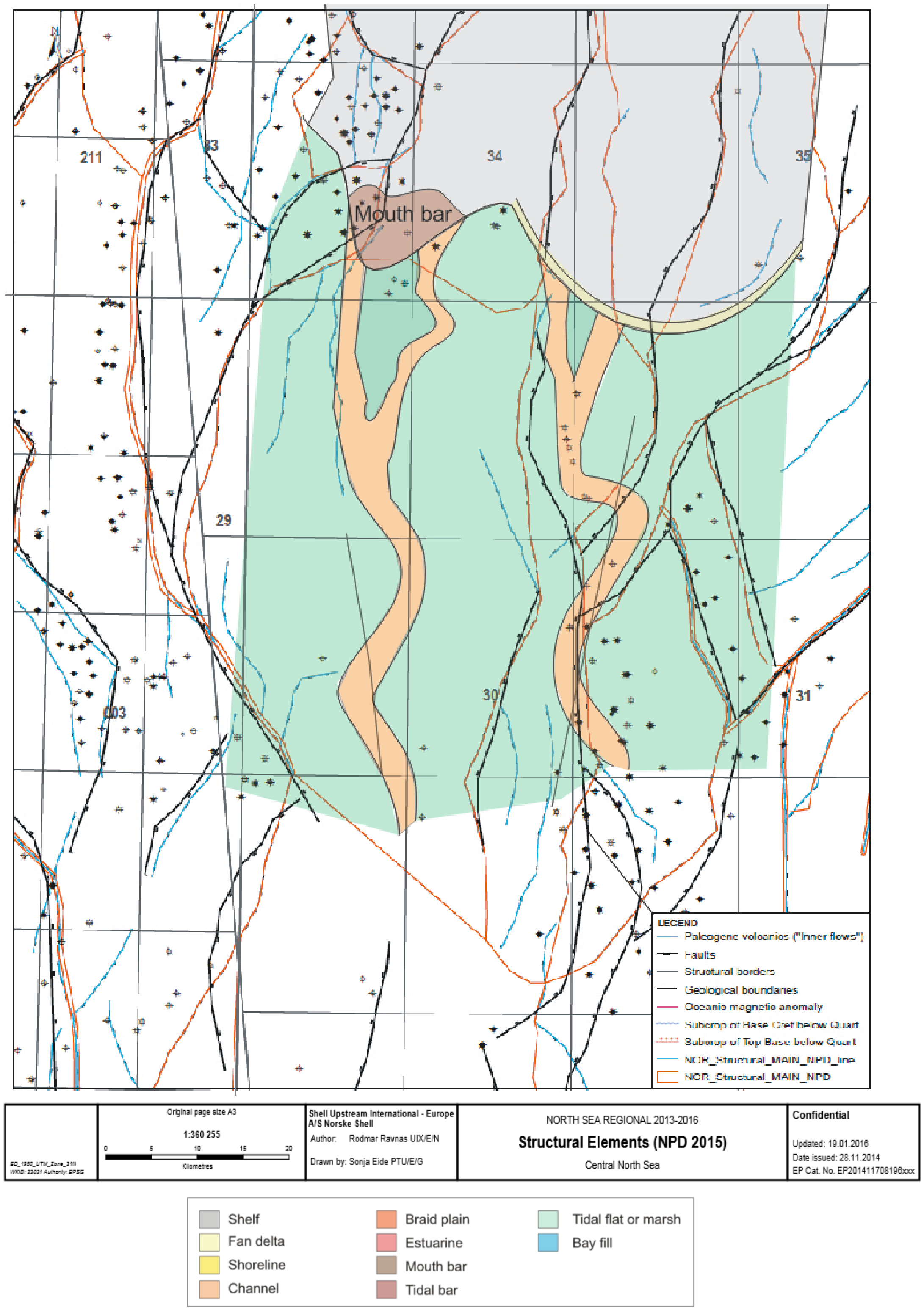


Figure 6.10: Schematic models for palaeogeography during stage V, Etive channals prograde across Kvitebjørn-Valemon area

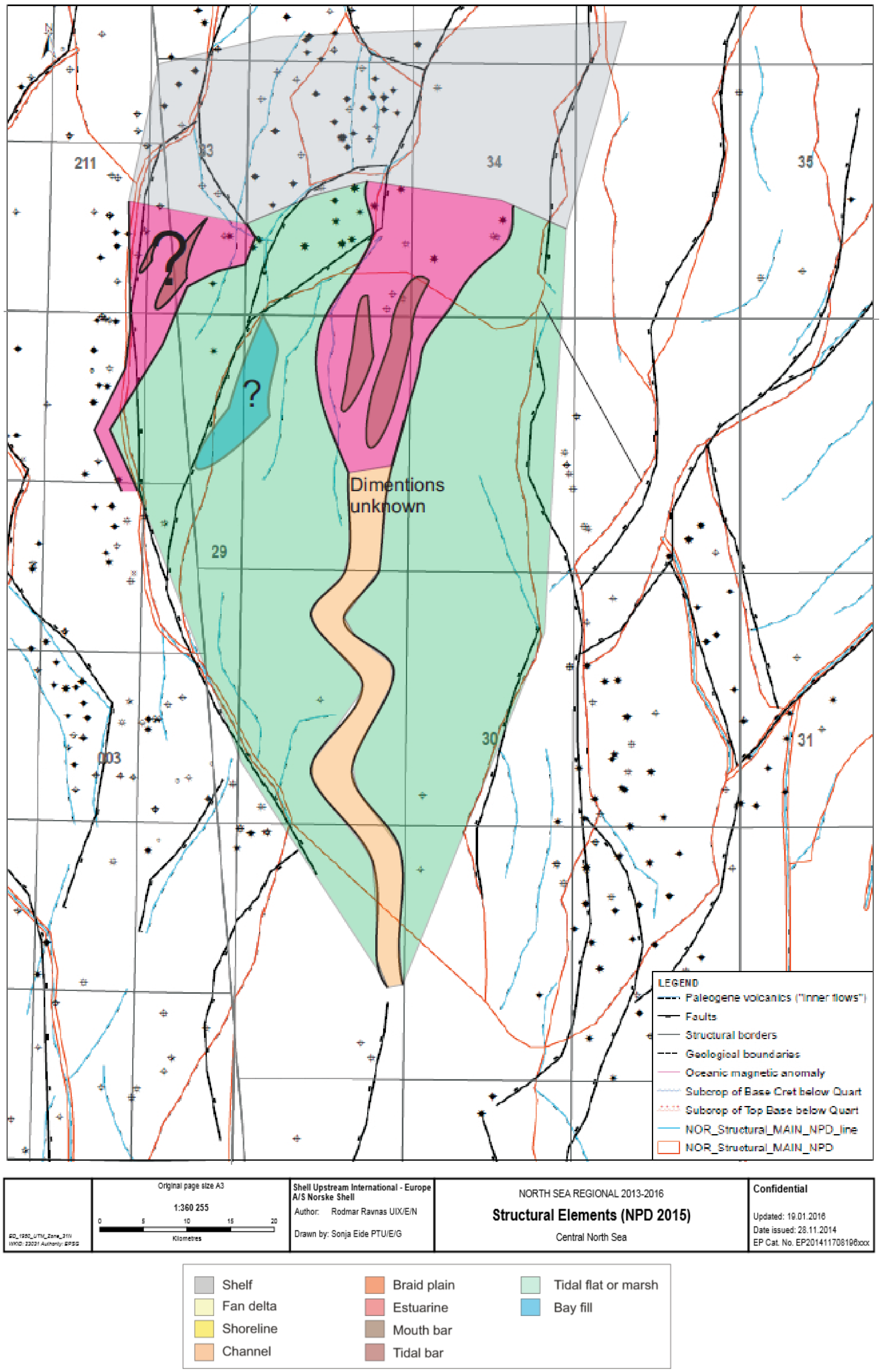


Figure 6.11: Schematic models for palaeogeography stage VI, shows a transgression and deposition of the Etive Formation Estuary

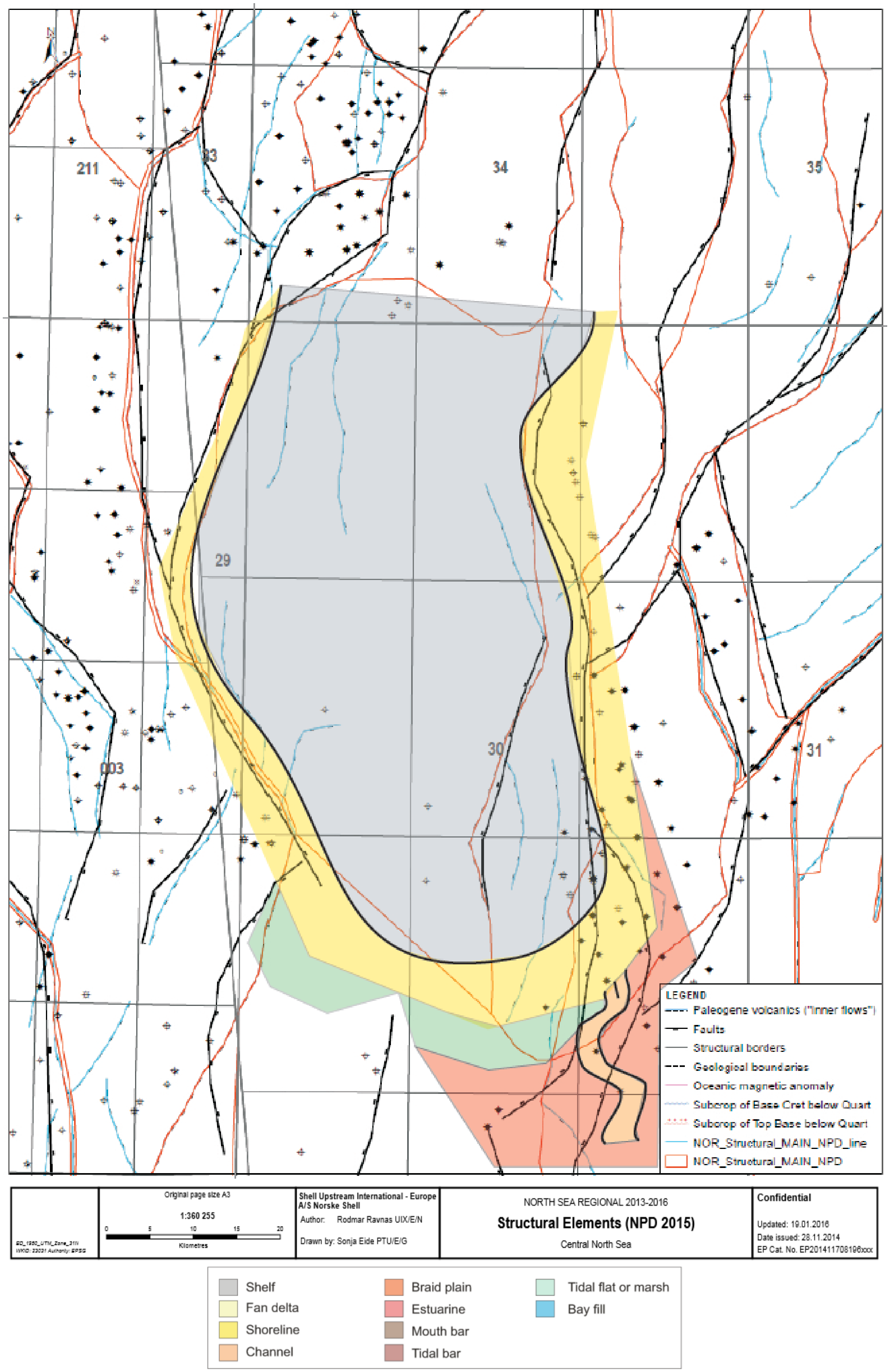


Figure 6.12: Schematic models for palaeogeography of stage VII and the drowning of the brent delta, resuting in deposition of middle Ness bay deposits.

7.0 Reservoir quality

The sandstone of the Brent Group are primarily comprised of sublith-arentite, although they have been extensively modified during diagenesis. Brent Group sediments are underlain by a thick sequence of mudstones and siltstones of the Drake Formation and overlain by Heather Formation mudstones which provide a stratigraphic seal for the reservoirs.

Deeply buried reservoirs with moderate to good porosity can have a very low permeability, related to dominance of micro-porosity due to extensive illitization. On the contrary moderate to high permeability values in other deeply buried reservoirs occurs where kaolins are little affected by illitization (Ramm, 2000). Illitzination requires potassium, which derived mainly from dissolution of K-feldspar. Sediment of the Brent Group were sourced from K-feldspar poor provinces during maximum progradation. Sandstone deposited during this time are less exposed to illitzation and has better permeability at deep burial than reservoir sandstones that initially contained more K-feldspar. In the Rungne sub-basin the Brent Group is buried to depths of <3000 m, K-feldspar and kaolins coexist whereas illitzed kaolins are expected to be of little impact (Ramm, 2000).

The Oseberg formation massive sands forms connected lobes that has good reservoir potential. The cross stratified sandstone has also good connectivity and has good reservoir qualities. However, the Oseberg is thinning towards the north, and will then not be present in the area of interest.

The Rannoch Formation comprises of a series of stacked upwards coarsening very fine to fine grained micaceous sandstones. The Rannoch Formation shoreface sandstone form laterally continuous sheet sandbodies, indicating initially good reservoir potential (Daws, 1992). The tidal channel and estuarine sandstones from the Etive Formation is well sorted and has good lateral and vertical connectivity. Both the Rannoch and Etive Formations thickens towards the North and is likely present in the deep Rugne Sub-basin, likely with thickened unit relative to the adjacent fault block/terraces.

However, the deep burial in consort with initially high content of mica and finer sediments suggests that compaction impairment may be severe. Accordingly poor reservoir properties is the likely scenario for finer grained, mica rich or silty/muddy sandstones like the Rannoch Formation lower middle shoreface succession and the Etive Formation middle upper tidal flat strata.

8.0 Discussion

8.1 Oseberg formation

The Lower Brent Group is generally divided into two separate systems the Oseberg and Broom Formation representing an older basin margin developed or lateral/transverses system, and the Rannoch, Etive and Lower Ness as the younger axial system derived from the uplifted part of the Central North Sea (Graue et al., 1987, Helland- Hansen et al., 1992, Steel et al., 1993).

The Oseberg Formation fan delta in the Oseberg Field comprises the delta top, while the Huldra Field comprises a delta front, with shoreline in the, the Oseberg and Broom flanks. The overlaying unit in the Huldra Field consist of shoreline deposits of the Rannoch Formation, in the Oseberg Field the overlaying unit comprises a tide influenced braid plain deltaic deposits time-equivalent with Rannoch Formation shoreline sandstone. The Oseberg fan/braid plain is sourced from the uplifted basin margin, and a braid plain located behind the Oseberg fan delta. High amount of sediment supply during falling relative sea level created by the dome caused rapid outbuilding of the coarse sediments of the fan/braid plain deltaic system. When sedimentary supply and accommodation space were in equilibrium the delta started to aggrade. As sedimentary supply diminished, the Oseberg Formation were drowned in the Huldra field. A sea level fall caused the delta to start prograd and with flooding reading as far south as the Oseberg Field where tidal flats were established between the coarse distributary channels, creating fan -/braided plain which is the time-equivalent unit of the Rannoch

Formation. When the system prograded it transitions into a shoreline. Which indicates that the Shoreline deposits of the Rannoch Formation in the Huldra Field will be located at the distal end of the fluvial succession. In well (30/2-1, 30/2-3, 30/3-1 and 30/9-19) there are observed coarse isolated sand bodies in the Rannoch Formaiton shoreline deposits. This sandbodies are emplaced by debris flows from the Oseberg Formation fan delta.

These Observation indicates an interfingering between the Oseberg and Rannoch formations. Subsequently this indicates that the Rannoch Formation in the Oseberg Field is recording a transition from fan deltaic/braid-plain deltaic conditions into a braid-plain delivery system feeding the frontal Rannoch-Etive deltas and shorelines. Which is used as an argument to state the Oseberg system as a part of the main Brent system.

8.2 Processes of Rannoch and Etive Formations

The Lower Brent delta is in general interpreted to be a wave dominated delta (Richards and Brown, 1986, Graue et al., 1987). However, there are abundant tide dominance in the Rannoch Formation. The lower part of the Rannoch Formation is mainly composed of hummocky cross stratificated, swaley cross stratificated, and parallel laminated sandstone with bioturbated intervals. However occurrence of single and double mud drapes in the lower part of Rannoch Formation indicate tidal influence. In the upper part of the Rannoch Formation there are mainly tide dominated deposits with double and single mud drapes in well sorted sandstone. Another criterion for the tide dominance is the presses of tidal bundling strata. This is displayed by repetitive mud drapes and sand layer thickening and thinning within cross strata forests and bottom sets reflecting tidal frequency of slack water periods (e.g Wei et al., 2016, Steel et al., 2012). The Etive Formation consist of well sorted sandstone with mud layered sections, and cross stratified sandstone, which indicates channels and estuarine deposits. The cross strata has sigmoidal and tangential shape, enclosed within mud drapes. The sigmoidal shaped cross strata is deposit in channels or at margin of bars in an estuarine environment, and indicates tidal influence. This indicate that both the Rannoch and Etive Formation within the Rungne sub-basin area represent units of tide influence. The

Rannoch Formation show interaction of storm-wave and tidal current possesses, while the Etive Formation shows tidal influence. This indicates a more tide dominated delta then predicted ealyer studies of Richards and Brown (1986) and Graue and coworkers (1987).

8.3 Post-rift tectonic activity

The exact timing of the mid Jurassic rifting has been discussed in several studies. The Jurassic rifting is poorly understood due to subtle rift initiation indicators (Davies et al 2001, Folkestad et al 2014). It has been suggested that the rifting started during late Bajocan with the deposition of the Tabert Formation (Johannessen et al., 1995; Løseth et al., 2009) other workers suggest that the rifting started in the Bajocan with deposition of the upper most Ness Formation (Helland-Hansen et al. 1992, Fjellanger et al. 1996, Færseth 1996). However, Ravnås et al (2000), Olsen and Steel (1995) Folkestad et al (2014) interpreted the rifting to start as early as Late Aalenian to Early Bajocian.

The Oseberg Formation shows a change in thickness, which indicates faulting. The formation is thinning in the upthrown areas while thickening in the downthrown areas which is argued to be a result of fault-block rotation. The thickness change of Rannoch Formation is not significant. But it shows thickening towards north which can be explained by deepening of waterin front of the underlying Oseberg succession. Fault movement could lead to increased subsidence which caused the irregular delta-front morphology (e.g Folkestad et al 2014). There is a facies change of the Rannoch Formation from wave dominance to a more tide dominated shoreline. This change in shoreline facies tracts argues for a change from an exposed to a more protect shoreline, likely in response to continued fault activity. The Etive Formation shows large thickness changes especially in well 34/10-23, and a thickening towards north. The Lower Ness also shows thickness variation when flattened on the flooding surface. Hence the faulting inferred to here started during deposition of the Oseberg Formation continuous into the Rannoch and Etive formations, as well as early Ness.

8.3 Future work

Because of the time limit there was not time to get the biostratigraphy delivered. To get a better understanding of the Lower Brent Group investigation of biostratigraphy is preferred. To get a better prediction of the advance of the Brent delta areas in the east should be investigated. Seismic should be interpreted to better tie the date together.

10.0 Conclusion

In this thesis a well systematic documentation and illustration of the stratigraphy, reservoir architecture and reservoirs qualities of the Lower Brent group (Oseberg, Rannoch, Etive and Lower Ness Formations) in the central parts of the Northern Viking Gragen or the Rungne Sub-Basin and adjacent terraces.

In this study 19 facies were distinguished in the Lower Brent Group (Oseberg, Rannoch, Etive and Lower Ness Formation) in the Northern North Sea, based on core description. The facies were used to characterize 12 facies association representing a depositional sub-enviornment. Three depositional systems where interpreted comprising; braid-delta depositional systems, shoreline depositional system, estuarine depositional system and delta plain depositional system.

4 well correlations were produced to illustrate the stratal architecture, based on the facies, sequence stratigraphy and partitioning of depositional sub-environments. The first well corelation from southern area (Oseberg), the second from east to western are (Valemon-Kvitebjørn), the third from south to north (Huldra- Valemon-Kvitebjørn) and the fourth east northwest (Valemon-Kvitebjørn). The Oseberg to Lower Ness are represented by two sequences. Each with a regressive and transgressive segments and bound by a flooding surface.

Higher order sequences forming a forstepping sequence set constitute the second sequence or the REN regression. The Oseberg sequence is represented by a prograding fand delta, aggrading channals, with a transgressive surface and a not significant flooding surface on top. The Rannoch to Lower Ness Formations are represented by a prograding shoreline, a transgressive Estuary and a major flooding which is candidate for a maximum flooding surface.

7 palaeographic maps were drawn to show the palaeogeographic evolution of the Oseberg, Rannoch, Etive and lower Ness Formations. The Maps were based on the facies association, stratigraphy and sequences.

The Brent delta is interpreted to be a more tide dominated delta, then earlier predicted. This is based on observation of single and double mud drapes and tidal bundles in the Rannoch Formation, and the amount of estuarine deposits in the Etive Formation.

The Oseberg Formation was interpreted to be a part of the main Brent system, based on the lateral interfingering of the Rannoch Formation, indicating that the Oseberg delta was still prograding in the Oseberg Field during deposition of Rannoch Formation.

The current study imply that the Oseberg, Rannoch and Etive formations is effected by the Jurassic rifting event. This is seen by the change of thickness in the Oseberg Formation across the Oseberg and Huldra area, thickness chancges of the Etive Formation in the Valemon-Kvitebjørn area, and the changes of facies in the Rannoch Formation in Huldra, and Valemon-Kvitebjørn area.

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