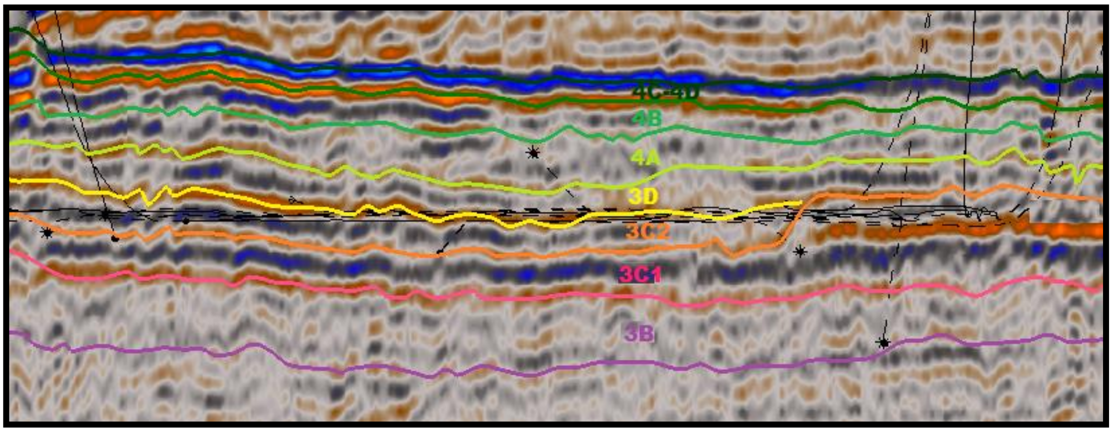
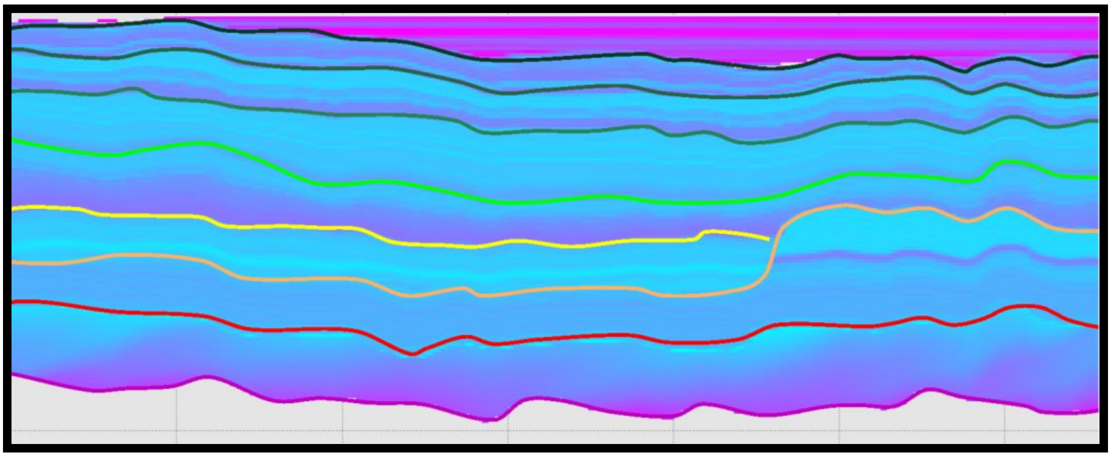
# AES/TG/13-15 High resolution reservoir characterisation in the Troll West Gas Province

**August 2013 Willemijn Ogg**



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**High resolution reservoir characterisation in the Troll West Gas Province**

Master of Science Thesis
For the degree of Master of Sciences in
Reservoir Geology

Willemijn Ogg
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Delft University of Technology

## *Abstract*

Just like many other shallow marine fields, the Troll field is steadily increasing its recovery factor by performing an extensive infill drilling procedure. Well planning requires an ever increasing knowledge of the geological and sedimentary characteristics of the field, as higher drilling precision demands a more detailed reservoir model. The most important reservoir units of the Troll field consist of a stacking of shallow marine sand- and siltstones that were deposited in an asymmetric coastal spit system. The spit system consists of progradational surfaces including clinoform structures that contain heterogeneous and complex sediment accumulations which are difficult to map in the subsurface.

A thorough literature investigation into the characteristics of asymmetric delta spit systems, clinoform deposition and the Troll geological history forms the basis of a new method to model the heterogeneous sediments in the field. Seismic interpretation and well log correlation between the many multilateral wells are used as input for the model. The model itself is built in the Compound Earth Simulator, a software package developed by Statoil’s research department. Using the Compound Earth Simulator, the sediments (logs and seismics) are brought back to their time of deposition with a backward time engine. The undeformed nature of the sediments at time of deposition makes it possible to find better correlation between the different wells, resulting in the construction of a high resolution sediment distribution. A forward time engine then brings the sediments forwards through time to their present day situation, in which all complexity of deformation is present again, but the high resolution sediment characteristics are still visible as well. The construction of synthetic seismics and virtual well logs show a quality check of the modelling procedure. The Compound Earth Simulator and the presented method offer a fast and easy routine to improve the modelling detail of a field by introducing a high resolution reservoir characterisation in problem areas.

The results of the procedure show that the clinoform progradation direction in the Troll field is more heterogeneous than described in earlier work. For multiple parasequence in the specific area of interest within the field, the main progradation happens towards northwest or north, which is contradicting the earlier described west to southwest build-out direction that corresponds to the longshore current direction. Multiple possible explanations for this observation are presented.

The concluded heterogeneities may be taken into account during future geomodel updates. The high resolution reservoir characterisation can moreover be used for well planning and drilling purposes. As the most important result, the method that is developed in this thesis may be used to create a high resolution reservoir characterisation in other parts of the Troll field or other fields as well.

## *Acknowledgement*

I would like to take the opportunity to thank the people that helped me to write this thesis. It has been the most inspiring project of my education at TU Delft, which is all because of my supervisors. I could not have written this thesis without the trust and help of dr. Steen Petersen and dr. Stefan Luthi. Thank you for all your help, always being patient to answer yet another one of my questions and motivating me to get into the project a little bit further, step by step. Also thanks to dr. Rick Donselaar, for opening my eyes to the sedimentary aspects of the project in the many discussions we had. Thank you dr. Gert-Jan Weltje for being in the assessment committee of the colloquium.

I would like to thank Knut Georg Bjørnø, Kristine Nilsen and Jakob Gjengedal, all experts of the Troll Field’s geology and geophysics. Without your contribution my project would not have been here. I hope that the report offers something back in return. Also, many thanks to Jan-Arild Skjervheim and the research group, for welcoming me into the department. Many thanks to Eirik Øygaard and Alexandre Ferre for introducing me to the Statoil software and databases. Thanks to Statoil Bergen and the research department for supplying the research facility and accommodation. Also many thanks to the Statoil’s Troll department and the partners Petoro, Norske Shell, Total E&P Norway and ConocoPhillips Skandinavia for supplying the data that this thesis was based on.

Thank you Orianna Dos Ramos, my CES-partner in crime, for many discussions and helping me find the use of each and every button in the Compound Earth Simulator. Thank you Janneke van Ginkel and Diede van Delft for proof reading the drafts of the thesis and the colloquium. Without you no one except me would have actually been able to understand what I have been doing these last months. Thanks to my friends and my brother and father. Getting through these two master’s years has not been easy. You were always there for me. I would not have been able to finish my master’s degree without your help and support.

## *Nomenclature*

| | |
|---|---|
| CES | Compound Earth Simulator |
| CP | Centipoise |
| EOR | Enhanced oil recovery |
| FSST | Falling stage systems tract |
| GOC | Gas-oil contact |
| HST | High stand systems tract |
| LST | Low stand systems tract |
| OIIP | Oil initially in place |
| OWC | Oil-water contact |
| PETEC | Petroleum Technology |
| TST | Transgressive systems tract |

## *List of tables and figures*

Figure 11: An example of clinoforms that are penetrated by the I-12 wells. Although sigmoidal shapes appear rather obvious, it is unclear if these represent the actual clinoform surfaces or are linked to a different type of internal parasequence heterogeneity. Therefore it is dangerous to use sections like these (that furthermore only contain apparent length and dip) for measurements of size and angle of the clinoform.

Figure 12: a) Location of the wells of interest on top of the geomodel (x-axis scale is 5 kilometres).
b) Gamma ray well logs in top view on well paths, with high gamma rays indicating silt rich areas coloured purple or blue in a wide pattern and low gamma ray regions in much thinner green patterns. c) Location of the cross sections of figure d and e on top of the seismic top view at reservoir depth. d) Cross section C with well paths and location of the 3B, 3C, 3D and 4 reservoir zones indicated. e, f) Cross section E, F with well paths and location of 3Cc and 3Dc and 4 reservoir zones indicated.

Figure 13: a) Schematic representation of the two sequences of the Compound Earth Simulator. The first, so-called data restoration sequence (dR) brings the reservoir properties like seismics, cores and wells back through every geological step to their time of deposition. The second so-called model reconstruction (mR) sequence forwards data in the opposite direction towards the present day again. b) c) The build-up of clinoforms in CES is done by creating arcmod and along functions using random log distributions (internal communication with S.A. Petersen, 2013. All three figures were either edited from publication or unpublished).

Figure 14: The CES modelling results. a) b) c) A representation of the original seismic sections as defined in figure 12. d) e) f) The gamma ray distributions along these three sections. g) h) i) The synthetic seismics retrieved from the different log distributions. A colour legend may be found in appendix 1.

Figure 15: a) A comparison between the true well logs and the modelled well logs in the two models that were constructed in CES. b) The gamma ray distribution of section D using the H-1 AH model. c) The gamma ray distribution of section D using the I-12 Y2H model.

Figure 16: a) The homogeneous well log correlation represented along the section within which it occurs. Also, an example of how the progradation direction can be different than one would expect looking at the longshore current, in the upscaled and turned top views of b) the Mississippi delta c) the Ebro delta.

Table 1: List of wells that were studied in the area of interest.
Table 2: Reservoir data and oil column thickness of the Troll Field (Horstad and Larter, 1997)
Table 3: A summary of the main characteristics of the seven parasequences that are investigated within the area of interest.

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# 1. Introduction

## 1.1 Problem Statement

Fossil fuels are the most important energy resource of our society, having a share of over eighty percent in primary energy consumption in the world (Van Roekel, 2008). Energy demands are growing rapidly and are expected to keep on doing so, especially in third world countries.[1] Although new oil- and gas fields are still found, the amount of discoveries has started to decrease. This development has put an increasing emphasis on enlarging field life and Enhanced Oil Recovery procedures. With the high amount of detail that is required to perform these operations, our understanding of the field's characteristics has to grow as well. It is essential to update static models of the reservoir to a level as precise as possible in order to reach the highest recovery factor, because a heterogeneous reservoir is not depleted equally throughout the field. Therefore it is useful to gain insight into the build-up of specific target areas within a reservoir to judge factors that have the largest influence on production, like compartmentalisation, flow paths and fault patterns. Investing in sufficient geological research is of high importance in order to be cost efficient when extending field life.

The focus of this master's thesis is on Norway's largest field, the Troll field, which located about 100 kilometres northwest of Bergen. The field's recoverable reserves amount 1410.9 billion $Sm^3$ gas, 27.7 million tonnes NGL, 1.6 million $Sm^3$ condensates and 255.8 million $Sm^3$ oil (Norwegian Petroleum Directorate, visited 19-08-2013). The Troll field is one of the biggest gas fields in the North Sea, capturing about 60% of Norway's gas reserves in a thick gas column. Underneath this extensive gas column, a thin but widespread oil zone is located. Although the overlying gas cap prevents the oil layer from undergoing major pressure drops, the field is not depleted easily in every area and contains multiple locations in which infill drilling is economical. In these areas, a dense multilateral well setting is created, for which a solid geological model is needed.

The Troll field is located in a heterogeneous and heavily faulted area, within three large tilted fault blocks of the Horda Platform (a.o. Leiknes and Osvoll, 2005). The main reservoir sediments are of Upper Jurassic age and consist of a stacking of shallow marine sand- and siltstones that were deposited in a west to southwest progradational coastal spit system (Dexter et al., 2005). This spit system formed numerous low angle clinoform parasequences that were each deposited over a timespan of around 500.000 years, composing a total system of around 8 million years (Evensen et al., 1993).
The Sognefjord Formation is the main reservoir unit of the field, containing about 90% of the oil reserves. Within the two composite sequences of the formation – the Upper and Lower Sognefjord – 17 internal reservoir bodies are identified. Five of these bodies are basic series (Evensen et al., 1993). Their individual reservoir zones carrying names like 3Ac, 3Bc and 3Cc correspond to system tracts (Osivwi, 2009). The boundaries of the basic series are mostly flooding surfaces.
The sands of the reservoir formations can be divided into so-called C-sands, good reservoir quality calcite rich sands, and M-sands, which are micaceous sands with a lower reservoir quality. The target sands have a very small thickness, of between 5 and 13 meters, which requires high precision horizontal drilling. Reservoir simulation has shown that the cumulative oil production has an optimum when a well is placed at about 0.5 meters above the oil water contact, and it is this small distance to the OWC that complicates the drilling even more. Characteristic vertical resistivity curves are used to determine the presence of the oil during drilling, whereas gamma ray and density logs are used to determine sediment type and sand quality, zonation and fluid fill in order to enable steering. Azimuthal (real time)

gamma ray is the most important feature enabling lithological determination. A high resolution geomodel forms the basis of each drilling campaign. The information gained from each drilling campaign offers a large database which forms the basis of this thesis.

### *1.2 Objectives of the thesis*

The objectives of this thesis form a threefold. First of all, the thesis should give a better insight into the depositional settings of asymmetric delta spit systems in general. Secondly, it should provide a more detailed mapping of the Troll Field's parasequence stacking and reservoir characteristics in the area of interest. Thirdly, and most importantly, it should bring a method in which challenging areas in the geomodel can be remapped in a fast and easy way. This means that the method that is offered in this thesis is actually the most important part of the results.

The Troll field geomodel is constructed using an extensively mapped (high frequency) 3-D seismic dataset, combined with 4-D seismic observations and very densely gridded well dataset. However, even when using this large amount of data, major uncertainties are still present in the mapping of the high permeability sand. Not all parts of the geomodel contain the detail on the presence of the M-sands, C-sands and silt that is required for the planning and geosteering of the wells. In the 1-13 area, which is one of the challanging areas in the field and the main interest of this thesis (see figure 2) fine grained micaceous sands were found where coarse grained C-sands were expected. Although the model is regularly updated with new well- and 4D seismic data, there are similar areas in the field that are not understood well enough in terms of sediment type. This thesis offers a method to update the geomodel in these areas.

### *1.3 Methodology*

There are many questions related to the goals described above. When it comes to the first goal of investigation, the description of delta spit systems in general, the following questions arise: How do asymmetric delta spit systems form and what is their build-up? How are the progradational bodies visible in logs and seismics? In which cases are clinoforms found, and what is their appearance?

Concerning the Troll Field's build-up the following questions arise: How heterogeneous are the deposited sand bodies? Why was the Troll geomodel unable to predict the correct sediment type in the I-13 area? Were there problems in seismic interpretation or in well log correlation? Can we make a better correlation for the area, and thereby make a better interpretation of facies content?

In an attempt to find an answer to these problems using the Compound Earth Simulator with its capability to restore data and next reconstruct the model, even more questions arise: How can CES be used to model the Troll sediment? How can CES be used to model progradational surfaces and clinoforms in general? To what horizontal and vertical scale is correlation and interpretation using seismic images and logs in CES doable?

Three different approaches are used to answer the questions and fulfil the goals that were specified above.

1. Literature review

In order to improve the understanding on asymmetric spit systems and clinoform deposition a thorough literature review was performed. The Troll Field geological history was studied in order to be able to put the deformational events of folding and faulting, as well as the depositional events of sedimentation and erosion in a historical framework. This framework is needed in the CES model (see below). An example of such a framework can be found in table 3 of chapter 3.

2. New interpretation

The first thing that was done to construct a new interpretation for the I-13 area was the consultation of the Troll geomodel and the revision of interpretations that were already done in the area. Log data for all wells of interest were gathered from the Openworks Database and a correlation panel was constructed in RMS (Roxar's Reservoir Modelling Solution), DSD (Decision Space Desktop) and Stratworks (both Landmark software packages). Simultaneously multiple seismic cross sections were made. Using the depth definition of the different basic series in the correlation panels (in MD), the series could be identified in the seismic section using measured depth functions in the well paths while they were represented in DSD. Seismic interpretation was then done to judge the areal extent of the basic series and their internal sand bodies. Interpretational problems were found in the presence of bright spots at the Oil Water Contact and in the gradual changes of one unit's facies into the next. The Compound Earth Simulator was used to improve the interpretation by constructing a high resolution reservoir characterisation in an attempt to overcome these problems.

3. The Compound Earth Simulator

In order to create a high resolution reservoir characterisation, the Compound Earth Simulator was used. There are multiple steps that need to be taken in order to construct a model in CES. These steps are described below, and are made visible in the figures of Appendix 1. Every number used in the text below refers to a figure in Appendix 1.

A CES simulation should always start with the definition of an area of interest (1). Within the area of interest, one or multiple seismic sections should be created, including an indication of well paths that run through the section (2). After defining the target horizons and zones in the well logs (3), these can be transferred to the seismic sections using their measured depths in the wells (4). Finally, the geometry of the different faults and horizons should be marked in the seismic section(s) (5). Once this is done, all input objects are present and the simulation can start.

The easiest correlatable sedimentary body is an undeformed layer cake stratigraphy. Therefore, the Compound Earth Simulator attempts to bring the sediment back in time, removing all faults and folds, hereby creating a presumed geometry of the parasequences at the time of deposition (6). In the example of this thesis, the presumed geometry did indeed approach a layer cake stratigraphy, which greatly enabled the seismic correlation between the wells of interest. Once a correlation was constructed, the lower and upper boundaries of the different parasequences could be defined in the seismic sections (7). Using the definition of these boundaries in the well logs, the seismic sections could then be overprinted with well log distributions of each parasequence on top of the other (8). By applying the knowledge of major depositional and erosional events (an example can be found in table 3, chapter 3) the contact between two parasequences can be chosen to be an onlop, offlap, toplap or downlap. The created distribution showed reservoir characteristics like gamma ray (a parameter for sediment type) and density at a very high (meter scale) resolution. However, the created image was still representing the state of the sediments at time of deposition, providing an oversimplistic view on the present day situation. Therefore, the parasequences were brought forward through time to the present day situation by incorporating a series of deformation events that re-introduced the faults and folds in the area (9). The resulting model of gamma ray, neutron, density and acoustic velocity distributions was used to create a synthetic seismic section (10) that could then be evaluated and compared with the original seismic data. Virtual wells were drilled in order to compare the modelled log distributions to original log signals, as well as predict log signals in areas where no wells were drilled before.

## 1.4 Definition of the area of interest

As mentioned, the Troll field is located some 100 kilometres northwest of Bergen, Norway. The field has an area of around 700 square kilometres (figure 1) and can be divided into the main Troll East and Troll West structures, which are located in blocks 31/2, 31/3, 31/5 and 31/6, each at approximately 1200 meters below the sea bed.[2] The field has a very high well density. The focus of this thesis is on the southern part of the Troll West Gas Province (figure 2). A list containing the wells of interest can be found in table 1.

## 1.5 The dataset

The dataset was made available by the Troll PETEC department of Statoil ASA in Bergen. A full trace 3D seismic cube named NH01M01R02 was used to interpret the area. The cube is available in the time domain and is of high quality, with a resolution of up to 10 meters, as the reservoir is located at relatively small depth (the OWC is found at 1557 meters below sea level). The top of the reservoir is easily identified, with an uncertainty of approximately 5 meters. Most of the 17 internal reservoir surfaces are clearly visible in seismics, and faults that have a throw of over 5 meters can be mapped with confidence.

Sequence stratigraphic interpretations as well as 3D geological models were present for parts of the area.

The list of table 1 shows which well logs were used for the thesis. The gamma ray and neutron density separation were of main interest during the well correlation. In Troll, Logging While Drilling is performed for the gamma, resistivity, density and neutron porosity measurements (Leiknes and Osvoll, 2005). The difference in production quality between the calcite cemented and micaceous sandstones makes that gamma ray measurements are essential for the identification of the sediment type and during steering of the drilling. The gamma ray measurements are made fully azimuthal in 8 sectors and in real time, enabling identification of the direction and orientation of a sand body (Gundersen et al., 2008). Both image logs and sectored gamma ray are available, which aids the structural interpretation of the wells and makes it easier to link sediment type to log reading (Leiknes and Osvoll, 2005). The distinction between M- and C-sand is defined to lie at a gamma ray reading of between 60-75 API.

## 1.6 Outline of the thesis

The thesis contains six chapters. After this first chapter of introduction, the second chapter gives some background to the study area, by introducing the geology of asymmetric delta spit- and clinoform systems, as well as the Troll field geology and petroleum characteristics.

Chapter three contains the renewed geological interpretation of the area. Well log interpretation and seismic analysis are the first topics covered. The correlation of log characteristics is shown in correlation panels and explained by seismic analysis. Interpretation in the Compound Earth Simulator (CES) is covered after that, in chapter four.

Chapter five provides a discussion of the results, and chapter six summarizes the main conclusions of my work.

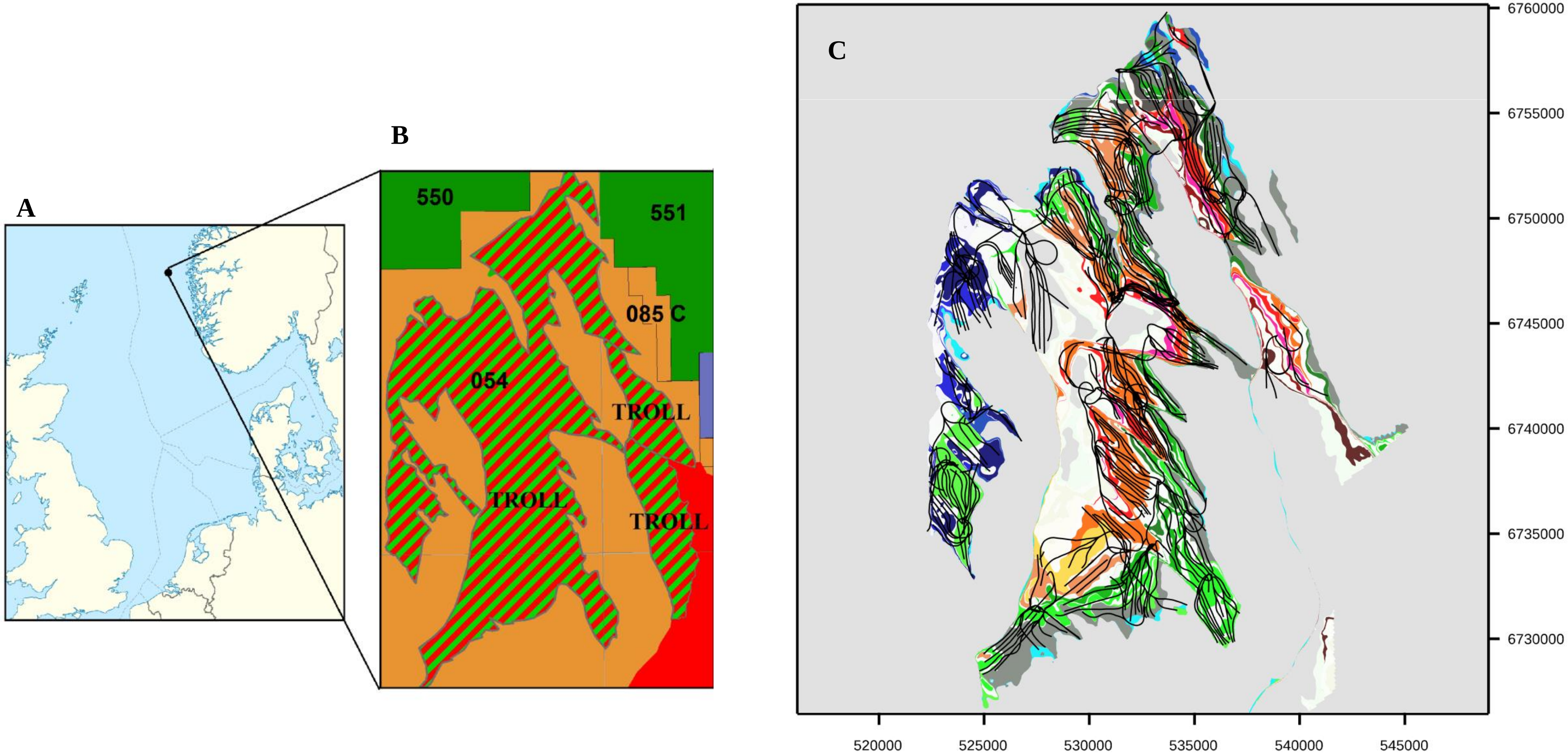



*Figure 1: Area of interest. a) The Troll Field location in the northern North Sea (Gundersen et al., 2008). b) A Troll Field template map (Gundersen et al., 2008). c) Illustration of well complexity in the Troll field displayed in an RMS map on top of the geomodel.*

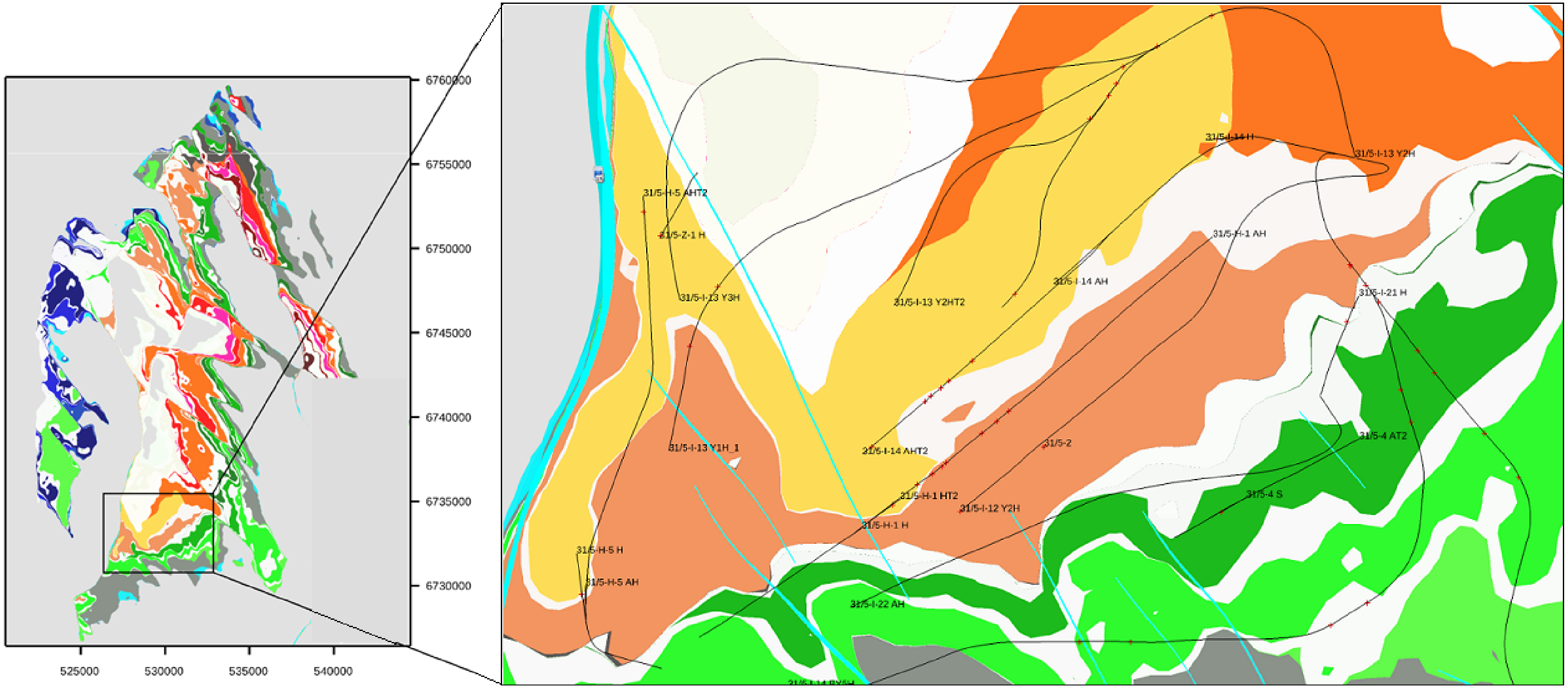



*Figure 2: Area of interest of the thesis, in the south western part of the Troll West Gas Province. Names of the wells are displayed next to the well paths, which are represented on top of the official geological model. Meter scale is given in the x- and y-axis of the left figure. Series of interest in the thesis are 3B, 3C, 4A, 4B, 4C and 4D, a colour legend may be found to the right.*

| **Wells of interest** |
|---|
| 31/2-1 |
| 31/2-10 |
| 31/5_2 |
| 31/5-4_AT2 |
| 31/5-4_S |
| 31/5-H-1_AH |
| 31/5-H-1_H |
| 31/5-H-1_HT2 |
| 31/5-H-5_AH |
| 31/5-H-5_AHT2 |
| 31/5-H-5_H |
| 31/5-I-12_Y2H |
| 31/5-I-13_Y1H |
| 31/5-I-13_Y2H |
| 31/5-I-13_Y2HT2 |
| 31/5-I-13_Y3H |
| 31/5-I-14_AH |
| 31/5-I-14_BY1H |
| 31/5-I-14_BY5H |
| 31/5-I-14_H |
| 31/5-I-21_H |
| 31/5-I-22_AH |
| 31/5-I-22_H |
| 31/5-I-23_AH |
| 31/5-I-23_H |
| 31/5-J-13_AY1H |
| 31/5-J-13_AY2H |
| 31/5-J-13_H |
| 31/5-J-14_AY1H |
| 31/5-J-14_AY1HT2 |
| 31/5-J-14_AY2H |
| 31/5-J-14_H |
| 31/5-Z-1_H |

*Table 1: List of wells that were studied in the area of interest.*

## 2. Literature review of spit system and clinoform geology and Troll field characteristics

The construction of a simulation in the Compound Earth Simulator requires the definition of the different sediment bodies of interest. The location of these bodies in the field should be known, and their boundaries should be mapped and divided into onlap-, offlap-, toplap- and downlap surfaces. Erosional surfaces should be pointed out as well.
The internal characteristics of the bodies need to be studied in order to be able to recognise them in seismic sections and well logs. This means the general build-up of the sediment in the reservoir should be known. Heterogeneities in depositional environment will be reflected in the expression of the sediments in seismics and logs. In order to make a high resolution reservoir characterisation, these heterogeneities need to be mapped in the data. The characteristics and heterogeneities in the sediment should therefore be well known. For this goal the next two subchapters provide basic insight into the geology of asymmetric delta spit systems and clinoform deposition. The third and fourth subchapter contain a more detailed description of the Troll field itself and the sequence stratigraphy of the reservoir zones that will be modelled in chapter 4.

### 2.1 Geology of asymmetric spit systems

The traditional definition for delta systems was developed in the 1970s by multiple authors amongst whom Broussard, 1975. The definition uses a tripartite classification into wave-, tide-, and river dominated systems (figure 3, Bhattacharya and Giosan, 2003). Investigation in the past decades has however shown that a strict division like this should not be made, as delta systems are much more often a combination of the three influences and many more factors like grain size, water depth and feeder type (Reading and Collinson, 1996). Also, delta’s worldwide show a strong internal difference between different lobes in the same system. This asks for a new delta definition or model, a topic heavily debated in the last two decades. Many authors like Ashton and Murray (2005) and Bhattacharya and Giosan (2003) try to resolve the problem by describing the difference between symmetric and asymmetric spits.

In contrary to symmetric delta build-up, the asymmetric delta spit system is not only influenced by water currents that transport the sediments from the fluvial system at a more or less straight line into the coastal system, but a second long-shore drift and/or wave asymmetry is present. This explains internal heterogeneities that are less easily described in the traditional definition. Bhattacharya and Giosan show that the asymmetry in delta systems is important in terms of reservoir characteristics because of the high amount of river derived mud sediments that may be found in the downdrift area and high amount of good quality sands that is often found in the upstream direction. Examples of these features can be found in the Tiber, Nile, Ebro and Danube river spits. In these systems, the deflection of the river path and river mouth led to series of randomly distributed, quasi parallel sand spits and channel fills. These heterogeneities strongly complicate the interpretation of delta systems in the subsurface (Bhattacharya and Giosan, 2003). Furthermore, the depositional complexity is often overprinted by additional complexity that is introduced by post depositional (structural) processes. Combining this with the often limited amount of data present in petroleum exploration leads to the oversimplification of many delta system schemes (Bhattacharya and Giosan, 2003). Most of these schemes incorrectly divide the delta systems according to either fluvial- or marine processes, which can be rather misleading. To make sure that this misinterpretation does not happen, the systems should be interpreted at a larger scale to prevent overestimation of properties like facies architecture and reservoir quality. When introducing an asymmetric delta spit into the definitions, even strongly heterogeneous systems may be placed in a large scale interpretation (Bhattacharya and Giosan, 2003). Depositional environments within the asymmetric delta spit system include strandplain deposits, deltaic foresets and river dominated areas.

Delta asymmetry can be quantified by using the so-called asymmetry index A, which is the ratio between longshore transport rate and river discharge (figure 3, Bhattacharya and Giosan, 2003). If the index reaches a number over 200, the delta is clearly asymmetrical. There are three main causes for delta asymmetry, which are internally correlated. The first cause is a longshore current or drift that reworks the deposited sediments or carries the suspended sediment into a direction that is no longer perpendicular to the shore. The second cause has its background in a wave approach angle asymmetry. Ashton and Murray (2004) attempt to define the asymmetric and symmetric delta spit systems by quantifying the wave crest and deep-water wave orientation in a numerical model. Small variations in these wave angles can have a major influence on sediment deposition location. A third cause for delta asymmetry may be found in a heterogeneity of tectonic dip of the ocean floor. The related difference in accommodation space may force a delta to prograde in different directions than would be expected when only taking longshore current and fluvial influx into account.

### *2.2 Geology of clinoform systems*

The first scientist who divided depositional settings on the shelf, slope and bottom of a basin into undaform, clinoform and fondoform depositional settings was John L. Rich, in 1951. He defined an undaform surface as shallow water sediment deposited on the shelf, a clinoform surface as sediment deposited in the deeper water that overlies the slope and the fondoform surface as sediment deposited in the deepest water, covering the bottom of the basin (Friedman, 2001). He also defined a clinothem as the volume between each pair of clinoforms. Within the clinothem a logical proximal-to-distal ordering of facies is found. More modern clinoform definitions divide the structures into three parts, the topsets, the foresets and the bottom set (Tetyukhina, 2011). The topsets are relatively flat (<0,1 degree) and are deposited in the proximal regions of the system, which often contain alluvial, deltaic or shallow marine deposits that can form clinoform surfaces themselves. The sloping foresets (>1 degree) form the steeper dipping portion of the basin-margin profile. These sets often contain deeper water deposits that are characteristic of the slope. Finally, relatively flat bottomsets are composed of deep water sediments.
Although these definitions are used for depositional systems at the shelf edge, the same shapes can be found in clinoforms at many scales, of which basin margin clinoforms are the largest examples, and fluvial clinoforms most probably belong to the smallest examples. Both the fluvial- and basin margin clinoforms are disregarded in this thesis. From now on, when the word ‘clinoform’ is used, I mean to refer to sigmoidal progradational surfaces that were deposited in an asymmetric delta spit system, in a marine environment. The clinoform bodies have a height of between twenty and fifty metres. Occasionally, not the complete clinoform is visible in seismic sections and logs, for instance when top sets have disappeared due to erosion or when bottom sets become invisible in seismics due to their gradual change into underlying sediment. Although it would be better to talk about progradational surfaces in that case, I still use the word clinoform to stick to a uniform reference to the subject of this thesis.

The geometry of a clinoform preserves the depositional morphology of an area, whereas the spatial arrangement of a clinoform shows the progradation history (Jackson et al., 2009). The shape of a clinoform is mainly influenced by the sediment supply, and in marine settings also by wave-, storm-, and tidal energy in the basin. Sediment is brought into the system before or inside the topset area, within which river transport transforms into wave- and or current transport. The larger the water depths become, the bigger the gravity component of the transport becomes. Sediment grain size is the most important controlling factor on the steepness of the clinoform foresets, as coarser grains result in a higher stability in the slope (Helland et al., 1994).

There is a clear relationship between clinoform trajectories and depositional environment. Differences in sea level and sediment influx through time have a major influence on the heterogeneity of the sediment characteristics in the subsurface. Periods of sea level fall are reflected by erosional features in the sediments deposits. The clinoform topsets are bypassed and the total thickness of the clinoform bodies becomes smaller. Periods of sea level rise are characterised by climbing shoreline trajectories. Depending on the amount of sediment that is brought into the system, the shoreline either moves basinward or landward. The best way to distinguish between these situations is by defining three parasequence stacking patterns: retrogradation, aggradation and progradation. A retrogradation occurs when the sediment supply is smaller than the sea level rise. The sediments become drowned and the shoreline will step backwards. Depending on the amount of sediment that is supplied, the shoreline can either move backwards and vertical, or lack any vertical component at all. In this last scenario, a transgression takes place. In the case of an aggradational stacking pattern, the sediment influx and sea level rise are exactly in balance. The shoreline moves vertical but lacks a horizontal direction, and one parasequence is stacked on top of the other. When the sediment supply is larger than the accommodation space, in other words, when the sea level rise is smaller than the sediment supply, the shoreline moves forwards into the basin. This system is sensitive to erosion of the topsets of clinoforms. All scenarios are summarized by the schematic overview of figure 4 (Emery and Meyers, 2005).

Depending on the sea level and influx fluctuations, the sediment is deposited at a more proximal or more distal location. This location is connected to the energy levels of the system and therefore to the internal heterogeneities in sediment type. Higher energy levels lead to a better sorting and deposition of larger grain size. Lower energy levels result in less sorted, smaller grain size deposition. Five main log trends can be distinguished: the cleaning upwards, dirtying upwards, box car, bow and heterogeneous trends. The cleaning upward trend characterizes progradational clinoform bodies and reflects an increase in depositional energy, resulting in an upwards increase of the deposition of larger grained, better sorted sediments. The dirtying upward trend shows the contrary. The decrease in depositional energy is reflected in an upwards increase of smaller grained less sorted sediment. Boxcar trends show more homogeneous depositions of thick sand bodies that were deposited within silt packages. Bow trends comprise a cleaning upward followed by a dirtying upward trend of similar thickness, without any sharp break between the two. A trend like this can be formed when high energy levels are alternated with lower energy levels, for instance in a period of fast changing accommodation space. A heterogeneous profile reflects a depositional system in the proximal part of the basin, where wave influences are present. All scenarios are summarized by the schematic overview of figure 5 (Emery and Meyers, 2005).

Changes in sea level and sediment influx clearly have a large influence on the appearance of parasequences and clinoform bodies in the seismics and moreover the well logs and cores of a field. This means that once major erosional and depositional events in the history of a field are known, parasequences and clinoforms can be recognized and placed within a timeframe. The other way around, if a parasequence or clinoform was already dated using for instance biostratigraphy, the sediment characteristics can be used to refine the description of the depositional history of the field and may offer characteristic markers. In this thesis, the recognition of the different parasequences forms the basis of the simulation in CES, which is why the next chapter will give an extensive description of the geological history of the Troll field.

## *2.3 Troll Field Geology*

### *2.3.1 Regional geology*

The Troll field is located in the northern North Sea, on the edge of the Horda Platform. The Horda Platform is located in the eastern part of the North Sea Mesozoic Rift System which evolved in an extensive rift phase resulting in the 40-100 kilometre wide, NNE-trending Viking graben. The graben is flanked by terraces of fault blocks on each side, of which the Horda Platform is a part. The most important deformation of the Platform was the east-west extension that took place during the Early Triassic rift event. The graben is filled with sediments that were deposited between the Devonian and Tertiary (Osiwvi, 2009). The Horda platform itself is mainly filled with Bathonian and Callovian sandstones from the Krossfjord, Fensfjord and Sognefjord formations. The Troll West Gas Province comprises both Lower Sognefjord and Upper Sognefjord sequences.

### *2.3.2 Structural geology*

Structurally speaking, the Troll field is divided by two major north-south trending faults which separate it into the Troll West Oil Province, the Troll West Gas Province and Troll East (Figure 6a). Troll East contains between 0 and 4 meters of oil. The Troll West Oil Province contains a much thicker oil zone, of between 22 and 25 meters. The Troll West Gas Province has an oil column of 12-14 meter below a 200 meter gas overburden. Efficiently draining the thin oil sands is the main challenge for Troll (Jones et al., 2008).
Besides these large faults, the field is cut by many minor northwest-southeast trending faults, which segment the area into 21 compartments (Dexter et al., 2005). The structural dip in the area is generally less than 1 degree (Evensen et al., 1993).
The sealing capacity of the faults differs throughout the field. Although 4D seismic shootings reveal flow paths that curve around multiple compartmentalised areas, which points to sealing faults characteristics, the aquifers between other areas are communicating, pointing to non-sealing faults. Studying the offset and communicating sediment types around the faults should enlarge insight into the individual sealing capacity of the different faults. Most of the faults in the Troll field are post-depositional, as the Horda platform was in a period of tectonic quiescence during deposition of the Sognefjord formation. No growth faults are found in the isopach maps that were made in earlier investigation by Thomas Osivwi in 2009.

### *2.3.3 Depositional history*

The reservoir was deposited in a period of rising sea level and relative tectonic quiescence during the Upper Jurassic rift event (Dexter et al., 2005), after the Brent Delta got drowned (Fraser et al., 2003). It consists of a stacking of off-lapping marine sandstones in three composite sequences, of which two are composed of the Sognefjord formation and one belongs to the Draupne formation (see figure 6, 7). Intervening siltstones are members of the Heather Formation, named Heather A, B, and C (Leiknes and Osvoll, 2005). Tilting of the platform during the Kimmeridgian resulted in the reworking of the upper part of the Sognefjord Formation sediments (Dexter et al., 2005). The field became sealed during the early Tertiary by the Upper Jurassic to Lower Tertiary mudstones and marls.
Deposition took place in a widespread coastal spit system, which had a sedimentary inflow in the north, a tidal backbasin in the east and prograding upward coarsening wedges in the west

(Figure 9a, b). The supplied sediment was transported in a majorly southward directed longshore drift, creating spit- and strandplain-, as well as localised mouth bar deposits. The system consists of multiple spit phases that have prograded to the west and southwest, resulting in multiple low-angle clinoforms that are separated by major flooding events (Leiknes and Osvoll, 2005). The base of these clinoforms is usually marked by bioturbated sands, above which transitions from lower shoreface sands to clean, coarse grained upper shoreface to foreshore sands can be found. The base can either be sharp, or contain up to 40 meter thick packages with alternations of siltstones and sands. These alternations comprise a coarsening upward succession that was deposited in a stormy environment on the spit platform. Most sand and silt bodies in the Troll Field have a thickness of between 100 and 170 meters each (figure 8), and the total spit system reached into the sea of tens of kilometres in a south to southwest direction (Gundersen et al., 2008). The calcite cemented marine sandbodies must have had a positive topographic expression, downlapping onto underlying surface. This can be seen in various seismic cross sections (Evensen et al., 1993). It is estimated that each clinoform was deposited in approximately 500 000 years, making that the total sequence has been deposited in around 8 million years.

### *2.3.4 Burial history*

The burial history of the area is complex, as multiple periods of uplift have occurred after deposition. Although it is not possible to give any note to absolute date and timing, apatite fission track data suggest that the field must have been buried between 500 and 1000 meters deeper than its present day depth (Evensen et al., 1993).

### *2.3.5 Sequence stratigraphic description of the field and target area*

Before elaborating on the sequence stratigraphic description of the field, some extra information about the reservoir zone naming might be needed. The names of the reservoir zones (e.g. 3Cc, 3Dc and 4Ac) are built up out of three parts. The first part shows whether the zone is a member of for instance the 3 or the 4 series of the Sognefjord formation. The second part distinguishes between the different parasequences of the series that are defined by sequence stratigraphic interpretation. They are marked using letters A to D. The third part of the name indicates the difference between the so-called M- and C- sand (e.g. 3Cm or 3Cc). Because this thesis does not attempt to make a distinction between reservoir zones and other sediment, in other words between high permeable (calcite rich) C-sands and low permeable (mica rich) M-sands, the last part of the naming is not used in this thesis.

Within the Sognefjord Formation 17 internal reservoir bodies are identified, each having a particular stratigraphic significance that was mapped (Dexter et al., 2005, Osivwi, 2009). Five of these bodies are basic series, which are referred to as the 2-, 3-, 4-, 5- and 6-series. Each of these series has a characteristic upward-shallowing trend. The 2-, 3-, and 4-series were deposited during the southward growth of the coastal spit system (Dexter et al., 2005). The 2-series is built up of two sandstone wedges in a lobe shaped delta that shows a backstepping parasequence stacking pattern that formed during a transgressive system tract. After a major flooding event that took place during the Callovian, the 3 series was deposited in an asymmetrical delta system that was mainly dominated by a north-south spit elongation direction. Relative sea level falls resulted in the formation of estuaries located in incised valleys, which are characteristic for the 3C series. More and more wave- and tide dominated sediments were deposited in the 4C series, which was formed during the Oxfordian. This wave influence became even more influential in the upper 4 and 5 units, which show tide-dominated deltaic systems. From proximal to distal location, the series are characterized by tidal channels filled with inshore sediments, tidal flats, high energy mouth bars and sandridges, and eventually muddy shelf and prodelta deposits (Dexter et al., 2005).

The members of the 3- and 4 series of the field are of main focus for this thesis. A detailed description of the 3-series sediments was made by Tom Dreyer in 2005 and Thomas Osivwi in 2009, and it is his thesis that forms the basis of the stratigraphic description of the area of interest. His investigation gave reason to start this thesis in the area. Osiwvi finds that the work of Dreyer et al (2005) offers a very thorough model for the 3 series in the northern part of the field, but also states that the model is unable to explain why fine grained sands are encountered where coarse grained sands were predicted.
Although most interpretations of the 3-series suggest the series was formed during a forced regression, Osivwi concludes something different (figure 9). He states that the 3-series is composed of four system tracts that developed in a north-south elongated prograding delta spit system and describes the reservoir zones inside the 3 series as following:

3Ac
After the 2-series got drowned, a prograding wedge was deposited on top of it. This happened in a period of early highstand, in which a prograding spit system was formed.

3Bc
On top of the prograding wedge, a series of clinoforms was deposited in a westward and southward direction, showing a clear transition from shelf facies to strandplain and spit sediment.

3Cc1
During a period of forced regression, the clinoforms were stepping basinward and offlapping structures were formed, resulting in an expression of linear features and dip change along the clinoform break.

3Cc2
The 3Cc2 unit represents a stacking of lowstand wedges that show a complicated facies build-up with incisions in the east and upward coarsening clinoform structures in the west. Within these a transition from lower shoreface fine sands to cross bedded upper shoreface and planar bedded foreshore sands is found. Silty sands are merely found in the proximal part of the lower 3Cc2 lobe. The complete 3Cc2 system tract is interpreted as a westward prograding asymmetric lowstand delta system, in which heterogeneities are found in the more coarsely sedimented updrift areas and more silt rich sediments in the downdrift area.

3Dc
Above the 3Cc2 unit, a well deformed clinoform break of a spit system can be found, that was deposited in a transgressive system tract.

Furthermore, Tom Dreyer describes the 4-series as following:

4Ac
The unit was deposited after a major flooding event, therefore it shows mainly shallow marine sandstones. It is composed of wave- and storm dominated sediments that are coarsening upwards. Dreyer et al. (2005) determined the unit was deposited during a period of early highstand.

4Bc

The unit shows two main types of sediment, wave dominated and shoreface sediments are found in the west, whereas the sediments in eastern part of the field resemble the 3-series sediments much more. Dreyer et al. (2005) determined the unit was deposited during a period of late highstand and early regression. The unit moves further basinward than underlying units. Also, it is more heterogeneous due to increase of tidal range. This may have resulted in less influence of longshore current, which might explain the lack of elongated spits.

4Cc-4Dc

The heterogeneous sediments of these units were formed during a period of incision and the reworking of older sediment. The sediments within the unit are mainly tide dominated, possibly formed in a deltaic environment.

### *2.3.6 Sedimentary and fluid fill characteristics*

The reservoir quality of the sediments in the field is varying strongly. Especially the spit bar sandstones and tide-dominated sandridges are good quality targets, with permeabilities between 1 and 20 Darcy. The inshore channel fill deposits are also of good quality, but these are much more difficult to map. All finer grained sediments, that contain around 40% of the Oil In Place, are of less reservoir quality but offer potential for EOR (Evensen et al., 1993).

As mentioned in the stratigraphic description above, the basic series can be divided into distinct reservoir zones that represent the finer- and coarser-grained portions of prograding wedges like 3Am, 3Ac, 3Bm, 3Bc (Dexter et al., 2005). The sandstone in these wedges can be divided into two major sand types; the micaceous so-called “M-sand” and the calcite cemented “C-sand”. Differences in log response between C-sand and M-sand can be found in Figure 10. The C-sands have a permeability of between 1 and 10 Darcy, occasionally up to 30 Darcy. They are well sorted and have a good porosity. The M-sands have a permeability of between 1 and 100 milliDarcy. The sorting of these sands is much poorer and the porosity is lower as well (Jones et al., 2008). Most Troll Field reservoir layers have an extremely high horizontal permeability (Kossack et al., 1987). The finer grained and more micaceous the sand becomes, the bigger the difference between the horizontal and vertical permeability gets (Evensen et al., 1993).

The field’s most common reservoir zones are found in the coarser parts of the prograding wedges, which are easily mapped. Within these wedges, the oil is present in series of parallel curvilinear belts, at the exact locations where the coarse clinoform sands intersect the oil zones (Osivwi, 2009). Horizontal in-filling wells are supposed to drain the area as efficient as possible. The water saturation is generally lower than 10% in oil bearing intervals and lies between 3 and 4% in calcite cemented sands (Evensen et al., 1993). The amount of Oil In Place in the C- and M-sands is respectively 60% and 40% (Evensen et al., 1993).

### *2.3.7 The Troll Geomodel*

In the past decades, stochastic modelling of the Troll reservoir heterogeneities was combined with deterministic modelling (a.o. Evensen et al, 1993). Many layer models and reservoir layering schemes were developed for the field, reflecting the enormous amount of detail and purposes possible for a model like this. Stochastic models were used at a large scale, including both object based (clinoform and floodplain containing) and pixel based flow models. The high amount of geological data from seismic and the 300 well trajectories in the area, as well as the strongly heterogeneous nature of the field, makes that the recent targets require the introduction of 3D models (Leikness and Osvoll, 2005).The main challenge in the models are the large area of the field, the presence of many faults and saddle points and the different (moving) fluid contacts, involving local flow phenomena and coning (Kydland et al., 1988). Furthermore, the drilling of wells pose great challenges, in particular in reservoir uncertainty as reservoir models are rarely predictive at the spatial and temporal scale needed (Dilib et al., 2012). Combined with traditional map-based models, the 3D models should be improved to form the basis of well planning and geosteering in the field. CES will offer a method to construct high resolution reservoir characterisations for small areas of interest in which high detail is needed. The Compound Earth Simulator does not update the geomodel itself.

## *2.4 Petroleum characteristics*

The Troll gas consists of around 93 mol% methane, and the trapped gas saturation is approximately 30%. Oil properties are rather heterogeneous. Oil viscosity ranges between 1.3 and 2 cp, and there is a high residual oil saturation below the Oil Water Contact (Kydland et al., 1988). The oil can be divided into two different populations that were also found in other oilfields on the Horda platform (Horstad and Larter, 1997). The populations have migrated into the field through two distinct migration systems, of which the first population was created in a biodegradation of oil and gas in the reservoir itself, and the second population was created as fresh oil kept on migrating to the reservoir and mixed with the first type. During a tilting phase in the Neogene the hydrocarbons remigrated and some gas may have spilled to the east of the Troll field. The main movement of the oil in this process was upward, where the gas was moving in a more lateral direction. As the Oil Water Contact in the field shows great variations in depth, the lateral communication in the field is probably restricted (Horstad and Larter, 1997). Conford et al. (1986) states that due to the large distance to mature rocks, the Troll field must have been filled with oil and gas necessitated in long-distance secondary petroleum migration. Burrus et al. (1991) however concludes that only gas could have migrated from the deep graben across the Horda Platform Slope, as primary generated oil must have been stopped by impervious faults. He states that the currently present oil had segregated from a gas phase that migrated into the field. It is not easy to identify the source rock of this gas, but the gas-prone silts of the Heatherfjord and Statfjord Formation, or the Brent group may pose an answer to this question. Thomas et al. (1985) used carbon isotope data to define a source kitchen to the northwest of the field, in the Viking graben. Schou et al. (1985) furthermore found spill points from Troll to the Brage field, which in turn was filled by spillage from the Oseberg field. The petroleum characteristics and migration history are not of main interest of this thesis and were only used as a minor background for the timing of deformational events.

| Region | STOOIP $10^6$ sm³ ($10^6$ bbl) | GOIP $10^9$ sm³ ($10^9$ scf) | GOC (mMSL) | OWC (mMSL) | GWC (mMSL) | Oil Column Thickness (m) | GOR sm³/sm³ (scf/bbl) |
|---|---|---|---|---|---|---|---|
| TWOP | 155 (975) | 27 (964) | 1540.0–1546.0 | 1566.5–1569.0 | – – | 22–26 | 174 (988) |
| TWGP | 440 (2766) | 570 (20,357) | 1541.0–1547.0 | 1552.0–1559.5 | – – | 12–14 | 1295 (7354) |
| Troll East | 83 (522) | 1072 (38,286) | 1547.0–1548.5 | 1551.0–1553.5 | 1545.5–1548.0 | 0–4 | 12,916 (73,345) |

*STOOIP = stock tank oil originally in place, GOIP = gas originally in place, GOC = gas-oil contact, OWC = oil-water contact, GWC = gas-water contact, GOR = gas-oil ratio, TWOP = Troll West oil province, TWGP = Troll West gas province.

*Table 2: Reservoir data and oil column thickness of the Troll Field (Horstad and Larter, 1997)*

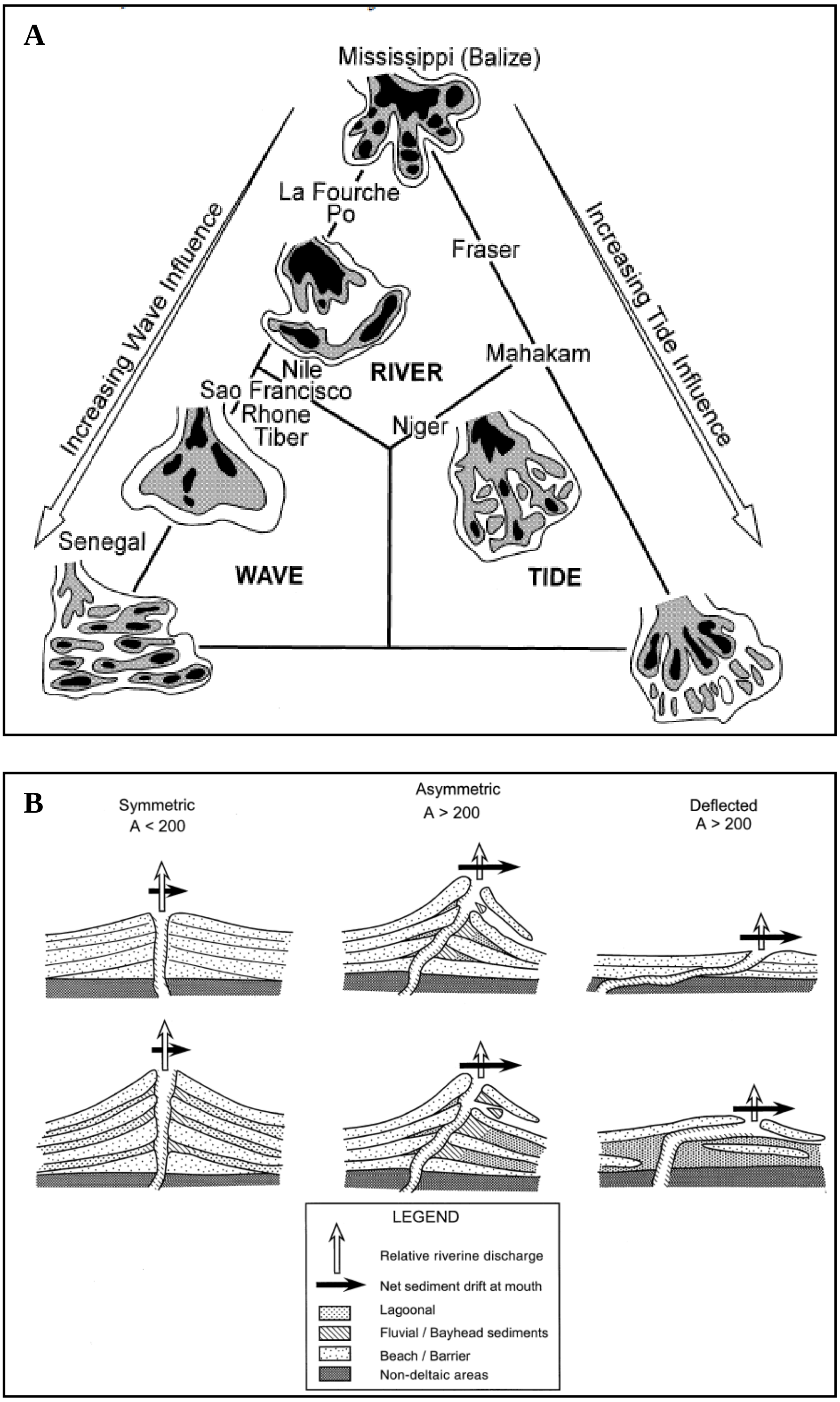



*Figure 3: a) The distinction between river, wave and tide dominated deltas, including examples and scaled to relative wave and tidal influence. b)  The different types of asymmetric delta's classified by asymmetry index A (Bhattacharya and Giosan, 2003).*

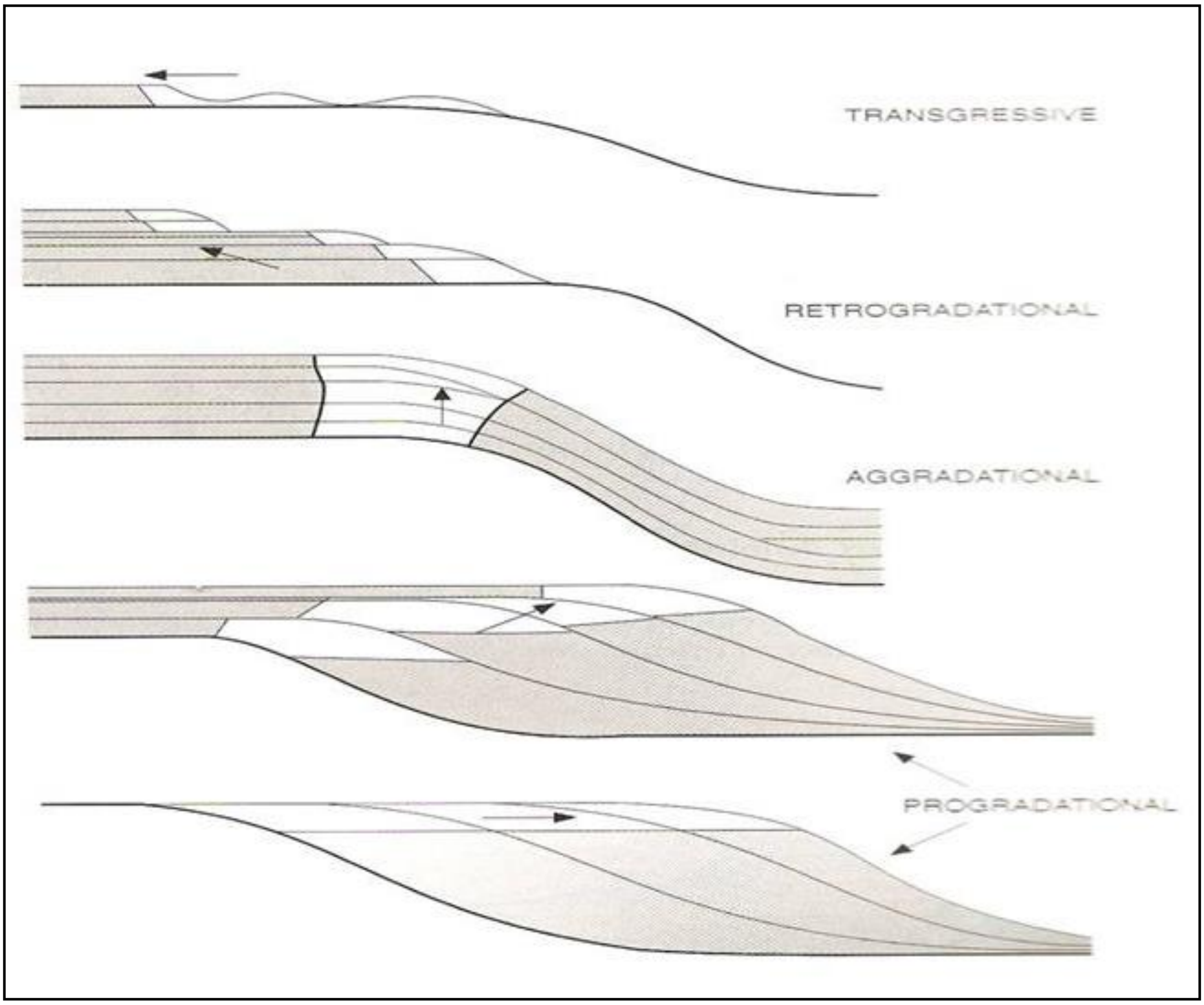



*Figure 4: Four types of coastal build-out, in transgressive, retrogradational, aggradational and progradational sedimentary systems (Emery and Myers, 2005).*

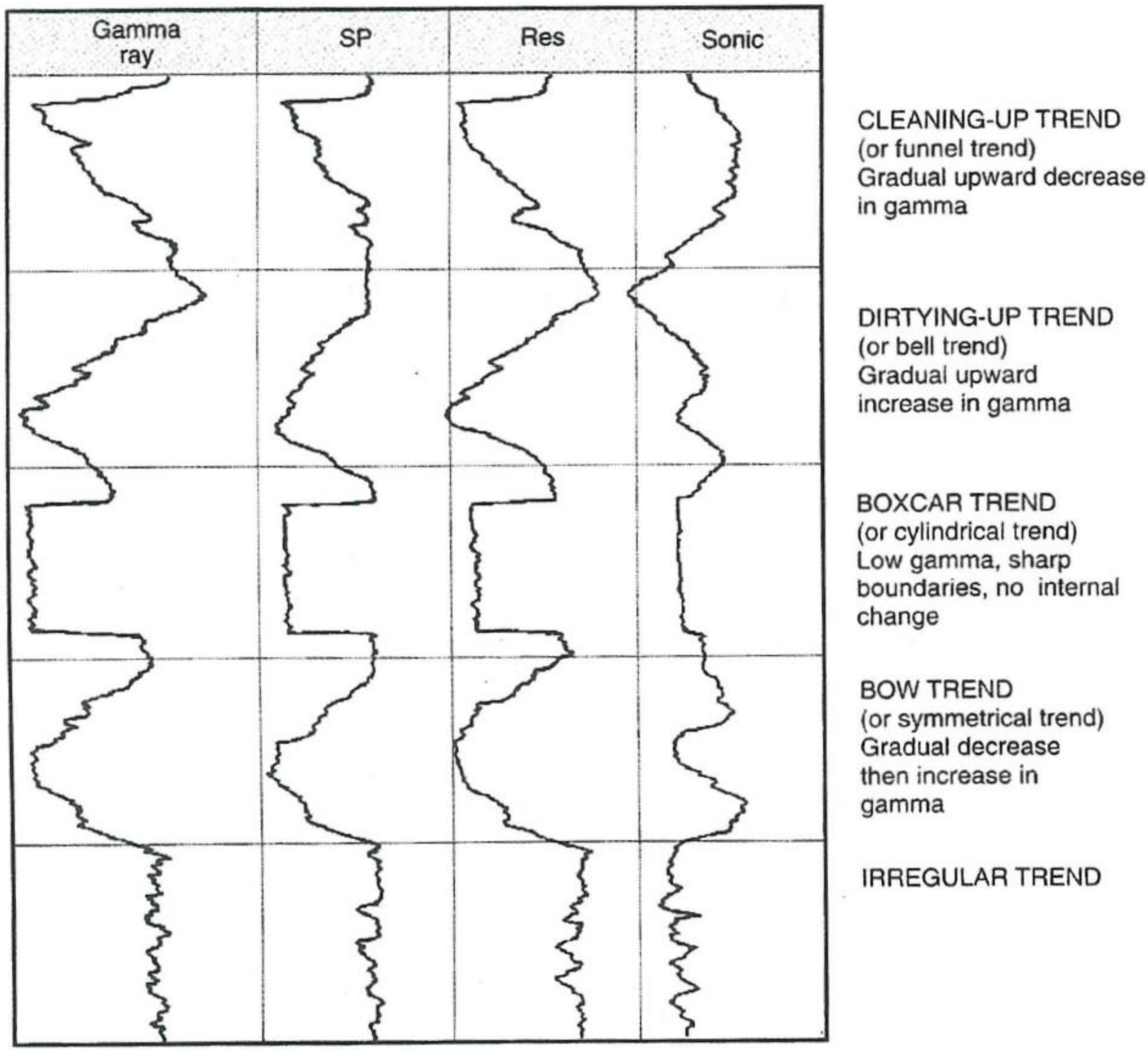



*Figure 5: Five types of clinoform log patterns for gamma-ray, spontaneous potential, resistivity and sonic log readings (Emery and Myers, 2005).*

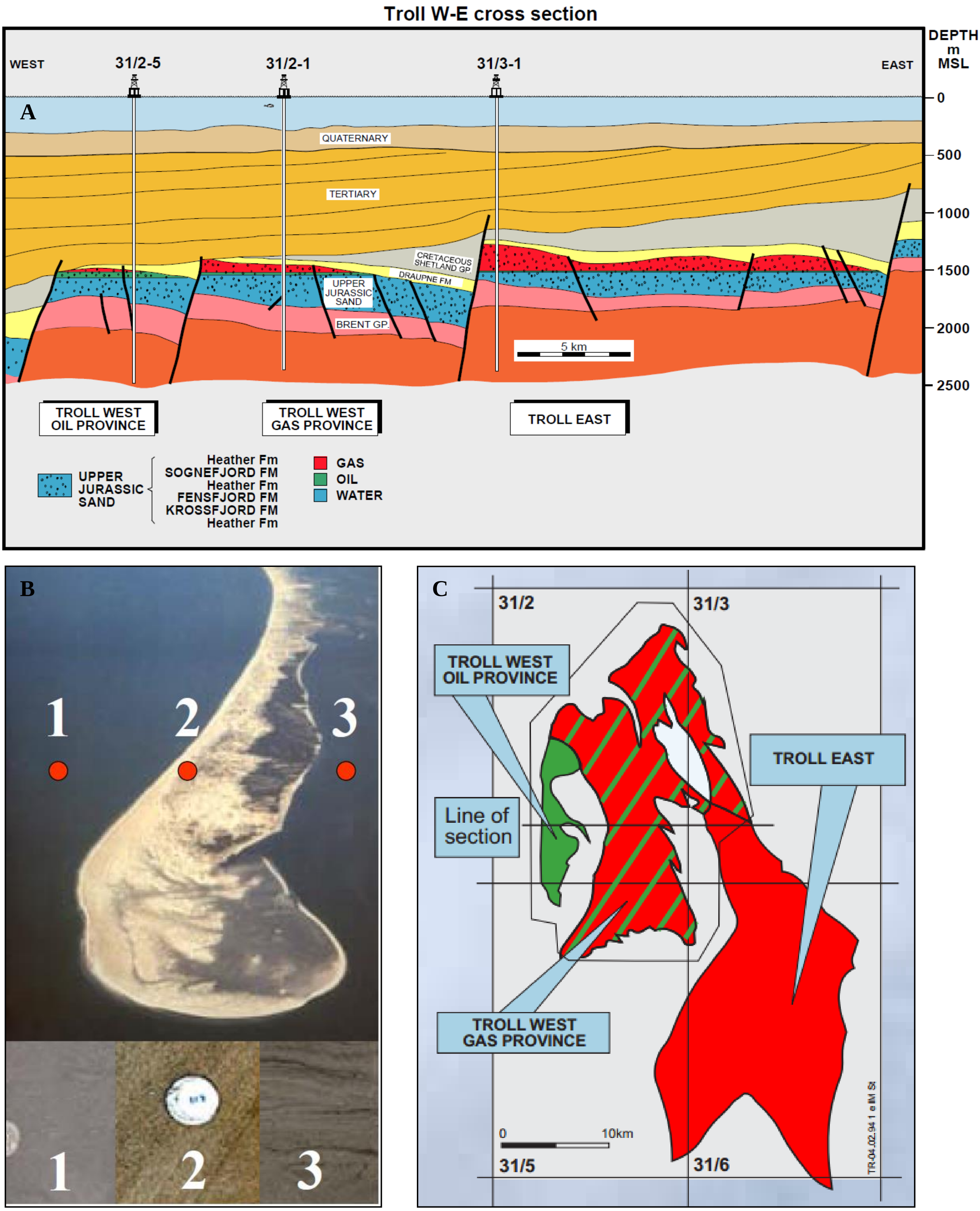



*Figure 6: a) Compartmentalisation of the Troll field and location of the thin oil column and overlying gas column. b) Example of a Sognefjord-like delta spit system. c) Location of the cross section in figure a represented on top of a map that divides Troll East from the Troll West Gas Province and the Troll West Oil Province (Leiknes and Osvoll, 2005).*

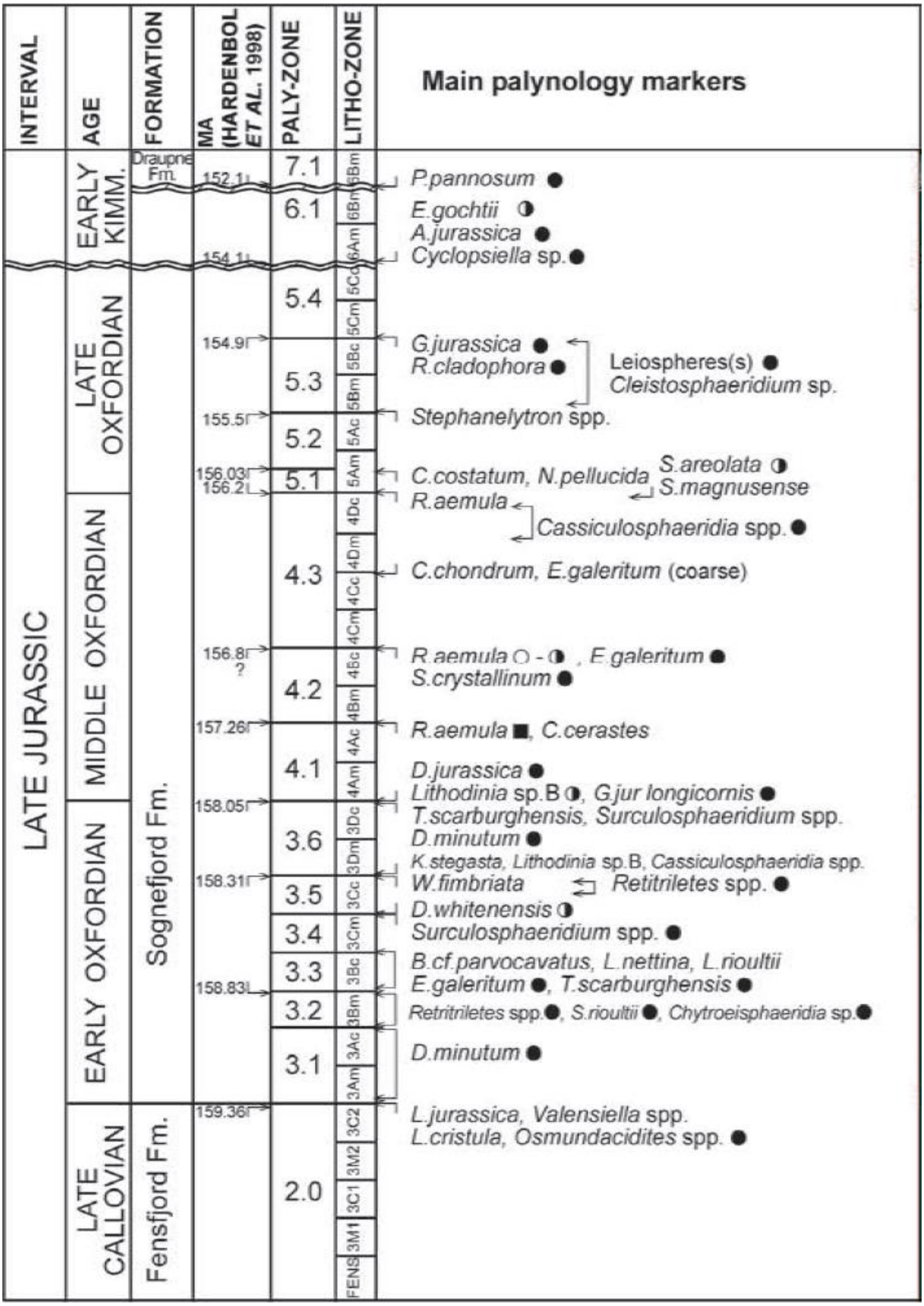



*Figure 7: Stratigraphic placement of the Troll field, including palynologic markers that were used to define the deposition of the field in the geological timescale (Dreyer et al., 2005).*

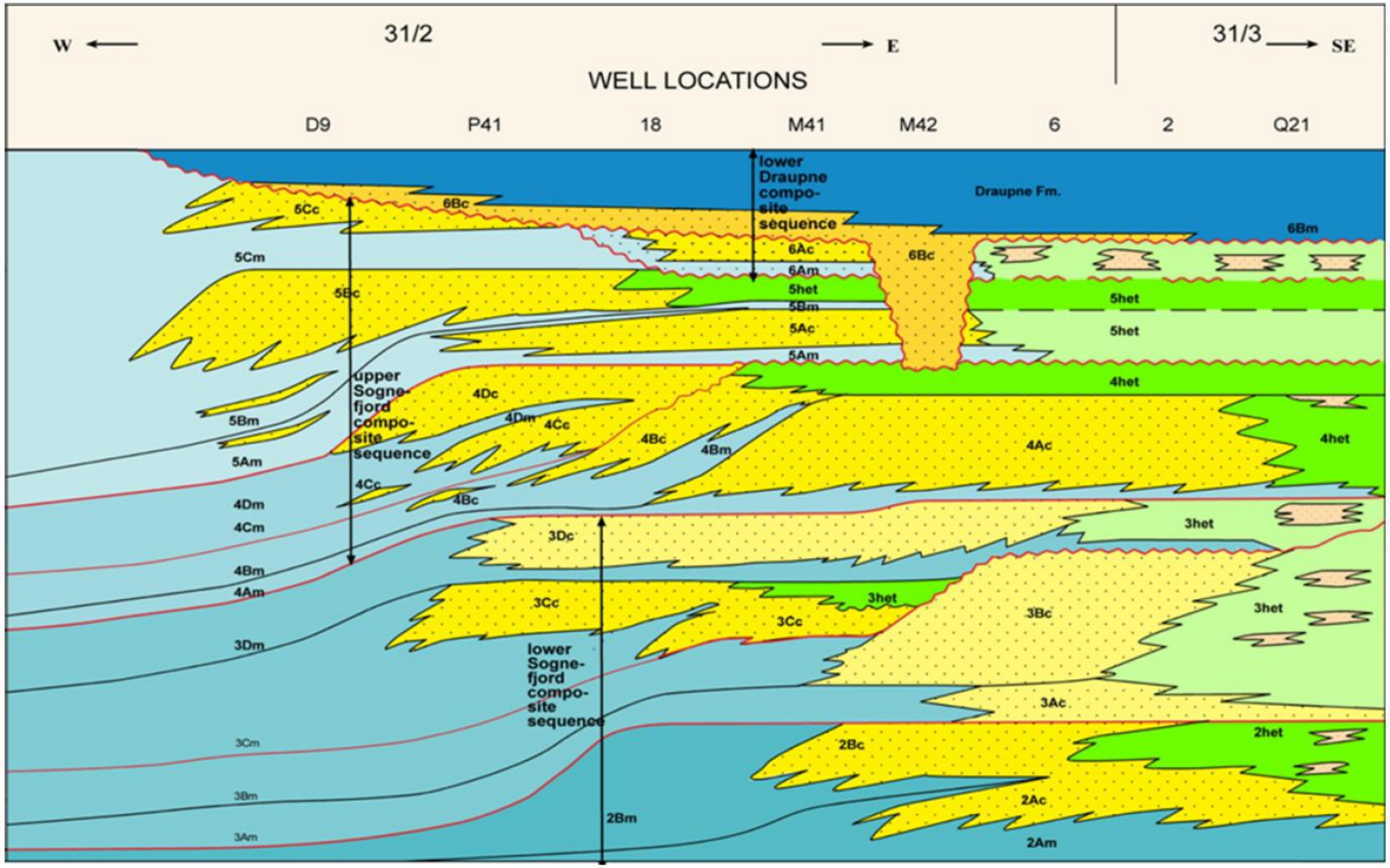
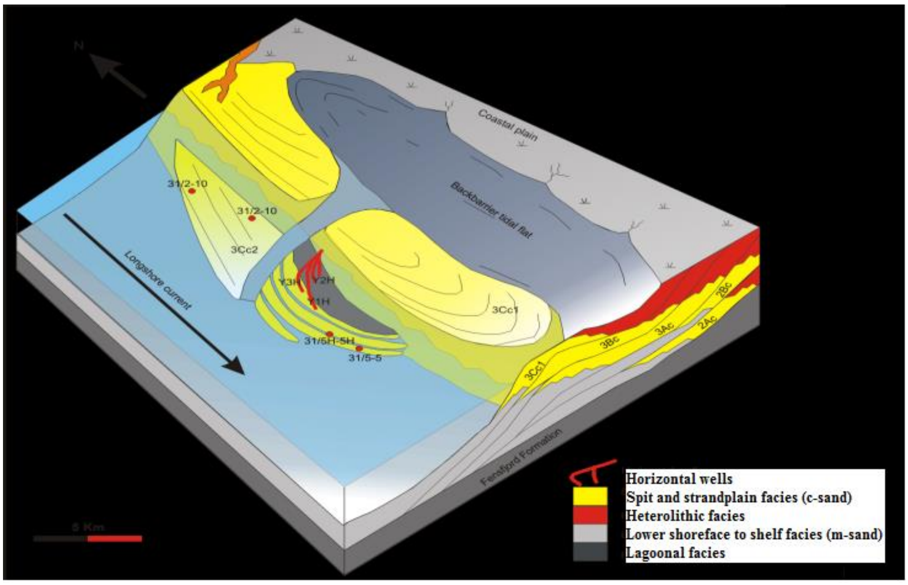



*Figure 8 : A schematic representation of the three composite sequences and their basic series, bounded by the red lines that show the downshift surfaces. Flooding surfaces are visible as the boundaries between composite and basic sequences, with the exception of the unconformity at the base of Lower Draupne. The colour coding is applied as following: yellow=sand dominated, blue=mud dominated, darker blue=higher organic content, beige=distributary channel, green=heterolithic coastal plain deposits (Dreyer et al., 2005). The area of interest of this thesis is located south of the cross section and does not resemble this figure completely. The figure should be used to become familiar with the overall Troll geology. Cross sections for the area of interest may be found in the results of chapter 4.*

A




B

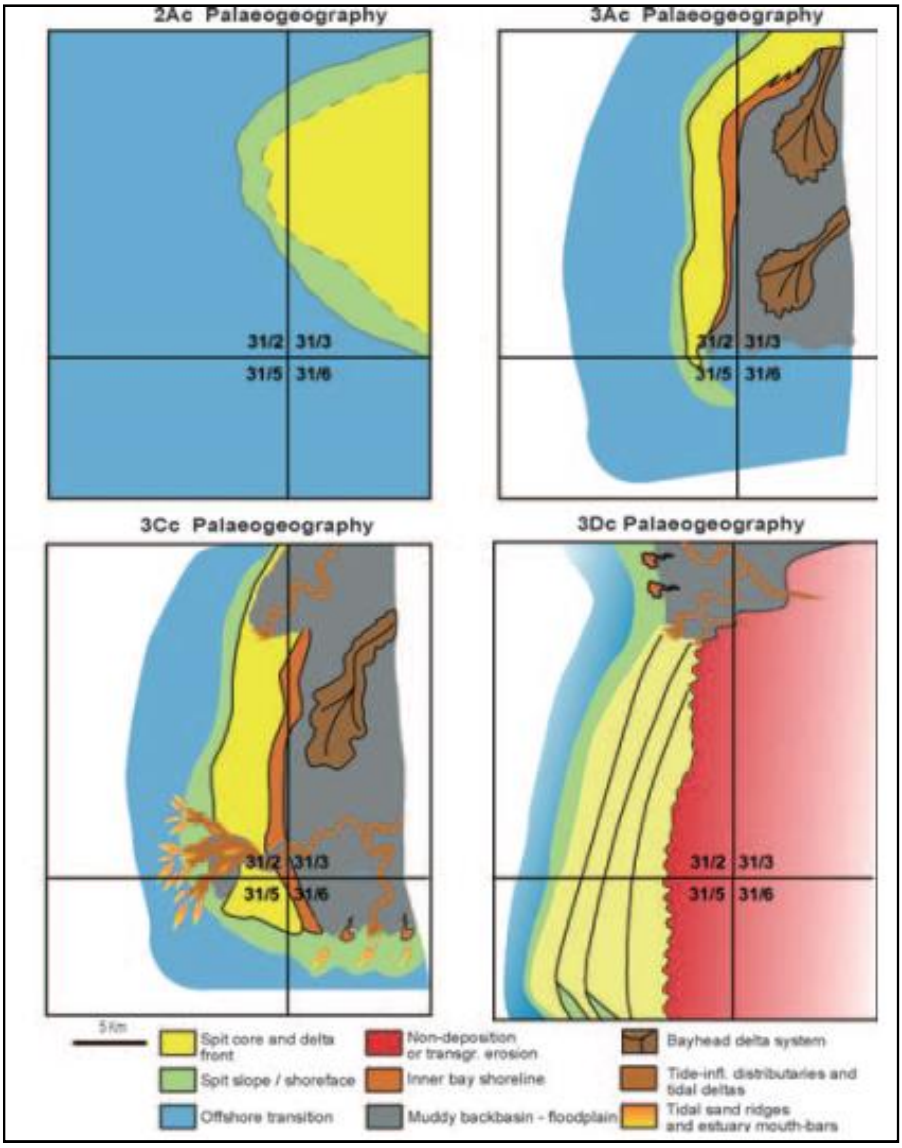



*Figure 9: a) Thomas Osivwi interpretation of the depositional system in the 3Cc reservoir zone of the study area. b) Tom Dreyer paleogeographical interpretation of the 3 series in the area of interest.*

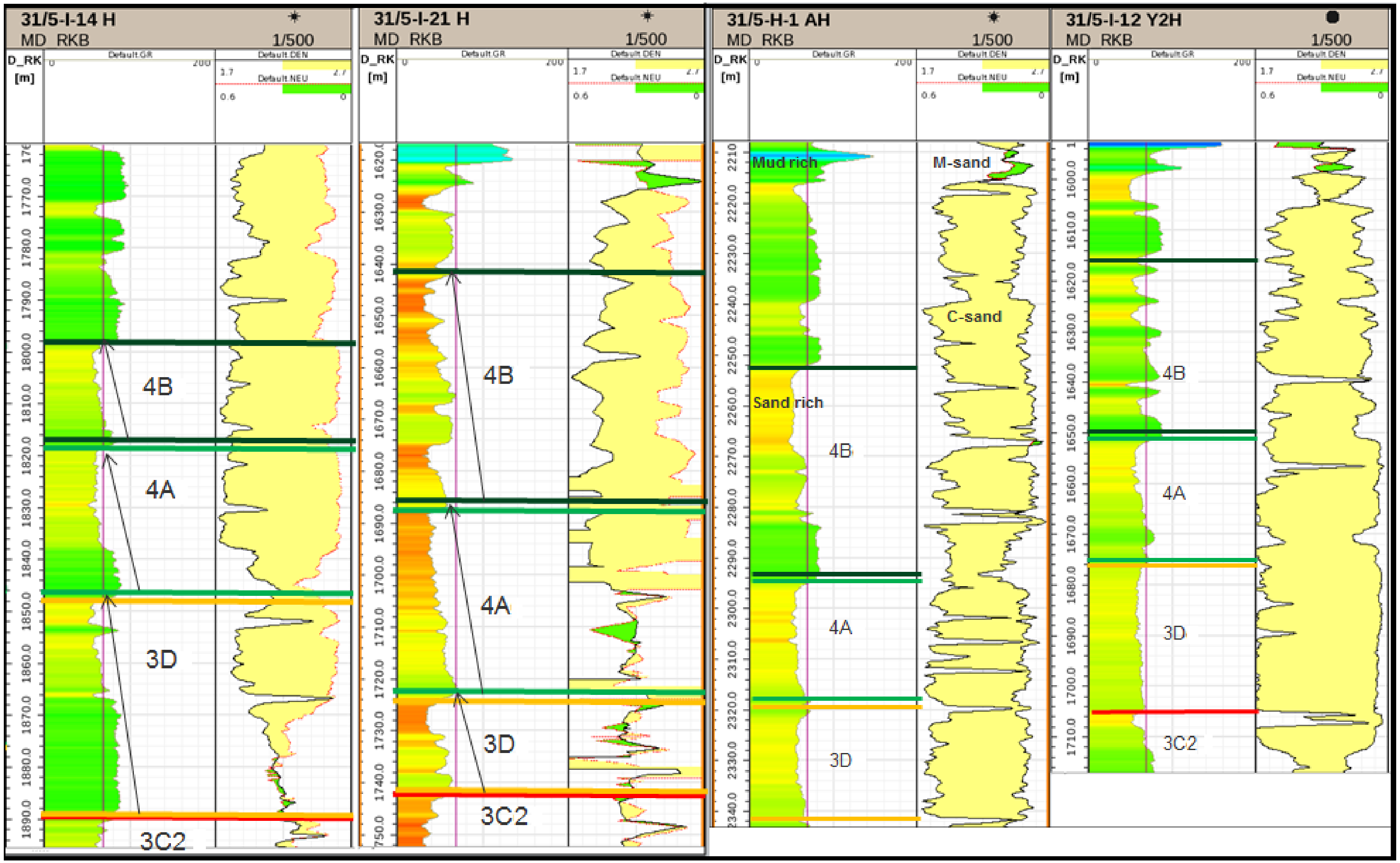



*Figure 10: A view on the gamma ray log response and neutron-density separation for the formations of interest in the 31/5-I-14H, 31/5-I-21H, 31/5-H-1 AH and 31/5-I-12 Y2H wells. The difference between mud rich and sand rich, as well as the difference between C-sand and M-sand is marked.*

## 3. Geological interpretation of the study area

The geomodel of the Troll Field (figure 12a) contains some areas that could be remapped in order to improve the drilling precision and production success. In the I-13 area multiple branches encountered silt rich sediments instead of the good reservoir quality sandstone that was mapped in the geomodel. This means that there may be some flaws in the well log correlation and seismic interpretation. A detailed geological interpretation of the problem area is needed to find where improvement may be possible. Moreover, a systematic approach to remap problem areas could be of great use in EOR target locations of the field.
Using the extensive literature investigation of the last chapter as a background, the well log correlation and seismic interpretation of the I-13 area are redone in this chapter. First, observations on the retrieved data are summarized, after which an interpretation is given that is then compared to the interpretation of other authors as well as the geomodel. The well log observations start with a general inspection of the different reservoir zones in the upper 3 and lower 4 series of the wells of interest. Their presence, thickness and log characteristics are described and compared between wells. Using the gained knowledge about the presence of the reservoir zones, three cross sections through the area are chosen for a seismic interpretation. This will then form the basis of the high resolution reservoir characterisation that will be made using the Compound Earth Simulator in the next chapter.

Both for the well log correlation and for the seismic interpretation the Top Fensfjord and Top Sognefjord are used as guiding horizons. Interpretation is only done for the sediments between both horizons. The upper 3 and lower 4 series are of greatest interest in the thesis, as these are located at and just above the oil water contact in this specific study area. One may find that these are the main topics in the next two subchapters.

### 3.1 Well Log Correlation

The most important and therefore most intensively studied log signals in the Troll Field are gamma ray logs and the density neutron separation. Using the gamma ray, the sand rich intervals can be distinguished from the silt rich intervals, whereas the density-neutron separation is used to describe the difference between the so-called M- and C-sand. Typical well log patterns for the 3 and 4 series may be found in figure 10 and Appendix 2.
In figure 10, four different wells are depicted at similar TVDs of approximately 1700 meters. The location of cleaning and coarsening upward clinoform progradations is marked with arrows. If multiple arrows are present in one reservoir zone (Appendix 2), this points to a stacking of progradational wedges or delta lobes within the same series. The names of the series are given and the coloured horizons of the figure mark the different series. The 3B and 3C intervals are coloured purple/red and orange, whereas the 3D is yellow and the lower 4 series have green colours. These colours may also be found in the original Troll geomodel of figure 12a, which moreover shows the location of the wells of interest. A list of wells that were used may be found once more in table 1. In order to prevent duplicates, not all wells were incorporated in Appendix 2, as some of the multilaterals contain similar logs for multiple branches at correlation depth.
In Appendix 2 the logs are presented at a small scale of around 200 meters MD log data per well, which makes that only the upper 3 and lower 4 series are visible. All logs were flattened to Top Sognefjord, which can be seen in the high gamma ray signals at the top of each well.
Due to the strongly varying drilling pattern in the area, the wells were not represented on the line of a cross section, but grouped according to their multilateral well names. The well names are built up out of three components. The first component shows in which of the four

North Sea blocks, 31/2, 31/3, 31/5 and 31/6 the well was drilled. The second component shows the well name, while the third part gives the name of the multilateral. From upper right to lower left in the correlation panel of the Appendix, one may find two vertical appraisal wells; 31/5-2 and 31/5-4 AT2, and multiple deviating or horizontal wells; the 31/5-H-wells, H-1 and H-5, the 31/5-I-wells, I-12, I-13, I-14, I-21, I-22 and the 31/5-J-wells, J-13 and J-14.

The well log description is based on the very thorough sedimentary and paleontological description of Dexter and Dreyer (2005) and Osivwi (2009). This thesis uses the knowledge gathered by these authors to increase the modelling precision. It does not attempt to redo any definitional work or biostratigraphy, it only describes the appearance of the zones in the different wells in the area of interest. This means that the observations below are made in this thesis, but they are based on information from earlier authors.

The high gamma rays of the Top Sognefjord and Top Fensfjord are used as guiding horizons for the well log correlation in the area. They can be found in every well log and are therefore fairly easily correlated throughout the field. Even along the different faults, the wells can be connected to a scale of up to tens of metres using these horizons. Starting at Top Fensfjord, the first zone above it that is of interest for the thesis is the 3B zone. It is recognised in wells as a package of cleaning upwards, coarsening upwards sediments of average thickness (10 to 30 meters). Gamma ray values range between 50 and 100 API.
The unit above 3B, the 3C1 zone, usually starts with an abrupt change to high gamma rays. Not far above this high gamma ray signal a lower more sand characterising gamma ray trend is found. The profile therefore shows an undulated boxcar-like trend. The zone has a strongly varying thickness that can reach up to 30 meters. Between the 3C1 and 3C2 again a jump to higher gamma rays is found, but this time the jump is followed by a cleaning upwards profile, starting at gamma rays of between 70 and 80 API. In parts of the area of interest the 3C2 zone pinches out and the 3D zone is found straight above the 3C1.
The 3D unit gamma rays are coarsening and cleaning upwards, but starting at relatively high gamma ray values of up to 110 API. The zone has a more constant thickness than the underlying zones, which can amount up to 45 meters. In some of the wells, mainly in the I- and J-branches, the top of the zone becomes rather heterogeneous with spikes to either increasing or decreasing gamma ray levels.
The transition to the next unit 4A happens rather abrupt again. In many wells the 4A unit is thicker than every 3 series' unit below it. Again, coarsening and cleaning upward gamma ray log profiles are found, but with much more undulating patterns. In some wells this even leads to the interpretation of two stacked cleaning upwards, coarsening upwards sequences.
In two specific wells the 3D and 4A show a strongly similar log pattern. The wells, 31/5 H-1 AH and 31/5 I-12 Y2H, may be found in figure 10 and are located over 2 kilometres apart. The patterns no longer show the nice cleaning upwards profile, their gamma ray values are undulated around a rather constant value.
The 4B unit shows a much more heterogeneous trend. Although the overall pattern is cleaning and coarsening upwards, the unit contains a stacking of heterogeneous sediment bodies. It has a rather constant thickness of between 25 and 50 meters.
Above 4B the 4C and 4D units are situated, which are strongly heterogeneous in nature, containing higher average gamma ray signals and internal erosional surfaces (Osivwi, 2009). Due to the strongly heterogeneous signal it is very difficult to make a distinction between the 4C and 4D units. Since they are located well above reservoir depth, no further interpretations on their boundaries are made and the unit is disregarded in the thesis.
Above this the high (up to 160 API) gamma ray signals of Top Sognefjord can already be recognised in the area of interest.

## 3.2 Mapping of the 3 and 4 series in three seismic sections

After finding the characteristics of the different reservoir zones in the log profiles of the wells of interest, this next subchapter will address the seismic mapping of the area. Three seismic profiles were constructed (Appendix 3) and may be found in figure 12d, 12e and 12f, their location is marked in figure 12c. The profiles were taken along the orientation of the southwest longshore current as well as perpendicular to it. The homogeneous correlation between the 31/5 H-1 AH and 31/5 I-12 Y2H wells forms the basis of the locations of the sections, because of the high level of confidence of interpretation in these wells. All three sections run through the middle of the I-13 area, the area of interest.

Again, Top Fensfjord and Top Sognefjord are used as guiding horizons to locate the 3 and 4 series. The Top Fensfjord shows a low amplitude reflector related to transition from the silt rich lower Sognefjord formation into the sandstones of the Fensfjord formation (Osivwi, 2009). The first reflector that is mapped above this horizon is base 3B, a mostly low amplitude reflector of varying quality and continuity. A relatively thick (about 20 to 30 meter) package of 3B is recognisable in the seismics, surprisingly enough with clear angular surfaces in the two sections that were taken perpendicular to the southwest-northeast section (figure 12e, 12f). The next mapped surface is base 3C1, which downlaps onto the 3B sediments. The surface is relatively flat in the area of interest, which is located between major faults. The 3C1 unit thins strongly to the west. At the base 3C2, an erosional truncation with the lower 3C1 sediment can be found. This causes the thickness variations in 3C1 and makes that the 3C2 shows a restricted areal extent. The 3C2 body furthermore shows a varying amplitude. The base 3D downlaps onto the 3C2 horizon in the central parts of the area, resulting in a restricted body of sediments that have a relatively constant thickness. It has a more undulating top that looks like it was influenced by deformation after deposition.
The 4A sediments downlap on top of 3D. Especially in the northwest-southeast sections clear angular surfaces may be found. The 4A has a relatively large thickness that gets bigger towards the south. The base 4B is more influenced by deformation than base 4A. The 4B interval does not contain any clear internal structuring nor large thickness variations. Base 4C is very similar to this. As explained in the last chapter, it is very hard to define a boundary between the 4C and 4D units, as these are strongly heterogeneous and contain internal erosional surfaces. This is why the units are represented as one in the seismic sections. The 4C-4D has a relatively small thickness but at the same time a clear bounding surface, as its top is located at Top Sognefjord in the area of interest, which itself is a low amplitude reflector often influenced by overlying reflectors. Especially in the western part of the area, Top Sognefjord shows an erosional truncation with the Cretaceous sediments.

## 3.3 Interpretation

In this chapter, an interpretation of the seismic sections and well log correlations is given. A summary of the findings can be found in table 3. This summary only applies to the specific area of interest of this thesis, it should not be used for the Troll field as a whole.

Before starting the interpretation of the seismics and well log correlation, some general remarks to differences in unit thickness and gamma rays signal are discussed. Using these general remarks and the literature investigation of the last chapter an interpretation on the depositional environment can be made.

### 3.3.1 Causes of thickness variations

As described in the observational subchapters above, it is clearly visible that the series vary in thickness. This is not only seen in the MD-correlation panels (which may point to a difference in well deviation), but also in the seismics and TVD correlation panels. TVD correlation panels were not incorporated in the thesis, because of their compressed nature of the log signals around the reservoir depth, where the wells start to deviate to a horizontal well path.

The progradational clinoform bodies have a thickness of between five and fifty meters. Differences do not only have a cause in periods of erosion, but may also be caused by differences in compositional stacking or the heterogeneity in accommodation space that the build-out of a progradational delta causes for itself through time. With the deposition of each new delta lobe, the accommodation space for the next delta lobe is restricted. This is most clearly visible in symmetric delta systems, but is present in asymmetrical systems like the Troll Field's Sognefjord formation as well.

It leads to the fact that the thickness of the units can not directly be correlated to the sea-level and therefore sequence stratigraphy of the area. Heterogeneous accommodation space restriction due to diverting delta spits should be taken into account.

### 3.3.2 Causes of gamma ray signal variation

Gamma ray values are used to distinguish between sand- and silt-rich sediments. In the Troll field they are also used to distinguish between M-sand and C-sand, and the division is located at a gamma ray of 67 API. Anything below this number is regarded as high reservoir quality clean sand, anything above is easier drillable but more difficult producible M-sand. Higher gamma ray values are often found at the boundary between the different parasequences and extremely high values (of for instance 150 API) point to the presence of flooding surfaces.

Since the depositional environments of the bottom sets and top sets should be more or less similar in the different parasequences, they are supposed to have similar start and end values of gamma ray. If the end values of a cleaning upwards, coarsening upwards gamma ray profile in a well divert from these average values, this points to erosion of the sediment.

Furthermore, the steepness of the cleaning upward profile gives some indication on the location of the well penetration in the progradational body of interest. The 3D and 4A series have the most constant thickness and clear cleaning upwards, coarsening upwards profiles, but the 4B series has a more varying gamma ray profile and thickness. Heterogeneous profiles in many cases point to a depositional system in the top of the progradational body or – in other words – in the topsets of the clinoforms, in which channels incide and storm and waves have an influence on the sorting of sediments.

### 3.3.3 Longshore current

From the literature investigation it is known that the depositional environment of the 3 and 4 series of the Troll field is mainly found in asymmetric delta spit systems. As a cause for the delta asymmetry a longshore current is given. However, since the prograding bodies are located well below wave base (average thickness of around 30 meters), the result of the longshore current's influence can be debated. Moreover, accommodation space differences due to tectonic dip may have an influence on the delta asymmetry in the Troll field. If that is the case, the heterogeneities in the clinoform progradation direction may be more easily explained, as accommodation space can differ largely within a scale of multiple kilometres, whereas a longshore current can not. Further work might bring more insight into the causes of the delta-asymmetry in the Troll field.

### 3.3.4 *Interpretation of the depositional system*

The major seismic tracers of Top Fensfjord and Top Sognefjord are easily recognised in both seismics and well logs and are interpreted as flooding surfaces. The Fensfjord is followed by the 3A, 3B, 3C1, 3C2 and 3D reservoir zones, the five mainly progradational wedges of the 3 series.

The first unit that is discussed in this thesis is the 3B. It has an irregular and rather vague seismic signal that points to heterogeneous sediment content which makes it hard to map the base of the unit. Due to the fact that the 3B sediments were deposited in a period of high stand, the delta spit system was able to prograde relatively far (Osivwi, 2009) and construct progradational surfaces that are large enough to be recognised in seismics. These surfaces are visible in all three seismic sections, but most easily recognised in seismic sections of figure 12e and 12f, pointing to a spit progradation that was strongest in a northwest direction. Gamma ray trends again show cleaning upward and coarsening upward profiles, representing a transition from shelf to strandplain or spit depositions.

The next unit, 3C, may be divided into the 3C1 and 3C2 zones, which are separated by an erosional truncation. Often the 3C1 unit starts with a clear erosional surface. It shows a strongly varying areal extent and major thickness variations. Apart from this, it has a rather homogenous appearance in the seismics and logs that may be related to the depositional system of the clinoform break area (Osivwi, 2009), in which the deposited sediments are clean and relatively well sorted due to high energy levels. Above the erosional truncation the 3C2 unit is found, which shows an incision into the underlying sediment. The 3C2 zone shows a clinoform progradation that is large enough to be visible in seismics. In the logs it has a relatively uniform cleaning upward, coarsening upward profile. Due to the restricted areal extent of both 3C units, as well as the presence of their erosional surfaces, they are interpreted to have formed during a period of forced regression and lowstand, in which incision was followed by deposition (Osivwi, 2009).

The 3D unit above this shows a good example of coarsening upwards clinoform break surfaces that appear as relatively homogeneous horizons in seismics. It shows a north south orientated elongation (Osivwi, 2009). The gamma ray trends of the 3D zone are similar to the 3C1 zone, as they do not show complete clinoforms, but only clinoform breaks. The signals are coarsening and cleaning upwards, but starting at higher gamma rays than for instance the 3B zone. The zone may have been deposited in a period of transgression, because log patterns show an alternation of silt and mud rich sands into cross bedded and upper shoreface deposits, and occasionally even into planar foreshore sands (Dreyer et al, 2005).

The separation between the 3 and 4 series can be found at the flooding surface that divides the upper and lower Sognefjord. The flooding surface is rather muddy and followed by the 4A, 4B, 4C and 4D reservoir zones, the four progradational wedges of the 4 series. The wedges are more widespread and located further basinwards than the 3-series.

The 4A sandstone contains a rather thick package of upwards coarsening storm- and wave influenced sediments in most wells. Only few wells do not show this upwards coarsening profile, but a constant and slightly undulated signal instead. Due to the fact that the zone was deposited to such a widespread scale just above the flooding surface it is concluded that the zone was formed during a period of early highstand. The very similar well logs in two of the wells show a homogeneity in the southwest direction, which contradicts a clinoform progradation in that strike. When looking at the seismic cross sections of figure 12e and 12f, the weak progradational surfaces that do become visible, point to a build-out direction towards the northwest instead.

The 4B unit is sedimentary very similar to the 4A, as it again consists of coarsening upwards wave dominated sediments. This time however, the sediments step much further basinwards and contain more heterogeneous alternations of wave dominated depositions. The 4B zone is also thicker and less uniform in seismic signal.

During the deposition of the 4C and 4D units, widespread erosion caused a rework of older sediments, which makes that the log signals appear more complex and heterogeneous. Wave dominated sediments have only remained in place in the depocentre areas (Dreyer et al., 2005).
The top of the reservoir is found at Top Sognefjord, which, in this part of the area, is located straight above the 4D unit and in some parts of the area shows an erosional truncation with the overlying Lower Cretaceous sediments.

### *3.3.5 Clinoform orientation and interpretation difficulties*

The two bodies with the clearest prograding surfaces in seismics, the 3B and 4A, contain sigmoidal surfaces that are most easily recognised in the northwest-southeast seismic sections of figure 11 and 12 and Appendix 3. Furthermore, the upper 3 and lower 4 series show a homogeneous log signal in a southwest direction. That makes that it is now known that the progradation of the clinoforms did not only happen in a south or southwest direction, but also towards the northwest. This is contradicting what was found in earlier research and may affect the depositional system interpretation as well as the geomodel for the small area of interest of this thesis. Although Dreyer et al. (2005) already points to a heterogeneity in clinoform build-out direction by stating progradation occasionally happens to the northwest, it has not been seen before that this is actually the main angle of build out. Moreover, it is hard to see that this is actually the main angle of progradation. Even though seismic quality is very well, observation and interpretation are required to be done at such a small scale in the problem area, the seismic quality becomes too poor again anyways. Only when using very trustworthy well log correlations, one can convert the depths of the different reservoirs parasequences in wells to the seismic sections in order to identify layers. However then still correlation between the wells in seismics is rather difficult at locations where the seismic signal appears vague due to fluid fill or reservoir heterogeneity. In many cases also it is not clear whether the seismic signal that is seen indeed represents a clinoform surface, or just an internal sediment heterogeneity or pore fill feature. The parasequences and clinoforms are thus hard to follow due to the presence of faults, the relatively small thickness of each zone, the low angle of the clinoform surfaces, the fluid contact presence and the heterogeneity within one parasequence. It would be useful to improve modelling resolution in the area of interest. This is attempted to be done in the next chapter.

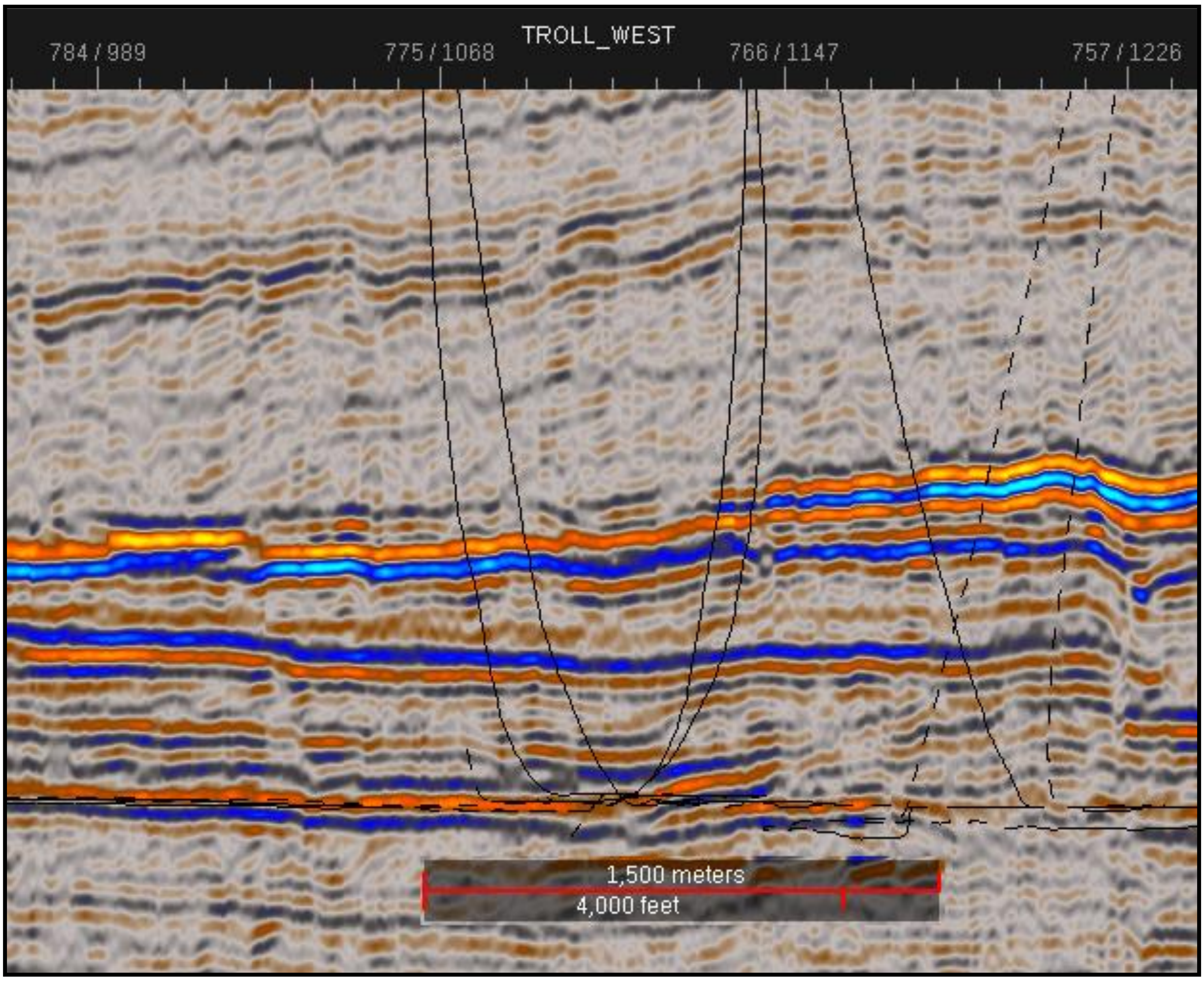



*Figure 11: An example of clinoforms that are penetrated by the I-12 wells. Although sigmoidal shapes appear rather obvious, it is unclear if these represent the actual clinoform surfaces or are linked to a different type of internal parasequence heterogeneity. Therefore it is dangerous to use sections like these (that furthermore only contain apparent length and dip) for measurements of size and angle of the clinoform.*

| Parasequence | Characteristics | Boundary with underlying unit | Depositional environment |
|---|---|---|---|
| 3B | Cleaning, coarsening upward<br>10-30 m thick<br>GR of 50-100 API | Downlap | Early highstand<br>Progradation in delta spit |
| 3C1 | GR shows boxcar trend<br>Up to 30 m thick | Abrupt transition<br>Downlap | Forced regression |
| 3C2 | Cleaning, coarsening upward<br>Gr of 70-80 API | Erosional truncation | Lowstand |
| 3D | Cleaning, coarsening upward<br>Start at high GR<br>Up to 45 m thick<br>Heterogeneous top sediments | Downlap | Transgression |
| 4A | Cleaning, coarsening upward<br>Smaller GR range<br>More undulated GR signal | Downlap | Highstand<br>Progradation in delta spit |
| 4B | Heterogeneous GR signal<br>Heterogeneous thickness | Erosional | Wave dominated |
| 4C/4D | Heterogeneous GR signal<br>Heterogeneous thickness | Erosional | Wave dominated |

*Table 3: A summary of the main characteristics of the seven parasequences that are investigated within the area of interest.*

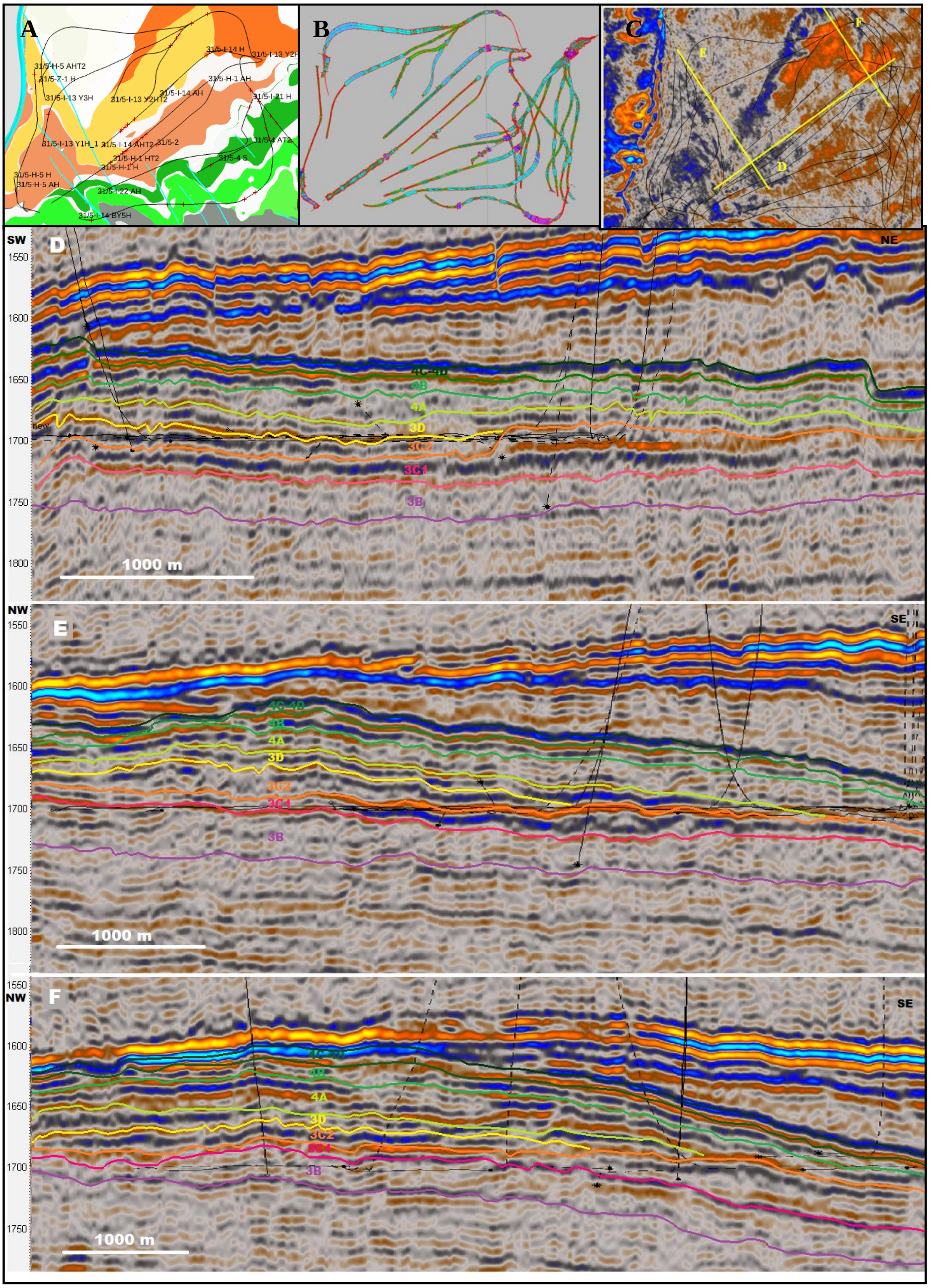



Figure 12: a) Location of the wells of interest on top of the geomodel (x-axis scale is 5 kilometres). b) Gamma ray well logs in top view on well paths, with high gamma rays indicating silt rich areas coloured purple or blue in a wide pattern and low gamma ray regions in much thinner green patterns. c) Location of the cross sections of figure d, e and f on top of the seismic top view at reservoir depth. d) Cross section C with well paths and location of the 3B, 3C, 3D and 4 reservoir zones indicated. e, f) Cross section E, F with well paths and location of 3Cc and 3Dc and 4 reservoir zones indicated.

## *4. High resolution reservoir characterization of the area of interest using the geological interpretation and CES, the compound earth simulator*

In order to provide a high resolution reservoir characterisation for the Troll field, this thesis aims to construct a detailed mapping of the 3 and 4 series and internal clinoform structures within a target area. To do so, an extensive analysis of the logs and seismic sections was performed in the last chapter. The high amount of multilateral wells of the field was used to find a correlation between well logs that penetrate parasequences that contain progradational surfaces that are large enough to be visible in seismic sections. Using the patterns that are recognisable in the data progradational bodies will be located in other areas as well, even if seismic data quality is not sufficient or detailed enough to find the structures in the seismic sections at first glance.

The workflow that will be given in this chapter should be seen as a general method. With this thesis it is not possible to fully describe the Troll depositional environment, nor does the thesis give an improved version of the geomodel itself. It provides a fast and thorough way to reinterpret problem areas in reservoirs like the Troll West Gas Province. The results of the model can be used by the Troll Field PETEC department to locally update the geomodel and reinterpret the seismic data. If the method proves to be useful the same workflow can be used in other problem areas or other fields to redo the mapping as well.
Summarizing, the next chapter will use the Compound Earth Simulator to give a method that may be used to improve the well log correlation and thereby provide a high resolution reservoir characterization for parts of the Troll field and other fields with a similar geology.

### *4.1 The Compound Earth Simulator – a conceptual explanation*

The Compound Earth Simulator executes different workflows to understand the past, the present day and the future situation of the subsurface (Petersen et al., 2012). Data used as input in the simulator include geological cores, well logs, seismic profiles and stratigraphic interpretations. The workflows in CES can be divided into two different sequences, a reverse and forward simulation of geological processes (figure 13, Appendix 1 and 4). In the reverse simulation (reverse time engine in figure 13, Appendix 1 and 4), a seismic time or depth section in picture format is uploaded into the program, after which it is altered using the geological history of the area. With this, the locations and depths of well logs and core data are altered as well. Different structural and erosional processes are combined to bring the section back to the time of deposition. The result of this reverse process therefore is a representation of the seismic section of the sediment body at its presumed state of deposition, presenting an undeformed sediment sequence (Petersen et al., 2012).

After the data are brought back to their undeformed state, the created sediment stacking approaches a layer cake stratigraphy, which greatly enables the correlation between wells and the interpretation of the different (para)sequences within the seismic section. Once the interpretation is done, a second simulation sequence is started by incorporating the reservoirs characteristics when uploading the well logs (in this thesis: gamma ray logs) into the model and redistributing these. The different mapped layers are thereby subjected to a simulation of sediment deposition. After incorporating the sediments, the section is subjected to a forward modelling of the geological processes (forward time engine in figure 13). Different deformation events incorporate faults and folds that are used to manipulate the deposited

bodies in order to reconstruct the present day situation. After this, synthetic seismic sections can be constructed using the modelled log distributions and acoustic impedance of the sediments. The synthetic seismic sections that are created can be compared to the original seismics to detect any large scale flaws in the sequences. However, since both the original seismic data and the synthetic data are low resolution features, the high resolution characterisation is only partly confirmed in the comparison of the synthetic and true seismic data.
The actual high resolution results are found when logs are extracted from the model. If this is done in sections where there are actual well paths present, the modelled logs can be compared to real logs, which provides a quality check (Petersen et al., 2012). By constructing logs in areas where no wells were drilled before, the modelled facies type can be retrieved. In terms of drilling, the model can thereby be used for log prediction at high resolution. Also, when wells are drilled in a environment containing dipping horizons and associated dipping barriers (like clinoforms), a detailed model of the progradation direction of these horizons may be used to determine how producer and injector well pairs should be placed.

With the presented workflow, common patterns in logs are used to improve reservoir characterisation resolution in the facies description, which is a quick way to improve the geomodel detail in areas that have a trustworthy well log correlation. The advantages of the methods are found in both the speed of the workflow and the improvement of geological understanding by reversing each process step by step. This last point offers a visualisation of the geological history after every important deformation, compaction, erosion or depositional process, which creates a much better understanding of the alteration of the sediments in a reservoir and makes it simpler to interpret horizons in the seismic sections. Even heavily deformed and compartmentalised sections can be interpreted when the horizons are brought back to their original depositional state (Petersen et al., 2012). Furthermore, the interpreter has a great freedom in incorporating the geological processes into the simulator. Multiple scenarios for the geological history of an area may be tested using CES as described here.

### *4.1.1 Clinoforms in the Compound Earth Simulator*

Clinoforms in the area were created using random functions in the Compound Earth Simulator (figure 13 b, c). The process responsible for the creation of these random functions is named Clino2D. It uses a start and an end shape of the clinoform and distributes a property variation in between. The progradational surfaces of this thesis have a low angle and relatively straight shape. The property variation is composed of a random variation along the start and end shape ('along') and a random so-called Arclength Modification ('arcmod') property that runs between the start and end shape. With this combination, the position of the along distribution is moved up or down the clinoform shape, thereby representing sea level or energy level changes.
Because the clinoforms in this thesis are created randomly, they were only used for the deposition of the 3B series, which has no well logs in the chosen sections. All other series contained convincing reservoir correlations and after careful consideration it was decided not to use these random functions in order to maintain the highest possible resolution in the model. This means that the clinoforms in all series above 3B can be recognised in two ways. First off all, if the well logs of parasequences show a cleaning, coarsening upwards gamma ray, this points to the presence of clinoforms. Secondly, when these parasequences are modelled in CES without a progradation of an inclined surface in the sediment fill, the created synthetic seismics should be analysed for the presence of inclined surfaces. If the synthetics do contain inclined surfaces, these point to the fact that the inclinations in the true

seismics might be an artefact. If the synthetic seismics show no inclined surfaces in the synthetic seismics, while the true seismics do, this points to the presence of a clinoform in the subsurface.
Further research might be able to use true well logs in the construction of the clinoforms, which will solve the issue. A thesis of Zhang (2011) has shown the possibilities to decompose well logs into the described 'arcmod' and 'along' functions. However, the process is time consuming and mathematically challenging, which is why it was not used in this thesis.

## *4.2 The CES workflow*

Practically speaking, the CES workflow consists of ten different steps, which were described shortly in the subchapter above, as well as in Appendix 1 and 4. In the appendix, the different processes are made visible using an overview of the results after each step. In order to make a model in the simulator, the following actions need to be taken:

1. The area of interest should be defined and seismic sections need to be chosen and formatted to a picture file.
2. Well trajectories need to be drawn on top.
3. Well logs need to be interpreted
4. The well log interpretation should be transferred to the seismic sections using the depth measurements of the wells in the seismic sections.
5. Deformation surfaces (folds and faults) should be marked.
6. The deformation events should be restored using the reverse time engine
7. Guiding horizons need to be found and lower and upper boundaries of the zones of interest should be defined
8. Sediment should be deposited within these boundaries
9. Faults and folds should be reintroduced in the forward time engine.
10. Synthetic seismograms should be constructed and virtual wells should be drilled, so a high resolution interpretation of the area can be constructed. Reliability of the model should be checked by comparing the synthetic seismograms to their original seismic sections and by drilling virtual wells through the model. When drilled at actual drilling locations, comparing the virtual log to the actual log may reveal the flaws in the model.

## *4.3 Results*

The sections that were chosen to perform a CES simulation may be found once more in figure 12 and (as larger figures in) Appendix 4. Along the northeast-southwest trending line of section D a clear correlation was found between both the 3D and 4A parasequences. It is known from the literature review of earlier chapters that these sequences were deposited in an asymmetric delta that had a main build-out direction towards the south and west, along the longshore current. Homogeneity in that direction contradicts this conclusion. Since the wells are situated over two kilometres apart, they should represent different timelines of the same parasequence progradation, and therefore they are not supposed to show such similar well log patterns. In none of the other wells in the area an equally clear correspondence was found.
This contradiction gave reason to use CES to perform a simulation in order to answer two questions.

1. If the log distribution of one of the wells is placed in the CES time engine and redistributed along cross section D, will a virtually drilled well at the location of the other well then show a good correspondence with the true log pattern? In other words,

can we use CES to find out if the two wells indeed show a redistribution of the same reservoir characteristics and were they thus deposited on the same timeline?

2. If we model two cross sections through the wells perpendicular to section D and incorporate a clinoform build-out in this perpendicular direction (section E and F in figure 12), do we then get a synthetic seismic section that is comparable to the true seismic section? Do we find inclined surfaces in the synthetic seismics even though we did not model clinoforms in parasequences above the 3B series?

In an attempt to find an answer to these questions, the three cross sections were brought into CES. Since all three sections fall within major bounding faults, it was not difficult to restore the deformation processes. Few faults were removed and the sediments were flattened to Top Sognefjord. Top Sognefjord is a flooding surface that offers the clearest reflection in the seismics and moreover can be trusted to have been deposited horizontally.

The mapping of the parasequences was less difficult once the sections were restored, since their straighter appearance enabled the possibilities to draw straight lines in the seismics. The sediments were then redistributed between the main parasequence boundaries. For the 3C1 and (in one of the four sections) the 3C2 series, this distribution was made using virtual well logs that were taken in the logs elsewhere or created randomly. This is because these parasequences were not penetrated by the local wells. However, since they were described extensively and are recognisable in the seismics, it was possible to find log patterns similar to the core descriptions and log patterns in literature. Because the horizons were incorporated in the section, a thicker parasequence stacking could be created, making the amount of reflectors larger, which greatly enabled the quality check using synthetic seismics. As mentioned above, the clinoforms of the 3B series were also modelled using virtual logs, which are brought into the model using randomly generated 'along' and 'arcmod' functions.

The results of the workflow are summarized in figure 14 and 15, as well as in the schematic workflow that can once more be found in Appendix 1 and Appendix 4. Appendix 1 contains the results of each step that was taken in the simulation of section D using the H-1 AH well logs.

For section D, the workflow could be performed using the distribution of well logs from two wells, the H-1 AH well and the I-12 Y2H well. This resulted in the construction of two very similar models that were compared in figure 15. Appendix 4 summarizes the results for all three sections.

### *4.3.1 Model results*

In figure 14 the result of the simulation of section D, E and F (defined in figure 12) can be found. Figures 14a to 14c show the original seismic sections. Figures 14d to 14f provide the gamma ray distributions within the clinoform sequence boundaries that were mapped at the presumed state of deposition and were then brought forward in time. Figures 14g to 14i show the synthetic seismics that were created from elastic logs similar to the gamma ray.

The first thing that strikes the eye is the fact that the overall structure of the synthetic seismics as well as the reflector location within 14g to 14i strongly resembles the original structure. This offers the discussed quality check of the backward and forward processing of the data during simulation. When analysing the synthetic section of figure 14h and 14i to find inclined surfaces, it is clear that section 14i lacks the surfaces that are visible in the true seismic sections. Instead, the parasequence stacking ends in an unconformity to the inclined surface of the interpreted incised valley of the 3C2 series. Section 14h does show some irregularities in the synthetics seismics. It would be advisable to build a model with true clinoform logs in this part of the research area.

Figures 14d to 14f present the high resolution gamma ray distributions of the sections. As mentioned, the 3C1 distributions are virtual and are only used for the creation of synthetic seismic. The clinoform fills are constructed randomly as well. However, parasequences 3C2 to 4D do offer a distribution of the true scenario and can be discussed as results.
The first observation that can be made is the clear fill of clean sands within the incised valley of the 3C2 unit in figure 14d. The second observation is the clear representation of the cleaning and coarsening upwards gamma ray distributions in the 3D and 4A parasequences. Also, the small heterogeneities within these cleaning, coarsening upwards profiles are recognisable in the darker coloured (higher) gamma ray lines. These heterogeneities have made that the I-12 Y2H and H-1 AH wells are so easily correlatable. The third observation that is made is the heterogeneous build-up of the 4B, 4C and 4D parasequences. This heterogeneous build-up, including the internal erosional surfaces that were described in literature (o.a. Dreyer et al., 2005) make the interpretation of the different horizons rather difficult in seismics. However now, with this gamma ray distribution along the section, future interpretations should be much easier.

### *4.3.1 Quality check*

Figure 15 provides an overview of the differences in the two models that were made for the D section. The first model was made using the H-1 AH well log (which does punctuate the 3C2 parasequence). This model is hereafter referred to as ‘section D H-1 AH model’. The second model was made using the I-12 Y2H well log (which does not punctuate the 3C2 parasequence, therefore the 3C2 parasequence well log was copied from the 3D log and should not be taken into account in the high resolution reservoir interpretation). This model is hereafter referred to as ‘section D I-12 Y2H model’.
When looking at figure 15a, the correlation between the H-1 AH and I-12 Y2H original logs can be found (first and fourth log). The easily correlatable 3D and 4A parasequences are visible (see top parasequence markings). The other logs in figure 15a were retrieved by drilling virtual wells through the modelled distribution at the location of the original well paths. In both scenarios, the section D H-1 AH model offers the best correlation to the original, but in any of the modelled logs a clear correlation to the true well can be found. This confirms that the progradation direction in the 3D and 4A series in this part of the Troll field might be perpendicular to the direction that was found in literature.

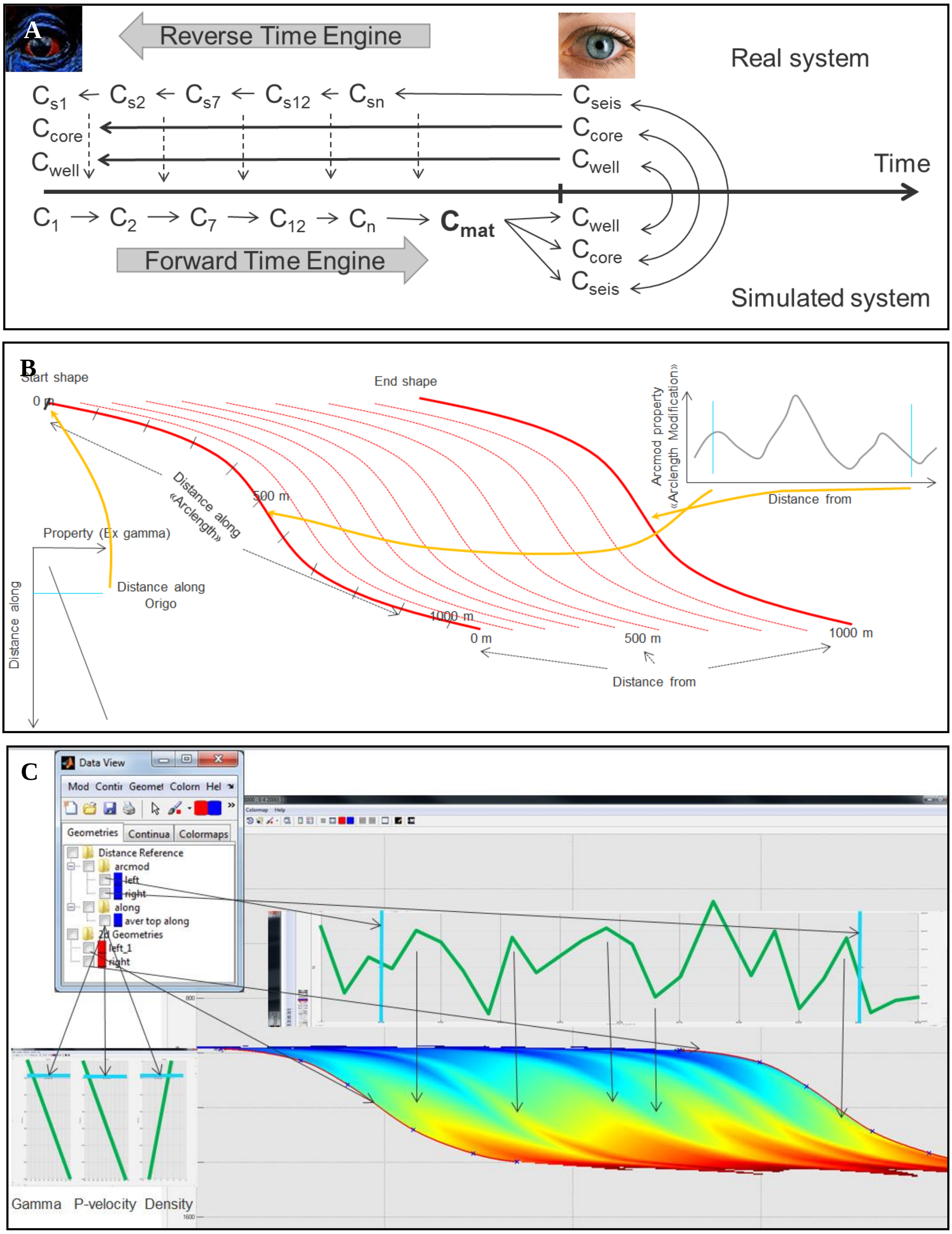



*Figure 13: a) Schematic representation of the two sequences of the Compound Earth Simulator. The first, so-called data restoration sequence (dR) brings the reservoir properties like seismics, cores and wells back through every geological step to their time of deposition. The second so-called model reconstruction (mR) sequence forwards data in the opposite direction towards the present day again. b) c) The build-up of clinoforms in CES is done by creating arcmod and along functions using random log distributions (internal communication with S.A. Petersen, 2013. All three figures were either edited from publication or unpublished).*

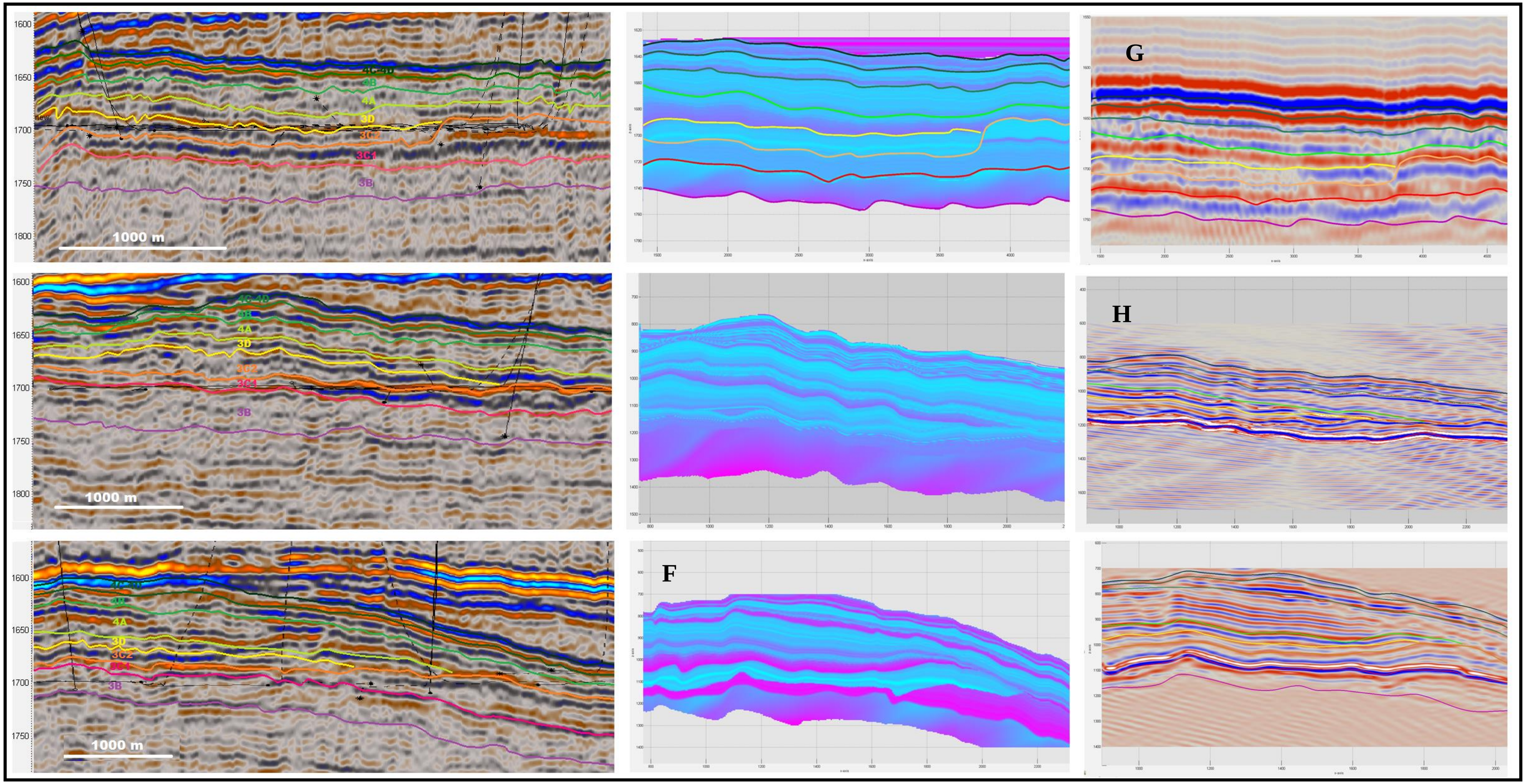



*Figure 14: The CES modelling results. a) b) c) A representation of the original seismic sections as defined in figure 12. d) e) f) The gamma ray distributions along these three sections.  g) h) i) The synthetic seismics retrieved from the different log distributions. A colour legend may be found in appendix 1.*

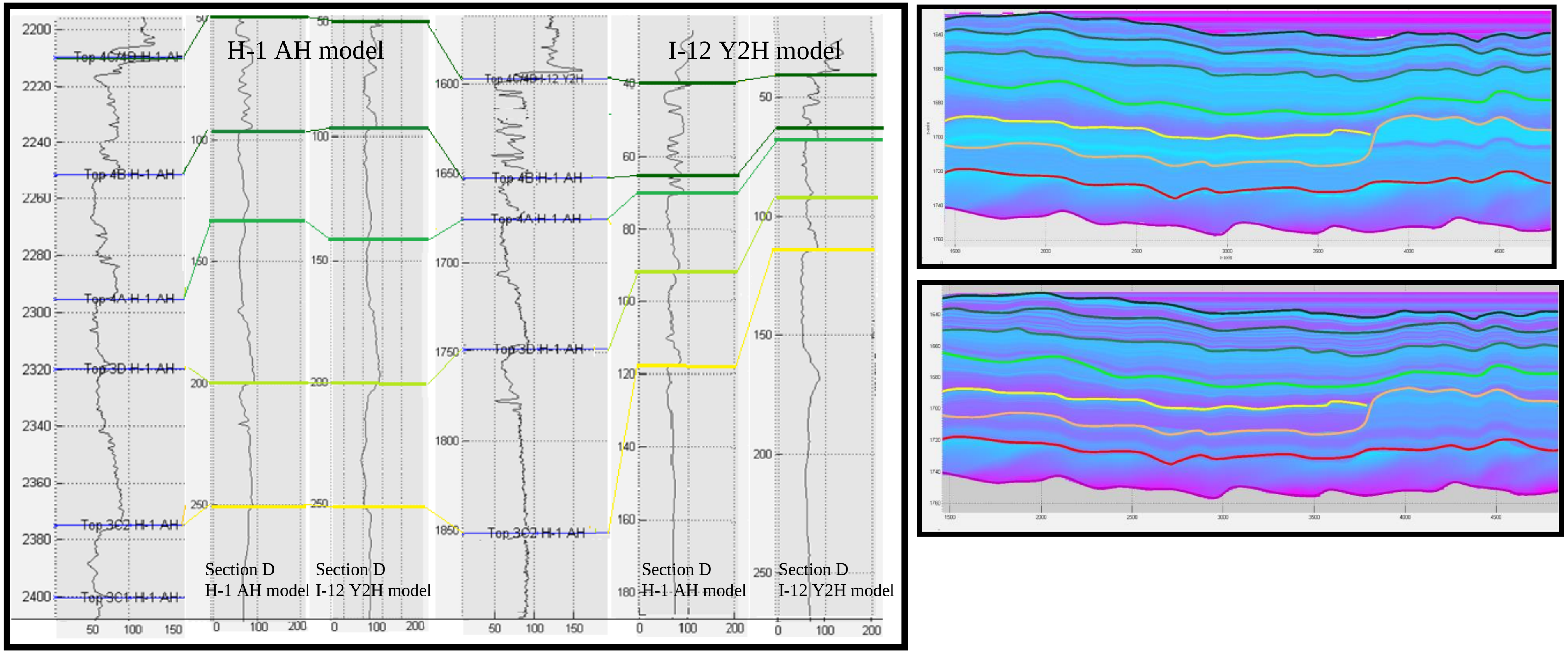



*Figure 15: a) A comparison between the true well logs and the modelled well logs in the two models that were constructed in CES. Measured depth of both original logs is given in meters at the left side of the two graphs. Measured depth of the synthetic logs is calculated from the top of the synthetic sequence as drawn in figures b and c and shown on the left side of the graphs in meters. b) The gamma ray distribution of section D using the H-1 AH model. c) The gamma ray distribution of section D using the I-12 Y2H model.*

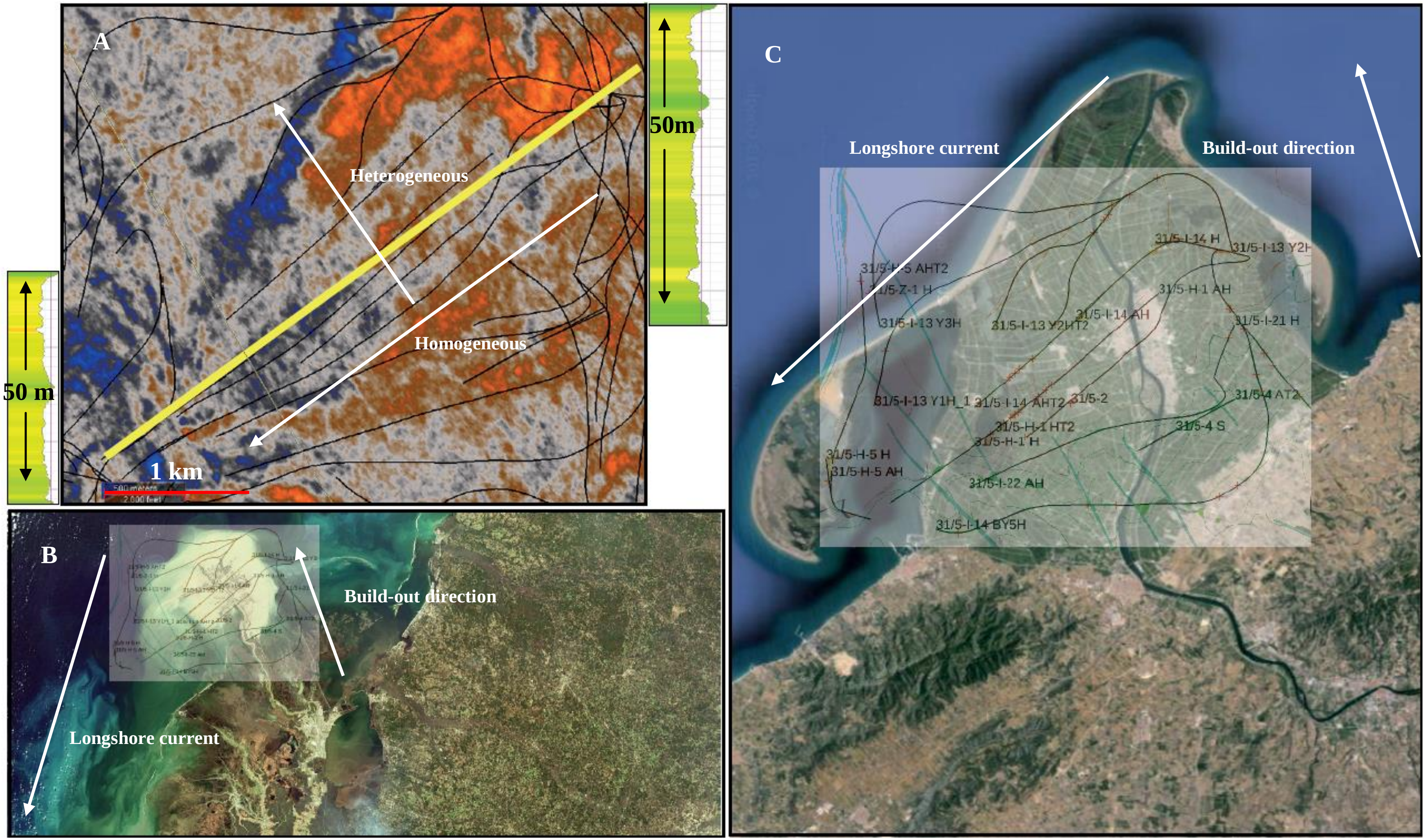



*Figure 16: a) The homogeneous well log correlation represented along the section within which it occurs. Also, an example of how the progradation direction can be different than one would expect looking at the longshore current, in the upscaled and turned top views of b) the Mississippi delta c) the Ebro delta.*

# 5. Discussion

The thesis has offered a new method to create a high resolution reservoir simulation in asymmetric delta spit deposits. As an example, it modelled the upper 3 and lower 4 series of the I-13 area in the Troll Field. The Compound Earth Simulator used log correlations to design homogeneous layers within the reservoir. By making a stacking of different homogeneities a more detailed and heterogeneous high resolution reservoir simulation was created. There are multiple remarks to be made about this process.

## 5.1 The results

The results lead to the confirmation of an anomaly in the local build-out direction. Instead of finding a clinoform progradation southwards or westwards along the longshore currents, there was a homogeneity found in the upper 3 and lower 4 series of the I-13 area.

It is difficult to state whether the before considered homogeneity in progradation direction towards the south and west is the cause of the interpretation differences between this thesis and the Troll geomodel. However, it can be defended that an investigation in CES, going backward and forward through the geological history step by step, enables the interpretation of multiple depositional and deformational scenarios. The results of the operation offer a higher detail in the sedimentary mapping of the area.

Causes for a progradation direction difference are numerous. When looking at modern day analogues of (asymmetric) delta systems at different scales, it is possible to imagine many causes for a build-out direction perpendicular to the longshore current. As mentioned in the chapters before, within one delta lobe, the strike of the sigmoidal surfaces can already be strongly heterogeneous, as the delta builds out at both the front of its lobes and at the sides. Also, channel avulsions in the hinterland can bring a fluvial mouth to many different locations and approaching angles, irrespective of the longshore current. Once arrived at the shoreface, tectonic dips may cause differences in the basin floor topography, forcing a progradation in the direction of the largest accommodation space. In figure 16, both the Ebro and Mississippi delta were turned and brought to a different (and incorrect) scale to elaborate on these scenarios in the I-13 area. In both delta systems the main delta lobes have a progradation direction component angular to the longshore current. The figure also shows that a progradation direction difference should be considered at the correct scale. An anomaly in a section as small as the I-13 area may not change the overall geological interpretation of the field, but only point to a local variation.

In this thesis, it is not possible to find a firm conclusion on the reason of the progradation direction anomaly. However, the thesis has shown that it is important to take anomalies and heterogeneities in the system into account in order to build a trustworthy geomodel. The method that is offered to do so should be seen as the main result of the thesis. Further investigation should provide more insight into the value of the new I-13 area interpretation as well as the refinement of the description of the Troll geological history.

## 5.2 Asymmetric spit systems

Concerning the build-up of asymmetric delta spit systems the thesis shows that a geologist should never lose sight of the large heterogeneity in depositional environment that is linked to these systems. Only once these heterogeneities are known and mapped, a trustworthy geomodel can be constructed.

## 5.3 The Compound Earth Simulator

Concerning the presented method to model a high resolution reservoir in the Compound Earth Simulator, it can be stated that the thesis shows a workflow that improves interpretation quality by correlating logs over a large (multiple kilometre) distance. Detailed geological knowledge about a field's history is needed to be able to make a trustworthy well log correlation and seismic interpretation. Homogeneities in the system have to be mapped in order to make this well log correlation and seismic interpretation. Heterogeneities in the system have to be mapped in order to construct a high resolution reservoir model. Detailed geological knowledge about the build-up and depositional setting is needed to be able to find these heterogeneities.

Log information can be used to make a meter-scale correlation within heterogeneous reservoirs even in wells that are as far as two kilometres apart. Logs are the main input for high resolution reservoir characterisation. Log distributions are also the main output of a high resolution reservoir characterisation in CES.

Original seismic images are often of a quality too poor to make a detailed correlation between wells. Seismics in CES should mainly be used to trace major guiding horizons and to define depositional and structural characteristics. CES can construct synthetic seismics by using the acoustic impendence in the area, but the synthetic seismics are of no better resolution than the original seismics. CES quality can be checked by comparing the structures of the synthetic seismics to the original seismics as well as by drilling virtual wells trough the log distribution and by comparing these to true well log patterns.

CES is easy to use and can or should be implemented on a broad scale. It is both cost and time efficient. In order to better map heterogeneous systems, a 3D version of the Compound Earth Simulator should be made.

A major advantage of the Compound Earth Simulator is that modeller can play with geological history. Multiple scenarios can be tested and compared. Furthermore, the modeller has a great freedom in creating these scenarios. The extent and timing of deformational events can be varied and contacts between the different sedimentary bodies can be chosen to be an onlap, offlap, downlap or erosion. Also, in one and the same program and window, the modeller can map parasequences in both seismics and well logs.

The largest advantage of modelling in the Compound Earth Simulator is that CES can bring the modeller back and forward in time step by step, removing and adding deformation events and sedimentation one step at a time. This offers great insight into the placement of a field's history in the general geological history and makes the different scenarios of a field's history more alive.

The Compound Earth Simulator also knows a number of shortcomings that will be improved in the near future. Most shortcomings are already being implemented at this point in time, but were not ready in the CES version that was used for the thesis.

First of all, although the seismics and well paths are brought back in time by alternating them in the restoration of the deformation events, the well logs are not altered simultaneously. This means that the logs are not decompressed nor faulted. For the I-13 area model that was

presented above, this was not a large problem due to the lack of major faulting events. However more complex areas will suffer from this shortcoming more.
A second shortcoming can be found in the fact that the model is not 3D. The mapping of a progradational body in a field could be improved strongly if it were possible to create a build-out in a 3D model.
Also, due to the overprinting of the original seismics with well logs, good reservoir features may be accidentally filtered out because they are not represented in the logs. Because the synthetic seismics have a low resolution, it will be difficult to detect this problem.
Another shortcoming can be found in the fact this version of CES is unable to merge the log distribution of multiple wells in one cross section. It would have been interesting to find out what the log distribution of section D would have looked like if the results from the H-1 AH model were merged with the I-12 Y2H model in one cross section. The option to merge logs existed in the previous builder and will be implemented in the near future.

## *5.4 Thesis limitations*

Concerning the limitations of this thesis in general, I can state that it is a shame that time did not permit me to look at the seismics or wells outside the area of interest. Therefore, I have little clue on how the area falls into a bigger perspective. For instance, I did not investigate where river input came from, or where the main depocentres in the area are. This is the greatest shortcoming when trying to find an explanation for the progradation direction that was concluded. Also, I performed no form of geostatistics on the results, so although the progradational angle is heterogeneous in the described scenario, I am not sure if this is a one-time exception or seen more often. I regret not investigating the cores myself, which restricts the amount of conclusions I can make about the sequence stratigraphy of the area of interest. I had to use the investigation of Thomas Osivwi and Tom Dreyer to do that. I also regret not building the clinoforms using true log signals. Earlier research has shown that it is possible to decompose log signals into an along and arcmod signal. However, the process is time consuming and requires a larger mathematical insight than I have at this point.
Finally, I have only little clue on how CES is built up mathematically, which limits the amount of knowledge I have about the processes that take place behind the results that I show.

# 6. Conclusion

## 6.1 General conclusions

In a world where the growing energy demands require an ever increasing field life, high resolution geological modelling can increase the recovery factor of oil and gas fields by enabling well planning and drilling precision, and is therefore worth the investment.

Updating the structural framework of the geomodel of a field using well log data is a fast and easy way to reduce modelling uncertainties and increase the understanding of the depositional history of an area. The Troll field offers an excellent example of how the accumulation of data throughout the years can be used to make such improvements, especially when taking the high information density of the field into account.

Asymmetric delta spit systems can form heterogeneous sediments that require small scale interpretation in areas where normal interpretation caused flaws in the geomodel.

Deltaic clinoforms are not necessarily visible on high resolution seismics. Inclined surfaces in seismics are not necessarily the reflections of clinoform surfaces themselves. Looking for the homogeneous part of a clinoform (which is perpendicular to the progradation direction) in well log correlation may be simpler than trying to find the progradation direction in seismic sections.

The heterogeneities in reservoir characteristics that are caused by the depositional system of a prograding delta spit can lead to complex well logs and seismic patterns.

Reservoir heterogeneities offer great interpretation problems for geologists. Finding patterns in heterogeneities is a key factor in the creation of a high resolution reservoir characterisation.

Using well log patterns and well log correlation in areas where correlation was done with a high degree of confidence, reliable high resolution reservoir characterizations can be created with CES. Densely drilled reservoirs are a good environment for trustworthy well log correlation.

Well log correlations are most easily made when layers are brought back to their original angle of deposition.

The Compound Earth Simulator offers a fast and simple method to backward model the geological (erosional or deformational) events, making it possible to observe the build-up of the reservoir at the time of deposition. Well log correlation at the time of deposition is easier than well log correlation after erosion and deformation altered the layer-cake sediment stacking.

The Compound Earth Simulator furthermore offers a fast and simple method to forward model the geological events, making it possible to convert a well log correlation at depositional time to a well log correlation at present time. Synthetic seismograms can be converted simultaneously with the well log correlations.

Comparing the synthetic seismograms to the seismic sections and comparing true well logs to modelled well logs can offer an internal quality check of the processes that were chosen to be modelled backwards and forwards.

## *6.2 Field specific conclusions*

The Troll Field's parasequences that are located at or just above reservoir depth in the I-13 area are the 3B, 3C1, 3C2, 3D, 4A and 4B zones. The zones form a stacking of progradational bodies that are occasionally separated by flooding or erosional surfaces and contain a heterogeneous reservoir build-up.

The detailed sequence stratigraphic works that were done for the Troll Field in the past offer a great basis for well log correlation and, combined with a thorough seismic study, led to a new view on the distribution of the parasequences in the field.

These differences in parasequence modelling should be seen as an example of the high amount of interpretation possibilities that can be found when working in a heterogeneous reservoir like the Troll Field.

The 3B, 4A and 4B parasequences offer the best examples of cleaning upwards, coarsening upwards progradational bodies that may be interpreted as clinoform depositions.

In the area of interest, these clinoform depositions show a build-out direction that is perpendicular to the build-out direction that is generally described for the Troll Field. Instead of a south to southwest progradation, these clinoforms show a northwest to north progradation direction.

Causes for this difference in progradation direction are numerous, but the most important might be found in the avulsion of the delta spit channel, in a possible basin floor topography caused by older delta lobes, or in a tectonic heterogeneity triggering a difference in accommodation space or paleocurrent direction.

## *6.3 Recommendations*

High resolution reservoir characterisation has proven to be useful and should be considered in other problem areas of the Troll Field or other fields with a similar depositional history as well.

However, both the method presented in this report and the Compound Earth Simulator itself should be improved by practice. It would be interesting to find out if the Compound Earth Simulator can be able to link the interpretations in multiple seismic sections to thereby create a three dimensional interpretation of the reservoir.

On a more short term, the findings of this report could be integrated into Decision Space Desktop (DSD) or Reservoir Modelling Solutions (RMS) to offer an alternative view on the Troll reservoirs structural framework. Possibly, a trial version of a new geomodel for the I-13 area could be made that may be considered in well planning along with the old geomodel.

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