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The Cook Formation Reservoir Architecture, Stratigraphy and Paleogeography in the Tampen Spur Area

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Abstract

This thesis describes the development of the prograding and aggrading, Lower Jurassic Cook Formation across Knarr Field and Garantiana discovery located in the Tampen Spur area in the Northern North Sea. 11 facies, 5 depositional element and 7 facies association has been combined to established three correlation. The Cook Formation has been divided into three higher order sequences lower middle and upper Cook member. The Lower and Middle Cook Formation have been interpreted to be deposited in a main tide-dominated environment, and Upper Cook Formation is deposited in a mix tide- and wave-dominated environment. The lower Cook member represent two prograding tide dominated deltas, oriented east-west. The middle Cook member display and aggrading unit, representing two prograding delta which retreats an changes to estuaries, which is oriented south-east to north-west. The upper Cook member display a tide dominated prograding delta in the Knarr Field, and a faintly wave-dominated shoreface in the Garantiana discovery. The systems got transgressed and a faintly wave-dominated lower shoreface was established in both the Knarr Field and Garantiana discovery before the whole system got drowned. The lower Cook member was deposited during tectonic quietness, while middle and upper Cook member was deposited a minor rifting event.

Acknowledgment

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1.0 Introduction

1.1 Background and problem

The Cook Formation sandstone is distributed throughout the Norwegian Northern North Sea. The formation is proven hydrocarbon bearing and is an important secondary reservoir unit in the Statfjord, Gullfaks and the Veslefrikk Fields. In 2008 the Knarr Field was discovered in the Tampen Spur area, by the Jordbær well 34/3-1S, where the Cook Formation is the main reservoir (Churchill et al., 2016). In 2012 there was confirmed oil in the Cook Formation in the Garatiana structure in the Tampen Spur area, this discovery is currently being developed (Offshore Technology, 2016). The unexpectedly good reservoir properties of the Cook Formation have led to some published papers on aspects of the stratigraphy, gross sedimentary structure reservoir architecture and recently work have focused on the potential of persevering reservoir property with burial. As the focus on discovering new oil and gas resources continues, an increase in interest in the hydrocarbon potential in the Tampen Spur area have appeared. Subsequently, the Cook Formation in this area is of interest due to its productivity potential in and around the Tampen Spurs (figure 1).

The Cook Formation in the Knarr Field is argued to be an overall transgressive succession with tide-dominated lower interval, and a wave-dominated upper section (Churchill et al., 2016). Tidal-dominated facies were usually associated with transgressive estuaries, but recent studies has proven that there is also observed tidal influence in regressive deposits (Burton et al., 2016). It is often hard to distinguish if there is a transgressive tide-dominate estuarine system or a regressive tide-dominated delta system, because both systems accumulate similar facies. It is of great importance to distinguish these systems because the larger scale architectural styles and facies trends are different (Legler et al., 2013,) in estuaries and deltas. The different facies trends are important to understand, to create realistic paleographic reconstructions, which can be used to understand heterogeneities and preservation potential of the deposits. To distinguish between tide-dominated deltas and estuaries the identification of the facies stacking pattern is the key (Dalrymple et al., 2003). This in turns requires a detailed interpretation of the facies.

There are also observed a high amount of double and single mud drapes in the upper section of the Cook Formation indicating of more tidal dominance, than interpreted earlier. In addition there have been recent developments in the understanding of tide-dominated deltas and estuaries and several articles are published (e.g. Dalrymple et al., 2003; Yoshida et al., 2003; Willis, 2005; Dalrymple & Choi, 2007; Legler et al., 2013; Ravnås et al., 2014; Burton et al., 2016; Wei et al., 2016). This new knowledge of tide dominated deltas makes it necessary with a new look at the Cook Formation.

1.2 Aim of the study

This thesis will focus on providing a detailed stratigraphic framework of the Cook Formation, to evaluate a more semi-regional evaluation of the wells in the Knarr Field and Garantiana discovery across the northern Tampen Spurs i.e. the area between the Marflo Spur to the east (proximal part of the Cook system) and the Morl Horst to the west (distal part of Cook system). The aim of the study is to get a better understanding of the Cook Formation by interpreting and using different sets of data such as core and well log data. The main object with this thesis was to:

- To build a detailed facies, depositional element and facies association scheme for the core section based on the sedimentological description of 10 cores, in order to provide a better understanding of the stratigraphic and spatial sedimentological variations.
- Incorporate wireline logs (Gamma Ray, Neutron/Density, and Porosity) from the studied wells and wells with no cores present, with the intention to investigate the stratigraphic relationship within the formation. To identify if the tidal reservoir in the Cook Formation in the Tampen Spur area is associated with deltaic (regressive) or estuarine (transgressive) environment.
- Use the observations to comment on sequence stratigraphy of the studied interval and to create paleographic maps for the area at different stages through the development of the Cook Formation.
- Were changes in basin physiography a response to tectonic activity, or was there a more complex control on the local shoreline bathymetry.

1.3 Previous work

There has not been written a lot of papers about the Cook Formation and most papers are written before the discovery of the Knarr Field and Garantiana Discovery. Regional evolution and sequence stratigraphy paper of the Cook Formation is written by Partington et al., (1993), Steel, (1993), Marjanac and Steel, (1997), Husmo et al., (2003), and Charnock et al., (2001). There is also written some semi-regional papers about local fields. (Livbjerg and Mjøs, 1989) described the stratigraphy of the Cook Formation in the Oseberg area located south of the Knarr Field. Dreyer and Wiig (1995) and Gupta and Johnson (2001) gave a detailed description of the Cook Formation reservoir architecture and sequence stratigraphy in the Gullfaks Field located south of the Knarr Field. Marajanac (1995) described the architecture and sequence stratigraphy of the Dunlin Group in the Veslefrikk Field located south of the Knarr Field. Folkestad et al., (2012) gave a detailed sedimentological description of the Cook Formation in the Kvitebjørn Field in the Valemon area. Churchill and Coworkers (2016) discussed the stratigraphic architecture of the Cook Formation in the Knarr Field, which is part of the study area in this thesis (figure 1).

1.4 Deliverables

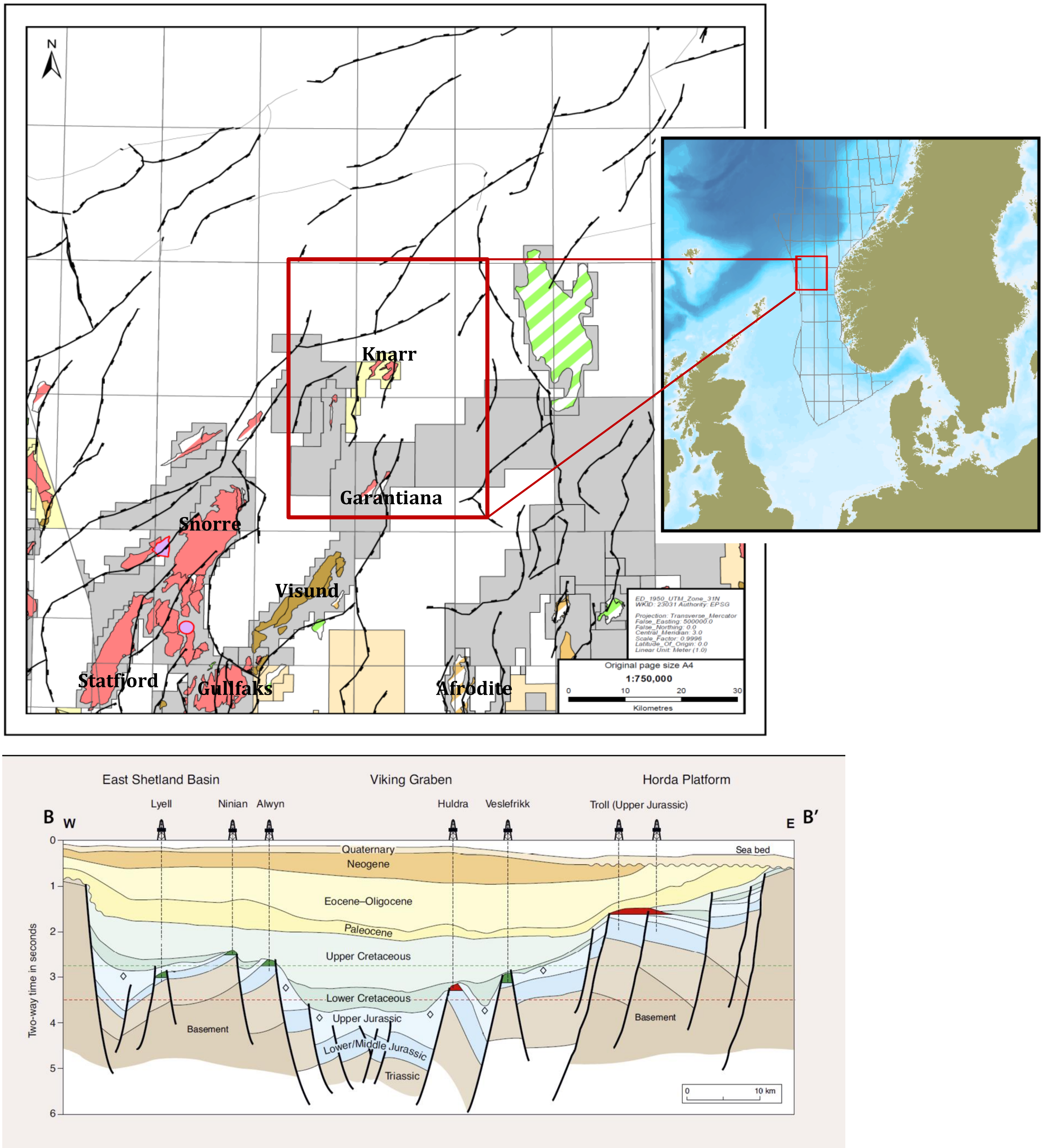
- A core description of the Cook Formation from 10 core samples in the Tampen Spur area, interpreted in facies, depositional element and facies association.
- Detailed well interpretation divided into sequences and correlated.
- Paleographical maps that displays the evolution of the Cook Formation in the Tampen Spur area.

1.5 Study area

The study area is located over the north-eastern part of the Tampen Supr, Marflo Spur and Mort Horst area in the northern North Sea; more specific the Knarr Field and Garantiana discovery (Figure 1). The Knarr Field was discovered in July 2008 and production started in March 2015 (Churchill et al., 2016). Garantia was discovered in 2012, and is not yet producing (Offshore Technology, 2016).

The study area encompasses the Norwegian Blocks 34/2, 34/3, 34/4, 34/5, 34/6, 35/1 and 35/4 located about 120 km form the west coast of Norway. The water depth is about 400 meters, and the Cook Formation burial depths are between 3500 to 4100 meters below sea level (NPD factpages).

A)



B)

Figure 1A) Location of the study area in the Northern North Sea, with the main structural elements and the fields located in the study area B) Regional geosection across the Northern north sea (source Millennium Atlas modified form NPD)

2.0 Geological Framework and Evolution

2.1 Structural setting of the northern North Sea

The basic structural framework of the northern North Sea is mainly a result of repeated periods of crustal stretching and thinning and relative post-rift subsidence during Permian-Early Triassic and Late Jurassic (Ziegler, 1990; Færseth 1996; Faleide et al., 2010). As a consequence the area is characterized by large rotated fault blocks and sedimentary basins in asymmetric half grabens, formed during the lithospheric episodes of extension and crustal thinning (Badley et al., 1984; Færseth 1996; Faleide et al., 2010).

The Paleozoic tectonic framework developed during two continental collisions to terrane accretion events; the Caledonian and Variscan Mountain building events (Coward et al., 2003). The basement of the Northern North Sea consists of an extensionally thinned continental crust representing the eroded and stretched Pre-Cambrian to Caledonide basement (Badley et al., 1998; Coward et al., 2003). The Mesozoic basins floor was filled by eroded sediments from the mountains formed in the Paleozoic as well as by cannibalization of older sediments from the basin margin (Badley et al., 1984, Husmo et al., 2003).

The first major rifting event took place in the Late Permo to the Early Triassic, generating series of half grabens within a broad depression bounded by N-S-trending faults. The middle to late Triassic was a period dominated by post-rift subsidence (Badley et al., 1988; Steel and Ryseth, 1990). During the Early and Middle Jurassic, the Norwegian-Greenland Sea rift evolved, forming post-rift unit to the underlying Permo Triassic and pre-rift strata to the overlying upper Jurassic syn-rift succession (Nøttvedt et al., 2008; Færseth and Lien, 2002; Ravnås et al., 2014,). Varying subsidence and riffing within the region generated variable structure influence on the infill patterns of the Early to Middle Jurassic succession (e.g. Gjelberg et al.,1987; Corfield & Sharp, 2000; Corfield et al., 2001; Martinius et al., 2001; Ravnås et al., 2014). In the Early Jurassic the Northern North Sea was located in relatively warm and humid paleoclimate setting (Hallman, 1994; Ravnås et al., 2014). There was a high rate of sedimentary supply during the Early Jurassic which gradually wanted in the middle Jurassic (Ravnås et al., 2014). As a consequence the Early to Middle Jurassic is marked by overall retrogradational, layered package of alluvial, fluviodeltaic, shallow marine and shelfal strata (Coward et al., 2003, Ravnås et al., 2014), in the Northern Province this is represented by the outbuilding of the Cook Formation. In the Middle Jurassic volcanic doming caused uplift and erosion over the Central North Sea, and the subsequently deposition of the northward orientation Brent Delta (Underhill and Partington, 1993; Husmo et al., 2003)

The second rifting episode lasted into the Early Cretaceous, forming structural configuration (Færseth 1996; Badley et al. 1984). During this tectonic episode, major block faulting caused uplift and tilting, creating considerable local topography with erosion and sediment supply. Cretaceous post rift cooling, thermal subsidence and sediment filling resulted in deep burial of the Jurassic succession (Badley et al., 1988, Husmo et al., 2003).

2.2 Cook Formation

The Cook Formation was deposited during early Jurassic (Pliensbachian to Toracian) across the north-eastern part of the Northern North Sea. The Cook Formation is distributed throughout the eastern parts of the East Shetland Basin, the Tampen Spur, the northern Viking Graben, the Sogn Graben and on the northern part of the Horda Platform (Vollset and Doré, 1984).

The Cook Formation is included in the Dunlin Group, which is subdivided into five lithostratigraphic units; the Amundsen, the Johansen, the Burton and the Drake formations (Vollset and Doré, 1984) (figure 2). The Cook Formation sharply overly the Burton and Amundsen formations, and is overlain and some places interbedded with the Drake Formation (Marjanac and Steel, 1997).

The Cook Formation is mainly interpreted as marine sandstone formed in a variation of marine settings. In The Statfjord area the Cook Formation is interpreted as marine shoals by Dalrymple (2001). Dreyer and Wiig (1995) interpreted the Cook Formation in the Gullfaks Field as shelf to shallow marginal marine deposits formed in a variety of tide dominated settings, including tidal flats, bays, tidal channels and estuaries and shallow marine deposits formed in an overall transgressive setting. Charnock and coworkers (2001) interpreted the Cook Formation on the Horda platform to be offshore and lower shoreface of wave dominated shoreline and estuaries. The Cook Formation in the Kvitebjørn Field and the Valemon area is interpreted by Folkestad and co-workers (2012) as a regressive mixed tidal-fluvial delta to transgressive wave-dominated estuary. In the Oseberg Field the Cook Formation is interpreted as a tide dominated subtidal marine sand body, representing mud banks and offshore sand ridges by Livbjerg and Mjøs (1989). The Knarr Field and Garantiana discovery which is the focus of this thesis is interpreted by Churchill and co-workers (2016) to form a bipartite unit: the thicker Lower Cook respectively represent a tide-dominated system with tidal channel, tidal bars and intertidal bar facies, and the thinner upper Cook Formation a shoreface succession, consisting of shoreface facies to offshore transition zone.

There it is argued that the Cook Formation is prograding from east to west (Churchill et al., 2016, Charnock et al., 2001) in the Knarr Field. But thickness trends and facies distribution show indications that the system is changing orientation (see chapter 5, 6 and 7). By looking at the deposit form Garantiana discovery to Knarr filed there are indication of a more south-east sedimentary supply in the middle and upper Cook members. This indicates a much more complex Cook Formation basin-fill architecture than recognized in previous studies.

The Cook Formation forms the core of the Cook megasequence (PR 5) (Steel, 1993, Marjanac and Steel, 1997). The Cook Formation is interpreted to form parts of the regressive segment of the megasequence composing the upper parts of stacked upward coarsening units. Dreyer and Wiig (1995) established six main types of a higher order sequence set for the units, with the higher order sequence bounded by surfaces; (1) sequence bounding unconformity, (2) marine downshift surface, (3) transgressive surface, (4) ravinement surface, (5) maximum flooding "surface", and (6) minor flooding surfaces (figure 3). Dreyer and Wiig interpreted higher order sequences, which he divided into Cook-1, Cook-2 (representing the first sequence) and Cook-3 (representing the second sequence. Charnock and coworkers (2001) recognized 5 flooding surface in the Cook Formation J14, J15, J16A, J16B and J18 (figure 2), which has been used as guidelines in this study.

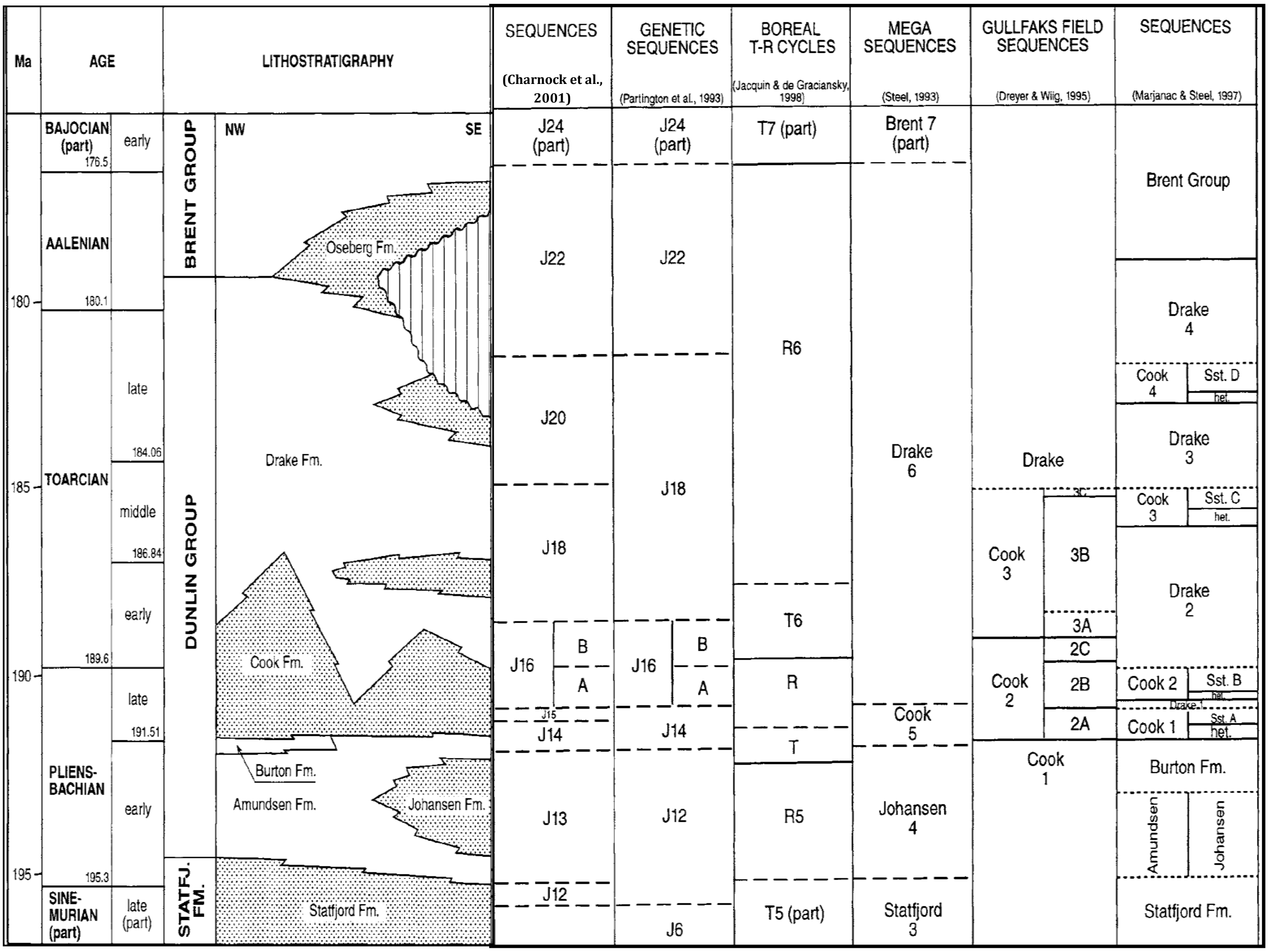


Figure 2 Lithostratigraphy and sequence stratigraphy of the Dunlin Group in the northern North Sea, red square represent the Cook Formation (modified Charnock et al., 2001).

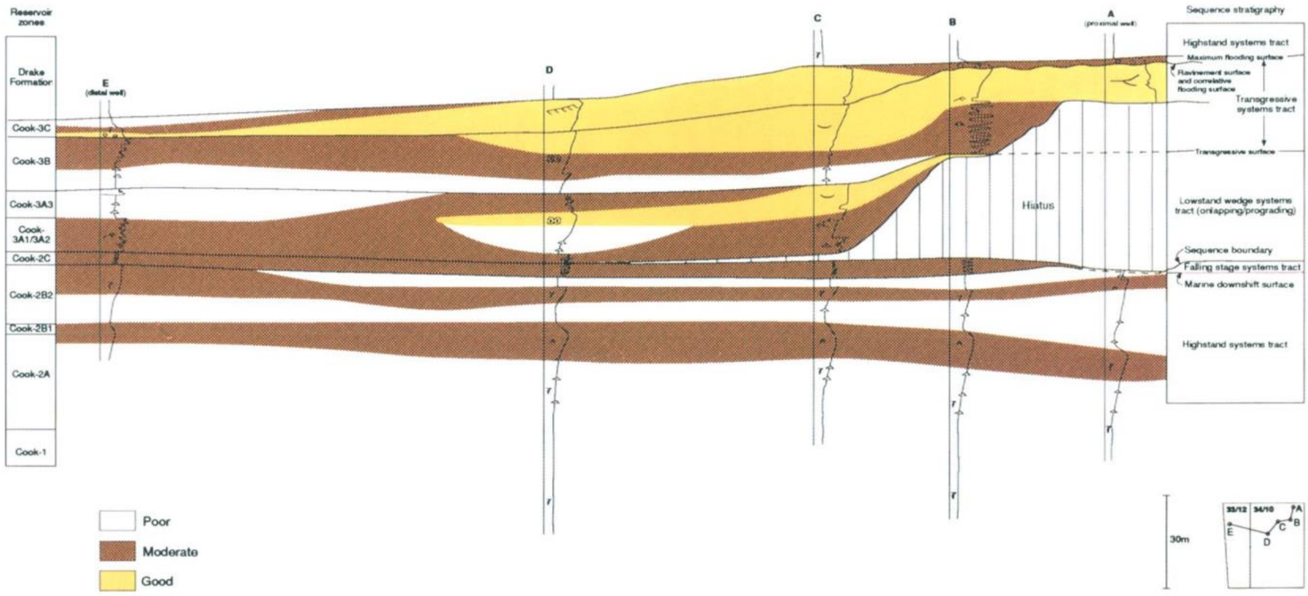


Figure 3 Cross-section of the Cook Formation displaying the sequence stratigraphic framework (Dreyer and Wiig, 1995

2.3 Mechanisms to explain Cook Formation advance

The Cook Formation was deposited during the Pliensbachian to early Toarcian. This indicates that the Cook Formation forms part of the post-rift unit to the underlying Permo-Triassic and the pre-rift strata to the overlying Upper Jurassic syn-rift succession (Færseth & Lien, 2002; Ravnås et al., 2014). This periods show less tectonic activity compared to both the preceding Middle to Late Triassic and succeeding Late Jurassic rift episodes, but some structuring is observed (Ravnås et al., 2014)

The Cook Formation was deposited during a post-rift phase, resulting in a thickness distribution that is potentially controlled by an N-S trending fault pattern (Badley et al., 1988; Charnock et al., 2001). During the latest Pliensbachian to early Toarcian there is documented periods of minor footwall uplift in the Oseberg Fault (Livbjerg and Mjos 1989; Ravnås et al., 2000), the Alwyn-Ninian-Hutton alignment (Johnson and Essautier 1987; Sawyer and Keegan 1996, Ravnås et al., 2000), and in the Statfjord-Gullfaks area along the western flank of the northern Viking Graben (Roberts et al, 1987; Ravnås et al., 2000). The Footwall uplift and erosion led to the deposition of the Cook Formation in the Oseberg area(Livbjerg & Mjos 1989, Ravnås 2000) and the retreat of the rift marginal Cook Formation shoreline to the west (Steel 1993, Ravnås 2000). In the Gullfaks area the

Cook Formation may have similar origin but, is interpreted to represent tidally influenced shorelines or tidal estuaries (Dreyer & Wiig 1995: Marjanac & Steel 1997, Ravnås 2000).

Previous studies has documented varying rate of subsidence and sedimentary supply across the northern north sea during the Triassic to middle Jurassic (e.g. Gabrielsen et al., 1990; Steel and Ryseth 1990; Fæerseth and Ravnås 1998; Ravnås et al., 2000). Ravnås and co-workers (2000) (2014) suggest that there was a slow stretching creating minor extensional tectonics during the Early to Middle Jurassic, resulting in a repeated structuring of the basin.

A relative sea-level rise took place in the end of the Early Toarcian during the deposition of the Upper Cook Formation (Dreyer and Wiig, 1995; Parkinson and Hines, 1993). These interpretations indicate that the Cook Formation deposition was controlled by tectonic changes, as well as sea level changes (figure 3).

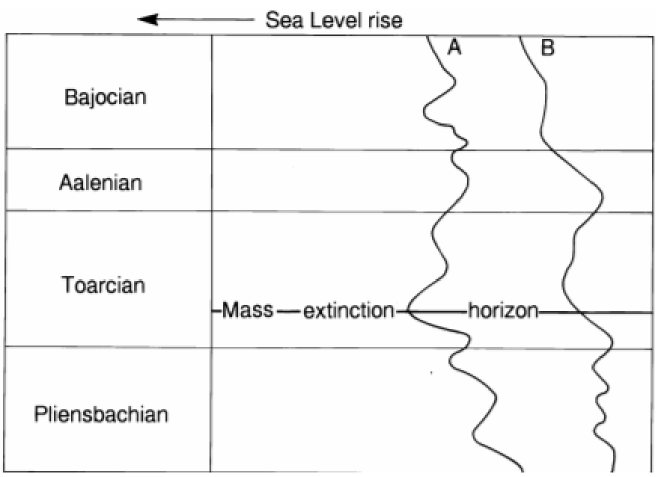


Figure 4 Eustatic sea-level curve of Lower Jurassic. (A) after Hallam (1988) and (B) after Haq et al., (1987) (Hallam and Wingnall, 1999).

3.0 Dataset and Methodology

3.1 Dataset

This thesis is based on core and well log data from wells containing the Cook Formation in the Tampen Spur area. The dataset was provided by A/S Norske Shell and comprises core data from 10 wells and additional well logs data from 15 wells from the Knarr Field to Garantiana discovery, supplemented by data on the Marflo Spur to the east (proximal part of the Cook system) and the Mort Horst to the west (distal part of Cook system).

3.1.1 Core data

The bulk of the core data are form the Knarr Field and adjacent structures (wells 34/2-2, 34/2-4, 34/3-1 ST2, 34/3-2S, 34/3-3S and 34/5-1S), the Garantiana discovery (34/6-2S, 34/6-3S), Marlof Spur (35/4-1) and Mort Horst (34/4-5). A total of 446 meters of cores have been interpreted of the Cook Formation in the Tampen spure area, 217 meter in the Knarr Field, 137 meter in the Garantiana area and additionally 92 meter in the adjacent structures.

3.1.2 Well logs

The gamma ray, neutron and density and porosity well log data are from 15 wells located in the Tampen Spur area (Knarr Field and Garantiana discovery). The well logs data comprises the wells 34/2-2, 34/2-4, 34/3-1 ST2, 34/3-2S, 34/3-3S, 34/3-5, 34/4-5, 34/5-1A, 34/5-1S, 34/6-1, 34/6-2S, 34/6-3S, 34/6-4, 35/1-1 and 35/4-1. Jointly this well data set provides a framework for prediction of the strata architecture of the Cook Formation in the Tampen Spur area.

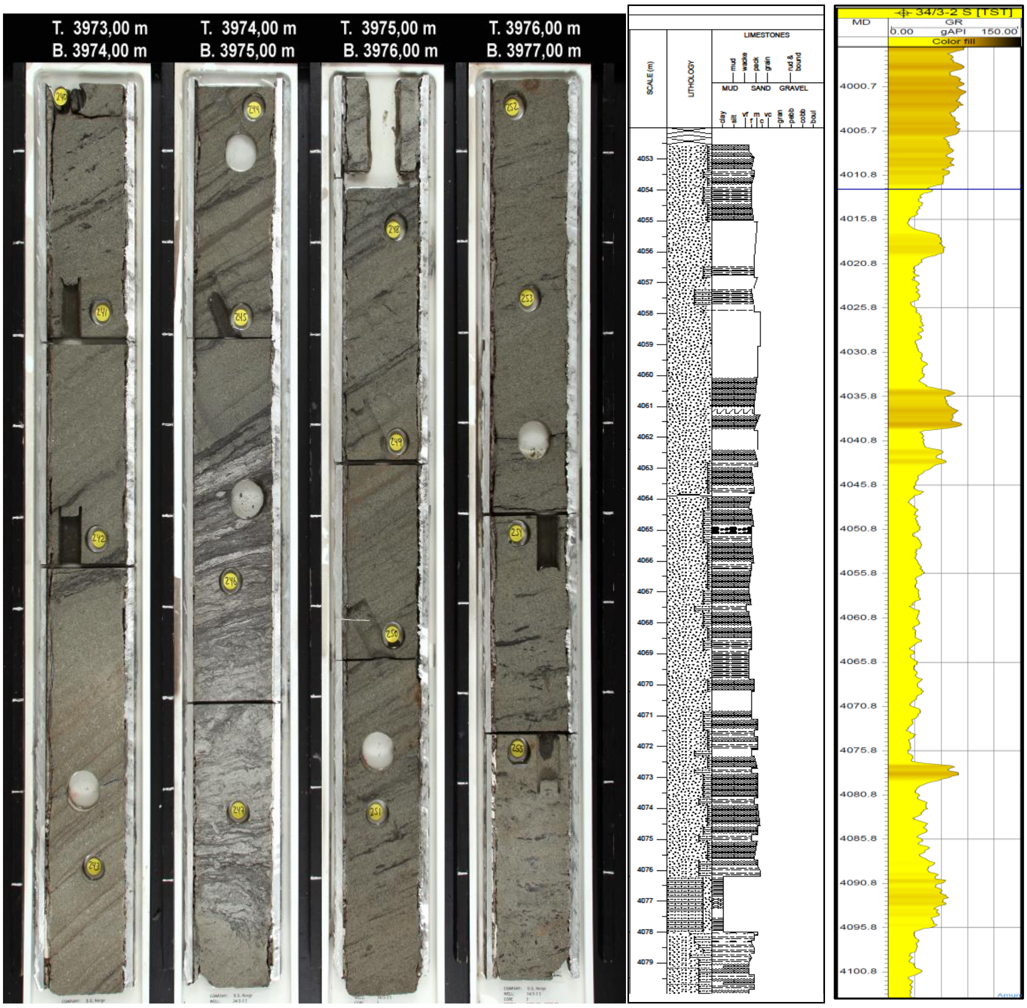


Figure 5 Example of the type of data used: well logs and core photo

3.2 Methodology

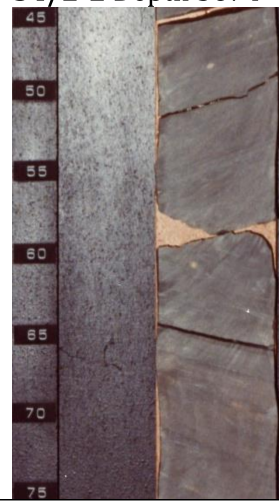
The first step of this thesis was to preform core interpretation. The 10 cores were studied lateral, i.e. along depositional strike and proximal to distal i.e. depositional dip profile over the study area. Cores were interpreted to identify facies, depositional/architectural elements and facies associations in the Cook Formation. The core interpretation was based on lithology, mineralogy, grain size, bed boundary, bed thickness, texture, sedimentary structures, and degree of bioturbation. The software sedlog 3.1 was used to create graphic sediment logs of the interpreted cores. The interpretation of the cores were tied to gamma ray, neutron and density log and porosity log signatures, which was used to identify similar facies, depositional elements and facies associations in the uncored section of the wells. The graphic sedimentary logs and the well logs were used to create three correlations across the study area. Then the wells were interpreted into higher-order sequences to ensure a more solid and confident correlation of depositional packages. This was semi-regional stratigraphic and more detailed (field spathic) to develop a more detailed framework for the depositional subenvironments, gross and reservoir architecture. As the Cook Formation in the study area were comprised of series of flooding surface bounded, higher order stratigraphic units, a genetic sequence stratigraphic approach was favored. Paleographic maps of the study area were created after integrating the different facies and well correlations, to investigate potential aspects of structuring, thickness trends and orientation of the Cook Formation.

4.0 Lithofacies, Depositional Elements and Facies Association

Core data analysis was performed on 9 wells; 34/2-2, 34/2-4, 34/3-1 ST2, 34/3-2S, 34/3-3S, 34/4-1, 34/4-5, 34/5-1S, 34/6-2S, 34/6-3S and 35/4-1, to record the occurrence of lithofacies, architectural elements and facies associations. The core coverage in the different wells varies (34/2-2 and 34/2-4), but together they provide fairly good core coverage of the Cook Formation in the Knarr Field to the Garantiana discovery and wells in more distal (seaward, 34/2-2, 34/2-4, 34/4-5 and 34/5-1) and proximal (landward, 35/4-1) positions. A total of 446 meters of cores have been interpreted (thicknesses of the Cook Formation and core coverage in the interpreted wells in table 4.6). Wire line log responses of uncored wells were correlated to the facies analysis based on the core description. In order to do this a general classification of identified associations based on well log response had to be established. The well log response is based on the gamma ray log, porosity log, neutron and density log (only gamma ray log is presented in the well correlations; figure 12, 13 and 14). Gamma ray log response is extremely sensitive to grain size and clay content, which makes it very useful in identifying lithology and subsequently interpreting depositional environment.

In the Cook Formation a total of 11 lithofacies were recognized (table 1). This can be grouped into 5 depositional elements (table 2) and 6 facies associations (table 3). Lithofacies identification and characterization was based on lithology, degree of bioturbation, grain size, bed boundaries, bed thickness, texture, sedimentary structures and log motif.

4.1 Facies

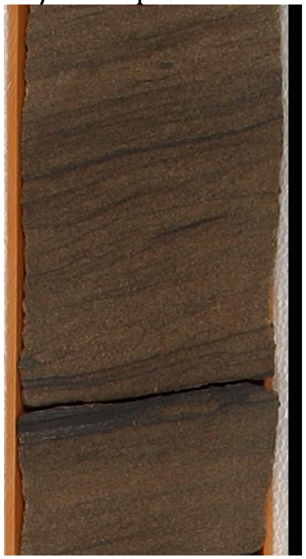
Facies		Description	Core Photo	Bed thickness	Interpretation
1. Mudstone	A. Bioturbated mudstone	Dark grey to black mudstone. No internal structure to faintly planar laminated. Sharp to gradational contacts. The degree of bioturbation is high with high diversity, common traces are *Diplocraterion, Teichicnus* and some vertical burrows. The contact is sharp.	**34/2-2** Depth 3674 	Centimeter to decimeter thick intervals	The mud stone is interpreted to be deposited during low energy conditions in fully marine environment, as evidenced by the marine ichnofacies.
	B. Massive mudstone	Massive dark grey to black organic rich mudstone. No internal structure. Degree of bioturbation is low to absent and represented by rare *Planolites*. Upper and lower sharp contact to unbedded facies (normally sharp)	**34/3-3** Depth 3938 	Millimeter to centimeter thick intervals	The dark color of the mudstone together with plant debris indicates that the sediments contain abundant organic materials (Arthur and Sageman, 1994) which suggest a terrestrial origin. The unbioturbated nature suggests deposition by rapid setting from high density suspension fluid muds.

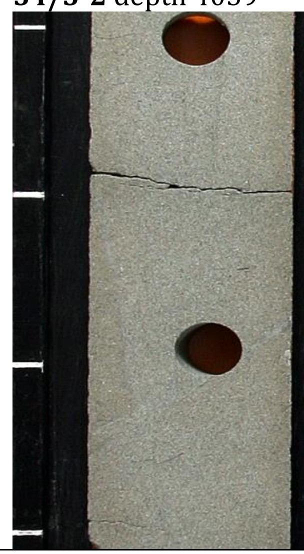
2. Lenticular bedded heterolithics	Dark grey mudstone with brown very fine grained sandstone lenses. Some places there are asymmetrical ripples x-lamina, ripples with opposite direction or mud drapes present in the sandstone lenses. The degree of bioturbation is moderate to low, with low diversity. Bioturbation is represented by *Arenicolites, Planolites* and *Teichicnus.* Locally a higher diversity is observed with additional traces of *Asterosoma, Diplocraterion, Roselia* and vertical burrows. Gradational to sharp contact.	**34/5-1** depth 3642 	Decimeter to meter thick intervals	Lenticular bedding are produced in environment where deposition and preservation of mud is favorable (Reineck and Singh, 1980). Deposition of sand occurs from episodic low energy currents. The occurrence of mud drapes and opposite x-lamination in the sandstone lenses indicate tidal current reworking of the sediments (Visser, 1980; Dalrymple and Choi 2007; Wei et al., 2016). The low diversity marine ichnofauna suggest a stressed marine environment, the locally increased diversity of bioturbation suggest more open marine setting. Interpreted to be formed in shallow marine settings as distal part of tide dominated delta or more open bays.
3. Wavy bedded heterolithics	Grey to brown fine to very fine grained sandstone, and mudstone alternations, moderate to poorly sorted with subangular to subrounded grains. The internal structures consist of wavy bedded parallel laminated sandstone, opposite directed ripple x-lamination and occasionally cross bedding. The degree of bioturbation is moderate to high represented by *Arenicolites, Planolites, Roselia* and *Teichicnus*. Gradational contacts.	**34/3-3** depth 3980 	Decimeter to meter thick intervals	Produced in environment where deposition and preservation of both sand and mud are favorable (Reineck and Singh, 1980). Deposition in moderate to slow energy current. The occurrence of mud drapes and opposite directed asymmetrical ripples cross lamination indicate tidal current reworking of the sediments (Visser, 1980, Dalrymple and Choi 2007; Wei et al., 2016). Interpreted to be formed in a delta front, prodelta environment or higher energy setting of tide infill/drowned bays.

4. Flaser-bedded sandstone	Grey to brown, fine to medium-grained sandstone, variably sorted. Subangular to subrounded grains. The internal structure consists of organic rich millimeter thick mud drapes, opposite directed x-lamination mud drapes, mud clast and cross bedded to planar horizontal laminated sandstone. The degree of bioturbation is low to moderate with low diversity, mostly focused in the muddy layers, represented by *Planolites*. Gradational contacts.	**34/3-3** depth 3990 	Decimeter to meter thick intervals	This structure implies that both sand and mud are available in the system and deposited during periods of current activity alternating with calm periods. During periods of current activity the sand are transported and deposited as ripples, when the current decrease and increase mud is deposited. Produced during environment where conditions for deposition and preservation of sand is higher than for mud (Reineck and Singh, 1980). The occurrence of mud drapes and opposite directed asymmetrical ripples indicate tidal current reworking of the sediments (Visser, 1980; Dalrymple and Choi 2007, Wei et al., 2016). The thick organic rich mud drapes indicates terrestrial influx, probably from a fluvial channel. Interpreted to be formed in a relatively high energy upper delta front environment and interbedded tidal flats.
5. Hummocky cross stratified sandstone	Dark grey, fine to medium sandstone with subrouded grains. The internal structure consists of hummocky cross stratification, in some places single and double mud drapes occur in uppermost part of beds. Bioturbation varies from absent to a low degree of bioturbation normally of low diversity represented by *Archichnius, Teichichnus* and *Planolites*. Gradational contacts.	**34/5-1**depth 3650 	Centimeter to decimeter thick intervals	This structure is interpreted to be deposited under high-energy combined flow processes associated with large storm waves (Hunter & Clifton, 1982; Klein & Marsaglia, 1987; Duke et al., 1985; Yang et al., 2006). The occurrence of single and double mud drapes suggest variating tide influences, varying storm conditions and transition into background conditions with slack water structures (Visser, 1980, Dalrymple and Choi 2007; Wei et al., 2016). The alternation of storm intervals and tide intervals suggests that storms were dominant regime while tidal signals were preserved in the inter-storm periods (Wei et al., 2016). Interpreted to be formed in a mixt wave tide energy lower delta front environment or shoreface.

6. Highly bioturbated fine grained sandy siltstone	Grey to brown very fine to fine muddy strongly bioturbated sandstone. Well sorted subrounded grains. Occasional layers with mud drapes and wave and current ripple x-lamination. The grade of bioturbation is high varying from high to low diversitry. The bioturbation is represented by *Arenicolites, Planolites, Palaeophycus, Terebelina, Teichichnus* and horizontal and vertical burrows. Gradational to sharp contact.	**34/5-1** depth 3678  **34/3-1** depth 3868 	Decimeter to meter thick intervals	Deposited during intervals with slow sedimentation rate, allowing biogenic reworking processes. The sediments with higher diverse ichnofauna indicate open marine shelf, while the sediments with low diversity indicate more protected settings (Pemberton et al., 2001). Interpreted to be deposited in a restricted or stressed offshore setting such as outer parts of embayment lower delta front or shoreface enviornment.

7. Massive, Parallel planner laminated sandstone	Grey fine to medium grained sandstone with subangular to subrounded grains and very well to well sorted. The internal structure consists of massive to parallel planar lamination. Bioturbation is absent	**34/6-2** depth 3683 	Decimeter thick intervals	Parallel planar to low angle lamination were deposited in times of high sediment supply and energy conditions (upper flow regime) during for example river floods (Reading and Collinson, 1996) The clean and well sorted nature of the sandstone is interpreted to be deposited in a upper shoreface to beach environment.

8. Cross stratified sandstone	Grey to brown fine to medium grained sandstone with subangular to subrounded grains and very well to moderately sorted. The internal structures consist of cross stratification that are tangential, sigmoidal or planar, with occasionally of single or double mud drapes. Which sometimes have a rhythmic appearance with up to 25-30 mud drape organized in middle to lower sand part. Low to moderate degree of bioturbation represented by *Arenicolites, Asterosoma, Planolites, Rosselia*. Gradational contacts.	**34/3-2** depth 4054  **34/3-1** depth 3887 	Centimeter to meter thick Intervals	Cross bedding is a result of migrating 2D or 3D bedforms, unidirectional flows (Reineck and Singh, 1980). The mud drapes deposited within sandstone, indicating fluctuating energy levels, where sand is transported under relatively higher-energy conditions and mud deposited during low-energy slack-water periods double mud drapes is produced by repeat periods of slack water during neap-spring tidal cycles (Visser, 1980, Dalrymple and Choi 2007; Wei et al., 2016). The rhythmic occurrence of mud drapes are interpreted to represent tidal bundles with a dunal origin. Interpreted to be deposited as bars and channels in delta front, delta plain or estuarine settings.

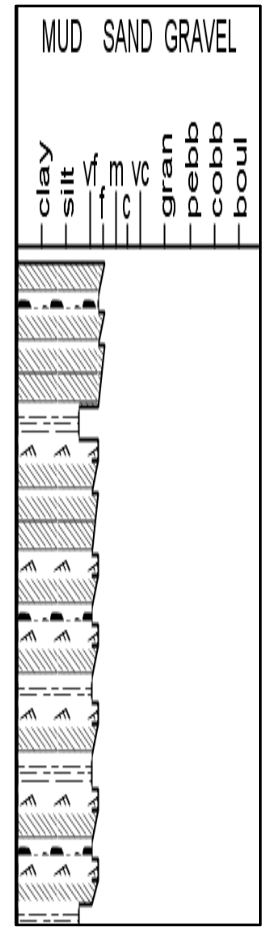
9. Cross stratified sandstone with mud clasts/ Pebbly sediments		Grey to Brown fine to coarse grained sandstone with subangular to subrounded grains and very well to moderately sorted. The internal structure consist of cross stratification defined by alignment of mud clasts, the mudstone intraclasts are locally sideritized. Low to moderate bioturbation with low diversity, represented by *Planolites*. Gradational contacts to cross bedding.	**34/3-3** depth 3978 	Centimeter to decimeter thick intervals	Cross bedding is a result of migrating 2D or 3D bedforms, unidirectional flows (Reineck and Singh, 1980). Produced during high energy conditions. Mud pebbles are common in the channel bottom and in bars/dunes in tide-dominated environment. Thick mud drapes get deposited, and then currents are sufficiently strong to rework these drapes (Dalrymple and Choi, 2007). Interpreted to be deposited as bars/dunes and channels in delta front.
10.	A. Massive sandstone	Grey medium grained structure less massive sandstone with subrounded to rounded grains and well to very well sorted. Structure less with occasionally scattered granules. Low degree of bioturbation, some shell fragments present. Gradational and occasional sharp contact.	**34/3-2** depth 4059 	Decimeter to meter thick intervals	Interpreted to be sandy bank transitioned intsandy debris. Sandbank failure are reported from large sandy bedforms. Grain flow failure represent deep fluvial channels, delta fronts or estuarine channels by breaching (van den Berg et al., 2017)

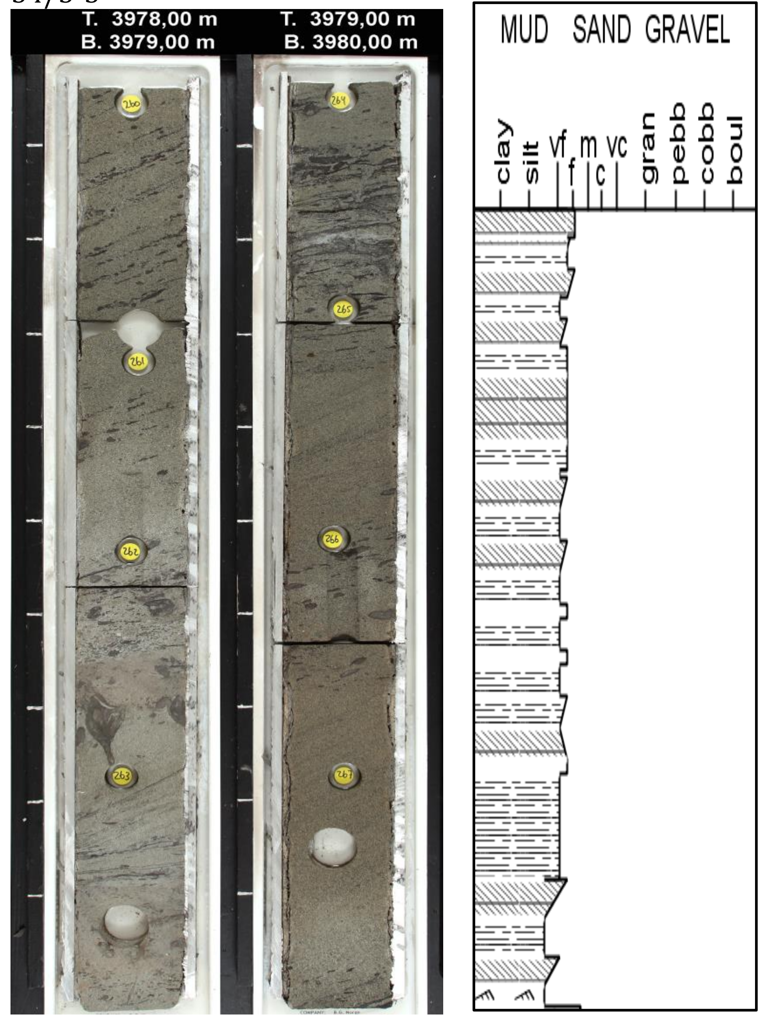
	B. Channel-like massive-type sandbodies	Grey medium to coarse sandstone, with subrounded to rounded grains well sorted. Alternations between mud layers and massive and normally graded strata with occasionally mud clast. The internal structure consist of steeply overthrown to near vertical lamination. Bioturbation is absent. Sharp to gradational contacts, often occur with facies 9A and 9C	**34/3-2** depth 4060 	Decimeter to meter thick intervals	Interpreted to represent transitional sand banks filure i.e slumping transition into debris flows
	C. Parrallel plannarr bedding	Grey medium grained sandstone with subrounded to rounded grains and well to very well sorted and some mud stone and mud draped horizontal laminationl. The internal structure consists of parallel plannar bedding and occasionally mud clast. Low to moderate degree of bioturbation. Gradational and occasional sharp contact, often occur with facies 9A and 9B.	**34/3-2** depth 4057 	Decimeter to meter thick intervals	Interpreted to be the more proximal part of compared to facies 9A and 9B in of sandbank failure.

11.	Lags	The lithology consist of dark gray to grey, poorly sorted, medium to coarse grained sandstone to poorly sorted matrix supported pebbly sandstone to mudstone. The boundaries are sharp. The composed are pebbles. Low degree of bioturbation. Sharp contact.	**34/3-3 s** depth 3981 	Centimeter to decimeter thick intervals	Interpreted as a transgressive lag were sediments were reworked into transgressive sheets, wave winnowing of fine sediment transported alongshore by coastal currents (Harris et al., 1996). Interpreted to be deposited in a low delta front to prodelta or lower shoreface environment.

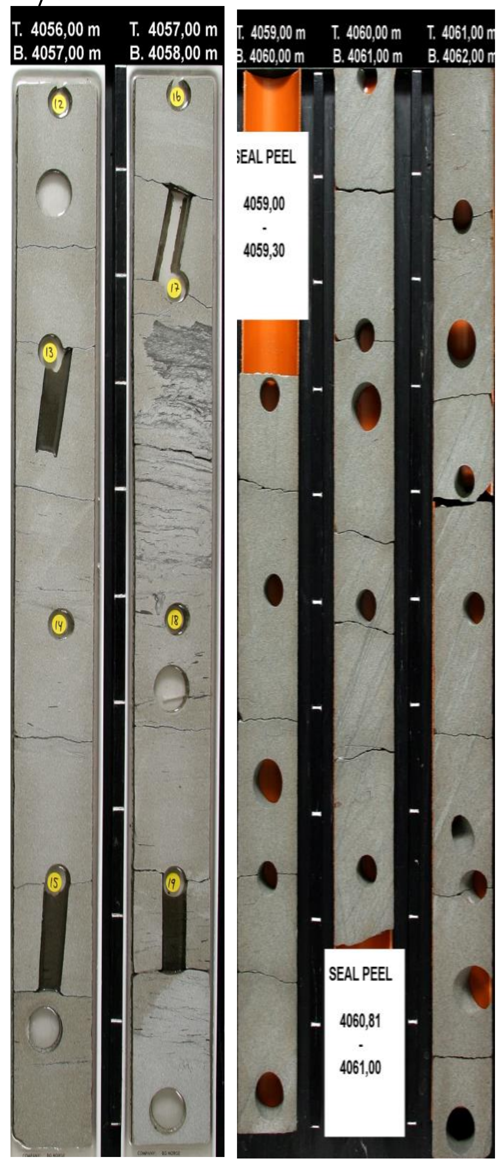
Table 1 Observed facies from the 9 cores and core photos.

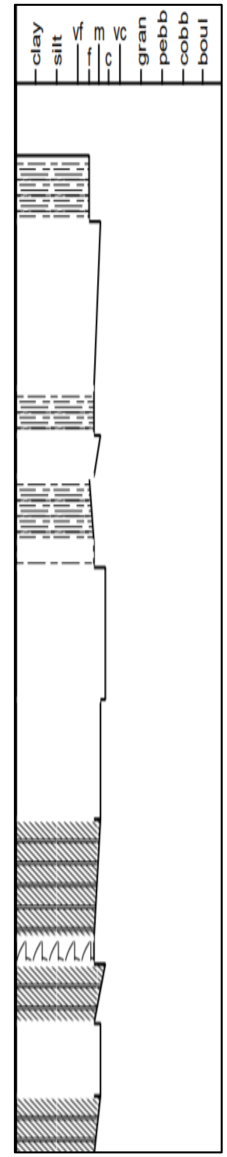
4.2 Depositional elements

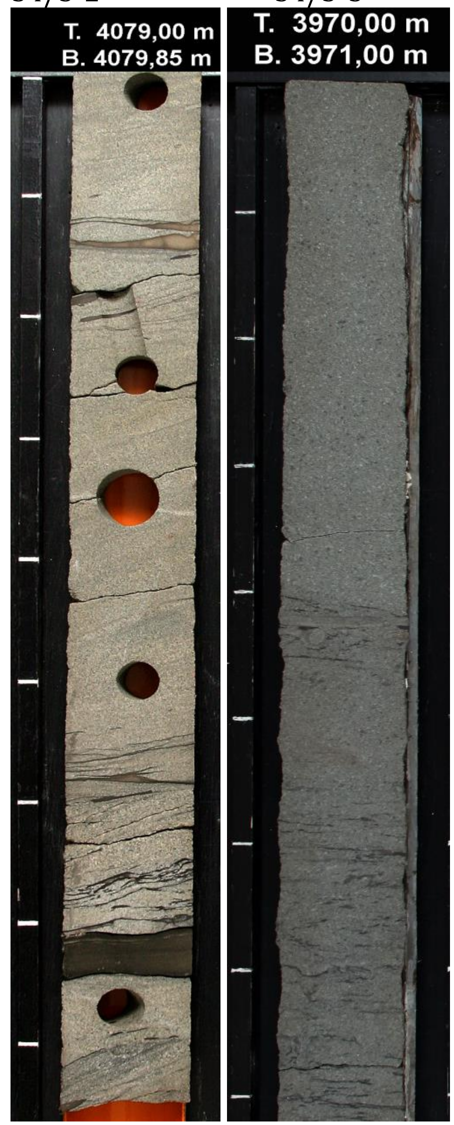
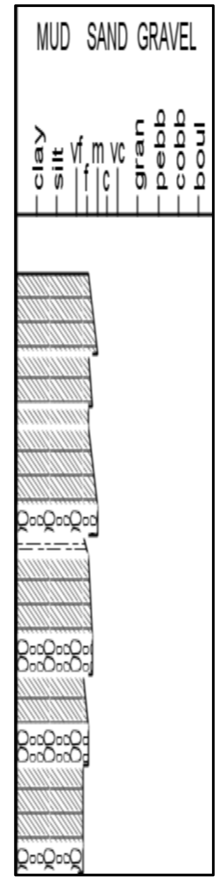
Depositional element	Description	Core photos	interpretation
1. Mouth bars	The sandstone is moderate to well sorted and fine to medium grained. The base of the mouth bars consist of thin mud layers (facies 1B) wavy bedding (facies 3) going over to flaser bedding (facies 4) and overlain by low angle cross bedded layers with and without mud clasts (facies 8 and 9). Bars are stacked on top of each other in an upward coarsening and cleaning succession. Stacks bars form tens of centimeter up to tens of decimeter thick units. There is no bioturation to low degree; bioturbation is more common in fluid muds represented by *Asterosoma* and *Planolites*. The Gamma ray response shows a fairly low to moderate value, coarsening upward blocky signature.	34/3-3  	The lack of wave or tide dominated structures and limited bioturbation indicate a distal deposition environment between prodelta to delta front.

2. Dunes	A. Simple dunes	The sandstone is moderate to well sorted and fine to medium grained. The simple dunes form coarsening upward motif up to 1,5 meter. The base of the dunes consist of cross bedding (Facies 8) which turn into cross bedding with mud clasts (facies 9) and the topset consist of flaser bedding (facies 4).There are also mud duble and single mud drapes present. DE1 is organized in a coarsening upward succession with several upward fining simple dunes. The contact is gradational. The degree of bioturbation is moderate to low, sandstone is not effected by bioturbation, while occasionally mud drapes are bioturbated mostly by *Planolites*. The bioturbated tops of the bars are represented by *chondrites, roselia* and *planolites*. The Gamma ray response shows a fairly low to moderate value, coarsening upward blocky signature.	34/3-3 	The increase in tidal dominated structures and marine bioturbation indicate that the simple dunes are deposited distal but more proximal then the mouth bars (DE1). The dunes are interpreted to be deposited in the delta front.

	B. Compound dunes	The dunes consist of cosets of cross bedded sandstone, with a coarsening upward motif. Comprises thick layers of well to very well sorted fine to medium grained sandstone. Double and single mud drapes are present. The succession is upward cleaning, coarsening and thickening. Stacks of compound cross-beds form tens of decimeter up to one meter thick units. The contact is gradational to sharp. The degree of bioturbation is low to absent and represented by *Planolites* and *Ophiomorpha*. The Gamma ray response shows a fairly low to moderate value, coarsening upward blocky signature.	34/3-1  	DE1B differs from DE1A by less mud, better sorted and less bioturbation which indicate either more proximal deposit in a delta front setting or more distal facies in a estuarine setting.

<table>
<tr>
<td>3. Collapsed (breaching) dunes</td>
<td>DE3 comprises thick layers of well to well sorted and fine to medium grained sandstone. The base consist of high angle cross stratification (facies 9B) intercalated with massive sandstone (facies 9A) and the top consist of parallel planar bedding (facies 8C). The succession is fining upward, with upward coarsening packages. The dunes form tens of decimeter up to two meter thick units. The contact is gradational. There are no bioturbation to low degree of bioturbation. The bioturbation is represented by escape structures and Planolites, and some shell fragments are present. The Gamma ray response shows a fairly low to moderate value, coarsening upward blocky signature.</td>
<td>34/3-2



</td>
<td>Breach failure generates massive sands. The massive sands of collapsed dunes can be found in various ancient shallow water environments and possible deep marine settings. Interpreted to be found in estuary, fluid channel or delta front.</td>
</tr>
</table>

4. Channel floor/thalweg	DE5 comprises thick sandstone layers of poorly to moderate sorted and medium to coarse grained. The base of the channel fill consist of centimeter thick mud stone (facies 1B), interbedded cross bedded sets with mud clasts (facies 9) which is cleaning upward to cross bedding without mud clast (facies 8). The succession is fining upward and has a sharp base. The succession forms tens of decimeter up to one meter thick units. Bioturbation is absent to low degree bioturbation represented by *Planolites*. The Gamma ray response shows a fairly low to moderate value, fining upward signature.	34/3-2 34/3-3  	Channel floors are formed in the deepest points and near the middle of the channel. thalweg shifting occurs within the active channel evidenced by overlaying compound dunes. Tide-segmented compound dunes restricted energy.

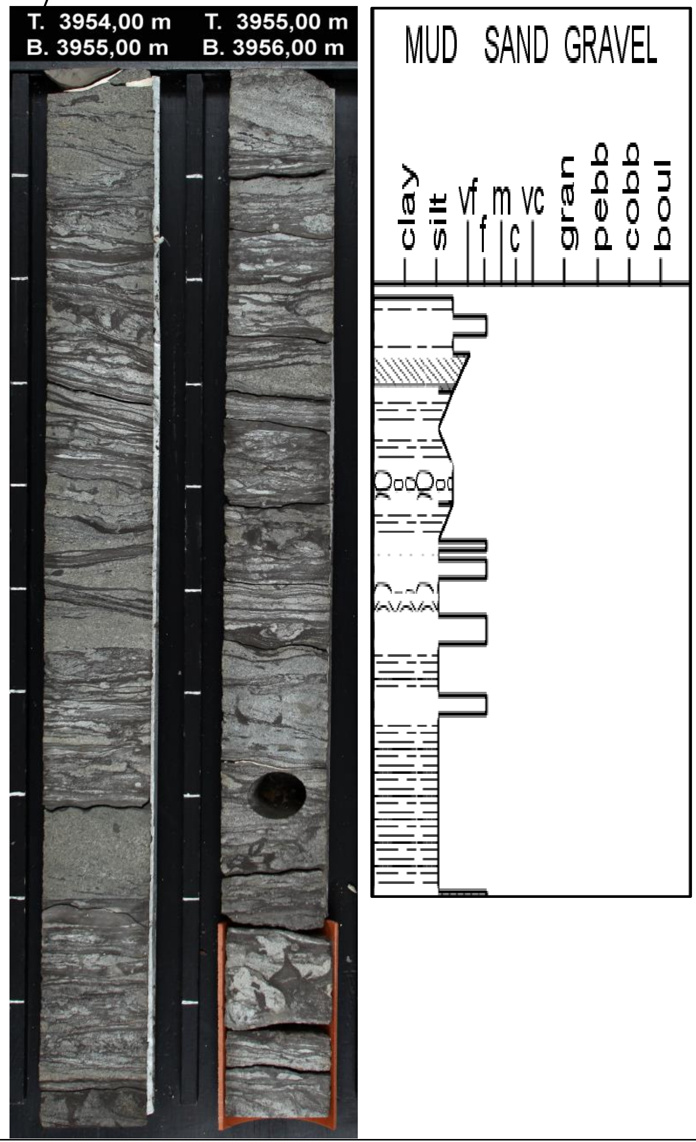
6. Abandoned channel /Bay-fill	DE6 consist of poorly to moderate sorted, very fine to fine medium grained sandstone, mudstone and silt. The base sometimes consist of lags (facies 11) overlain by lenticular bedding (facies 2), wavy-cross bedding (facies 3), flaser bedding (faices 4A), asymmetrical ripple x-lamination mud drapes (facies 7B) which are alternating with occasionally medium grained cross bedded sandstone with and without mud clasts (facies 8 and 9). The succession is coarsening upward. The contact is sharp. The succession forms meters thick units. The degree of bioturbation is moderately to high and represented by *Arenicolites, Roselia, Planolites* and *Teichichnus*. The Gamma ray response shows a variable low to high value, spiky signature.	34/3-3 	Varying energy, with high energy sandstone units and low energy heterolitic units.

Table 2 Depositional elements based on the facies (table 4.1)

4.2.1 Mouth bar DE1

Description. DE2 is a heterolithic depositional element consisting of very fine to fine grained sandstones interbedded with mudstone. The heterolitic basal part of the mouth bars consist of mud stone (facies 1B, table 1) wavy bedded heteroliths (facies 3, table 1) and flaser bedding (facies 4, table 1). Moving up-section the frequency and thickness of mudstone interbreeds diminishes. The sandstone beds consist of ripple cross-lamination to cross stratification (facies 8 and 9, table 1). The mouth bars define a coarsening upward motif, and the thickness of the individual sand beds varies from centimeter to decimeter. There are no bioturbation to low degree of bioturbation, sandstone is not affected by bioturbation and mud drapes are occasionally bioturbated by *Planolites* and *Asterosoma*. The Gamma ray response shows a fairly low to moderate value, coarsening upward blocky signature.

Interpretation. Tidal signatures are represented by single and double mud drapes in the cross bedded layers (facies 8, table 1) and hetreroliths with opposite directed ripple x-lamination (facies 4, table 7)(Visser et al., 1980; Dalrymple and Choi et al., 2007; Wei et al., 2016). There are occasionally centimeter thick structurless dark mudstone layers (facies 1B, table 1) at the base, the dark color of the mudstone and terrestrial debris indicates that the sediments contain organic materials (Arthur & Sageman, 1994) which suggest that the mud has terrestrial origin. These drapes are interpreted as fluid muds transported by a fluvial channels. Dalrymple and Choi (2007) suggested that mouth bars lays a short distance seaward form the turbidity maximum where fluid muds can be developed. The exposed position of the mouth bare will experience strong frequency wave action, consequently deposited mud that may be deposited has a high probability of being resuspended except in locally sheltered sites (Dalrypmle and Choi 2007). Tidal current action is stronger than river flow in the tidal mouth bars (Dalrymple and Choi 2007). The mud clasts present in the cross bedding indicates current reworked clay laminae deposited during slack water local erosion of fine sediments. The ripples cross lamination in the top of the mouth bars indicate rapid deposition from waning in flow (Ashley et al., 1982). The cleaning upward indicates shallowing toward a more proximal setting. The mouth bars are the part of the delta that contains the finest sand in the system (Dalrymple and Choi 20007).

The absence of bioturbation indicates rapid bedform migration and high rate of sedimentation which made it difficult for organisms to colonize the sandstone (Amos and Long, 1980; Wei et al., 2016). The occasionally occurrence of bioturbated mud drapes could indicate deposition during slack-water periods with slow sedimentation, indicating tidal influence.

These observations indicate deposition during high energy conditions, with occasionally low energy. The mouth bars are interpreted to be deposited in the upper dominated delta front environment with alternating tidal and fluvial influence.

4.2.2 Simple and Compound dunes DE2

Description. These are defined by a single thick set or stacked cosets of sigmoidal cross-stratified sandstones of (facies 8 and facies 9, table 1) bounded at their base and tops by flaser-bedding (facies 4, table 1) and occasionally massive mudstone (facies 1B, table 1). The sigmoidal cross-stratification is defined by mudstone lamina of varying thickness, often with an apparent cyclic partitioning; thinner mudstone lamina commonly alternate with thicker sandstones and thicker mudstone lamina co-occur with thinner sandstones. This is interpreted to represent tidal bundle sequences. The single sets define a simple fining occasionally coarsening-upward motif, whereas the cosets define more complex coarsening and thickening upwards motifs. Individual motifs stack to form overall coarsening upwards successions. Bioturbation is dominated by an impoverished *Cruziana* ichnofacies (commonly by *Asterosoma, Chondrites, Ophiomorpha, Planolites* and *Rosselia*), which may be present along topset, bottomsets and locally also along the sigmoidal foresets. Mud-drapes are often more intensely bioturbated compared to the sandstones.

Interpretation. The dominance of tide generated facies (e.g., double and single mud drapes, flaser bedding, current ripples with opposite direction and sigmoidal cross-bedding), suggest deposition in a strongly tide-influenced or –dominated environment (Visser et al., 1980; Dalrympole et al., 2007; Wei et al., 2016). The simple relatively thick sigmoidal cross-stratified sandstone sets hence are interpreted to represent simple large tide-generated dunes. The stacks of smaller scale dune bedforms or the coarsening upwards and fining upward coset are accordingly interpreted to represent more complex bedforms, formed by a series of smaller-scales dunes that amalgamate to form compound dunes. Compound dunes are commonly associated with tidal dominated environments (Dalryple and Choi, 2007). The increase in set thickness indicates energy levels increases (i.e., an upward transition from ripples into planar–tabular crossbedding)(Dalrymple and Choi , 2007). This occur because the current strength is less in the trough of the compound dune than it is at the crest (Dalrymple and Choi , 2007). The partitioning of mudstone into bundle sequences is related to tidal diurnal activity (Visser et al., 1980).). There are occasionally centimeter thick mudstone layers (facies 1B) sometimes bioturbated which suggest possible reworking, interpreted as fluid mud layers (Dalrymple and Choi et al., 2007). These observations indicate fluvial influence in a tide dominated setting. The thick fluid mud deposited in channels between dunes are only present in the lower part of the stacked dunes, indicating more tidal reworking of the dune succession. The common absence of bioturbation within the parts dominated by thicker sigmoidal cross stratified sandstone beds suggest that spring intervals were dominated by rapid bedform migration and high rate of sedimentation (Amos and Long, 1980). Conversely, the intervals dominated by thicker and relatively more intensely bioturbated mudstones suggest deposition during neap intervals dominated by near inactivity or abandonment and slow sedimentation rate. The presence of angular mudstone clasts within some intervals suggest rapid energy fluctuations with alternating slack water mud deposition and higher energy flows that were sufficiently strong to erode the muddy substrate and produce rip-up mud clasts. The commonly bioturbated topsets of the motifs suggest temporal dune inactivity and cessation of dune migration, perhaps as dune has aggraded to near sea-level heights.

The impoverished *Cruziana* ichnofacies hints to a stressed but fully marine environment. In consort this is taken as support for the formation in a stressed, but fully marine tide-dominated environment such as outer part of tidal deltas, i.e. the middle to lower delta-front, or outer parts of tide-dominated estuaries or on ebb-tidal deltas on the seaward side of wave-dominated estuaries.

The stacking of dunes to form thick successions suggests a gross near balance between sediment supply and background subsidence/compaction, in term reflecting a near stationary position of the shoreline-coastal delivery system (estuaries or deltas).

Compound dunes are differs from simple dunes by the less mud in the system, and better sorted grains and less bioturbation (Figure5). Mud-drapes are often more intensely bioturbated compared to the sandstones.

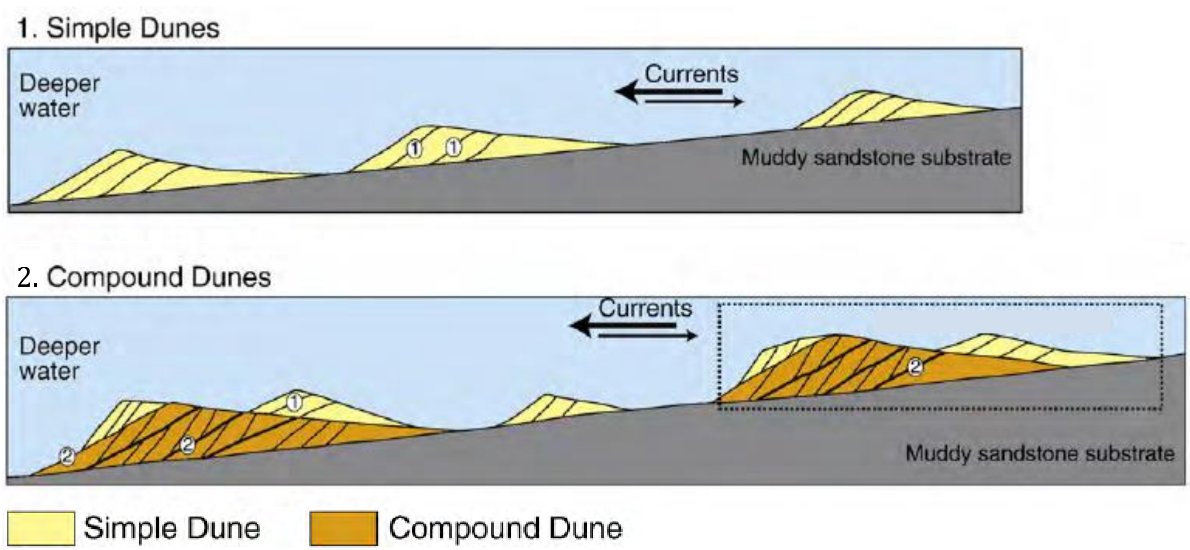


Figure 6 Simple and compound dunes by down-current bedform migration and superposition (modified from bens et al., 2010)

4.2.3 Collapsed (Breeched) dunes DE3

Description. DE3 comprises thick beds of high angle Diffusive and distorted cross stratified sandstone (facies 9B, table 1) intercalated with massive sandstones (facies 9A, table 1) overlain by irregular to parallel planar bedded heteroliths (facies 8C, table 1). The Collapsed dunes are coarsening upward. There are no bioturbation to low degree of bioturbation. The bioturbation is represented in the top sets by escape structures and *Planolites*, and some shell fragments are present. The Gamma ray response shows a fairly low to moderate value, coarsening upward blocky signature.

Interpretation. The intercalation of high angle irregular cross bedded (facies 9B, table 1) and massive sandstone (facies 9A, table 1) is interpreted to represent deposit cyclic release of sediments between a breaching and a sliding mode (van den Berg et al., 2017). Fine to medium grained Sandstone relatively tightly packed which gives a low void ratio. A slope fails gradually because shear force is applied by the retrogradation and create negative pore pressure, breaching sediments are released as massive sand gravity flows. During breaching the negative excess pore pressure dissipates locally, and deposits become less stable resulting in a phase of sliding. The sliding causes unloading and a drop in pore pressure which strengthen the deposits and switches the slop failure process back to the grain by grain mode (You et al.,2014Van den Berg et al., 2017). The cyclic release of sediments between a breaching mode and a sliding mode is named “dual-mode dilative failure” by You et al., 2014 (Van den Berg et al., 2017). The steep (up to vertical) cross bedding is preserved do to shear deformation which cause volume to expand making a negative pore pressure with respect to the hydrostatic and the underpressured pore water “glues” the sand grains together(Van den Berg et al., 2017). Horizontal planar lamination found together with massive sand bodies is interpreted as more proximal deposition (Van den Berg et al., 2007).

In the planar laminated sandstone there are escape structure which indicate that the deposition rate was very high. Shell fragments indicate shallow marine conditions. Breaching process is a result of slow retrogressive failure mechanism of steep subaqueous slope (Van den Berg et al., 2017). Breach failure is found in shallow water environments within deep fluvial and estuarine channels (Van den Berg et al., 2017).

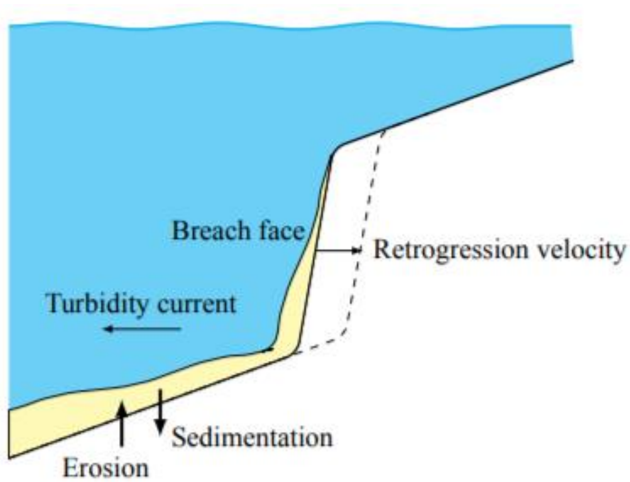


Figure 7 Schematization of breaching process (Weij et al., 2016)

4.2.4 Channel floor thalweg DE5

Description. DE5 comprises thick sandstone layers of poorly to moderate sorted and medium to coarse grained. The base of the channel floor consist of occasionally centimeter thick mud stone (facies 1B, table 1), overlain by cross bedding with mud clasts (facies 8, table 1) which is cleaning upward into cross-bedded sandstone with mud drapes (facies 7, table 1). The thick succession is built up of beds and bedsets that are either blocky or slightly fining-up from sharply to erosive based surfaces, commonly associated with lags of very coarse sand or granules. The fining upward successions initiate from a lower erosional base with abundant mudstone clasts. Some places the fining upward successions are not so clearly sharp based. A single set of cross-beds is typically a few tens of decimeters thick, but thinner and thicker sets occur as there is a high degree of amalgamation of beds in this facies. There is no visible bioturbation to low degree bioturbation represented by planolites. The Gamma ray response shows a fairly low to moderate value, fining upward signature.

Interpretation. The channel floor, or thalweg represent the deepest part of the channel and is depositis the coarsest material transported by the river. This channel lag is occationally represented by centimeter thick mudstone layers (facies 1B) interbedded with coarse sandstone. The dark color of the mudstone and terrestrial debris indicates that the sediments contain organic materials (Arthur & Sageman, 1994) which suggest that the mud has been transported form land toward the basin. The mudstone layers are interpreted to be fluid muds transported within a fluvial channel. Fluid muds are deposited in the topographically low area such as channel bottoms, because fluid mud is a dense suspension that hugs the bottom (Dalrymple and Choi 2007). The general medium to coarse grain size of the deposits indicates high energy conditions of this depositional element. The poorly sorted coarse grained cross strata represent migrating 2D and 3D dune bedforms that covered the active channel floor. The overall fining and cleaning upward trend suggests a reduction in flow strength upward onto channel bars (Dalrymple and Choi 2007) and an upward decrease in the amount of the suspended-sediment concentration (Ichaso and Darlymple, 2009).

The occurrence of double and single mud drapes (facies 7) suggest tidal current influence (Visser et al., 1980; Dalrymple and Choi et al., 2007; Wei et al., 2016). The ripples cross lamination in the top of the channel-fills indicate rapid deposition from waning in flow (Ashley et al., 1982). The fluvial and tidal signatures indicate a fluvial dominated environment with tidal influence. The low amount of bioturbation indicates stressed environment could be a combined effect of fluvial freshwater influence and high sedimentary rate.

The erosive sharp based fining upward sandstones unit are interpreted as fluvial channel floor/thalweg with tidal influence.

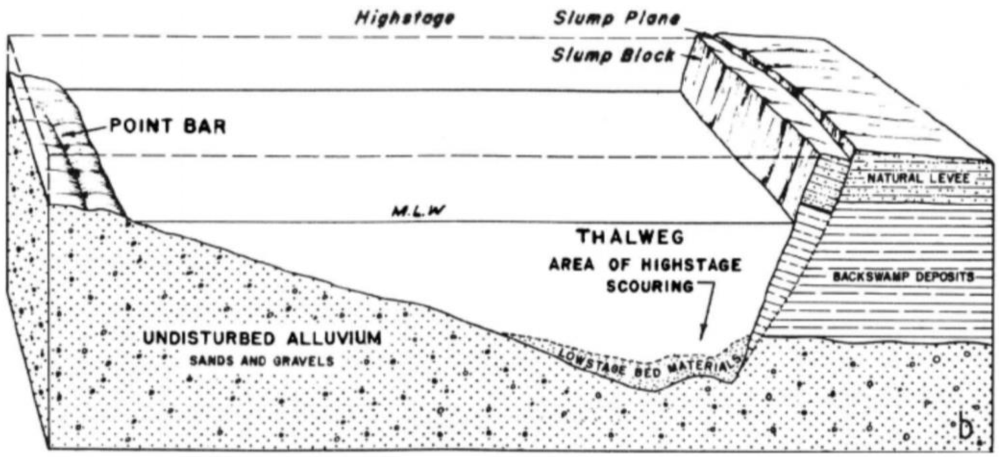


Figure 8 The location of the channel floor/Thalweg whitin a channel (Davis, 2008)

4.2.5 Abandoned channel DE6

Description. DE6 is mainly heterotic and have a higher mud content and higher degree of bioturbation then the surrounding depositional elements. The base consist of lags (facies 11, table 1) overlain by lenticular bedding (facies 2, Table 1), wavy-cross bedding (facies 3, table 1), flaser bedding (faices, table 4A), asymmetrical ripple x-lamination mud drapes (facies 7B, table 1) which are alternating with occasionally medium grained cross bedded sandstone with and without mud clasts (facies 8 and 9, table 1). Fine to medium grained sands are interbedded with more muddy deposits commonly organized in interbedds, which displays a coarsening upward succession. The depositional element is characterized by having a higher mud content and higher degree of bioturbation then the surrounding depositional elements. The degree of bioturbation is moderately too high and represented by the impoverished *Cruziana* ichnofaceis (common by *Roselia* and *Teichichnus*). The Gamma ray response shows a low to high value, spiky signature.

Interpretation. The coarse grained interbedded pebbly lags at the base usually indicate a transgression and flooding of the system. Coarse cross stratified sandstone is interpreted as channel deposits indicating a proximity to the source possible reflecting crevassing from adjacent channel in flood stage. The fine grained and heteroltic deposits indicate a more distal deposition and a lower energy level. The alternation of proximal and distal deposits and change in energy level could indicate a flooding or an switching and abandonment of the channel. The low diversity of bioturbation could indicate brackish waters conditions. *Roselia* generally associated with the *Cruziana* ichnofacies, representing a full marine setting (Pemberton et al., 2004). The *Theichicnus* are often found in bays and characterize brackish water. *Arenicolites* is usually associated with *Skolithos* ichnofacie which is shallower marine then the *Curziana* ichnofacies (Pemberton et al., 2004), this could indicate that there is not fully marine condition and a bay type of setting. Based on the local occurrence of this association DE6 can alternatively be is interpreted as an abandoned distributarychannel.

The higher content of finer grained sediments, and larger amount of bioturbation point towards and abandonment of a tidal channel.

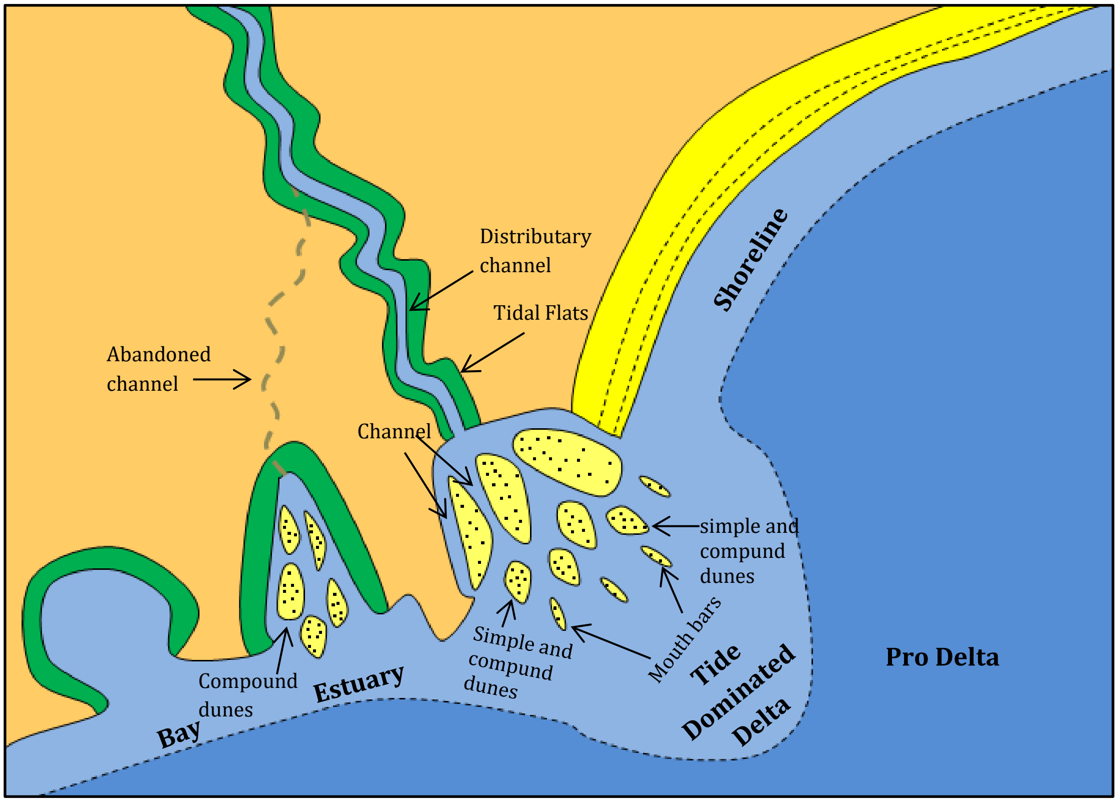
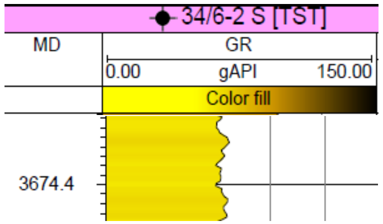
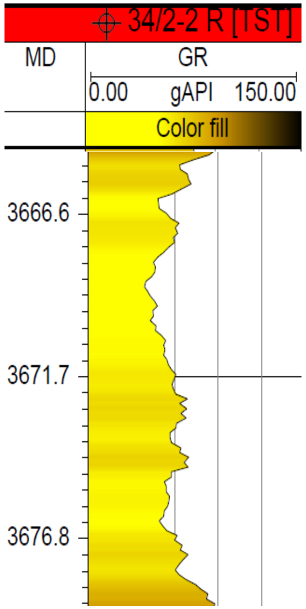
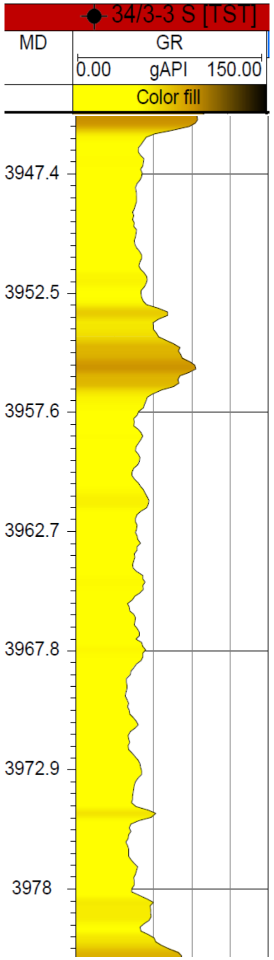
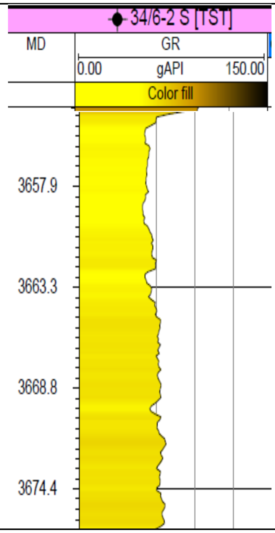
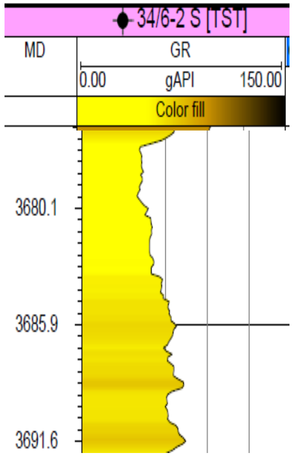


Figure 9 Conceptual model of the interpreted depositional environment and depositional elements and facies associations of the Cook Formation.

4.3 Facies Association

Facies Associations	Description:	Log motif	Processes
FA1: Shelfal	Massive black to dark gray mudstone (facies 1A) with occasionally thin beds of very fine grained sandstone or siltstone ripple. The degree of bioturbation is intensely, and represented by *Chondrites*, *Diplocraterion*, *Asterosoma*, *Arenicolites Terebelina* and *Teichichnus*.		Deposited in calm water below the wave or current, in Marine water as identified by impoverished Cruziana ichnofacies The sand or silt ripples can indicate periods of higher energy.
FA1: Prodelta	Overall dominated by mudstone; massive black to dark grey mudstone (facies 1A), lenticular bedding (facies 2) and wavy bedding (facies 3), however occasionally layers of very fine grained sandstone to siltstone alternating with mudstones layers. The internal structure consists of structuresless bioturbated sandstone or siltstone (facies 8A) and wavy bedding (facies 3). The degree of bioturbation is low to intense, represented by *Asterosoma*, *Arenicolites*, *Chondrites*, *Diplocraterion*, *Planolites* and *Teichichnus*.		Deposited below fair-weather base, mainly tide influenced, in Marine water as identified by impoverished Cruziana ichnofacies

FA2:	A Delta fron to possi ble delta plain	FA3 consists of fine to medium grained sandstone. Facies association 2 comprise mudstone (facies 1B) wavy bedding (facies 3), flaser bedding (facies 4A), asymmetrical ripple cross-lamination (facies 4B) low angle cross stratified layers (facies 7A and 8), sandstone with double and single mud drapes (facies 7B) and parallel planar to low angle lamination (facies 7C). This facies consists of distal tidal bars (DE 1), mouth bars (DE2) and channel fill (DE 4). The degree of bioturbation is low and represented by *Arenicolites, Chondrites, Planolites, Roselia* and some vertical burrows.		Deposited just above fair-weather wave base in marine waters. Tidal and fluvial dominated.

	B Lower shore-face	Fine to very fine grained muddy sandstone and siltstone. Moderate to well sorted. Upward sanding and coarsening. The facies association consists of locally structure less sandstone with occasionally ripple cross-lamination (facies 4B) and some cemented intervals. Intense to high bioturbation represented by *Asterosom, Rosselia, Planolites, Palaeophycus*, *Ophiomorpha, Terebellina* and bivalve burrows.		Deposited just above fair-weather wave base. Interpreted as wave dominated. Due to the intense bioturbation structures are hard to observe.
FA3 Upper shoreface/ forshore		Coarsening upward very fine to medium grained well sorted sandstone. The facies association consist mainly of cross-stratification (facies 8A), and parallel planar lamination (facies 7C). No bioturbation present.		Deposited in the zone of breaking waves and swash zone. Wave and tide dominated.

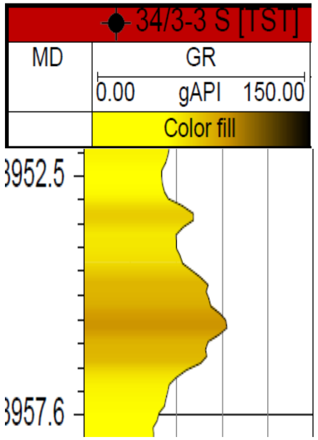
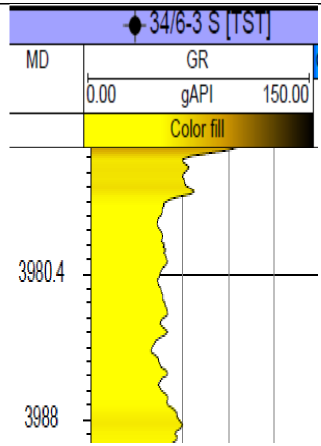
FA5: Bay-fill	Very fine to fine grained sandstone, mudstone, silt and occasionally coarse sandstone packages. The bay-fill usually consists of lenticular bedding (facies 2), wavy bedding (facies 3) occasionally hummocky cross stratification (facies 5), double and single mud drapes (facies 7B), cross stratification with and without mud clasts (facies 7A and 8) and parallel planar to low angle lamination (facies 7C). The bioturbation is moderate to high and represented by *Arenicolites, Asterosoma, Diplocraterion, Planolites* and *Theichicnus*.		Tide and wave dominated
FA5: Tide dominated Estuary	Mainly fine to coarse well sorted sandstone. The Facies association consist of mud stone (facies 1B), low angle cross stratification (facies 7A), mud drapes (facies 7B), parallel planar to low angle lamination (facies 7C), massive sands (facies 9A), high angle cross stratification (facies 9B) and parallel planar lamination (9C). FA5 consists of dunes of breaching (DE3) and estuarine bars (DE4). Bioturbation is low to moderate with low diversity and represented by *Ophiomorpha* and *Planolites.*		Deposited just above fair-weather wave base. Tide dominated with fluvial influence.

Table 3 Facies associations based on facies (table 4.1) and depositional elements (table 4.2).

4.3.1 Shelfal FA1

Description. Facies association 1 consist of massive black to dark gray mudstone (facies 1A) with occasionally thin beds of very fine grained sandstone or siltstone with occasionally ripple x-lamina (facies 4B). The completely bioturbated fine grained sandstone to siltstone intervals has a diverse ichnofauna (commonly by *Terebelina*). This succession is usually overlain by delta front (FA 3A, table 2), estuaries (FA 6, table 2) or upper to lower shoreface (FA 3B, table 2) deposits. The Gamma ray response shows a high value, and has an erratic signature.

Interpretation. The massive mudstone deposits indicated deposited in calm water below wave or current reach (Collinson, 1996). The bioturbation is of marine character represented by *Terebellina* which is only one found near shore to outer shelf (Chamberlain 1978). Because of the intense bioturbation there is hardly any sedimentary structure visible in this section. These observations indicate deposition in calm marine environment below storm wave base, which has led to the interpretation of FA1 to be shelfal.

4.3.2 Prodelta FA2

Description. Facies association 2 is dominated by mudstone (facies 1A, facies 2 and facies 3), however there are some sandstone layers alternating with the mud layers (facies 7). The sandstone intervals are developed as continuous layers of up to tens of centimeter thick upward thickening and coarsening succession. The mudstone intervals consist of plane-parallel lamination and sandstone lenses. Silt and sand content increases upward. The degree of bioturbation is low to intense, represented by impoverished *Cruziana* ichnofaceis (commonly by *Asterosoma, Arenicolites, Diplocraterion* and *Teichichnus*). The medium grained cross ripple cross-laminated sandstone layers are unbioturbated. FA2 is usually overlain by delta front (FA3A) deposits or lower shoreface deposits (FA3B). The Gamma ray response shows moderate to a high value spiky signature.

Interpretation. The muddy thick layers with lenticular bedding indicate deposition in calm water with low energy-deposition below fair-weather wave-base (Reading and Collinson, 1996). The sandstone and siltstone intervals were brought by high-energy event beds, suggested to be hyperphycnites/ density flows. The hyeperphycnites flows are produced by high-density fluvial discharge events, like floods. This results in turbulent sediment gravity flow along subaqueous slopes, which may extend to the prodelta (Reading and Collinson, 1996). The completely bioturbated fine grained sandstone to siltstone intervals have a diverse ichnofauna typical of marine fauna represented by *Terebelina*. Because of the intense bioturbation there is hardly any sedimentary structure visible in this section.

These observations with quiet water laminated, intensely bioturbated mudstone and mass flow turbidities hyperphycnites flow suggest deposition took place between storm and fair-weather wave base on the transition from inner shelf to prodelta and delta slope.

4.3.3 Delta Front to possible delta plain FA3A

Description. The regressive facies succession comprises laterally extensive coarsening upward sequences characterized by tide dominated facies. The delta front comprises (from distal to proximal); mouth bars (DE 1, table 2), simple and compound dunes (DE 2A and 2B, table 2), collapsed (breached) dunes (DE 3, table 2) and channel-floor/thalweg (DE 4, table 2) (possible distributary channels). There is an upward decrease in mud and increase in mean grain size and bed thickness. The succession is usually overlaying sheflal (FA 1,table 3) or prodelta muds (FA 2, table 3), and coarse and fine upward into estuarine deposits (FA 6, table 3) or shalfal (FA 1, table 3). The degree of bioturbation is varying from absent to moderate, and represented by the *Cruziana* ichnofacies and *Skolithos* ichnofacies. The Gamma ray response shows low to moderate value, blocky coarsening upward for the bars GRLR1 and fining upward signature for the channels.

Interpretation. The lower part of the succession shows basinet processes and reworking of the deposits, represented by mouth bars (DE 1, table 2) with heterolitic lamina (facies 2, facies 3 and facies 7) which is the most distal depositional element. The mouth bars (DE 1, table 2) is overlying single (DE 1A, table 2) and compound dunes (DE 1B, table 2) with occasionally channel floor/thalweg (DE 4, table 2) at the base. Dunes are very rare on bar flanks in deltas but common in channel bases, which is observed in this study by the alternation of compound dunes (DE 1B, table 2) and channel floor/thalweg (DE 4, table 2). There is also a possibility that some of the interpreted channel floor/thalwege deposits are distributary channels.

The channels observed in well 35/4-1 show the clearest sharp base with very coarse sandstone fining upward. In the other wells were channel-fills are observed the channels display sharper erosive contact in the lower Cook member then in the middle and upper Cook member. This indicates that well 35/4-1 and parts of the lower Cook member could represent delta plain.

The change of facies show that the secession is changing from more distal deposits toward more proximal deposits, indicate a regression. Corse sand that escapes form the distributary mouths bars into the delta front will form dune cross bedding with bimodal bedding (Dalrymple et al., 2003). There is a seaward increase in amount of mud which generates an upward-coarsening succession.

The absence of storm-induced structures combined with intense tidal reworking suggests a wave sheltered shallow marine environment, which in contrast with the coarsening upward mouth bars (DE 1, table 2) suggest tide dominated delta front.

4.3.4 Lower shoreface FA3B

Description. The sandstone is muddy, moderate to well sort and fine to very fine grained. The internal structure consists of structure less sandstone with occasionally wave or current ripples (facies 6) with some cemented intervals. The succession is cleaning and coarsening upwards with a sharp base. The degree of bioturbation is intense to high with varying diversity, represented by *Asterosom, Rosselia, Planolites*, *Palaeophycus*, *Ophiomorpha, Terebellina* and bivalve burrows. This facies association usually overlay prodelta (FA 1) or upper shoreface deposits (FA 4). The Gamma ray response shows a low to moderate value and a coarsening upward signature.

Introduction. This is an facies association with very intense bioturbation and with mud content. The intense bioturation and mud content in the sandstone reflects slow deposition and calm water conditions interpreted to be below fair-weather wave base (Dalrymple and Choi 2007). The intense bioturbation makes it hard to notice any sedimentary structure, but occasionally current and wave ripple cross lamination are observed. These observations can indicate a facies association with a more wave dominated environment than the other facies associations. The bioturbation is marine, where *Terebellina* is the only one found near shore to outer shelf (Chamberlain 1978). The deposits with higher diverse ichnofauna indicate an open marine shelf, while the sediments with low diversity indicate more protected settings (Pemberton et al., 2001). These observations suggest mainly basinal processes, which indicate deposition close to the fair-weather wave base. This is interpreted as the protected lower shoreline to an open lower shoreline.

4.3.5 Upper shoreface/foreshore or intertidal to higher subtidal flats FA4

Description. FA4 consists of thick well sorted, fine to medium grained, clean light grey sandstone. The sedimentary structures are represented by massive to parallel planar laminated (facies 7) and occasional local current ripples and cross stratification (facies 8). There is no bioturbation observed. FA6 is coarsening upward into. The shoreline is overlain by a prodelta (FA 1). Bioturbation is absent. The Gamma ray response shows low to moderate value and has a coarsening upward signature.

Interpretation. The massive to parallel planar laminae (facies 7) was probably deposited in the foreshore since it is the zone of maximum sediment movement (Reading and Collinson, 1996). This is consistent with swash zone deposition. The swash is a turbulent layer of water that washes up on the beach after incoming waves break, and moves materials up and down the beach. In the swash zone each wave produces a shallow high velocity landward-directed swash flow followed by an even shallower seaward-directed backwash, which may disappear by infiltration into the bed (Reading and Collinson 2003). Cross stratification reflecting higher-energy wave conditions. There is a coarsening upward grain size and upward increase in flow strength indicated by the sedimentary structure. These structures and the absence of bioturbation indicates deposition during moderate to high energy conditions. FA6 is interpreted as an upper shoreline/beach.

The alternative interpretation could be that the facies association represent intertidal to higher subtidal flats. Tidal flats and beach-shoreface often constitute the same end members in a depositional environment (Dashtgard et al., 2009). Tidal flats are dominated by tides during fairweater condition (Dalrymple 1992; Dashtgard et al., 2009), whereas shorface is dominated by wave processes during fairweather (Dahstgard et al., 2009). Hence the tidal flats will typically show a more complex facies association, due to the greater importance of tidal influence (Dashtgard et al., 2009). The uniform character of the sediments and lack of well-developed wave, combined flow favors the interpreteation of a shoreface/forshore depositional environment.

4.3.6 Bay-fill FA5

Description. FA 5 is dominated by mixed sandstone and heterolithic mudstone. FA5 usually consists of lenticular bedding (facies 2, table 1), wavy bedding (facies 3, table 1) occasionally hummocky cross stratification (facies 5, table 1), double and single mud drapes (facies 7B), cross stratification with and without mud clasts (facies 7A and 8, table 1) and parallel planar to low angle lamination (facies 7C, table 1). The bioturbation is moderate to high and represented by *Arenicolites, Asterosoma, Diplocraterion, Planolites, Roselia* and *Theichicnus*. The gamma ray log response varies from moderate to low with spiky GRLR4 signature to low with erratic signature.

Interpretation. High amount of heterolithic sediments represents a slow rate of deposition, due to sea level rise and switching between delta lobes and channels present in the delta (Reading and Collinson, 1996). Bay-fill contains deposits that reflect an interaction of fluvial and marginal marine processes. The mud stone facies indicate a flooded deposition, while the coarser sandstone indicates high energy flows of fluvial influx. Preserved sediment structures such as current wave ripple cross lamination indicates both tidal and wave activity. These occasionally increase in thickness in such instants as represent sandstone interval. In the base of the unit there is a pebbly lag, which resembles a transgressive lag (Facies 11, table 1). Hummocky cross stratification is formed due to high energy combined flow (slow wave currents) (Reading and Collinson, 1996). There is a relatively low intensity and low diversity of bioturbation present. This indicates the presence of brackish water conditions and high degree of instability of the sandy packages. *Roselia* generally associated with the *Cruziana* ichnofacies means that this facies is present in full marine settings (Pemberton et al., 2004). The *Theichicnus* are ofthen found in bays and characterize brackish water. *Arenicolites* is usually associated with *skolithos* ichnofacie which represents a shallower marine ichnofacie than the *Curziana* ichnofacies (Pemberton et al., 2004). This could indicate that there is not a fully marine condition present, which probably means that this facies association represents a bay type of setting. Based on the observations FA5 is interpreted as an Bay-fill.

4.3.7 Tide dominated Estuary FA6

Description. FA7 mainly consists of medium to coarse well sorted sandstone. The tide dominated estuaries is composed of compound dunes (DE 2B, table 2), collapsing (breaching) dunes (DE 3, table 2) and channel floor thalweg (DE 4, table 2). The estuarine deposits are usually overlain by a flooding surface prodelta (FA2, table 3), or bay-fill (FA5, table 3). Bioturbation is low to moderate with low diversity, and represented by *Skolithos* ichnofacies (commonly by O*phiomorpha* and *Planolites*). The Gamma ray response shows low to moderate values, and a coarsening upward signature.

Interpretation. Tide dominated estuaries are deposited as an embayment that has been partially infilled by sediments derived from both fluvial and tidal processes. There is a landward transportation movement of sediments (Harris et al., 1989; Dalrymple, 1992), where the clean and well sorted deposits indicate high current energy levels with frequent reworking of sediments. Because the estuary is close to a delta it will receive suspended sediments from nearby distributary channels, which will cause abundance of mud drapes. The compound dunes decrease in set thickness going upward, which indicates that the energy levels decreases. This suggests that the dunes moves downstream along the direction of sediment transport, meaning that they are moving from being more proximal to becoming more distal (Allen, 1980; Ashley, 1990; Dalrymple and Rhodes, 1995; Desjardins et al., 2012; Choi and Jo, 2015). Estuaries contain brackish water conditions (Dalrymple, 1992; Boyd et al 2006), which can be identified by the low rate and low diversity of bioturbation. The occurrence of mud drapes and fine grained well sorted sandstone indicate tidal currents reworking the sediments (Visser, 1980; Dalrymple and Choi 2007; Wei et al., 2016), while cross stratification and thick mud drapes indicates a fluvial influence (Dalrymple and Choi, 2007). These observations are used to interpret FA7 to be a tide dominated estuary.

4.4 Sedimentary logs/core descriptions

The core description is a detailed interpretation of the 10 cores taken for the Tampen Spures area. The interpreted cores have been drawn in Sedlog, to display graphic sedimentary logs. The interpretation consist of a column displaying the formation a second column with different facies association, a third column with depositional elements, a fourth column with the meter of the core, fifth column with the lithology, sixth column with a log description based on grain size, the seventh column display bioturbation and the eight column with some notes.

Core description of well 34/2-2

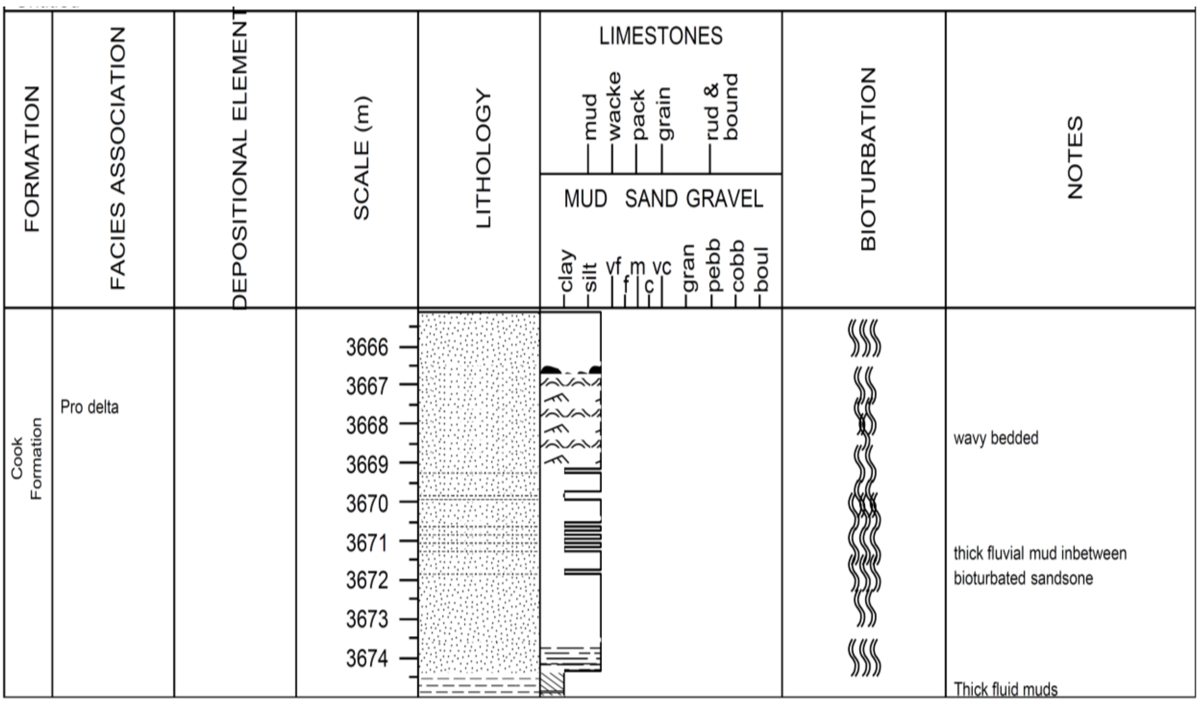


Table 4 Graphic Sedimentary log

Core description of well 34/2-4

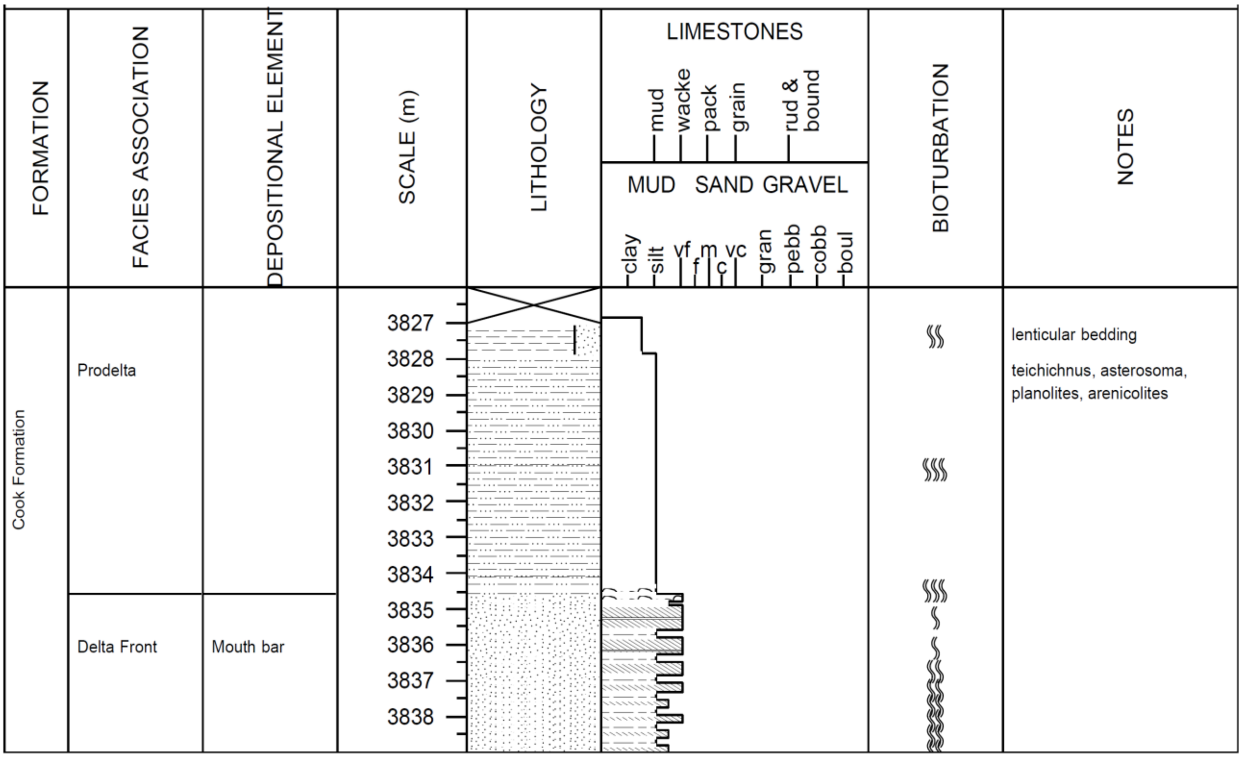
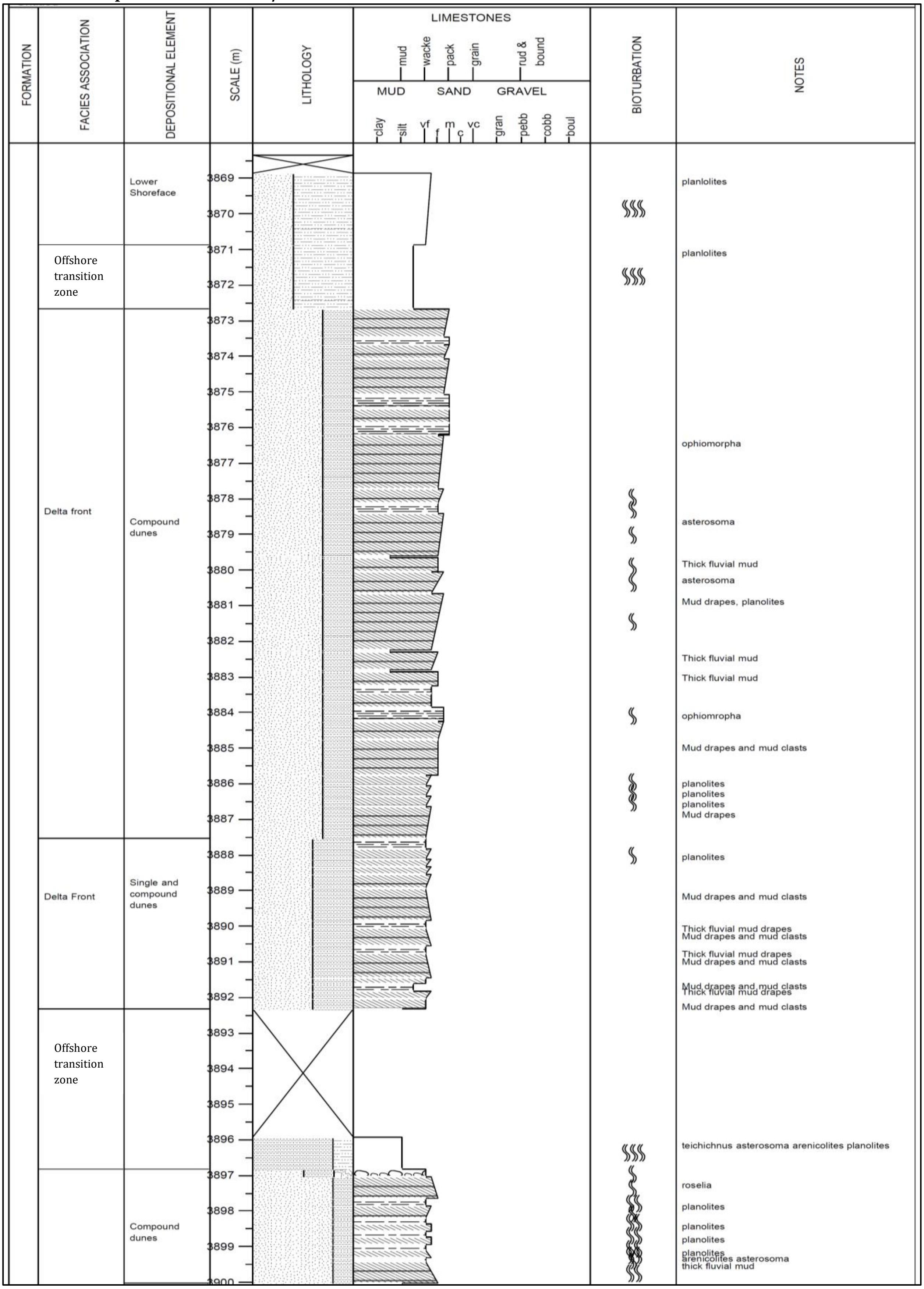


Table 5 Graphic Sedimentary log

Core description of well 34/3-1 ST2



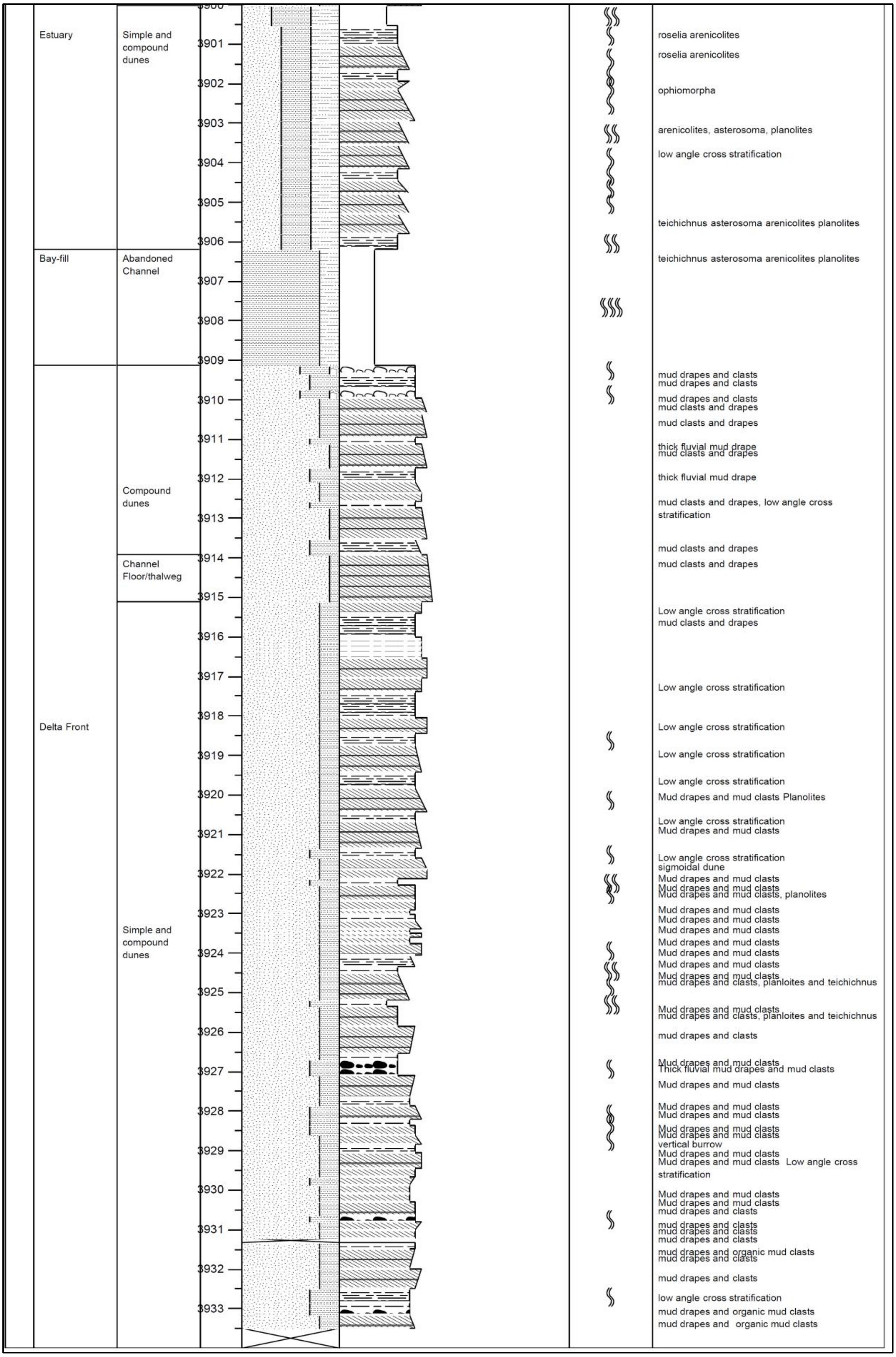
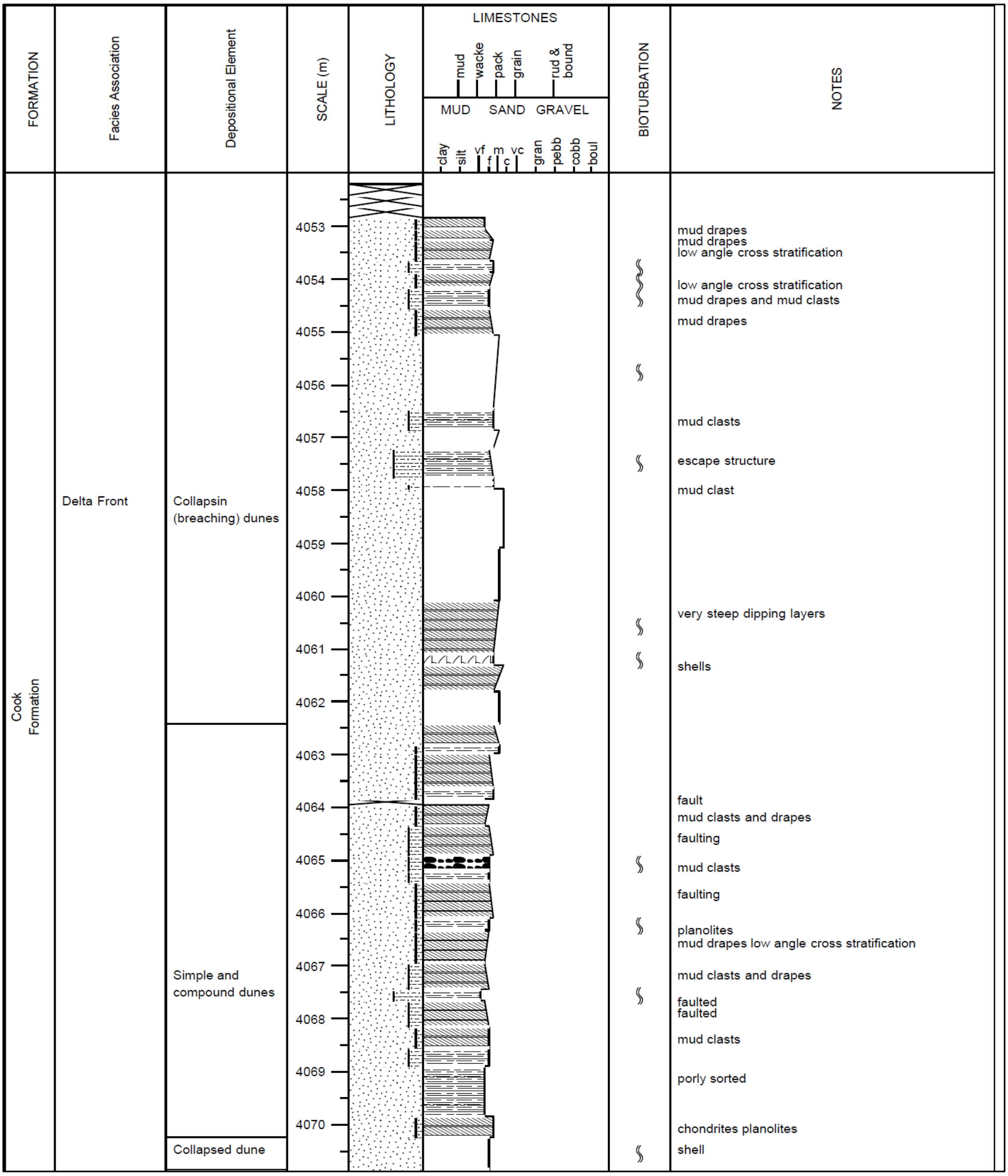


Table 6 Graphic Sedimentary log

Core description of well 34/3-2S



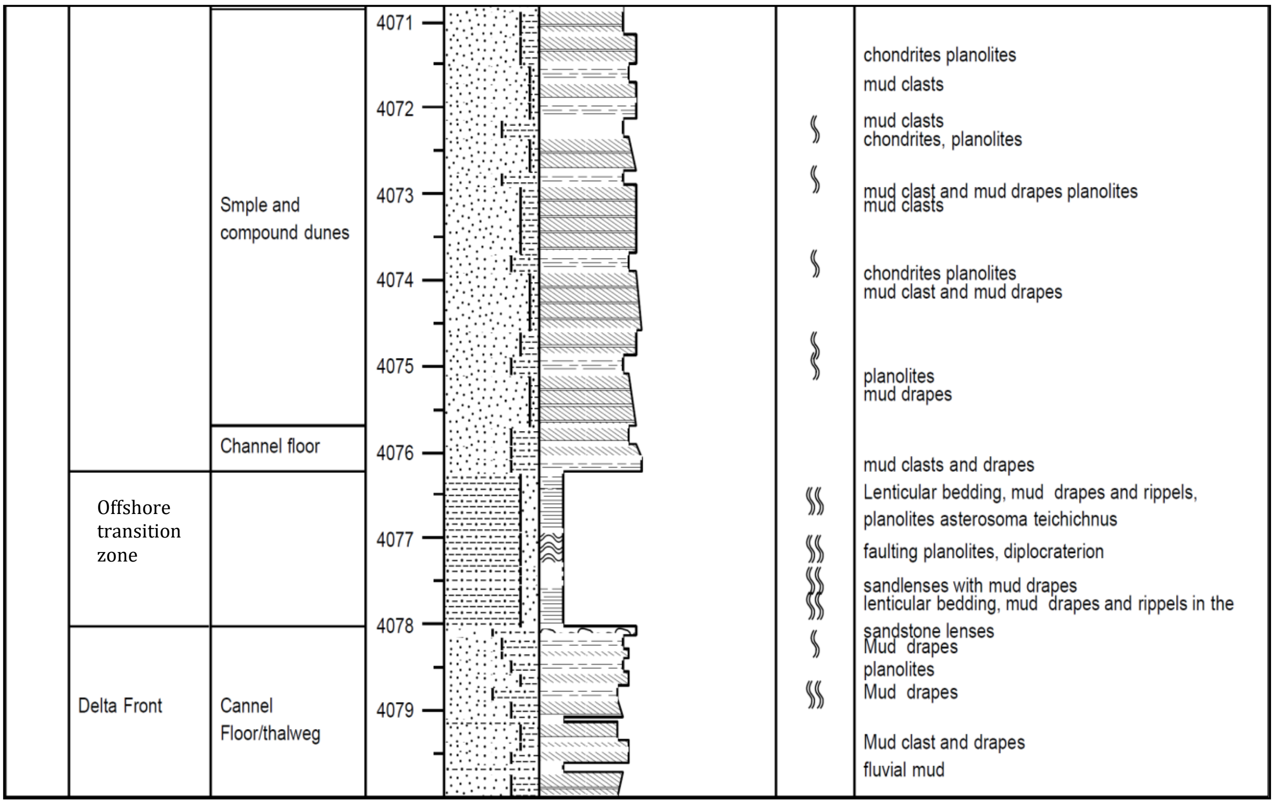
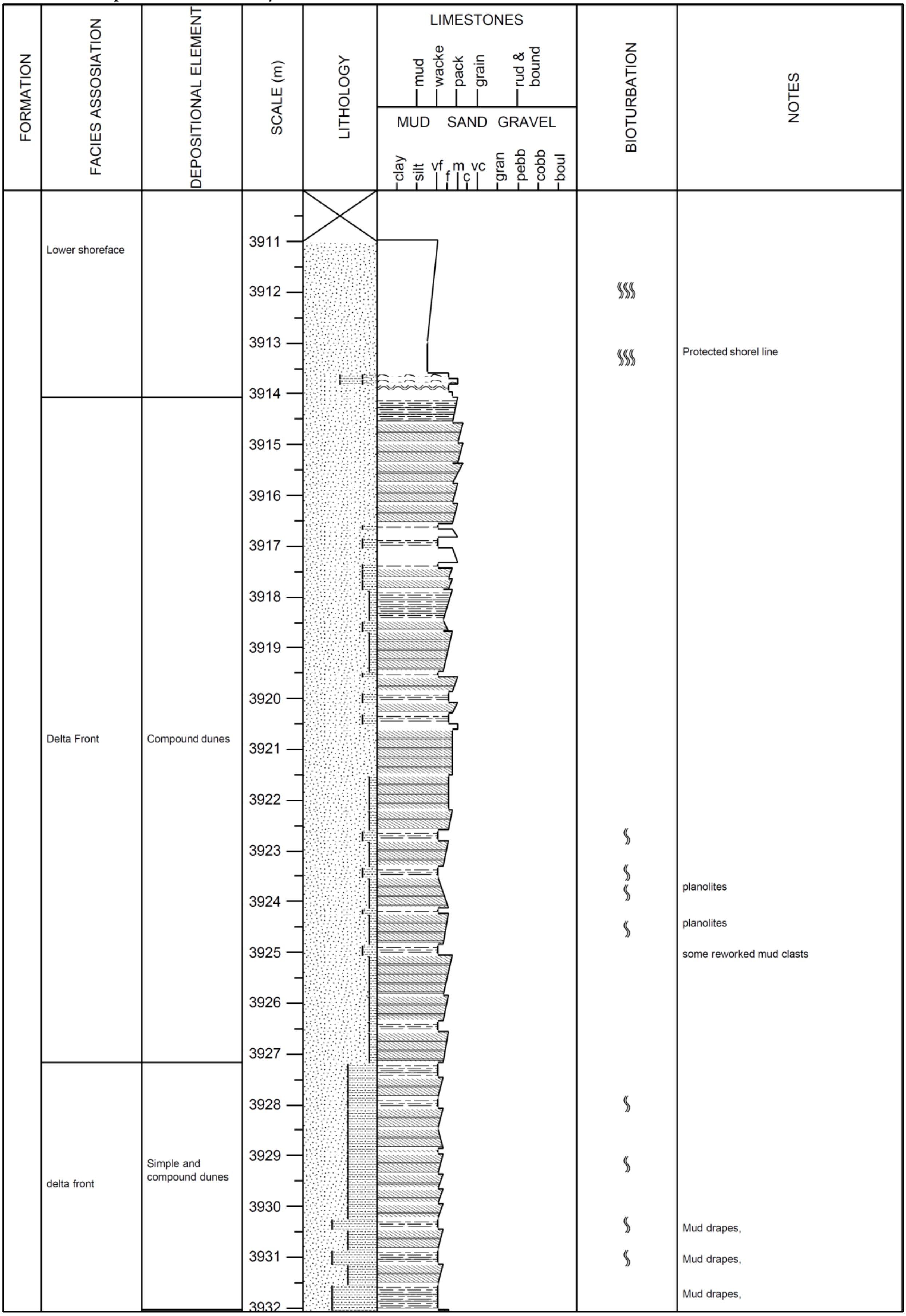
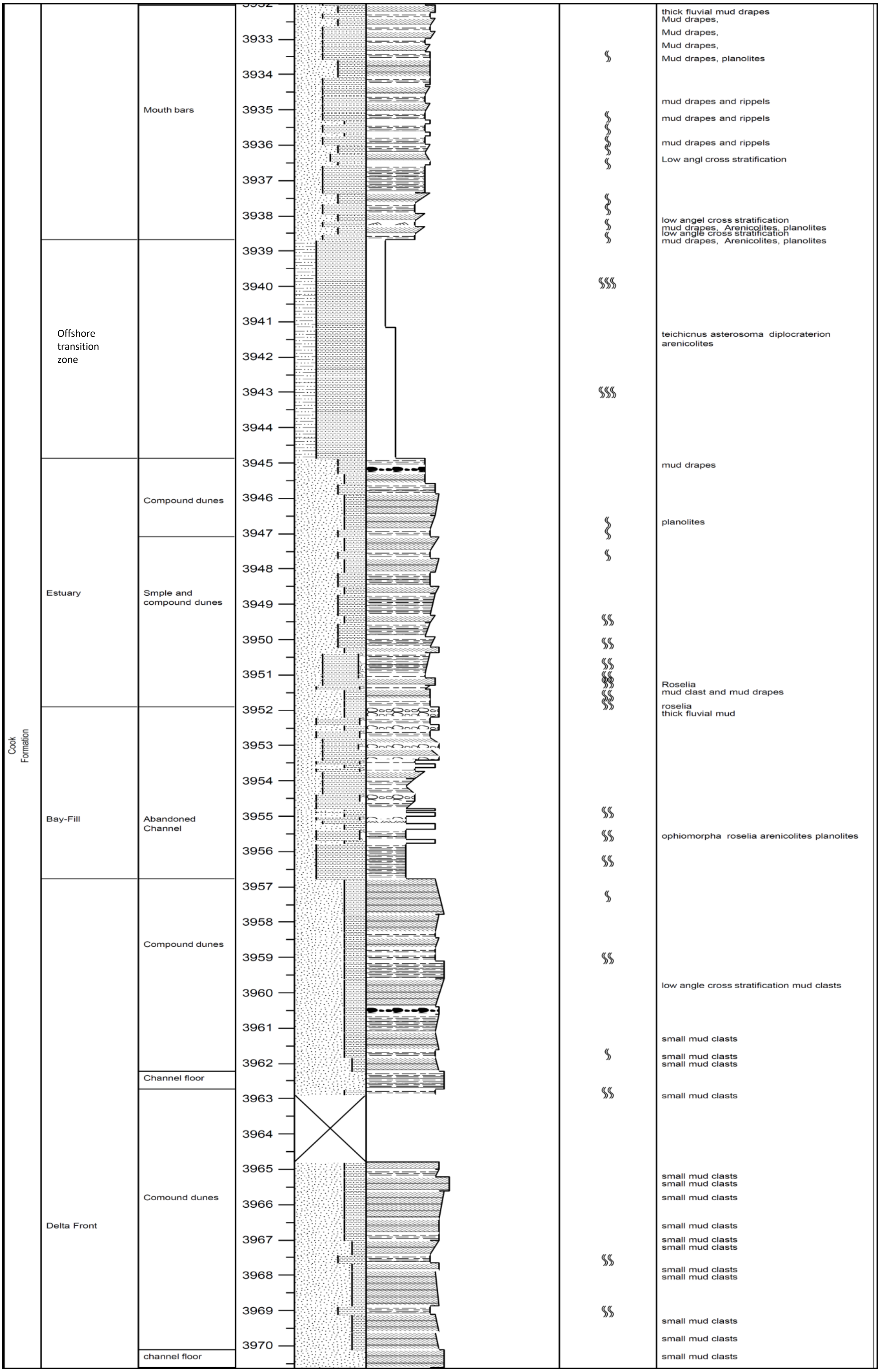


Table 7 Graphic Sedimentary log

Core description of well 34/3-3S




Cook Formation
Mouth bars
Offshore transition zone
Estuary
Compound dunes
Smple and compound dunes
Bay-Fill
Abandoned Channel
Delta Front
Compound dunes
Channel floor
Comound dunes
channel floor
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thick fluvial mud drapes
Mud drapes,
Mud drapes,
Mud drapes,
Mud drapes, planolites
mud drapes and rippels
mud drapes and rippels
mud drapes and rippels
Low angl cross stratification
low angel cross stratification
mud drapes, Arenicolites, planolites
low angle cross stratification
mud drapes, Arenicolites, planolites
teichicnus asterosoma diplocraterion arenicolites
mud drapes
planolites
Roselia
mud clast and mud drapes
roselia
thick fluvial mud
ophiomorpha roselia arenicolites planolites
low angle cross stratification mud clasts
small mud clasts
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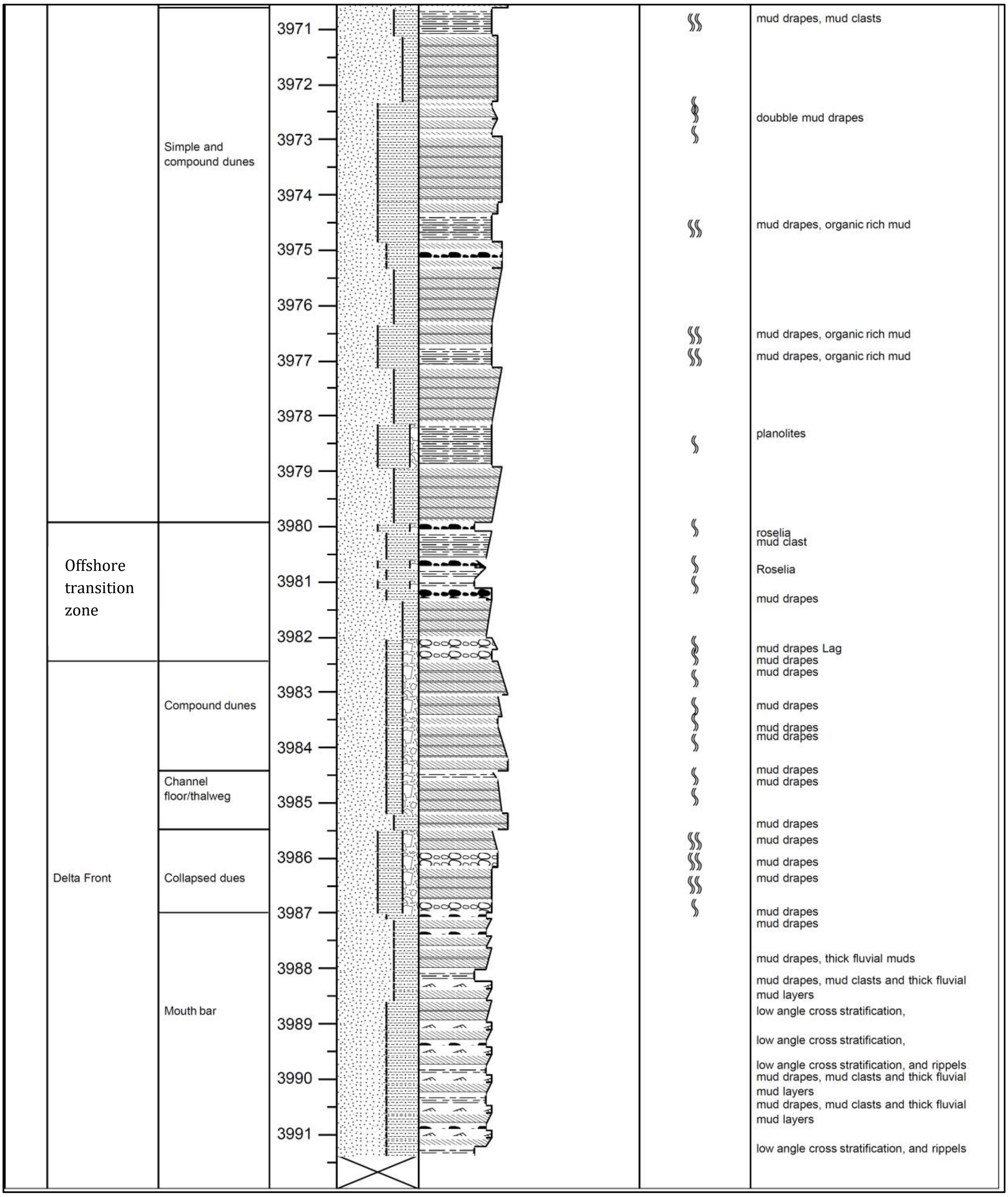
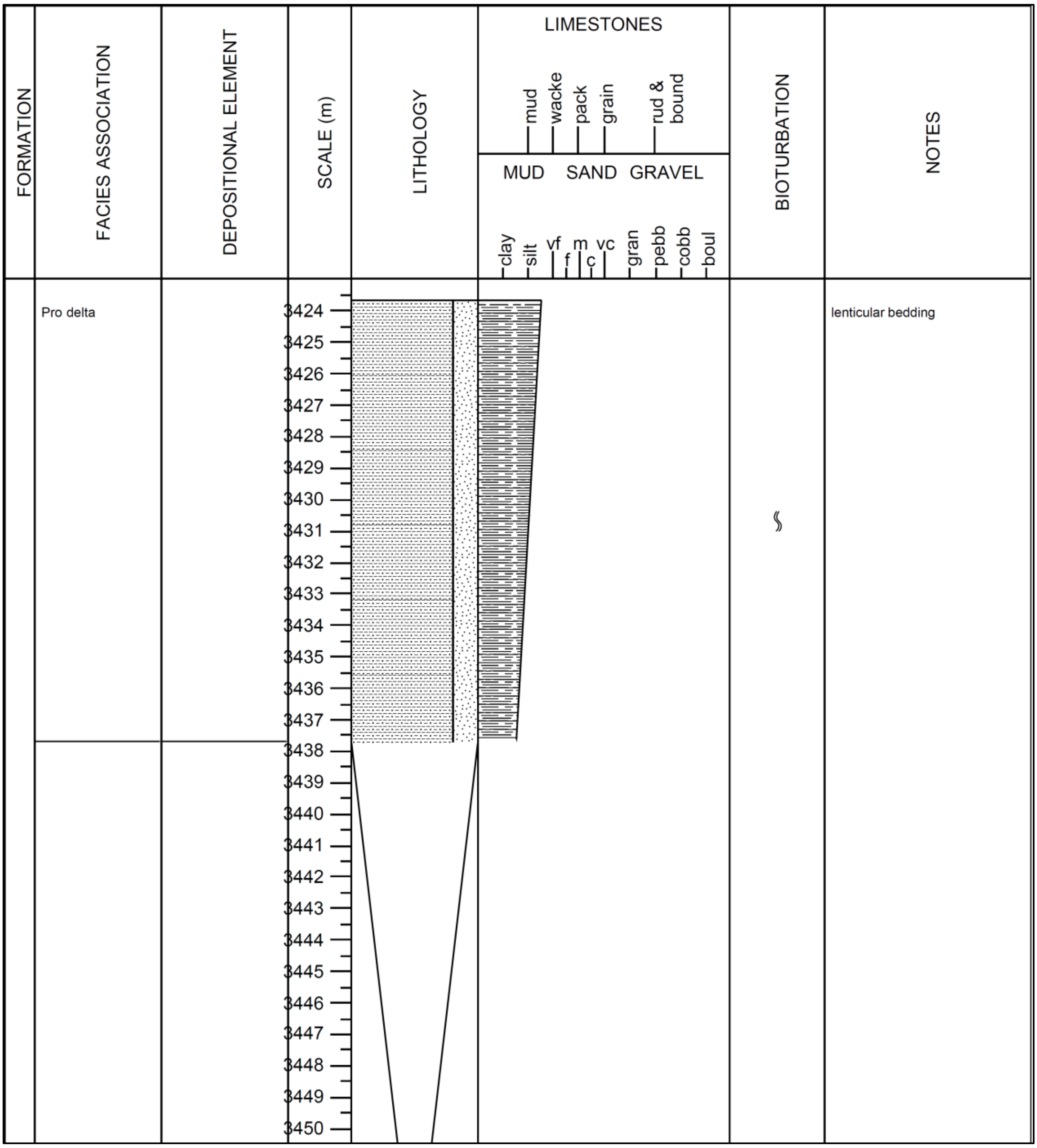


Table 8 Graphic Sedimentary log

Core description of well 34/4-5



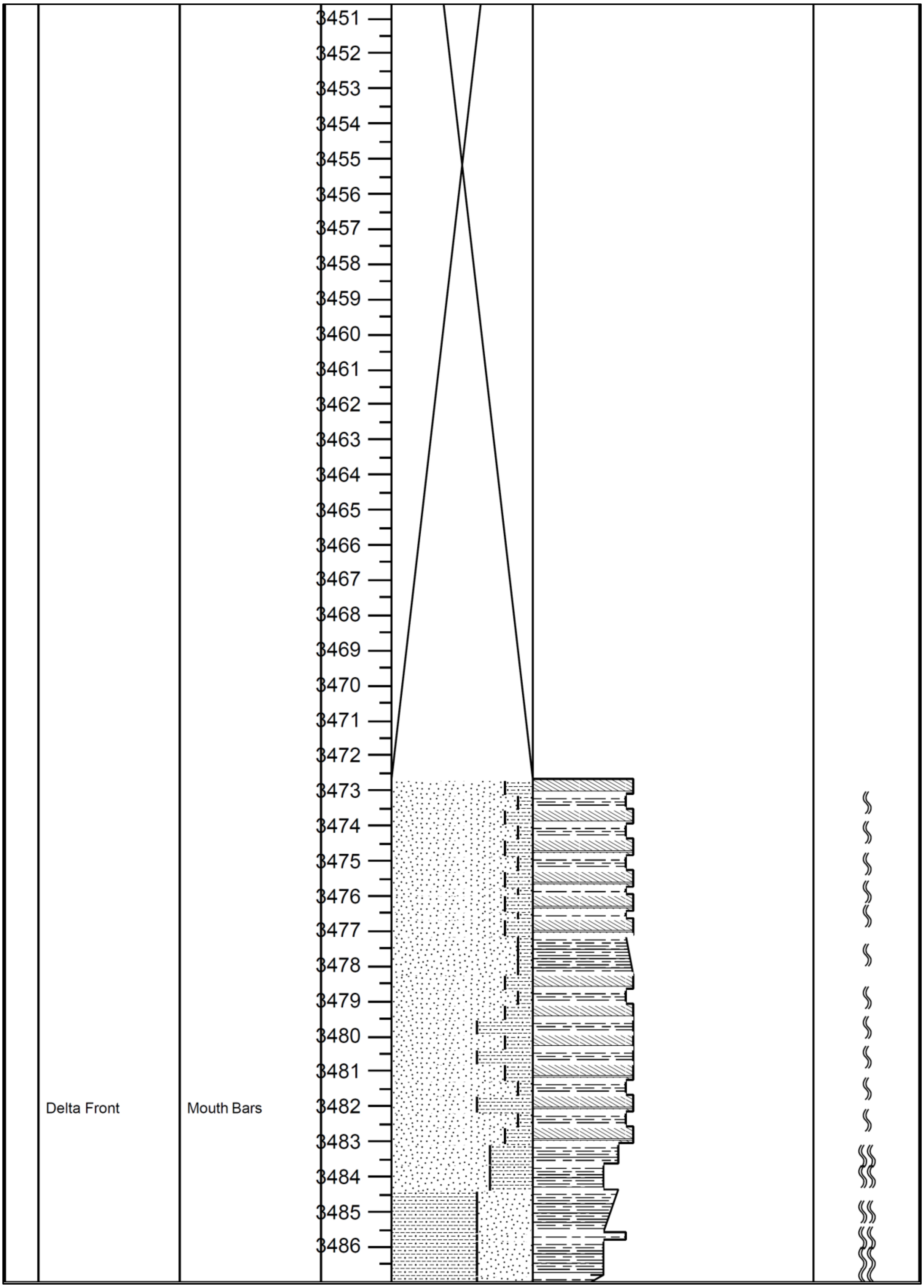


Table 9 Graphic Sedimentary log

Core description of well 34/5-1S

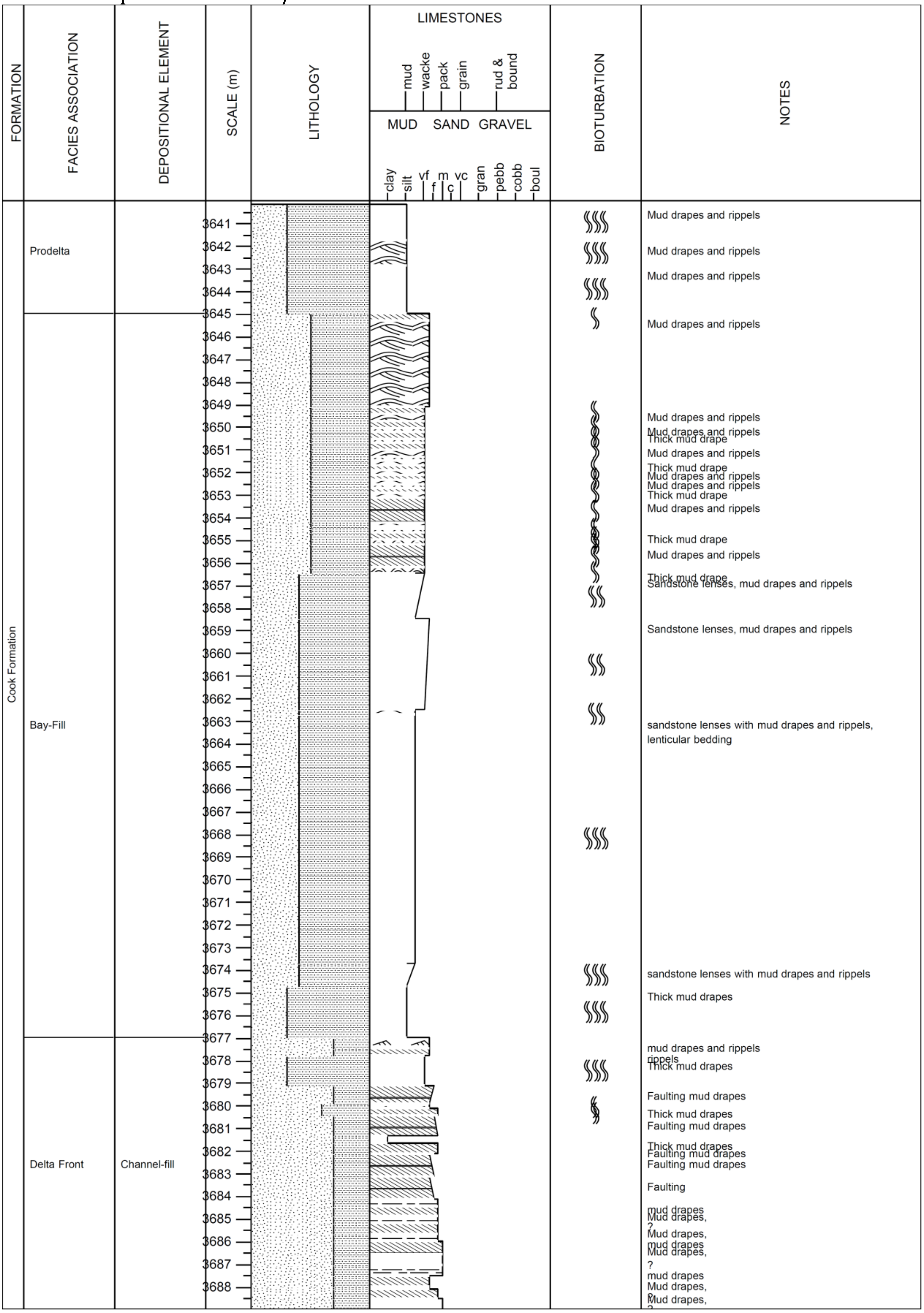
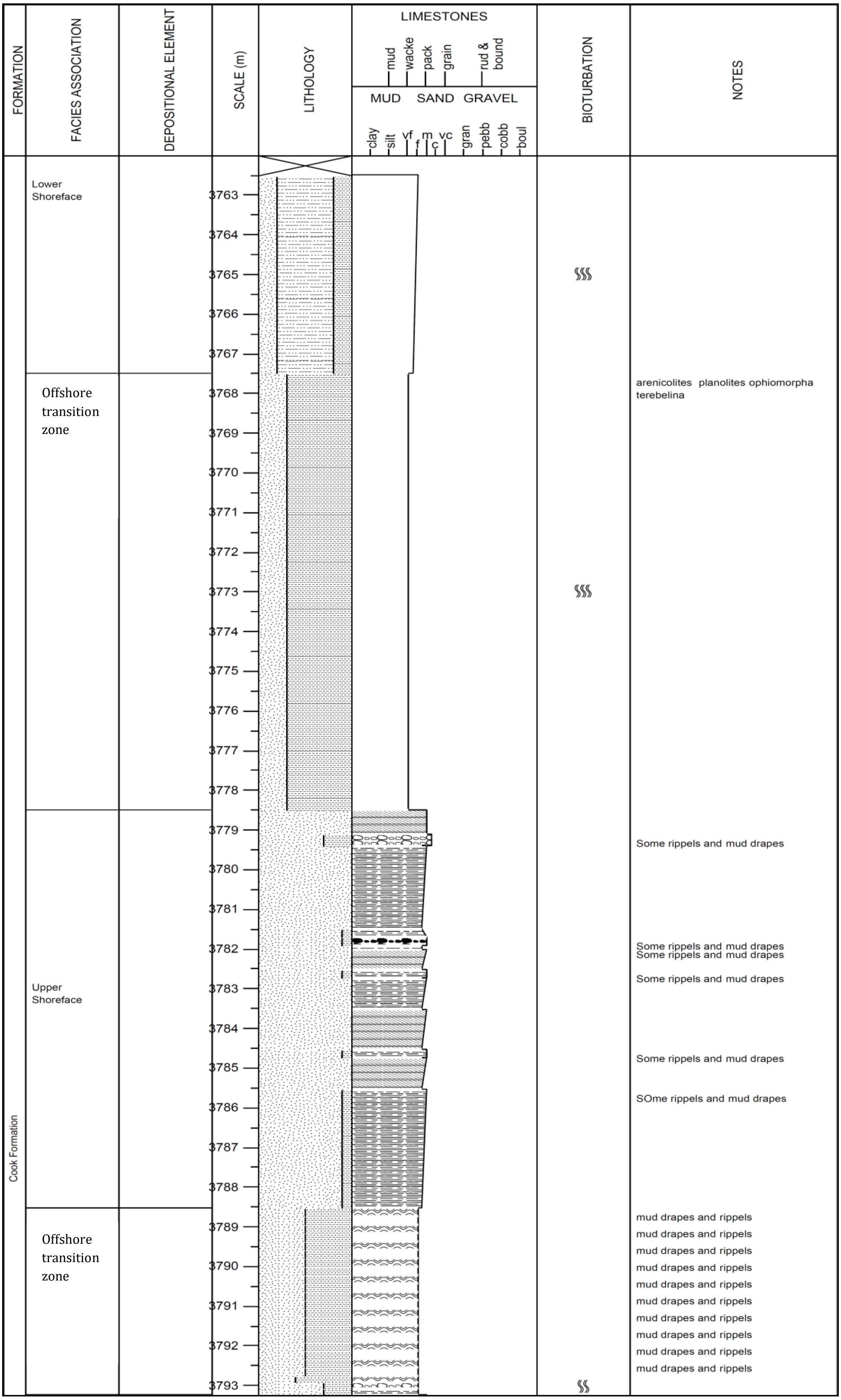


Table 10 Graphic Sedimentary log

Core description of well 34/6-2S



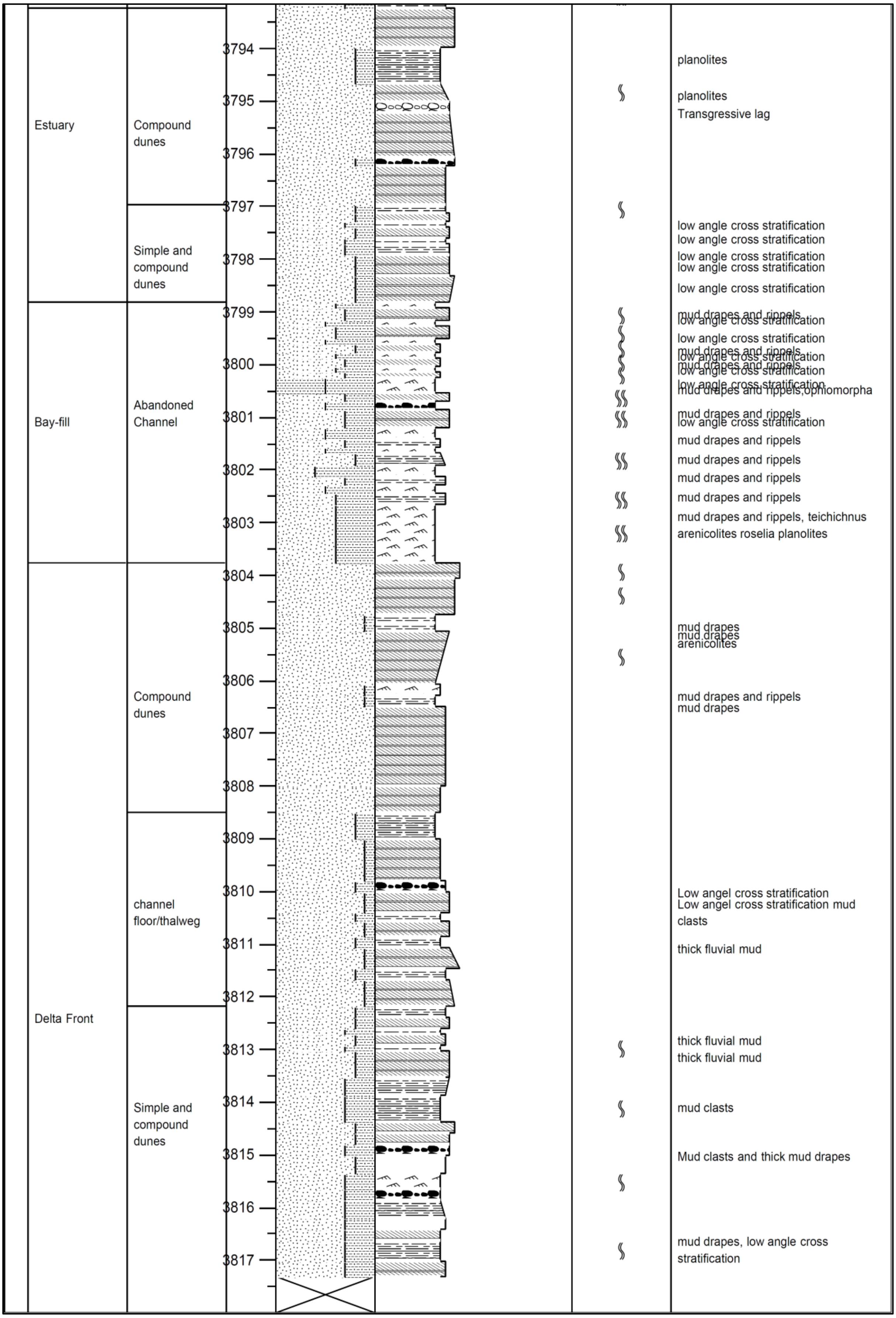
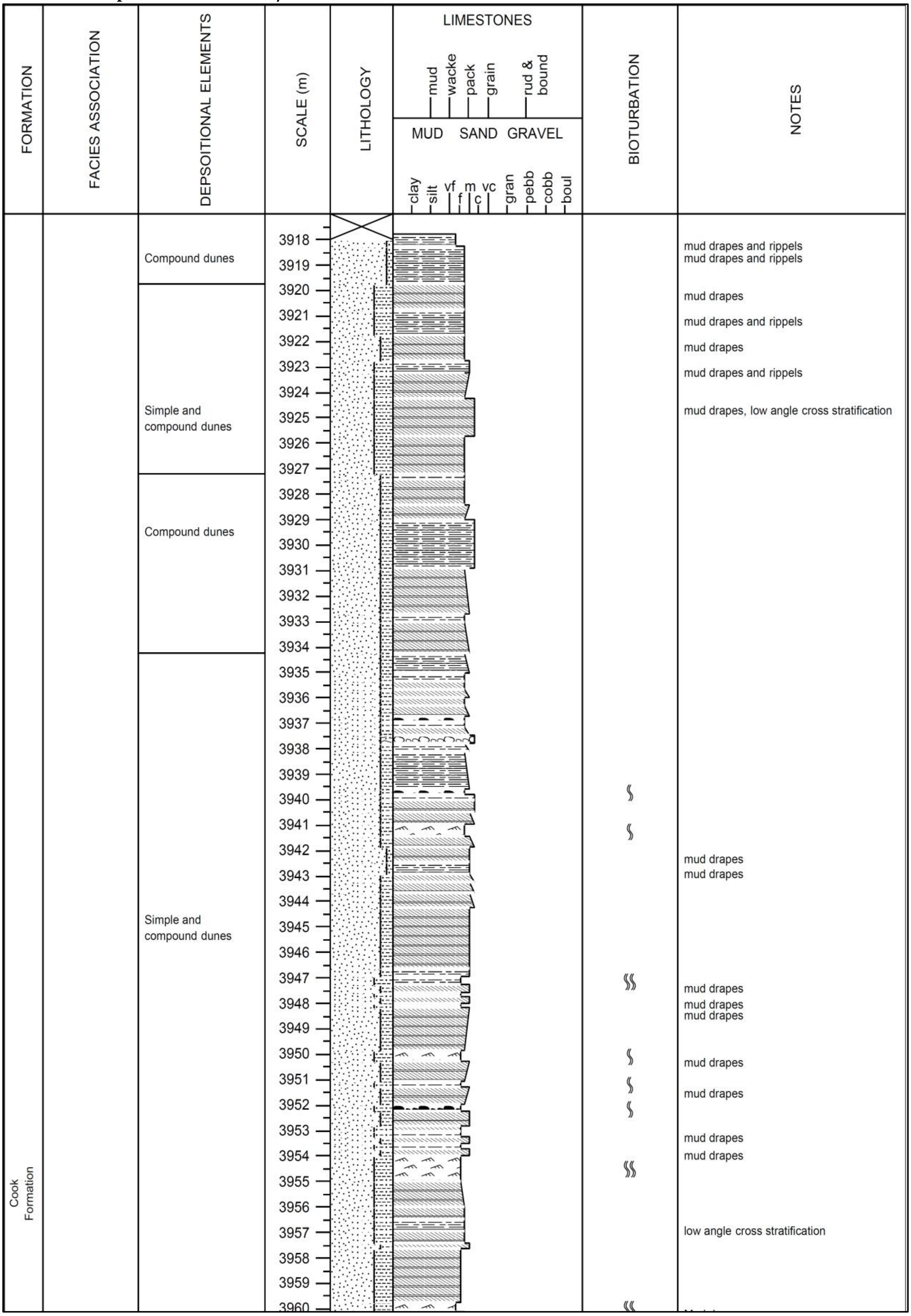


Table 12 Graphic Sedimentary log

Core description of well 34/6-3S



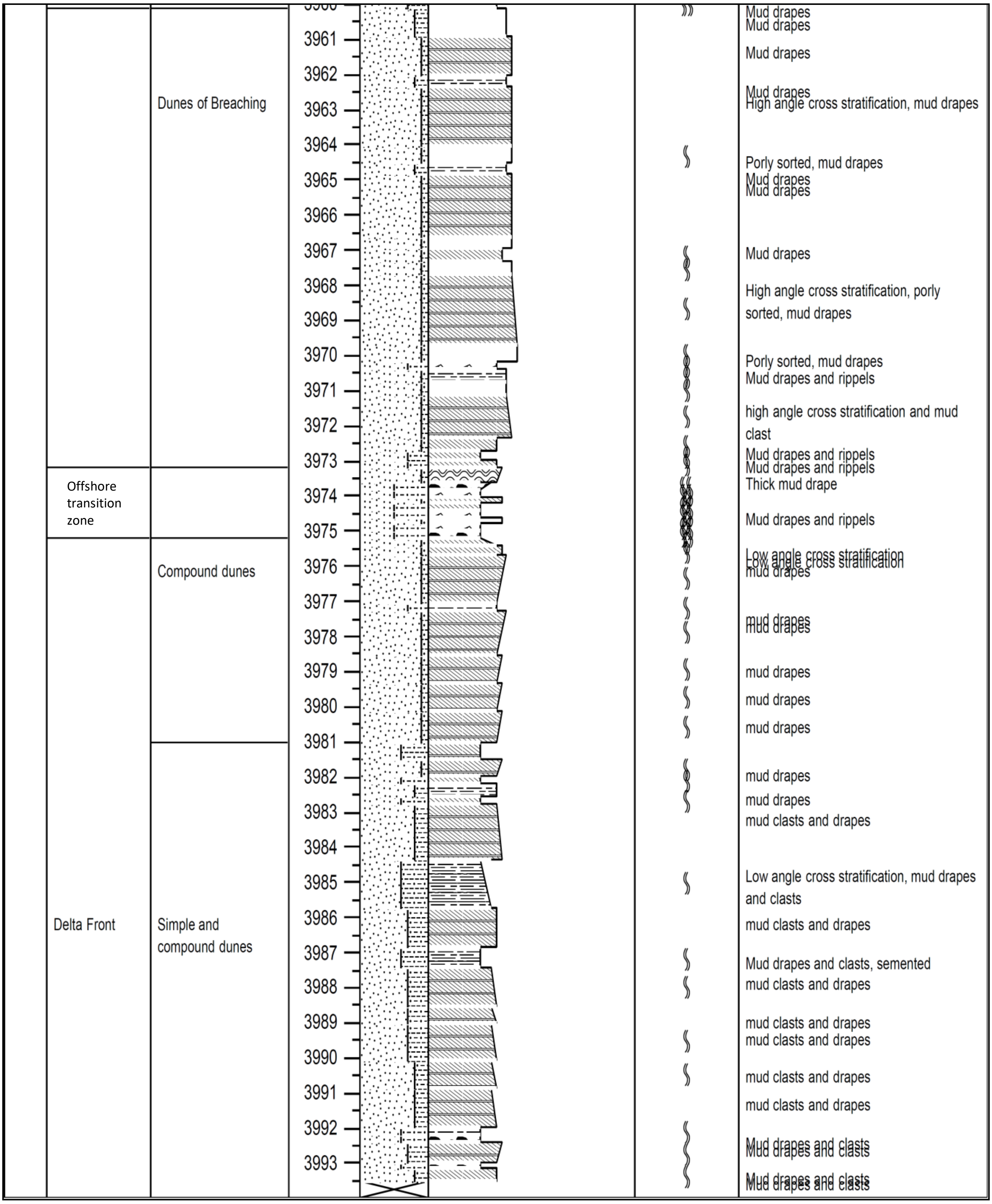


Table 23 Graphic Sedimentary log

Core description of well 35/4-1

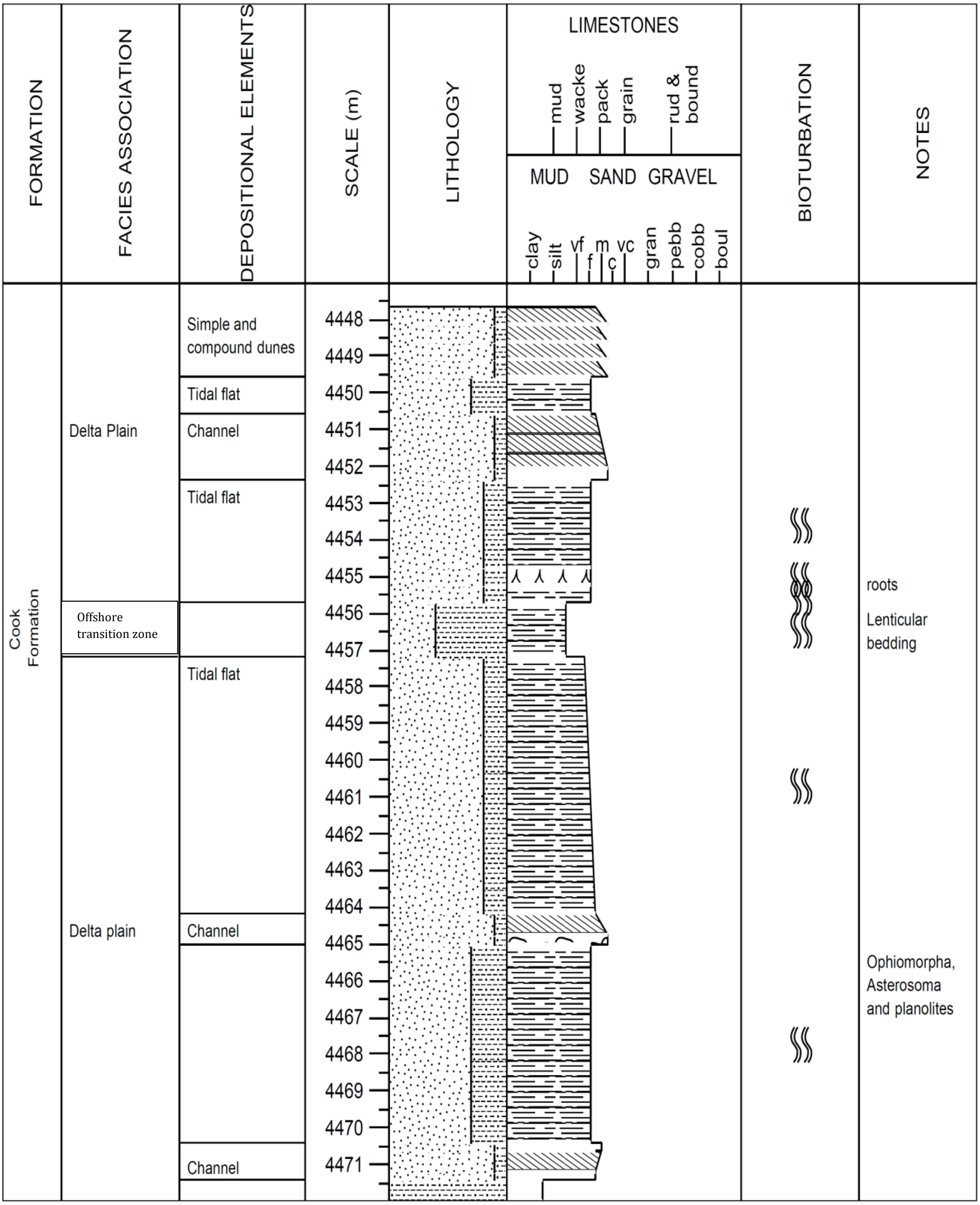
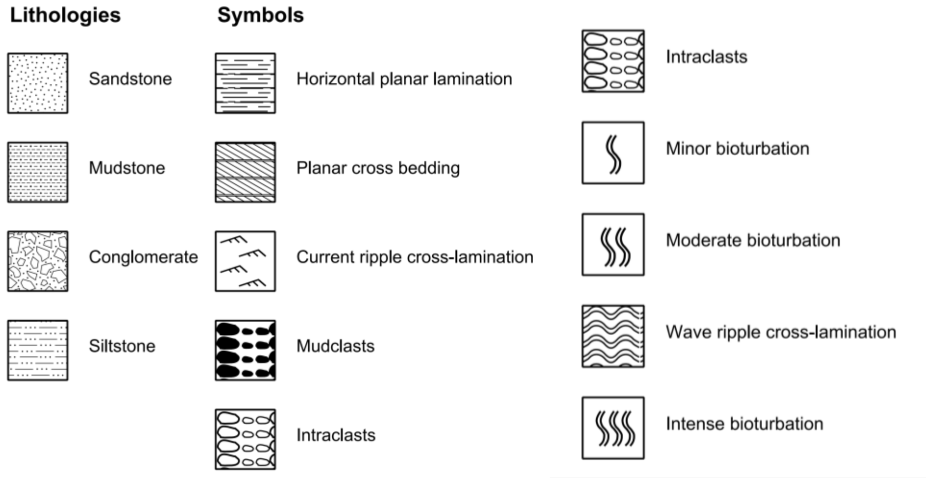


Table 14 Graphic Sedimentary log


Lithologies
Sandstone
Mudstone
Conglomerate
Siltstone
Symbols
Horizontal planar lamination
Planar cross bedding
Current ripple cross-lamination
Mudclasts
Intraclasts
Intraclasts
Minor bioturbation
Moderate bioturbation
Wave ripple cross-lamination
Intense bioturbation

5.0 Cook Formation - Tampen Spur

5.1 Cook Stratigraphy

During the Pliensbachian to the Early Toarcian the Cook Formation in the Tampen Spurs area formed an overall progradational to aggradational layered package of tidal-deltaic, tidal estuarine, shoreface, and shallow marine to shelfal strata. The formation can be organized into three upward coarsening units or higher order sequences; lower Cook member, middle Cook member and upper Cook member, which are present across the NE Tampen Spur (Figure 2). These three sandstone units are bounded by relatively thick to thin shale and mudstones, which represent flooding across the paralic deltaic to estuarine deposit.

5.2 Lower Cook stratigraphic architecture and GDE distribution

The lower Cook member forms up to 48 meter thick sandstone units. The units represents a prograding tide-dominated delta front (DE3A, table 3) represented by mouth bars (DE 1, table 2), simple dunes (DE 2A, table 2), compound dunes (DE 2B, table 2) and Channel floor/thalweg deposits (DE 4, table 2) and capped by a transgressive lag. The basal boundary is defined by a relatively thick marine claystone of the Burtone Formation, which represent a major marine flooding and subsequently the J13 flooding surface of Charnock et al., 2001.

Based on log signatures the lower Cook member is coarsening and thickening upward from a sharp (possible erosive) base. The base of the lower Cook is not cored, but the sharp transition from offshore mudstone to prodelta/delta front is interpreted to represent a regression formed during relative sea level fall, hence it is interpreted as a regressive surface of marine erosion (RSME) (e.g Marajanac, 1995).

Based on log signatures a fast prograding system is interpret below the Cook Formation. This could indicate a highstand system tract underlying the Cook Formation, which suggest that that the water was on its max point and started to fall during the deposition of the lower Cook Formation which coinsides with the interpretation of a regressive surface of marine erosion.

The upward coarsening sandstone unit consists of mouth bars (DE 1, table 2) overlain by simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2) with occasional intervening erosive channel floor/thalweg deposits (DE 4, table 2). This is the situation in the Knarr Field (wells 34/3-2, 34/3-1 and 34/3-3), in the Garantiana discovery (wells 34/6-1S, 34/6-2S and 34/6-3S) and in the east of the Knarr Field and Garanatiana discovery (well 35/4-1, 35/1-1).

Further west in the Knarr Field (well 35/5-1) mouth bar deposits (DE 1, table 2) are overlain by erosive channel floor/thalweg deposits (DE 4, table 2) (possible distributary channels). Further west from the Knarr Field and Garantiana discovery (wells 34/4-5 and 34/2-4) the Cook Formation consists of prodelta mouth bars deposits (DE 1, table 2). Mouth bars (DE1, table 2) are the most distal depositional element, which suggests that the area has a more distal prodelta position. In well 34/2-2 the lower Cook member is represented by prodelta deposits (FA2, table 3) with prodelta hyperphycnites/density flow deposits, which indicate proximity to the delta front (DE3A, table 3).

There are observed single and double mud drapes, sigmoidal cross bedding and heterolitic deposits that indicate tidal-influence in the deposits. The stacking pattern of the depositional elements shows distal facies that are overlain by proximal facies. These observations are interpreted to represent a shallowing upward motif from sharpe based prodelta to lower/upper delta front to distributary channel-fills, which is interpreted to represent a prograding tide-dominated delta.

These observations indicate that the proximal subenvironments are located to the east and the distal depositional subenvironments are located toward west (figure 12 and figure 13). This is a reflection of sediment input from the east. The Lower Cook member is overlain by marine mudstone representing the J14 flooding surface of Charnock et al., 2001, only separated by a ravinement surface and occasionally a thin transgressive lag.

5.3 Middle Cook stratigraphic architecture and GDE distribution

The middle Cook member forms up to 60 meter thick sandstone units, conditionally thicker than the lower Cook member. The sand consists of a tide-dominated delta front (FA 3A, table 3) and a tide dominated estuary-fill (FA6, table 3) represented by mouth bars (DE 1, table 2), simple dunes (DE 2A, table 2), compound dunes (DE 2B, table 2) collapsed dunes (DE3) and Channel floor/thalweg deposits (DE 4, table 2). The basal boundary is defined by the J14 flooding of Charnock et al., 2001. The upper boundary is capped by a thick mudstone of the J15 flooding of Chanrock et al., 2001.

The lower part of the middle Cook member is coarsening upwards from marine mudstone at the base. In the Knarr Field (wells 34/3-1, 34/3-2 and 34/3-3), the middle Cook member consists of mouth bars (DE 1, table 2) overlain by a stacked simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2) with occasional interbedded channel floor/thalweg deposits (DE 4, table 2). In the the Garantiana discovery (34/6-1S, 34/6-2S and 34/6-3S) and in the eastern part of the study area (well 35/4-1, 35/1-1) the middle Cook member consist of stacked simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2) with occasional interbedded channel floor/thalweg deposits (DE 4, table 2). The Channel floor thalweg deposits do not show as distinct sharp base as in the lower Cook member, which could indicate that the dunes are deposited within a channel, where the main channel is only occasionally recognized by coarser sands.

Further west of the Knarr Field and Garantiana discovery only prodelta (FA2, table 3) to shelfal (FA1, table 3) deposits are observed (wells 34/2-2, 34/2-4 34/5-1 or 34/4-5). These are distal facies associations, which suggest that the area represent a more distal prodelta position (figure 12 and figure 13). The well 34/6-4 which is located between the Knarr Field and Garantiana is not cored but based on well log signatures the well displays worse reservoir quality then the other wells. In this study the well is interpreted to represent a tidal flat deposit, which is also seen in well 34/4-1. This could indicate that the two systems are more separated in the middle Cook member compared to the lower Cook member.

A tidal signature are prevailingly and includes single and double mud drapes, sigmoidal cross bedding, heterolitic deposits and tidal bundles, no wave dominated structures are observed. These observations support the nature of a tide dominated setting. The stacking pattern of distal depositional elements in the base coarsening upward into proximal depositional elements is used to interpret a prograding tide-dominated delta front (DE3A, table 3). The middle Cook member did not prograde as far out into the shelf as the Lower Cook member (figure 9A).

In the Knarr Field the tidal dominated delta is overlain by a flooding (well 34/3-1, 34/3-2 and 34/3-3), which is not observed in Garantiana area, or in the eastern wells eastern parts of the study area (wells 34/3-2 45/4-1 and 35/1-1), which suggest that this is a local flooding. Well 34/3-2 is represented by breaching dunes which could explain why the flooding is not present in this well. The flooding is represented by heteroliths interpreted as an abandoned channel (DE5, table 2). Above the flooding a coarsening upward succession of simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2) are present. Biostratigraphy shows that the upper part of the middle Cook member has a more marine character than the lower part of the middle Cook member (e.g. Churchill et al., 2016). This suggests that the abandoned of the channel has resulting active delta turning into an estuary (FA6, table 3).

In The Garantiana Field the flooding is replaced by a fining upward of the sandstone, which consists of simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2) similar to the facies present in the Knarr Field. The middle Cook member in the Garantiana area also shows an overall cleaner character of the deposits with less mud in the system compared to the Knarr Field, but there are still some mud drapes present.

The well 34/5-1 display different character from the other well with marine shelfal deposits in the base coarsening upward into hummocky cross stratified sandstone representing prodelta deposits. The biostratigraphy of this well does not show fully marine conditions which could indicate that there are some embayed settings. Hummocky cross stratification is a wave dominated structure, contradictory to the tide-dominated structures observed in the other wells.

The upward fining sediments of the Garantiana discovery and the flooding of the Knarr Field with marine biostratigraphic character, indicates a sea-level rise and the deposits are interpreted to be estuarine (FA6, table3). The Middle Cook member is overlain by marine mudstone representing the J15 flooding surface of Charnock et al., 2001.

5.4 Upper Cook stratigraphic architecture and GDE distribution

The Upper Cook Member forms an up to 30 meter thick sand. It consists of yet another coarsening upward to fining upward motif representing a shallowing upward renewed progradaing to tide-dominated delta front and a retrograding faintly wave dominated shoreface . The basal boundary is defined by the J15 flooding, of Charnock et al., 2001.

The upper Cook member sandstone unit in the Knarr Field (wells 34/3-1, 34/3-2, 34/3-3 and 35/1-1) consists of coarsening upward deposits comprising mouth bars (DE 1, table 2) overlain by simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2). Further west of the Knarr Field prodelta mouth bars (DE1, table 2) are observed (well 34/2-2). Again tidal signatures are observed with single and double mud drapes, sigmoidal dunes and heteroliths. The vertical facies succession introduce a change from distal to proximal deposits, interpreted to represent the renewed prograding of a tide-dominated delta. The outbuilding represent and normal regression, indicating a sea level fall and a highstand system tract.

The upper Cook member in the Garantiana discovery consists of coarsening upward wave-dominated lower to upper shoreface deposits (FA 6, table 3), which suggest that the main depocenter has shifted away from the Garantiana area to the northern parts of the unbound fault block (figure 12 and figure 13).

A new flooding took place in both the Knarr Field and the Garantiana discovery. The overlying deposits represent a lower shoreface (FA3B, table 3) with a coarsening upward motif, suggesting that the delta retreated into a succession of offset backstapping delta-shoreline profiles. This indicates that the main depocenter has also shifted away from the Knarr Field. Then a final drowning of the Cook Formation took place, and marine mudstone of the Drake Formation represents the J16B flooding surface of Charnock et al., 2001.

5.4 Cook Formation stratigraphic architecture and GDE distribution Garantiana discovery to Knarr Field

The lower Cook member show similar outbuilding character across the Garantian Discovery to the Knarr Field. But there is observed some variability in stratigraphic structure, internal sedimentary architecture and energy regime (figure 12, 13 and 14). The lower Cook member is the unit that displays the most similarity pattern across the Garantian discovery to the Knarr Field (Figure 9A). In both the Garantiana discovery and Knarr Field a prograding tide dominated delta is interpreted.

The middle Cook member shows similar facies but there is variability in the stratigraphic structure (figure 9A). In both the Knarr Field and Garandtiana Discovery the lower part is interpreted as delta front (DE3A, table 3) and the upper part as an estuary(FA6, table 3). The Knarr Field consists of two coarsening upward backstepping units, which are separated by a local flooding, while the Garantiana Discovery displays a coarsening upward pattern in the base and a fining upward pattern toward the top. The well 34/6-4 which is located between the Knarr Field and the Garantiana discovery is not cored but the well log show different and worse reservoir quality in the middle Cook member compared to the other wells. In this study the well is interpreted to represent tidal flats. Tidal flat deposits are observed in well 35/4-1 which shows some similarities with in log signatures of the well 34/6-4, which coincides with the interpretation of tidal flats in well 34/6-4. These observations indicate that the systems are changing into more distinct separate system and the orientations of the systems are slightly changing. There is also observed wave dominated structures in well 34/5-1.

The upper Cook member is the unit that shows the strongest variability (figure 9A). The Cook Formation in the Garantiana Discovery represent of a backstepping lower to upper shoreface (DE4, table3), while the Knarr Field the formation represent of a prograding delta and a backstepping shoreface. This indicates that there is more sediments supply in the Knarr Field, while in the Garantiana discovery the deposcenter has shifted, which could indicate tectonic activity.

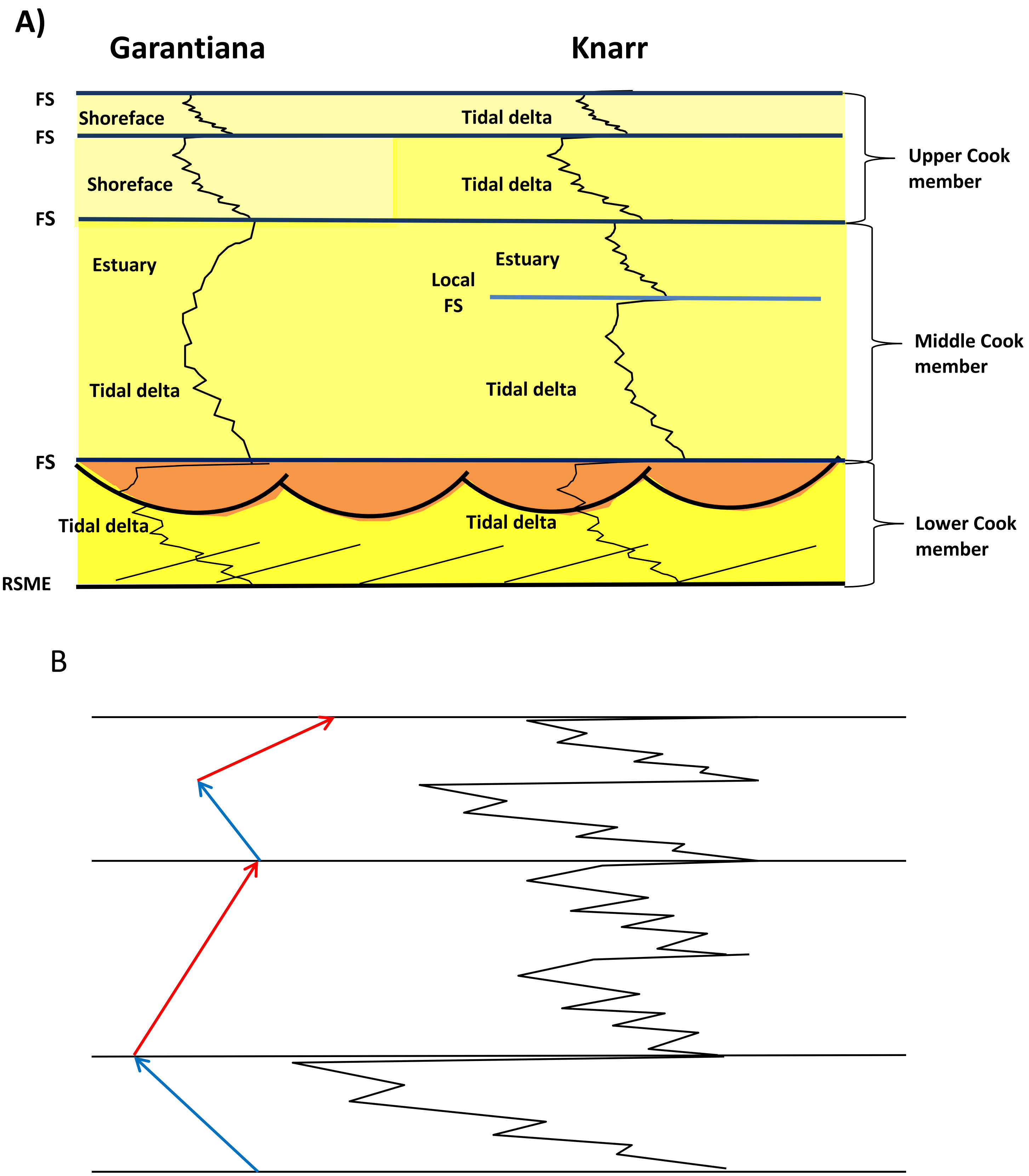


Figure 10 A) Shows the stacking patter of the Cook Formation B)shows the outbuilding an retreat of the Cook Formation

6.0 Thickness trends

The interpreted facies, depositional elements and facies associations of the Cook Formation (chapter 4.0) shows lateral and proximal to distal changes between the studied areas i.e. the 10 wells studied (figure 12, 13 and 14). The Cook Formation sandstone has accumulated across the Tampen Spur area. For full regional understanding of the outbuilding and retreat of the different Cook sandstone units and the Cook system it is useful to investigate the thickness variations of the sandstone bodies. The Cook Formation is divided into lower, middle and upper Cook member in this study (chapter 5). The sandstone units are thickening landward and thinning basinwards i.e. to the west, while the muddy heterolitic intervals that separate the sands thicken basinward.

6.1 Thickness variations - Knarr Field East-West

The overall thickness of the Cook Formation in the Knarr Field displays a thinning towards west (figure 13). In the lower and middle Cook member there is only small variability in thicknesses, while the upper Cook member shows more pronounced thickness variations.

The Lower Cook member is slightly thicker in the eastern end of the well correlation profile (Figure 12, well 35/1-1), and there is a thinning towards west. This suggests that there is more accommodation space available in the east, or that the western areas are not filled to seal level. There is some minor variability in thickness over the Knarr Field, but no large thickness variations are observed. Based on log signatures there is interpreted a prograding system underlying the Knarr Field. This system is not present in all wells in the Knarr Field, which could be one reason for the slight thickness variability in the lower Cook member.

The Lower Cook member has relative uniform thickness that is slightly thinning towards west. The thinning towards west combined with the distal facies located toward west interpreted in chapter 5, could suggest that the eastern part is located proximal while the western part is located more distal. The thickness variation of the Lower Cook member shows overall uniform thicknesses, interpreted as a thinning towards the more distal areas, which favors the explanation that the areas are not filled to seal level.

The heterolitic unit overlying the lower Cook member shows variable thickness varying from 2 meter (wells 34/3-3 S and 34/3-2S) up to 7 meter (34/3-1 ST2 well). This thickness variation could be due to difference in accommodation.

The Middle Cook member has a similar thickness trend as the lower Cook member and displays thinning toward west. This in paralleled with change of facies (distal depositional element to the west and proximal depositional element to the east) could indicate that the eastern part is located proximal and the western part is located distal. The thickening trend is accordingly interpreted to represent degree of infilled accommodation (not filled to sea level of the western end of profile). These thickness variations within the Knarr Field i.e. the sandy deltaic deposits are attributed to differential to combination with the amount of sediments removed locally during transgressive reworks.

Overlying the middle Cook member a heteroliths unit is present, which is thickening towards the northern part of the study area (well 34/2-4) and eastern part of the study area (34/3-2S, 34/3-3S and 35/1-1). The thickness change could be due to differences in accommodation space or some errors with the data/correlations.

The upper Cook member shows more variability in the thickness distribution. The thickest part over the Knarr Field has a thickness up to 33 meter (well 34/3-3S), where it is developed into sandier facies. There is a thinning present both lateral eastward towards well 35/1-1 (25 meter), where it remains sandy, and westwards towards wells 34/2-2, 34/2-4, 34/5-1A, 34/5-1S and 34/4-5 where the deposits consists of muddy deposits. The westward thinning is associated with a change of finer grained outer shelfal mudstone facies (FA1, table 3). Hence similar controls as interpreted for the middle Cook member are also predicted to the upper Cook member. In addition the eastward thinning toward well 35/1-1 may reflect less transgressive rework of the middle Cook member and the potential preservation of thinner eastern facies in the uppermost part.

of the Cook member in this well. Another possibility could be tectonic activity during the deposition of the upper Cook member creating more accommodation space.

6.2 Thickness variations Garantiana discovery East-West

The Cook Formation in the Garantiana Discovery is generally thinning towards west. In the lower and middle Cook member there is only a small variability in thicknesses, while the upper Cook member shows more pronounced thickness variations (figure 12).

Lower Cook member is remarkably thicker in well on the (well 35/4-1) Marflo Spur relative to wells located in the Garantiana area. From the Garantiana area to the Mort ridge (34/4-5) the lower cook member displays a thinning, this could be due to accommodation, sediments that are not filled to sea level or different compaction.

Separating the lower and middle Cook members there is a heterolitic unit present, that shows relative uniform thickness, which could represent different accommodation space.

Middle Cook member display relatively uniform thickness in all the wells expect for an abrupt thinning within well 34/6-1S. The thinning could indicate that the well is located at a distal position and that sediment is not filled to sea-level or different compaction. The middle Cook member is deposited during rising sea-level, and sediments could be locally removed during transgressive reworks.

Separating the upper and middle Cook Formation there is a heterolitic unit, which increases in thickness towards the north (well 34/6-1) and east (well 34/6-3) which could represent different accommodation space.

Upper Cook member maintains variable thickness distribution, with thicknesses up to 54 meter in well (34/6-1) thinning both lateral eastward (well 35/4-1) and westward (34/4-5). The westward thinning is associated with a change of finer grained outer shelfal mudstone facies (FA1, table 3), hence similar controls as interpreted earlier. In addition the eastward thinning toward well 35/4-1 may reflect less transgressive rework of the middle Cook member and the potential preservation of thinner eastern facies in the uppermost part of the Cook member in this well. Another possibility could be tectonic activity during the deposition of the upper Cook member.

The Cook Formation in the Garantiana area displaying relative uniform thicknesses with small thickness variability in the lower and middle Cook member. There is increased variability in the upper Cook member, which could be generated due to transgressive processes or tectonic activity.

6.3 Thickness variations - Knarr Field to Garantiana discovery South-North

The Cook Formation shows quite similar thickness trends in the Knarr Field and the Garantiana discovery. The Cook Formation is overall thicker in the Garantiana discovery (see table 5), which indicate more accommodation space or higher subsidence rate in the Garantiana discovery (figure 14).

The Lower and middle Cook member shows small thickness variations and both are thinning toward west. This favors the explanation that thickness changes most likely is created due to sediments not filled to sea-level. But the middle Cook formation show more variability in depositional environment, which could indicate some more complex control

The upper Cook member display more variability in thicknesses and there is also interpreted different depositional environments in the two system (see chapter 5). This indicates that there is probably some tectonic control in the upper Cook member, together with transgressive reworking.

Sandstone units	34/2-2 Depth (m)	34/2-4 depth (m)	34/3-1S Depth (m)	34/3-2S Depth (m)	34/3-3S Depth (m)	34/3-5 Depth (m)	34/4-5 depth (m)	34/5-1S depth (m)	34/5-1A Depth (m)	34/6-1S depth (m)	34/6-2S depth (m)	34/6-3S depth (m)	34/6-4 Depth (m)	35/1-1 Depth (m)	35/4-1 Depth (m)
Top Cook	3619	3821	3866	4012	3908	4140	3416	3629	4274	3807	3654	3851	3951	3970	4434
Base Cook	3683	3893	3958	4090	3996	4222	3480	3696	4345	3932	3777	4001	4066	4087	4556
Thickness of Upper Cook	-	10	29	23	32	28	-	-	-	54	31	51	17	24	26
Thickness of Middle Cook	-	-	37	38	34	37	-	-	-	30	49	58	70	60	54
Thickness of Lower Cook	-	-	17	12	15	10	11	18	12	21	22	27	26	20	37
Total Thickness	64	72	92	78	88	82	64	67	71	125	123	150	115	117	122

Table 5 Thicknesses of the Cook Formation in the Tampen Spur area.

7.0 Sequence stratigraphy and reservoir architecture

Sequence stratigraphic analysis of the Cook Formation was preformed to ensure realistic correlation of the facies associations defined in chapter 4.0 within a time stratigraphic framework. The facies associations and their vertical stacking pattern in wells have been used to define the genetic surfaces using Galloway (1989) method for genetic stratigraphic sequence where maximum flooding surfaces are defined as sequence boundaries. Parasequences stack into sets that display the longer-term migration of the shoreline, controlled by the larger-scale balance between the rate of sediment supply and accommodation space available (Howell and Flint, 2005). Maximum flooding surfaces were picked and correlated between the wells. This has then been used to identify the evolution trends for the Cook Formation depositional systems.

7.1. Sequence stratigraphy

The Cook Formation consists of a series of stacked deltaic units, ranging from shelfal (deeper marine) to shallow marine tide-dominated delta front (DE3A, table 3), estuary (FA6, table 3) and faintly wave-dominated shoreface. The Cook Formation in the Tampen Spur is divided into three higher order sequences; each consisting of a regressive segment and one transgressive segment. The sequences are bounded by flooding surfaces at the base and top.

7.1.1 Lower Cook member- Sequence I

The first maximum flooding surface which signifies the base of sequence I is placed below the Cook Formation and in a thick marine claystone unit of the Burton Formation, corresponding to J13 flooding surface Charnock et al., 2001. The Lower Cook member is interpreted in terms of delta front (DE3A, table 3) to prodelta deposits (FA2, table 3),. The formation is strongly progradational and is the sequence that extend most distal. Well log signatures of the underlying Burton Formation shows and fast prograding character. This prograding signature of the underlying system could reflect a highstand system tract that was completely drowned, and the flooding surface separating the two systems represents a maximum flooding surface (J13 flooding surface Charnock et al., 2001).

The boundary is defined by a sharp (possibly erosive, see chapter 4) surface, where the sediments are sharply placed on the basal boundary, and is accordingly interpreted as marine seaward facies shift. This surface is interpreted as a regressive surface of marine erosion (e.g. Marjanac and Steel, 1997) in turn reflecting the transition into falling stage system tract and a lowstand system tract. The regressive surface of marine erosion is formed due to reduced accommodation space due to sea level fall, and sediments start to erode underlying deposits to maintain equilibrium (Embry, 1997).

Overlaying (basal parts of the Cook Formation) sediments comprise mostly heteroliths, while the uppermost part of the sequence is more sand prone. The coarsening upward profile reflects a gradual transition from a deep, quiet part of the shelf into shallower areas, indicating a progradation. The lower Cook member advances with incised channels, that are down cutting during sea level fall, evidenced by the sharp/erosive channel floor/thalwege deposits. This implies that the facies belt is under net erosion during the falling stage of sea level. The abrupt facies shift is suggestive and the amount off erosional surfaces and prograding character is related to sea-level fall and a forced regression (Plink-Björklund and Steel, 2006; Ravnås et al., 2014). This geometry implies that the rate of sediment supply was greater than the accommodation space available, forcing the sediment out into the basin. The falling stage system tract is coincides with the interpretation of the underlying system representing a highstan system tract. Given that this predictions about a about a falling stage system tract the most proximal parts will of the delta would be effected by subaerial erosion. This could have affected well 35/1-1 and 35/4-1 which is interpreted as the most proximal well of the study are. The lower Cook member is not cored in any of these wells, which indicates an uncertainty if these wells are affected.

These observation is use to interpreted the Lower Cook member as an outbuilding tide-dominated delta during falling stage to early lowsatand stage. Forced regressive and lowstand units often continue the outbuilding patter from underlying high stand system (Ravnås et al., 2014), which is also interpreted here with the underlying Burton formation. The Lower Cook Formation is capped by bioturbated mudstone unit representing shelfal to protected embayed heteroliths, interpreted as a higher order flooding surface, corresponds to the J14 FS (Charnock et al., 2001).

7.1.2 Middle Cook member- Sequence II

The middle Cook member show a varied architectural motif, including aggrading to back-stepping of the delta, displaying a relatively thick transgressive succession. The Middle Cook member does not extend as far as the Lower Cook member. The middle Cook member is separated from the underlying programational lower Cook member by the mudstone unit J14 flooding of Charnock et al., 2001.

The Middle Cook member consists mainly of stacked simple (DE 2A, table 2) and compound dunes (DE 2B, table 2). Other features present are channel floor surfaces but they are not distinct erosive, which could indicate that the dunes have been deposited in a fluvial channel. These observations indicate a repeated advance of the basin-marginal delta, representing a normal regression. Normal regression form when sedimentary rate outspace the sea-level rise, which represent highstand system tract.

In the Knarr Field local flooding surface is placed above the prograding delta (discussed in chapter 4), interpreted as abandoned channel (FA 5 Table 2). The flooding is overlain by simple dunes (DE 2A, table 2) and compound dunes (DE 2B, table 2) interpret as an estuary (FA6, table 3). This implies that there is a retreated of the delta and the former deltaic deposits changes into estuaries. In the Garantiana area the flooding surface is not present, but the succession is fining and cleaning upward and also turning into an estuary (figure11). The change into estuary (FA6, table 3) could be due to higher rate of accommodation space created then sediment supply rate, or that the sea level rise is faster than the sedimentary supply. This could either be due to abandonment of channel creating an estuary (FA6, table 3) on a lager delta or there could be structuring creating a tectonic estuary (e.g. Ravnås et al., 2014).

The Garantiana discovery and Knarr Field show similar facies architecture but there are clear differences in in the aggrading unit. The Knarr Field is represented by a distinct and layered aggradation succession of tide dominated delta and estuarine facies (figure 10). The Garantiana Discovery forms and cylinder shapes cleaner sand unit of amalgamated sandy tide dominated deltaic and estuarine facies (Figure 10). The differences in the Garantian Discovery and Knarr Field could be due to variations in subsidence rate du to tectonic activity.

The near-vertical stacked sediment, with deltaic to estuarine character, and forward stepping basal part, is evidence of an aggradation (Ravnås et al., 2014). Aggradational stacking suggests increased rates of basinal subsidence rates during a sea level rise. The middle Cook member is capped by a bioturbated hetrolitic unit interpreted as a maximum flooding surface (E.G. J15 of Charnock et al 2001) defining the transition into the upper Cook member.

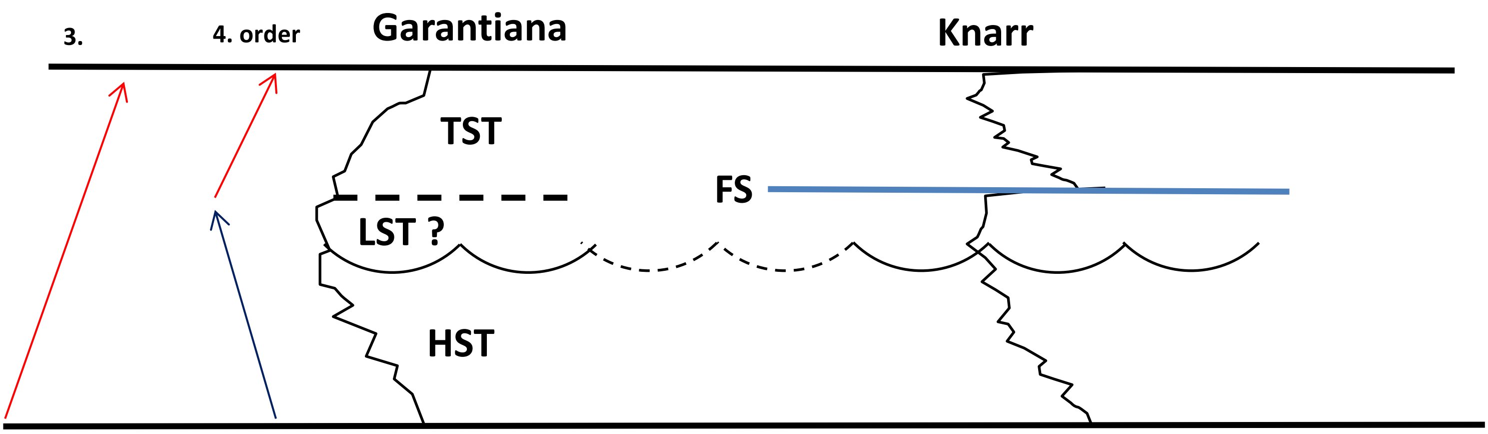


Figure 11

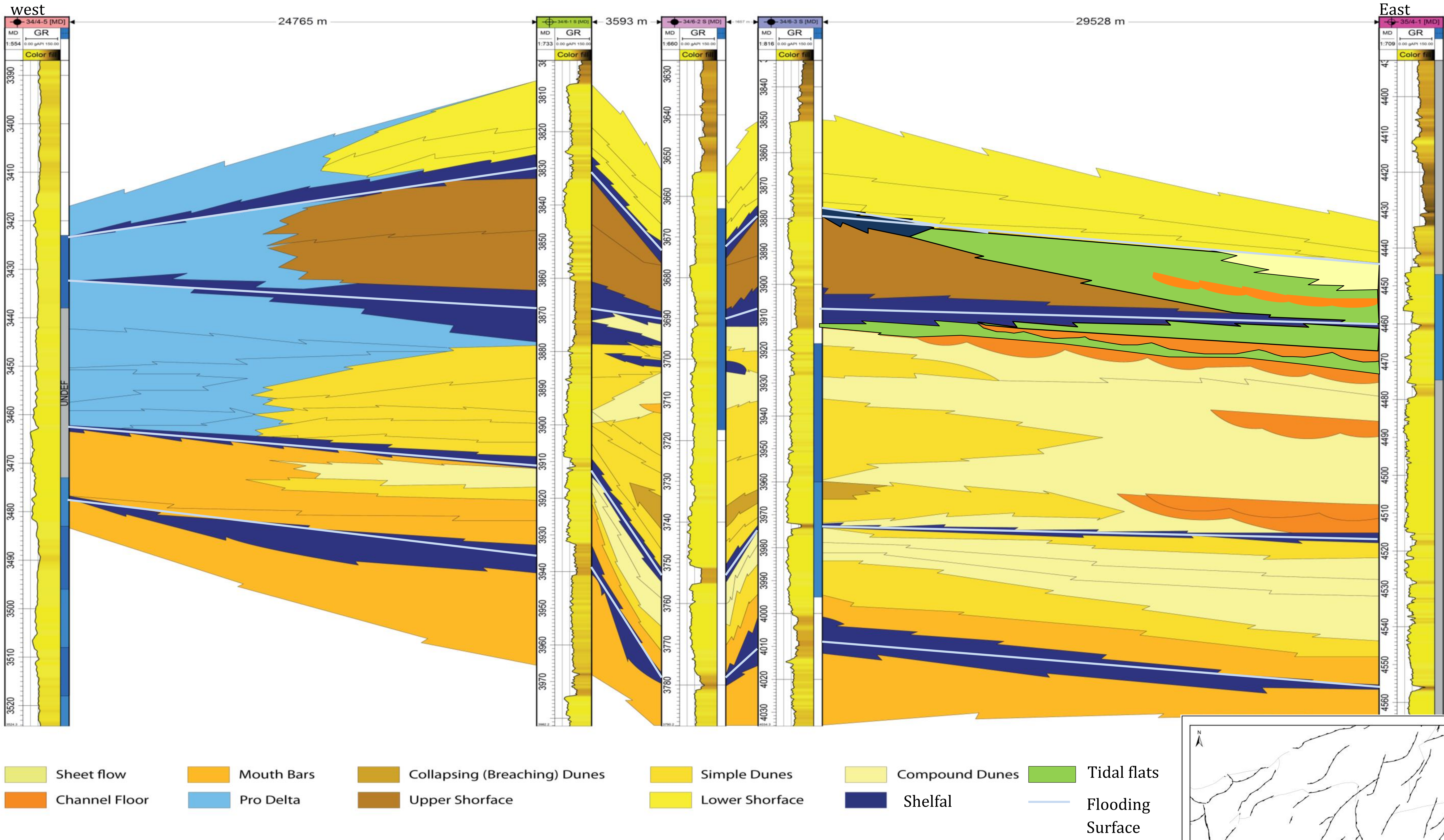
7.1.3 Upper Cook member- sequence III

The upper Cook member across the Garantiana discovery and Knarr Field shows laterally and stratigraphically infill variability. The sequence represents and overall back-stepping pattern of mixed tide- and wave-structured deltaic to shorface succession.

In the Knarr Field the upper Cook member consist of a relative thin renewed pulse of tide-dominated delta-front progradation, which extend further then middle Cook member but not as far as the Lower Cook member. While in the Garantiana disconvery the upper Cook member consists of a prograding upper shoreface (DE4, table3). Both systems show a coarsening upward motif, representing a normal regression, indicating a highstand system tract. This observation implies that there is variability of sedimentary supply in the two systems creating more local depositional system; there are also interpreted thickness changes in the upper Cook member (chapter 6). The variating rate of sedimentary supply implies that there is mild rifting.

There is a small flooding represented by marine strata and a final progradational event with lower shoreface (FA3B, table 3) strata building out during the retreat phase in both the Knarr Field and the Garantiana discovery representing the transgressive system tract.

Then a final drowning of the system interpreted as the maximum flooding surface which is placed on top of the Cook Formation, corresponding to J16B (E.G Churchill et al., 2016; Marajanac and Steel 1997). At this point, accommodation is being created at its most rapid rate, outpacing the rate of sediment supply and generating condensed marine deposits.



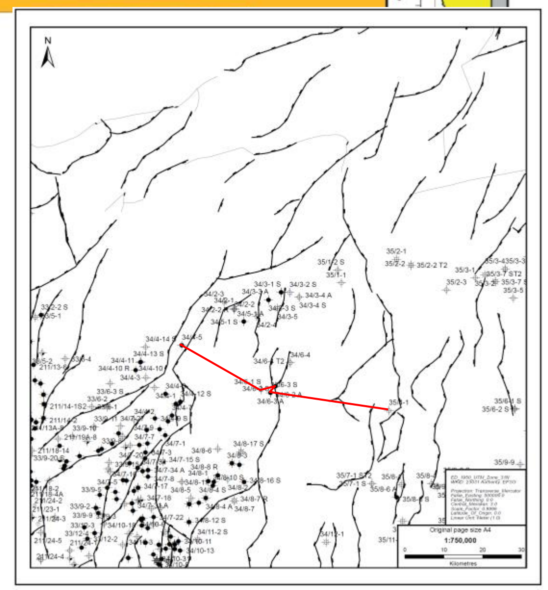


Figure 12 West-East oriented well correlation of the Cook Formation in the Garantiana Discovery.

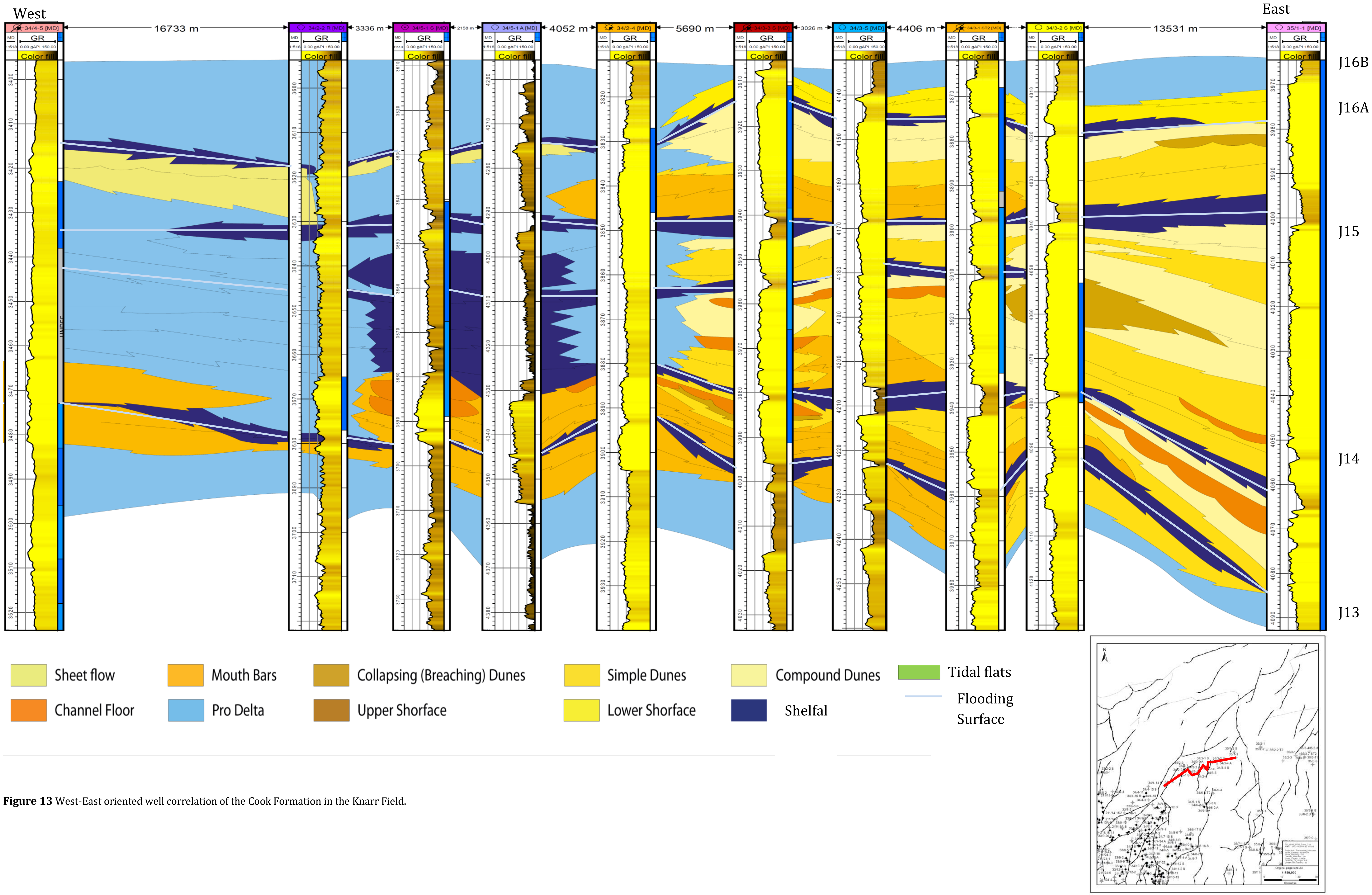


Figure 13 West-East oriented well correlation of the Cook Formation in the Knarr Field.

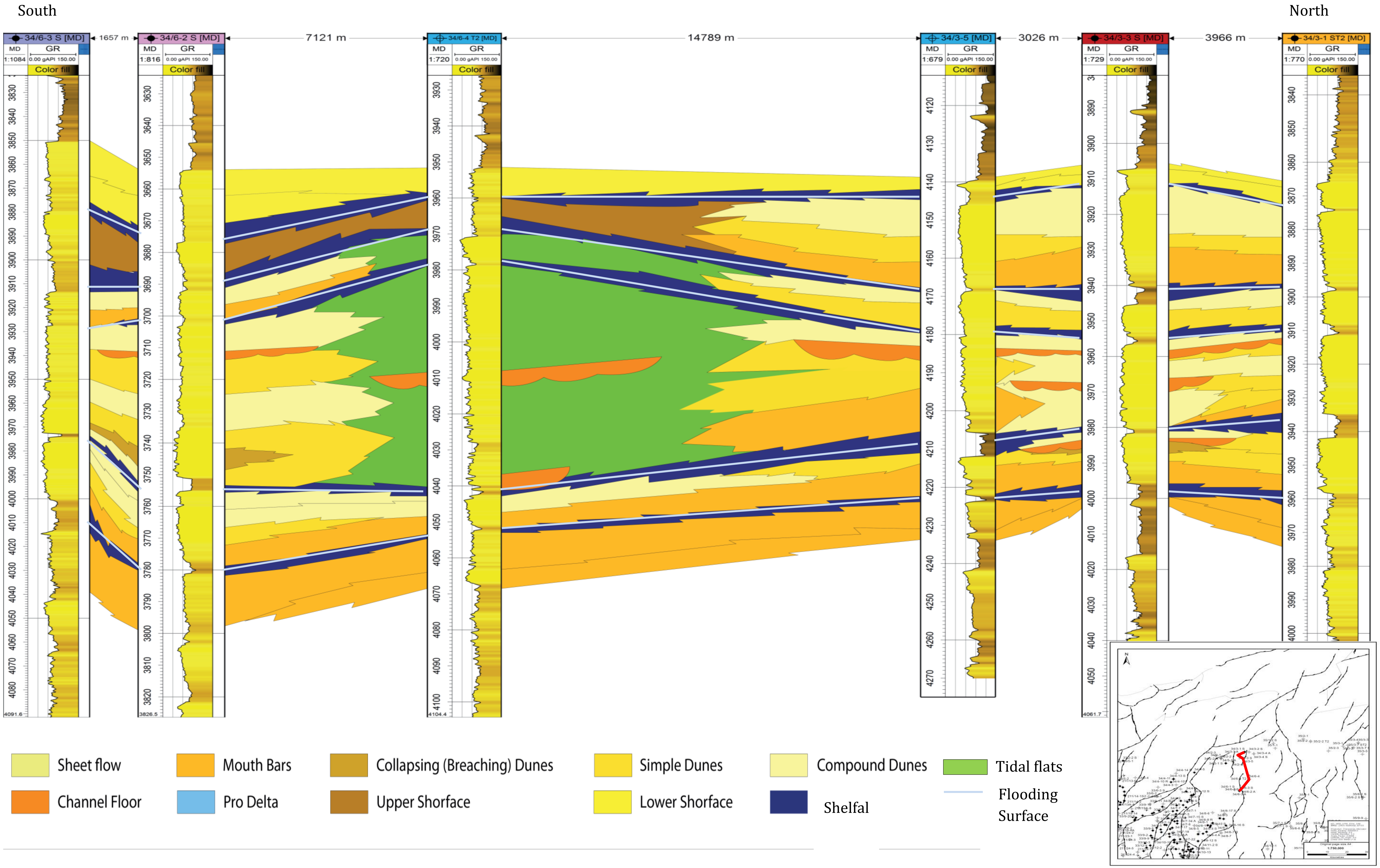


Figure 14 South-North oriented well correlation of the Cook Formation from the Knarr Field to the Garantiana Discovery.

7.2 Paleogeography

The Lower Jurassic Cook Formation represents one megasequence with three higher order sequences. The three higher order sequences represent the geological development of the Cook deltaic system through the main phases of progradation, aggradation, retrogradation and drowning (the lower part of the megasequence are represented by the Amundsen-Burton and Johannesen shoreline shelf). These observations are used to build a series of paleographic maps to illustrate the evolution of the Cook Formation.

7.2.1 Peak prograding of lower Cook member

Progradation of the Cook Formation led to establishment of a tide-dominated delta-front across and extending beyond the Knarr Field and Garantiana discovery. There are interpreted two separate deltas lobes one extending across the Garantiana Discovery, and one extending across the Knarr Field, but the facies are similar in both lobes. Based on the observations done earlier (chapter 4 and chapter 5) a thinning toward west and more distal facies observed in the west, is used to suggest a east-west orientation of the two systems. The Lower Cook Formation is interpreted to represent a falling stage system tract (see Chapter 6), and the falling-sea level forces the sediments far basinward. The lower Cook member is capped by a flooding, representing the J14 Flooding of Charnock et al ., 2001.

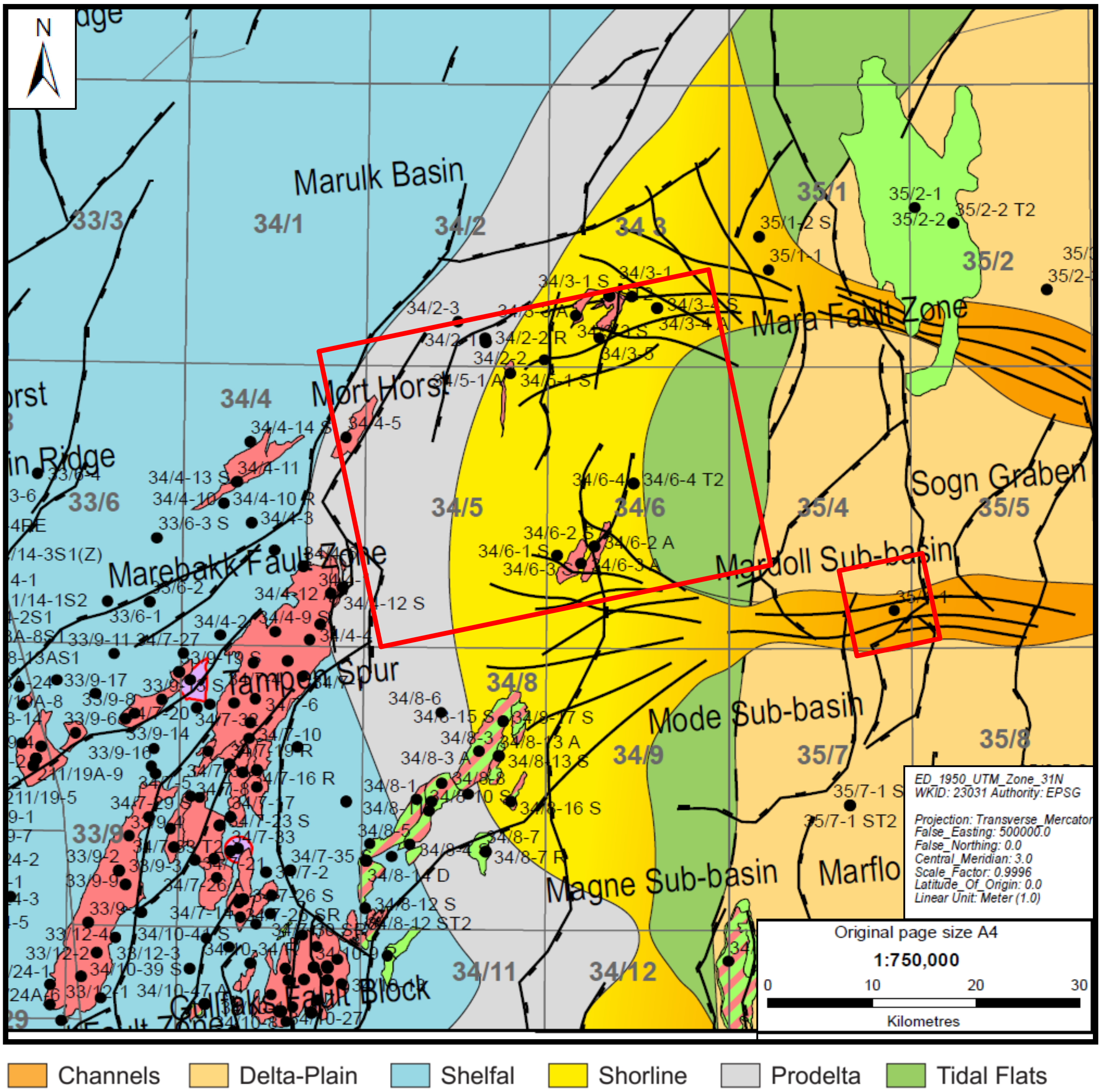


Figure 15 Paleographic map of the lower Cook member peak progradaion, the red squares marks the study area.

7.2.2 Peak aggradation of the middle Cook member

Following the Pliensbachian J14 flooding, the Cook delta started to prograde again across the Tampen Spur forming two delta lobes. The middle Cook member displays an aggradational stacking patter. Tidal flats are interpreted between the two systems. Well 34/3-5 was also very thin in the lower Cook member and were interpreted to display distal facies and in the middle Cook member the well has equal thickness and proximal facies compared to the other wells which could indicate well 34/3-5 is more proximal to the source in the upper Cook member. In the lower Cook wester well western 34/3-3 thicker than the north eastern well 34/3-1 and 34/3-2, while in the middle cook the opposite is observed. Well 34/6-4 which is located between the two systems also shows different signatures then the other wells, the well has been interpreted as tidal flats. This indicates that the systems are more separated in the middle Cook member then in the lower Cook member. These changes in thickness and facies could indicate that the system located in the Knarr Field has slightly shifted to a south-eastern source and is building out towards north-west. In the Garantiana discovery middle Cook member thickness and facies show similar trends as the in the Lower Cook member.

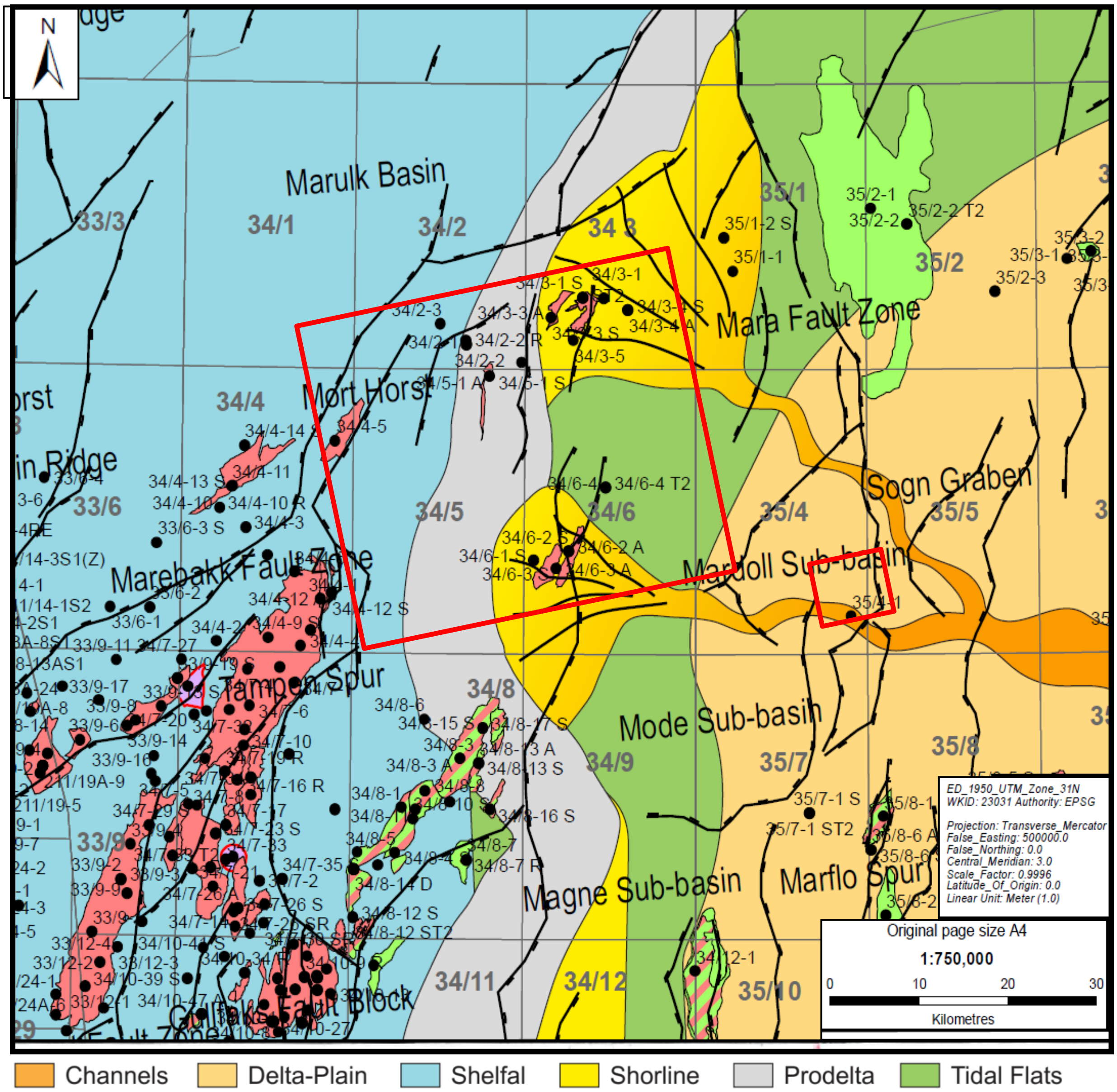


Figure 16 Paleographic map of the middle Cook member peak aggradation, the red squares marks the study area

7.2.3 Retrogradation of middle Cook Formation

The two deltas show different drowning stories: In the Garantiana discovery the retreat of the middle Cook member is represented by a change to tide-dominated estuary (FA6, table 3). In the Knarr Field the delta was flooded with the establishment of a short-lived bay or "inactive distributaries" before the middle Cook delta prograded once more. The final retreat off the system led to establishment of estuaries to Knarr-Garantiana (with an evasion south to the west). The middle Cook member was bounded by a flooding representing the J15 Flooding surface of Charnock et al., 2001. Well 34/5-1S displays wave-dominated structures, which is contradictory to the tide-dominance in all the other wells. The well is locates distal and to the north of the system. This can indicate this well is located between the two systems in a more open setting which allow the waves to rework deposits. This could also suggests that tides were weaker offshore and increased landward.

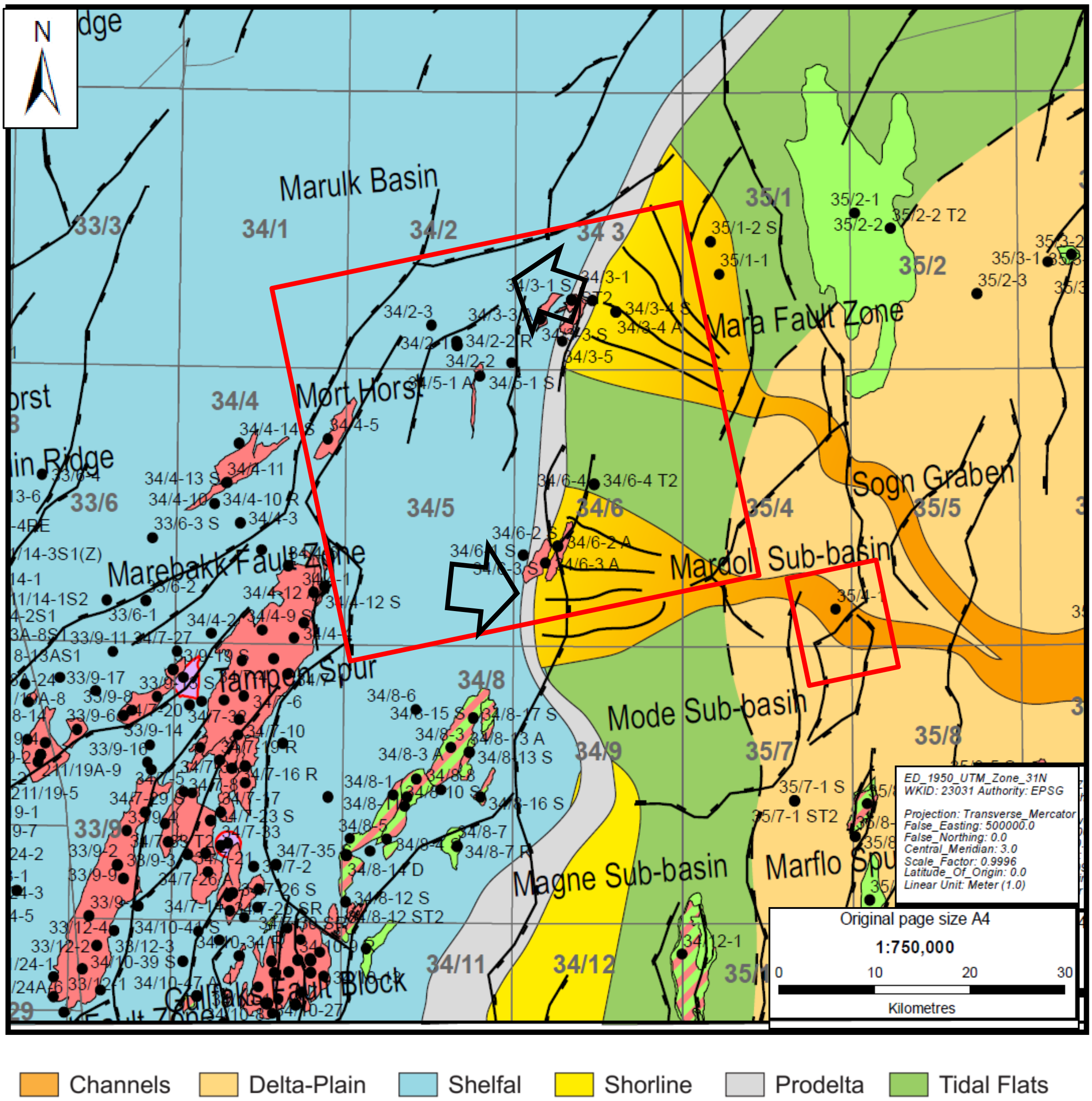


Figure 17 Paleographic map of the middle Cook member retrogradation, the red squares marks the study area.

7.2.4 Peak progradation of Upper Cook Formation

Following the latest Pliensbachian J15 flooding the upper Cook member represents the final progradation. In the Knarr Field the delta builds out again, while a shoreface formed across the Garantiana discovery. This stage of Cook delta formation is correlated with the preak progradation in the Kvitebjørn/Valemon and Gullfaks area (Dreyer and Wiig 1995, Folkestad et al., 2012) based on the biostratigraphy provided by Charnock et al., 2001.The marked deflection of the Cook delta with a northern and a southern branch is attributed to increased subsidence along the embayed Viking Graben (see also Ravnås et al., 2000).

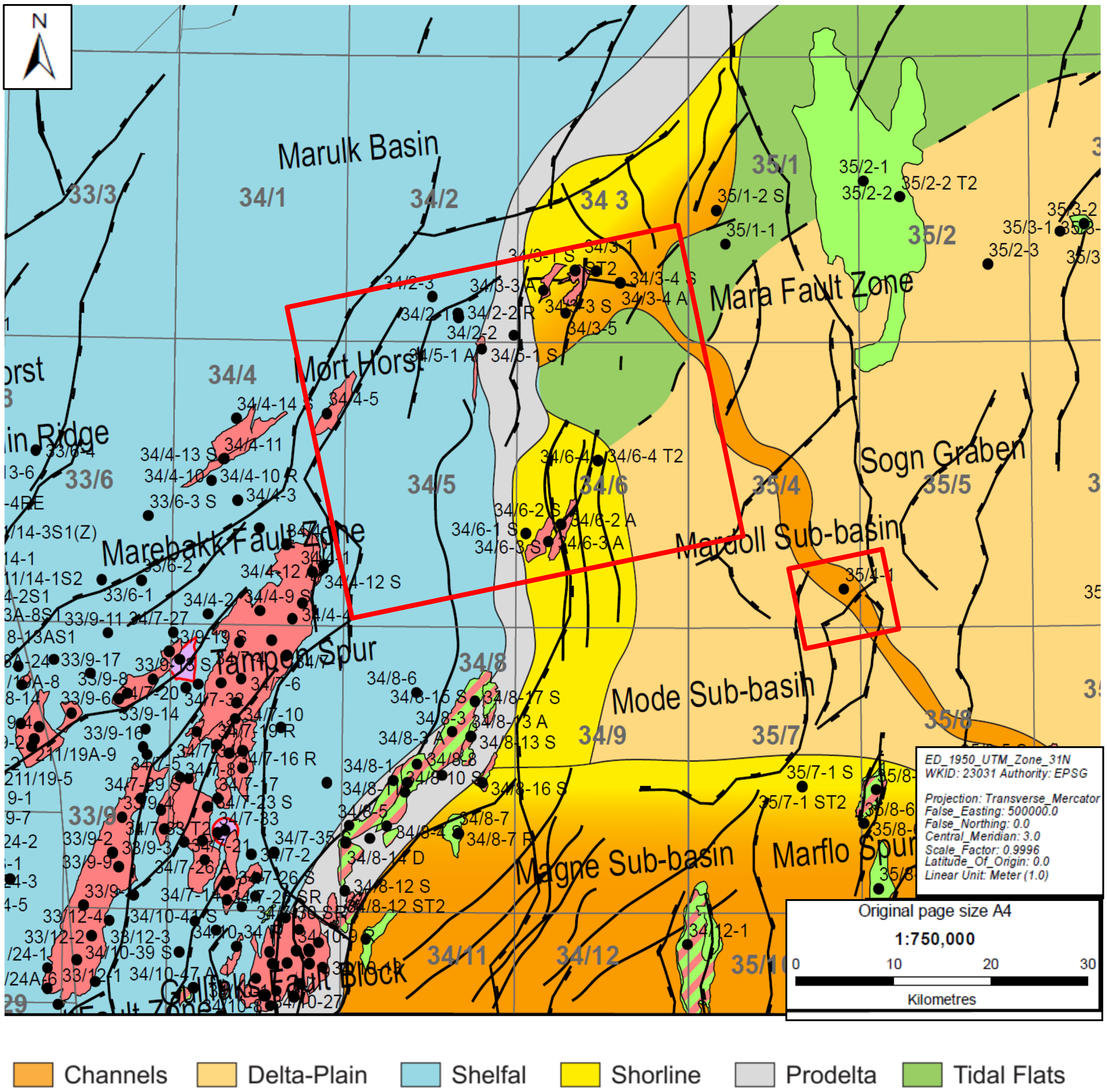


Figure 18 Paleographic map of the lower Cook member peak progradaion, the red squares marks the study area.

7.2.5 Retrogradation of Upper Cook member

The last stage of the retrogradation of the Cook Formation is represented by a transgressive faintly wave-dominated shoreface, across the Knarr Filed and Garantiana. This is the last stage before the whole system got drowned. The Cook Formation is overlain by marine mudstone of the Drake Formation representing the J16B maximum flooding surface of Charnock et al., 2001.

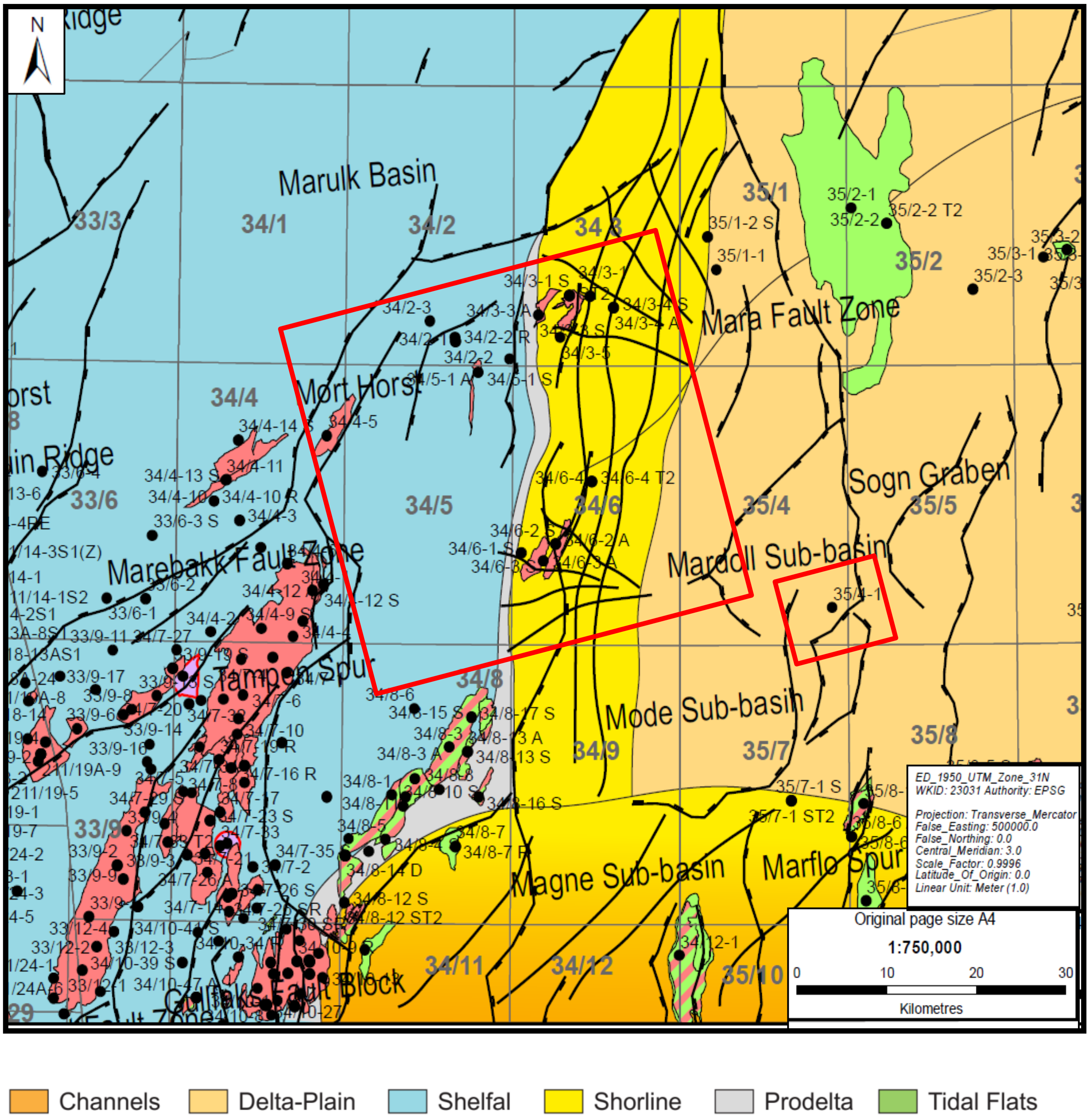


Figure 19 Paleographic map of the lower Cook member peak retrograding, the red squares marks the study area.

7.3 New observations and interpretations

The new observations and interpretations in this study are related to the link between the Cook Formation in the Knarr Field and the Garantiana discovery and the wells that are located fare more distal (seaward) and proximal (landward) positions; 34/2-2, 34/2-4, 34/3-2S, 34/4-5, 34/5-1S, 35/1-1 and 35/4-1.

The distinction between deltas and estuaries lies in the identification of the facies stacking pattern (Dalrymple et al., 2003). This in turns requires a detailed interpretation of the facies. The Lower and Middle Cook Formation interpreted as mouth bars (DE 1, table 2), Simple dunes (DE 2A, table 2), compound dunes (DE 2B, table 2), collapsing (breaching) dunes (DE 3, table 2) and channel floor/thalweg (DE 4, table 2) deposits, have previously been interpreted as tidal channel complex, tidal bar complex, intertidal bar complex and proximal intertidal bar complex (Churchill et al., 2016). The lower and middle part of the Cook Formation is interpreted by Churchill and coworkers (2016) as only delta. The detailed interpretation of the bar architecture gives a more complex interpretation of the delta advance then earlier interpreted. The change in bars from proxiamel to distal or form distal toward proximal can help identifying estuarine deposits. The upper Cook Formation interpreted as a prograding delta front (FA 2A, table 3) with estuarine deposite (FA 6, table 2) switching to shoreface deposit (FA 2A and FA3), which have previously been interpreted as only shoreface deposits (Churchill et al., 2016).

Churchill and coworker interpreted the orientation of the delta to be supplied form east and prograde toward west, which is similar to the interpretation of sequence I in this study. Observation done in this thesis suggests a change in direction in sequence II and III to sedimentary supply form south-east and prograding north-west.

The base of the Lower Cook Formation is interpreted to be influenced by tectonic processes. The variation in thickness and fast chang in facies of the Upper Cook Formation is possible due to tectonic activity fast transgression. Tectonic activity is the preferred explanation, and as a result it has a highly variable thickens distribution.

8.0 Discussion

8.1 Cook Formation structure and sedimentary architecture

Varying energy settings throughout a relative sea level cycle is a function of the coastal bathymetry, shelf width, tidal resonance and sea level behavior, which can change at any time during the relative sea-level cycle (Yoshida et al., 2007).

The lower Cook member developed during a relative sea-level fall (falling stage system tract to early lowstand system tract). There are lateral facies changes simply because of process variability laterally away from the river mouth. These are expressed as varying degree of marine erosion related to wave- and-tide ravinement in front of the falling stage shoreline, thickness and facies tracts within the falling stage shoreline-deltaic system and amount of incision and thereby focusing of the late stage (lowtand) fluvial to distributary channels. Distribution of facies tracts suggests an overall east to west porgradation. The thickness is relative uniform with only immoral thickness variations. The thinning toward the distal parts of the deltaic facies tracts is related to pinch-out and 'shale-out' of the delta-fron to prodelta facies, suggesting that the most distal parts of the delta was not filled to sea level. In consort observations imply that the progradation was mainly driven by lack of accommodation forcing the sediment to build out, with peak progradation and turn-around of the lower Cook lowstand deltas controlled by sediment availability. The relative sea-level fall is attributed to upwaping of the rift margin and its hinterland, which in turn forced the lower Cook delta basinward (Steel, 1993; Ravnås et al., 2014). This suggests that the main control of the lower Cook member hinterland structuring (in combination with any basinal structuring) and related relative sea-level lowering or fall(e.g Steel, 1993, Ravnås et al., 2014).

The middle Cook member was deposited during the subsequent sea-level rise, when accommodation creation started to balance sediment supply. The middle Cook Formation represents a relative thick aggrading sequence with relative uniform thickness. This suggests that the middle Cook member reflect sea-level rise with high sediment supply. Churchill et al.,2016 interpreted the Cook depositional system(s) in the Knarr Field to always have their distributary channels oriented east to west. In this study the middle Cook member deltaic systems at the Knarr Field is interpreted to have changed f to a more southeast to northwest orientation and progradation direction. This may be attributed to an increased control of accommodation creation related to reactivation of the inherited Permo-Triassic structural grain (e.g. see Gabrielsen et al. 1990; Steel & Ryseth 1990; Færseth & Ravnås 1998, Ravnås et al., 2000), with delta lobe swithcing partly controlled by enhanced subsidence along north-south oriented faults cross-cutting the NE Tampen Spur area (Norske Shell in-house Cook Formation isochore maps) in response to mild late Pliensbachian-early Toarcian tectonic activity (e.g. see Ravnås et al., 2000). The middle Cook member also show lateral variability in their backstepping and downing stories, which would indicate differential subsidence, which in turn is attributed to this renewed mild tectonic activity .

The upper Cook member shows increased variability in both thickness trends, facies tracts partitioning and distribution of depositional environments. The upper Cook member in the Knarr Field is represented by an outbuilding delta, while in the Garantiana Discovery the Cook Formation is represented by an embayed shoreface (DE4, table3). Also in the Gullfaks and Kvitebjørn-Valemon fields (Dreyer and Wiig, 1995; Folkestad et al., 2014) a progradational deltaic system developed, in the latter (Kvitebjørn-Valemon) area this was succeeded by a barrier-lagoon system during the delta drowning stage. The embayed upper shoreface (DE4, table3) on the Garantiana (Visund north) area is accordingly located between the two delta lobes, i.e the one across the northeasttern Tampen Spur (the 'Knarr Field lobe) and the one across the central parts of the Northern Viking Graben (the Kvitebjørn-Valemon-Gullfaks lobe), potentially representing a protected, embayment setting between two delta lobes. The marked deflection of the Cook delta with a northern and a southern branch is attributed to increased subsidence along the embayed Viking Graben (see also Ravnås et al., 2000). The variable sedimentary architecture of the transgressive segment or upper parts of the Cook system with rapid flooding and sediment shut-off in the Garantian discovery while on going subsidence and delta outbuilding in the Knarr and Kvitebjørn-Valemon-Gullfaks fields favors a combination of possible eustatic sea-level rise and tectonic activity leading to the final stage transgression of the Cook system.

Steel (1993) interpreted the main controlling factor of the early to middle Jurassic succession to be hinterland uplift, while Ravnås et al., (2000) argued for repeated structuring of the basin areas. The lower Cook member favours hinterland structuring while the middle and upper Cook members records gentle stretching and rifting within the basin. The repeated Late Triassic to Middle Jurassic mild rifting generated continuous background subsidence, which combined with sea level rise, resulted in gradual drowning of the Northern North Sea (Ravnås et al., 2014). There is earlier documented variable structural infill pattern the Lower to Middle Jurassic succession with evidence for varying subsidence and rifting within this region and also elsewhere on the Norwegian Continental Shelf (e.g. Gjelberg et al., 1987; Corfield & Sharp, 2000; Corfield et al., 2001; Martinius et al., 2001, Ravnås et al., 2014).

8.2 Tide-dominance

Tide-dominated deltas forms in areas with high tidal range and low wave-power (Willis, 2008). The Cook Formation is in this study interpreted as a tide-dominated delta, which is shown by a predominance of tide-generated structures such as single and double mud drapes, tidal bundles and sigmoidal dunes (figure 21 and 22). The abundance of mud in the system and with reslutant heterolitic deposits are also common in tide-dominated deltas (Willis, 2008, Goodbred and Satio, 2011). Abundance of tide-dominated facies is not enough to indicate a tidal dominance of gross depositional environments (Dalrymple et al., 2003). In some of the cores there is little direct evidence for the tidal nature of the deposits, however, as there is limited or no wave-generated structuresa wave-dominated setting is not considered likely., The limited indications of wave-generated deposits are only encountered in the shoreface deposits in the upper Cook member and in the middle Cook member bay to prodelta deposits present in well 34/5-1A and 34/5-1S. Bidirectionalpaleo current indicators are not common but current ripples with opposite facing directions can be seen in some of the heteroclite facies. The repeated coarsening upward motifs with facies transits from shelf-prodelta to delta-front deposits is taken as good indicator of facies successions related to the advance of deltas Abrupt coarsening upward pattern from prodelta muds, as observed in the lower Cook member, is a typical patter found in falling-stage to lowstand tide-influenced deltas (e.g Willis et al 2005).

It is often difficult to distinguish between tide-dominated deltas, estuarine and other tide-dominated or -influenced environments. However, based on the stacking patterns of the identified depositional elements, deposition from tide-dominated deltas are the preferred interpretation of the thicker and dominat parts of the lower, middle and upper and Cook member successions, whereas estuarine succession is interpreted present only in the middle Cook member. However, the thick units dominated by cross-stratified cosets representing compound dunes, could also have formed in estuarine settings (e.g. see Dalrymple and Choi, 2007), thereby maikng it difficult to confidentially place these deposits within either a deltaic or estuarine succession. Hence parts of the currently inferred deltaic succession may actually be estuarine in oroigin, or there may be repeated changes back and forth between deltaic and estuarine settings, represented by the succession dominated by compound dunes. Only detailed interpretation of stacking patterns may resolve this issue, which the current available dataset did not allow for.

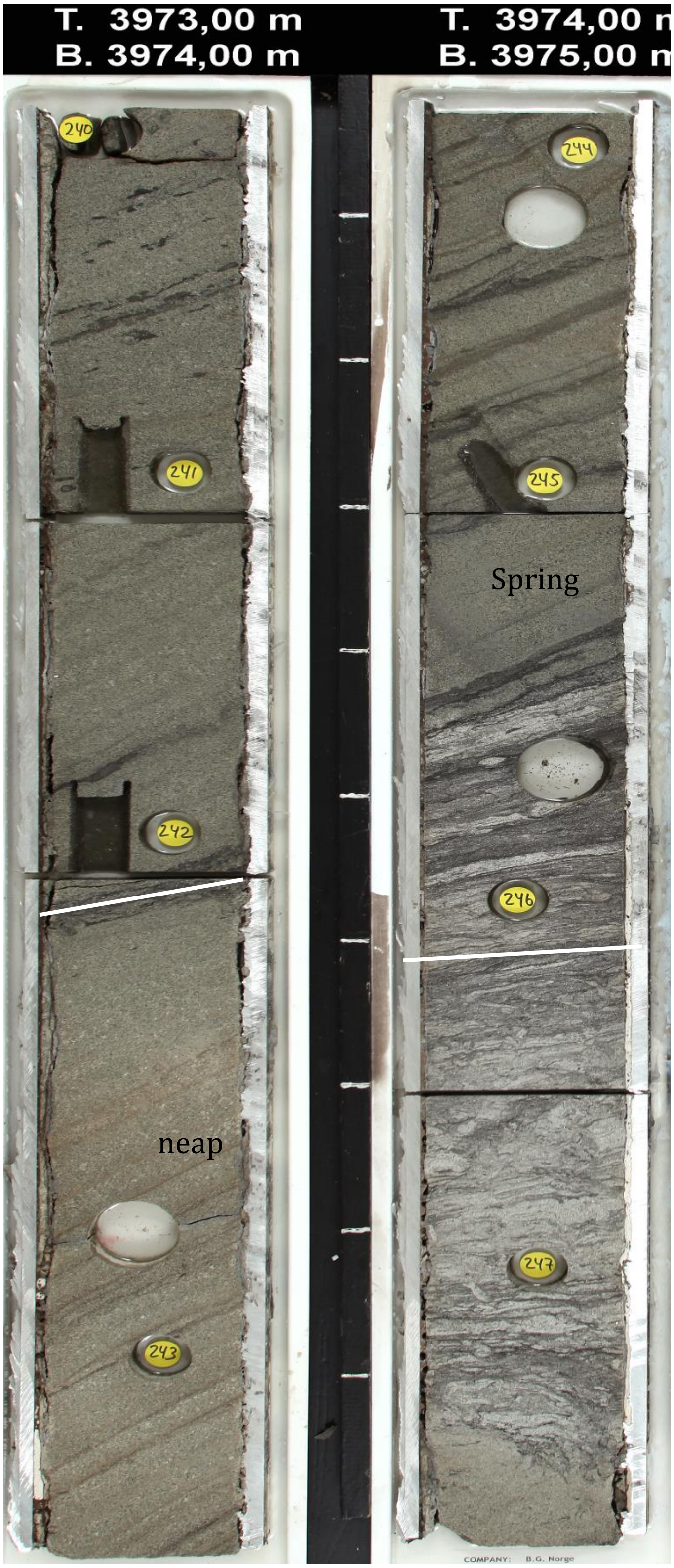


Figure 20 Crossbedding reflcting neap-spring cycle.

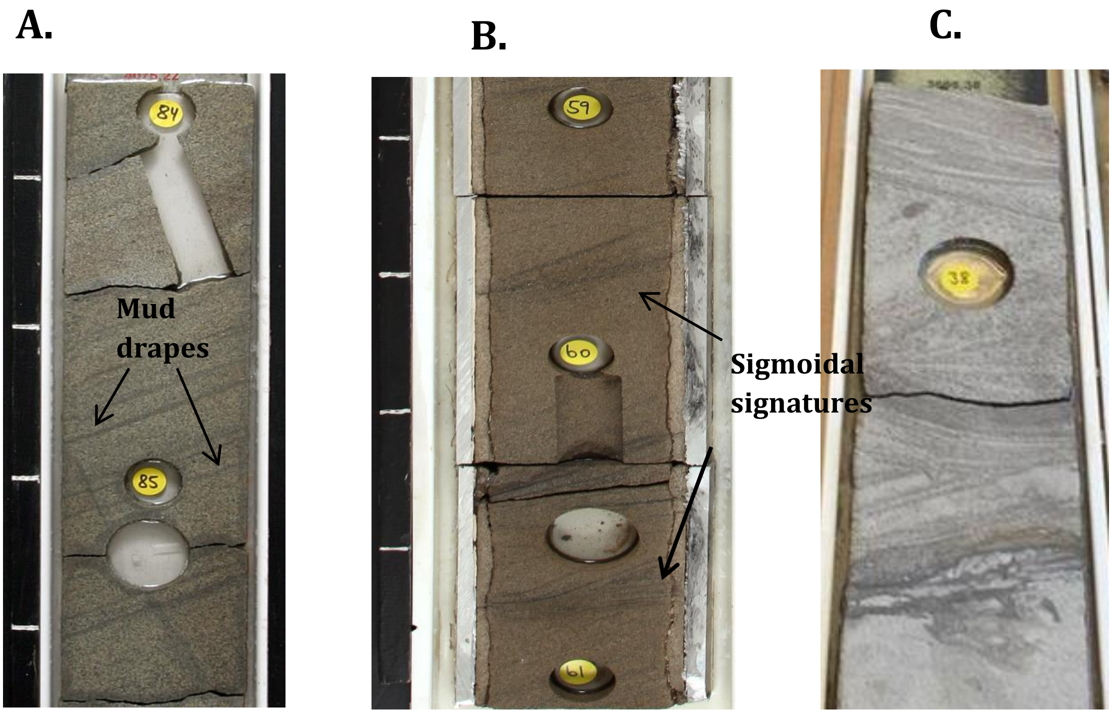


Figure 21 Tidal signatures in tide dominated facie. A. Mud drapes. B. Sigmoidal signatures. C. Bidirectional.

8.3 Sequence stratigraphic evolution

Yoshida and coworkers (2007) suggest that late stage transgressive system tract and highstand system tract favors the preservation of wave-generated facies tracts (e.g. hummocky and swaly cross stratified shoreface successions), whereas the falling stage system tract (forced regression), lowstand system tract and early transgressive system tract favor tide dominated facies tracts. This gross generalization does not fit with the observed and interpreted development of the Cook Formation 4. order sequences in the current study. The Cook Formation could possibly be divided into 3. rd order sequences, where the transegressive surface of marine erosion is possibly coinciding with a 2nd-order sequence boundary. In such a scenario the progradational or regressive lower Cook member would represent the falling stage system tract to early lowstand system tract, the aggrading middle Cook Formation represent the late lowstand to transgressive and early highstand system tracts, while the Upper Cook member represent the late highstand system tracts of a lower order or 2nd order sequence. This interpretation corresponds better to Yoshida and coworkers (2007) model, but there is no wave-influence interpreted in the Middle Cook formation transgressive system tract. An alternative interpretation of the upper Cook member is that it form parts of the transgressive systems tract, with the local progradation of the upper Cook deltas representing local reggressive perturbations of an overall transgressive or backstepping evolution. The time equivalent Tilje Formation in the Halten Terrace Show similar characters (Ravnås et al., 2014), with a similar sequence stratigraphic evolution.

8.4 Remarks

The Cook Formation is in general interpreted as marine sandstone formed in a variation of marine settings. A common character of the Cook Formation in the different fields is that the deposits are tide-influenced to tide-dominated.

Churchill and coworkers (2016) interpreted the lower part the upper Cook member in the Knarr Field as a tide dominated shoreline-to-shelf depositional system, with local evidence of wave- dominance. This stands in contrast to the tide-dominated deltaic regressive unit interpreted in this study. The high amount of tide-generated facies common also to this unit (Chapter 4) would favor a deltaic environment also for the thicker part of also this member. In this study there is not recognized any wave generated structures in the lower part of the Upper Cook Formation.

In the Oseberg Field the Cook Formation interpreted as a prograding tide-dominated subtidal marine sand body representing mud banks and transgressive offshore sand ridges by Livbjerg and Mjøs (1989). The lower prograding subtidal marine sand body could form part of a tide dominated delta succession. Livbjerg and Mjøs (1989) argue that tide-dominated sand ridges are interpreted as deposited during transgression due to the amount of tide-generated structures.

The present interpretation of a larger portion of the Cook sandstones in the North East Tampen Spur area actually representing deltaic deposits, may hence also applies to the Cook Formation in other parts of the Northern North Sea. Recent advances in our understanding of the tide-dominated to –influenced depositional systems warrants caution in interpretation of related deposits, and should stimulate new look at the Cook Formation in other parts of the basin where the unit forms a viable reservoir.

8.5 Analogues

8.5.1 Modern day analogue, Fly river delta

A modern example of a tide-dominated delta with similar evolution is the Fly River delta (figurer 12). Studies done shows that sedimentary supply is mainly restricted to the southern channel, while the northern has little sedimentary supply while the far northern channel are effectively abandoned inflow is stronger than outflow (Wolanski et al., 1998, Dalrymple et al., 2003). The active channel in the southern part generated deltaic deposits while abandonment channel in the far northern part generated estuarine deposits. The abandoned channel in the far northern part formed coarse-grained channel bottom facies alternating with dunes (Dalrymple et al., 2003)

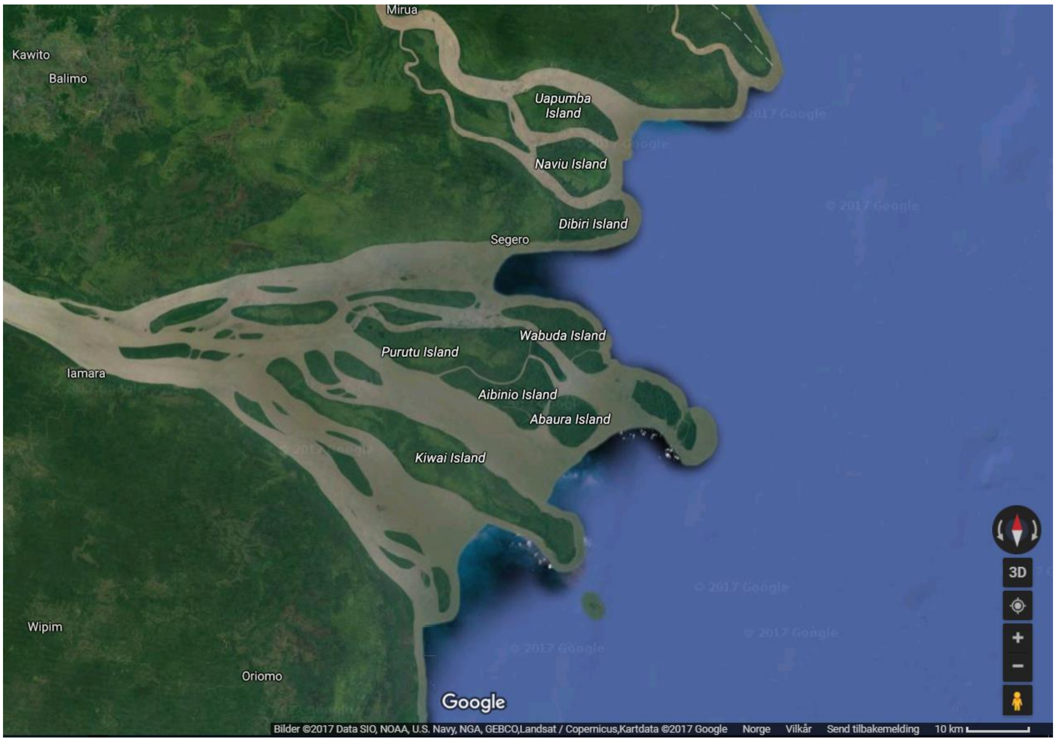


Figure 6-11. The Fly river delta (Google maps)

8.5.2 Ancient analogue, -Ile Formation

The Early Jurassic Ile Formation is time equivalent to the Cook Formation and has beed interpreted as a sucession tide-dominated deltas and estuaries (Gjelberg *et al*., 1987; Dalland *et al*., 1988; Harris, 1989; Pedersen *et al*., 1989; Ehrenberg *et al*., 1992; Saigal *et al*., 1999; McIlroy, 2004; Martinius *et al*., 2005, Ravnås et al., 2014).

8.5.2 Ancient analogue, -Tilje Formation

The Early Jurassic Tilje Formation is time equivalent to the Cook Formation and more or less facies equivalent. It is interpreted as a tide and fluvial dominated delta and tide dominated estuarine and (Ravnås et al., 2014). The Tilje Formation also has a similar sequence progradational-aggradation-retrogradational structure as the Cook Formation.

9.0 Conclusion and Future Work

The Cook Formation has been studied in 9 cores and 16 wells logs from Knarr Field to Garantiana discovery in the Tampen Spur area. A total of 446 meter of cores have been interpreted which is the basis for this thesis.

In this study 11 facies were recognized in the Cook Formation, based on lithology, grain size, sedimentary structure, bed boundaries, bed thickness, texture and degree of bioturbation. The 11 facies was used to distinguish 5 depositional elements and 7 facies associations, covering the progrdational deltaic and retrogradational estuarine and shoreface part of the Cook Formation. The deltaic and estuarine deposits are mainly influenced by fluvial input and tidal action, while the shorface deposits are mainly influenced by wave activity.

Based on the interpreted core logs three correlation profiles have been produced. One from west to east in the in the Garantiana discovery, another from west to east in Knarr Field and the last south to north from Garantiana discovery to Knarr Field. The Cook Formation is interpreted to represent one megasequence. Three higher order sequences were recognized in the Garantiana discovery and the Knarr Field, each consisting of a regressive and transgressive segment and bounded at their base and top by maximum flooding surfaces. Lower Cook member is dominated by porgrading delta front deposits (FA 3A table 3) in both the Knarr Field and Garantiana discovery which represents the regressive segment with sedimentary supply form east and progradation toward west. The middle Cook member comprises delta front deposits (FA3A, table 3) overlain by estuarine deposits (FA6, table 3) in both the Knarr Field and Garantiana discovery, which represent the aggrading segment with sedimentary supply form south-east and prograding toward north-west. The upper Cook member comprises delta front deposits (FA3A, table 3) and lower shoreface deposits (FA3B, table 3) in the Knarr Field, and in the Garatiana discovery the sequence consist of lower and upper shoreface deposits (DE4, table3).

Due to relatively uniform thickness and faices in the lower Cook member is interpreted to reflect eustatic control and hinterland structuring. In the middle and upper Cook members there are more variability in facies, outbuilding and thickness which indicate tectonic activity, with gentle rifting.

9.1 Further Work

Recommended future work would include interpreting seismic, to better tie the date together and get a better understanding on the structural settings.

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