High-resolution 3D seismic interpretation of a Lower Cretaceous delta system in the Hoop area, SW Barents Sea

Thea Sveva Faleide

Master thesis in Geosciences
Geophysics
60 credits

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Faculty of Mathematics and Natural sciences

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IV
Abstract

A detailed analysis of a Lower Cretaceous sedimentary lobe complex in the Barents Sea is compared to synthetic seismic data generated from a field analogue in New Mexico, USA, in order to constrain resolvability of depositional architecture. A delta system prograded from Svalbard to the SW Barents Sea during the Early Cretaceous, sourced from uplifted areas northwest of present-day Svalbard by High Arctic Large Igneous Province (HALIP) activity. The depocentre was a low-gradient epicontinental sea, with incipient Atlantic rifting along its western margin. This study looks closer into the most distal part of the delta system, located in the Hoop area, on the NW Bjarmeland Platform in the SW Barents Sea, where depositional lobes arriving from the northwest and northeast are stacked, in ascending order.

The database consists of a 4392 km\(^2\) 3D conventional seismic cube covering the entire Hoop study area. Within this area, two narrow high-resolution P-Cable 3D cubes of approximately 12 and 14 km\(^2\), and several wide-azimuth 2D P-Cable lines are included. Two exploration wells, Apollo and Atlantis, and a shallow borehole are also integrated in the study.

Well-calibration, 2D and 3D seismic interpretation, and synthetic seismic modelling of analogous outcrop data form an integrated approach that is used to constrain possible subsurface scenarios in the Barents Sea. A direct comparison between high- and low-resolution seismic imagery highlights how accurate interpretation of complex architecture is entirely dependent on data quality.

The downlap surface for the prograding system represents a lowermost Cretaceous condensed sequence that is difficult to resolve in the conventional data. In the P-Cable data, however, the thin unit is well resolved with several strong reflections within this sequence. The Barremian delta system prograded into the Hoop area from NNW and terminated before reaching the Apollo and Atlantis wells. The high-resolution P-Cable data, supplemented by the 3D conventional seismic data, offers a detailed mapping and characterization of the clinoforms, resulting in improved constraints on the extent and timing of the prograding delta system. The clinoforms have typically heights in the order of 50 m and dips of 1-2\(^\circ\). The wells within the study area indicate fine-grained lithologies within the Lower Cretaceous strata. However, the prograding clinoforms and clinothems have not yet been sampled. Coarser-grained material associated with the steepest clinoforms, can therefore not be ruled out.
A NE-SW trending bright event observed as a nearly continuous feature in the 3D conventional seismic data is interpreted to represent a channel along the front of the prograding delta system. The incision is likely linked to a slightly younger system that prograded into the area from the NE. An important rift event affected the Hoop area in Aptian time and faulting associated with this event postdates the prograding system.

The study demonstrates that high-resolution P-Cable seismic data reveal stratigraphic and structural features, such as clinoforms and channel bodies, which are not possible to interpret in the conventional seismic data. Seismic modelling shed light on the limitation of seismic data, and this combined with detailed observations in the P-Cable data, increase the confidence in the interpretation of the conventional seismic data.
Preface

This master thesis is submitted in the completion of the master program with specialization in Geophysics at the Department of Geoscience, University of Oslo. The master thesis has been supervised by Adjunct Professor Sverre Planke, Associate Professor Ivar Midtkandal and Associate Professor Isabelle Lecomte.

Acknowledgements

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I would also like to thank TGS, WGPS and VBPR for providing the data, Dr. Michel Heeremans for preparing the dataset used in the study, Schlumberger for making the Petrel software available and NORSAR for making the SeisRoX software available.

I also highly appreciated the good dialog with Anna van Yperen. Many thanks for sharing results of your fieldwork with me, making it possible to do seismic modelling from New Mexico.

Reidun Myklebust is acknowledged for all help related to seismic data transfer and permissions. Thanks to Mohammed Matar for guidance in Petrel, this has been very helpful and educational. I would also like to thank Ole Rabbel for helpful advice regarding the modelling.

I would also like to express my gratitude to my family for moral support throughout this period, and extra thanks to my dad for geoscience discussion and advice.

Finally, I would like to thank my friends, fellow student and staff at the University of Oslo.
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1 Introduction

The Barents Sea forms one of the broad continental shelves in the Arctic. It is bounded by young continental margins towards the Norwegian-Greenland Sea in the west and the Eurasia Basin in the north (Figure 1.1a). The western Barents Sea is typically divided into three regional geological provinces (Gabrielsen et al., 1990; Faleide et al., 1993; 2015): (1) a basin province in the south, (2) a platform province in the north including Svalbard, and (3) a mainly sheared margin in the west (Figure 1.1b). Deep sedimentary basins developed in the SW Barents Sea from Late Paleozoic to Early Cenozoic times when continental breakup occurred in the NE Atlantic. Svalbard offers a unique opportunity to study the Barents Sea geology, having the entire upper Paleozoic to Paleogene sedimentary succession accessible in outcrops (Steel and Worsley, 1984; Nøttvedt et al., 1993; Dallmann, 1999; 2015; Worsley, 2008).

The main study area of this thesis is the Hoop area on the NW Bjarmeland Platform (Figure 1.1b), which is located in a transitional area between the platform in the east and the deep basins in the west. The Hoop area has recently received considerable exploration interest (Kjølhamar et al., 2014), in particular after the Wisting discovery (Figure 1.2) having oil at shallow depth in Jurassic reservoirs of good quality. Two of the most recent wells, Apollo and Atlantis that are used in this study, were not successful from an exploration point of view. Atlantis was a small gas discovery, while Apollo was dry.

Figure 1.2  Map showing blocks, wells and discoveries in the wider Hoop area, SW Barents Sea. Location of the study area marked. (Modified from NPD, 2017a).
The main objective of this master thesis is to study the Early Cretaceous delta and basin evolution in the Hoop area. Different kinds of seismic reflection data are integrated and compared with respect to their resolution (Figure 1.3), and tied to the two recent exploration wells within the study area (Figure 1.2). The results of the integrated analyses of the seismic and well data are linked to the Lower Cretaceous sedimentary succession on Svalbard which was part of the same regional depositional system in the Barremian (Midtkandal et al., 2007; 2014; Midtkandal and Nystuen, 2009). This delta system prograded into a shallow epicontinental sea and was sourced from uplifted areas in the north associated with the formation of the High Arctic Large Igneous Province (HALIP; Maher et al., 2001; Polteau et al., 2016).

Figure 1.3 Comparison of P-Cable data (left) and conventional seismic data (right) having different frequency content and resolution. The formation tops that are plotted are described later in Chapter 4, and the seismic horizons (white text) are described in Chapter 5. Data courtesy of TGS, VBPR and WPGS.
The Lower Cretaceous depositional system in the Barents Sea is also compared to a field analogue in New Mexico in western USA. The Lower Cretaceous strata in New Mexico represent an extensive fluvial to marginal marine system (Holbrook, 1996; 2001) and covers a distance of ~350 km between the most proximal, fully fluvial expression (southeast Colorado), and the first indicators of marginal marine conditions (northeast New Mexico). The Mesa Rica sandstone is utilized as a field analogue to the Lower Cretaceous strata in the Barents Sea, based on its similar basin configuration and size. The strikingly similar fluvial expression within the Festningen Member sandstone on Svalbard and the proximal Mesa Rica sandstone in New Mexico, both deposited in similar low-gradient basinal settings, validate the analogue comparison in the distal components.

Geological models from New Mexico have been used as basis for seismic modelling to study how different units of a regional prograding system are imaged by seismic data having different frequency ranges. The synthetic seismic data are compared to both high resolution P-Cable data and conventional seismic data from the Barents Sea addressing what can be resolved by the different types of seismic reflection data.

A geological framework with emphasis on the Lower Cretaceous stratigraphy and evolution is presented in Chapter 2. This integrated and interdisciplinary study requires various data sets and methodologies, which are described in Chapter 3. The results of the study are presented in Chapters 4-6, one for each of the main components in the study (4: well log interpretation and seismic tie; 5: seismic interpretation; 6: seismic modelling). The results are integrated and discussed in Chapter 7 before the main conclusions are drawn in Chapter 8.
2 Geological framework

A regional understanding of the Barents Sea geological history and resultant stratigraphy is crucial in order to explain the deposition and timing of the Lower Cretaceous succession both in the SW Barents Sea and Svalbard.

2.1 SW Barents Sea structure and evolution

The SW Barents Sea comprises deep sedimentary basins (Figure 2.1) that formed in response to four main rift phases (Faleide et al., 1993; 2015; Glørstad-Clark et al., 2010; Clark et al., 2014): 1) Late Carboniferous, 2) Late Permian, 3) Late Jurassic-Early Cretaceous and 4) Late Paleocene-earliest Eocene (before onset of seafloor spreading). Major fault complexes (Ringvassøy-Loppa FC, Bjørnøyrenna FC and Leirdjupet FC) separate the Hammerfest Basin, Loppa High and Fingerdjupet Sub-basin from the much deeper Tromsø and Bjørnøya basins to the west. Further west, the Sørvestsnaget Basin developed along the mainly sheared margin. Figure 2.1b shows a regional seismic profile across the SW Barents Sea from the platform setting in the east to the western continental margin.

Carbonates and evaporites dominate the upper Carboniferous-Permian succession, the remaining part is dominated by clastic rocks (mudstone and sandstones) (Figure 2.2). The Barents Shelf was uplifted and eroded in Neogene time (Faleide et al., 1996; Dimakis et al., 1998; Henriksen et al., 2011; Baig et al., 2016) giving rise to an upper regional unconformity covered by a thin layer of Quaternary glacial sediments (Solheim and Kristoffersen, 1984).
Figure 2.1 Regional seismic profiles across the SW Barents Sea from the Finnmark Platform in the east to the deep basins in the west. Structural element map of the SW Barents Sea with location of the study area and the regional profile in a and b. Modified from Faleide et al. (2015).
Figure 2.2 Regional stratigraphic summary chart of the southwestern Barents Sea and Svalbard (modified from NORLEX, 2017).
2.2 Lower Cretaceous – stratigraphy and evolution

The Lower Cretaceous sequences, which as the focus of this thesis, belongs to the Adventdalen Group (Figure 2.3). The group comprises mudstones, siltstones and sandstones of Late Jurassic-Early Cretaceous age, and is documented on both Svalbard and the Barents Shelf with thicknesses of 750-1600 m and 1000-1750 m, respectively (NPD, 2017b). It overlies the Kapp Toscana Group of Late Triassic-Early/Mid Jurassic age and the boundary represents a change in lithology from mainly deltaic shallow marine sandstones below to Upper Jurassic marine mudstone above. In Svalbard, the Lower Cretaceous succession reflects a development from prodelta shales at the base followed by delta front to fluvial dominated delta plain sequences (Worsley and Aga, 1986). Upwards in the deltaic succession, the sandstone goes from being white and pale grey to dirty greenish-grey, which is a result of the volcanic material that was deposited during volcanic activity in the Early Cretaceous. Doleritic sills and dikes are evidence of this period, and the youngest intruded sediments are shales of Early Cretaceous age (Worsley and Aga, 1986).

![Figure 2.3](image)

**Figure 2.3** Correlation of the Lower Cretaceous formations between the SW Barents Sea and Svalbard (described in more detail in the text). Based on Smelror et al. (1998), Dallmann (1999) and Smith et al. (1976).


2.2.1 Regional setting and paleogeography

The Cretaceous had the warmest climate in Earth history caused by volcanic activity which was a result of the sea-floor spreading connected to the final breakup of the super-continent Pangea and the formation of the Atlantic Ocean. Parts of the Arctic Ocean also formed during the Cretaceous (Dallmann, 2015).

At this time part of Svalbard and the Barents Sea was under a shallow epicontinental sea and was located at 60-70 degrees north (Smelror et al., 2009). Igneous rocks found on Svalbard are evidence of Early Cretaceous volcanic activity that peaked in the Barremian (Corfu et al., 2013; Senger et al., 2014; Dallmann, 2015; Polteau et al., 2015; Midtkandal et al., 2016). Igneous rocks are also interpreted south and east of Svalbard based on seismic and magnetic data (Grogan et al., 2000; Minakov et al., 2012; Polteau et al., 2016). This activity was part of the High Arctic Large Igneous Province (HALIP) that was established during breakup and initial opening of the Amerasia Basin in the Arctic (Polteau et al., 2016). Formation of the HALIP caused regional uplift of a wide region in the Arctic that became the source area for major depositional systems prograding southwards past Svalbard and into the Barents Sea (Midtkandal and Nystuen, 2009).

2.2.2 SW Barents Sea

On the Barents Sea shelf the Adventdalen Group is divided into six formations (Figure 2.2): Fuglen Fm, Hekkingen Fm, Klippfisk Fm, Knurr Fm, Kolje Fm and Kolmule Fm. The last three, of Early Cretaceous age, are the main focus of this study and are described below. The fourth Lower Cretaceous unit, the Klippfisk Fm (Figure 2.3), was penetrated by a shallow corehole in the northern part of the study area (Århus et al., 1990; Århus, 1991; Smelror et al., 1998). The Upper Jurassic black shales of the Hekkingen Fm are known as a very good hydrocarbon source rock (Dallmann, 1999; Worsley et al., 1988).

The lowermost Cretaceous Knurr Fm and Klippfisk Fm formations are time-equivalent. Knurr Fm was deposited in the basins formed by Late Jurassic extension while Klippfisk Fm was deposited on the platforms (Smelror et al., 1998; Dallmann, 1999). The Knurr Fm consists of dark grey to greyish brown claystone and thin limestone/dolomite interbeds, deposited in an
open to generally distal marine environment. The suggested age of the Knurr Fm is Valanginian to early Barremian based on fossils that are found in the formation (NPD FactPages, 2017). The time-equivalent Klippfisk Fm represents a condensed interval in platform settings dominated by limestones which grade into marls and calcareous claystones towards the basins (Smelror et al., 1998).

The Kolje Fm is dominated by dark brown to grey shale and claystone, with thin interbeds of silt- and sandstone in the upper part of the formation (NPD, 2017b). It was deposited in early Barremian to late Barremian/early Aptian time, in a more distal open marine environment. Kolje Fm is the formation in the SW Barents Sea that correlates (lateral equivalent) with the sand-dominated Helvetiafjellet Formation on Svalbard.

The Kolmule Fm consists mainly of green claystone and shale indicating an open marine environment in the Barents Sea. It was deposited during the Aptian-Albian time in a shallow-marine environment, influenced by changes in sea-level and sediments supply (Smelror et al., 2009).

### 2.2.3 Svalbard

At Svalbard the Cretaceous part of the Adventdalen Group contains, from oldest to youngest, the Rurikfjellet, Helvetiafjellet and Carolinefjellet formations (Figure 2.3) (Midtkandal, 2010; Dallmann, 1999; 2015).

The Rurikfjellet Formation is the lowermost Cretaceous unit on Svalbard, and is the lateral equivalent of the Knurr Fm and Klippfisk Fm in the Barents Sea (Figure 2.3). It is about 400 m thick and consists of a lower shale-dominated part, with a gradual transition to an upper silt- and sandstone-dominated unit. This regressive change reflects an environment change from deep outer shelf to a shallow inner shelf, shoreface and delta-front (Dallmann, 1999; 2015). In eastern Svalbard a thin limestone-rich unit deposited on a shallow marine carbonate platform can be correlated to the Tordenskjoldberget Member of the Klippfisk Fm in the Barents Sea (Figure 2.3; Smelror et al., 1998).
The Helvetiafjellet Formation (Figure 2.4) is 40-155 m thick, consisting of a lower sandstone- and conglomerate-dominated unit and an upper heterolithic unit of alternating sandstone, carbonaceous shale and thin coal (>1 m). It represents a continental to near-shore marine depositional environment (Midtkandal et al., 2007; Midtkandal and Nystuen, 2009).

![Figure 2.4 Outcrop of the Lower Cretaceous formations in Svalbard (Photo: Ivar Midtkandal).](image)

As a result of tectonic uplift, tilting and subsidence of the Svalbard platform in this period, this succession represents a cycle of falling and rising sea-level (Smelror et al., 2009). Deltas prograded from uplifted areas in the north, across Svalbard and southwards to the Barents Shelf (Figure 2.5; Midtkandal and Nystuen, 2007). The base of the Helvetiafjellet Formation is described as a regional unconformity of Barremian age. The Festningen Member sandstone forms the first sandstone unit above this boundary (Figure 2.4).

The Carolinefjellet Formation was deposited during Aptian-Albian time, and is about 1200 m thick. It was deposited on a distal deepening, open marine and storm dominated shelf consisting of alternating sandstone- and shale dominated units. The sandstone dominated successions have a southward thinning wedge that represents environments on the inner shelf and shoreface. The shale dominated successions represent the outer and deeper shelf environments (Dallmann, 2015; Hurum et al., 2016; Grundvåg and Olaussen, 2017).
Because of the uplift and massive erosion of the Upper Cretaceous succession, the Carolinefjellet Formation is succeeded by the Paleocene succession, representing a regional unconformity. This unconformity increases towards the north, meaning that the largest uplift was in the north (Dallmann, 2015).
3 Data and methods

The seismic and well data used in this study cover the Hoop area and parts of the adjacent Bjarmeland Platform in the SW Barents Sea (Figure 3.1). The data and the main methods used in this study will be introduced in this chapter.

Figure 3.1 Location of the wells and high resolution P-Cable and conventional seismic data in the study area.
3.1 Well data

Two exploration wells, 7324/2-1 (Apollo) and 7325/1-1 (Atlantis), are located inside the study area in the SW Barents Sea (Figure 3.1). Both were drilled by Statoil in June and July 2014, respectively. The well data were released to the public two years later, in June and July 2016. General information about the Apollo and Atlantis wells are summarized in Table 3.1.

In addition to Apollo and Atlantis, information based on a short core from IKU corehole 7425/9-U-1 (Figure 3.1) was used to better understand the relationship between the Knurr Fm and Klippfisk Fm within the study area.

<table>
<thead>
<tr>
<th>Well name</th>
<th>7324/2-1 Apollo</th>
<th>7325/1-1 Atlantis</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS degrees</td>
<td>73° 51' 47.9&quot; N</td>
<td>73° 54' 48.7&quot; N</td>
</tr>
<tr>
<td>EW degrees</td>
<td>24° 32' 29.9&quot; E</td>
<td>25° 7' 0.17&quot; E</td>
</tr>
<tr>
<td>Drilling operator</td>
<td>Statoil Petroleum AS</td>
<td>Statoil Petroleum AS</td>
</tr>
<tr>
<td>Completion date</td>
<td>18.06.2014</td>
<td>21.07.2014</td>
</tr>
<tr>
<td>Type</td>
<td>Exploration</td>
<td>Exploration</td>
</tr>
<tr>
<td>Status</td>
<td>Plug and abandoned</td>
<td>Plug and abandoned</td>
</tr>
<tr>
<td>Content</td>
<td>Dry</td>
<td>Gas</td>
</tr>
<tr>
<td>Total Depth (MD) [m RKB]</td>
<td>1090.0</td>
<td>2865.0</td>
</tr>
<tr>
<td>Formation at TD</td>
<td>Snadd Formation (Late Triassic)</td>
<td>Havert Formation (Early Triassic)</td>
</tr>
</tbody>
</table>

3.1.1 Log interpretation

Geologists and geophysicists have different approaches when analysing well data. Geologists are interested in knowing at what depths the formation tops are located, and if there are intervals that are suitable for hydrocarbons and what kind can be assumed to find. As a geophysicist the question is if the well tops are predicted, porous zones and what does the synthetic seismic section show (seismic to well tie) (Mondol, 2015). In this study both approaches are followed before they are merged into one interpretation at the end.
The Apollo and Atlantis wells (Figure 3.1) are used for the well interpretation, well to seismic correlation and correlation between the seismic interpretation and lithostratigraphy in the SW Barents Sea. Lithologies are predicted by combining data from relevant logs. Synthetic seismograms are generated from well data for direct comparison to the P-Cable data and conventional seismic data. In addition, the two wells have contributed to the seismic modelling of the New Mexico field analogue with realistic petrophysical values, most importantly the P-wave velocity, S-wave velocity and density.

For this study, selected well logs are used for describing the lithology in the Lower Cretaceous units. The following logs are used and these are briefly described in Appendix 1: gamma ray (GR), density (DEN), neutron porosity (NEU), photoelectric factor (PEF), interval transit time compressional (AC) and interval transit time shear (ACS).

The porosity logs available are the neutron, density and sonic logs (Appendix 1), and these can give an indication of the lithology. None of these logs measure the porosity directly, but a combination of the porosity logs gives more correct values of the porosity and also a good indication of the lithology (Mondol, 2015). Neutron and density logs are based on nuclear measurements, while sonic log use acoustic measurements (Mondol, 2015).

The combined neutron and density logs plotted against each other and comparing the relative relationships between the curves, provide an important tool to give a good and accurate estimation of the lithology. It gives a good indication of what is shale and non-shale. The neutron porosity in shales is higher compared to the lower measurements in carbonate and sandstones. There is no separation for limestone, while it is a separation for sandstone and dolomite. The dolomite gives positive separation, and if there is shale present the positive separation is larger. On the other hand, the sandstone gives a negative separation and even larger negative separation if gas is present. When the shale volume decreases the positive separation decreases until a cross over. A small negative separation occurs in sandstones. The combined neutron and density logs are commonly used together with the PEF for lithology prediction (Mondol, 2015).

At the NPD FactPages (2017b) a reference well and type well is provided for each of the formation boundaries, and the boundary is described with the change in density, transit time and gamma ray. In addition to the two Hoop wells and the reference and type wells, three
wells from the Fingerdjupet Sub-basin (7321/7-1, 7321/8-1 and 7321/9-1; Figure 1.2) were used for correlation.

Another method to get a lithology and porosity description is to plot the Vp and Vs ratio versus the acoustic impedance (AI). Acoustic impedance is the product of the velocity and density ($v \times \rho$). Ødegaard and Avseth (2004) introduced this concept and it can be used for predicting lithology. Vp/Vs vs AI is a rock physics template (RPT) based on seismic parameters, which are typically outputs from elastic inversion of the seismic data (Ødegaard and Avseth, 2004). Different lithologies and fluid content plot in different parts of this cross-plot, and will be used for the formations of interest in this study in Chapter 4.

### 3.2 Seismic data

The seismic data utilized for this study comprise both 2D and 3D high-resolution P-Cable and conventional 3D seismic data covering parts of the Hoop area and Bjarmeland Platform (Figure 3.1). Some conventional 2D seismic lines are also included to establish ties to other structural elements adjacent to the study area. Table 3.2 gives a summary of all seismic data integrated and used in this study.

**Table 3.2** General information of the seismic data used in this study, in addition to the data owner.

<table>
<thead>
<tr>
<th>Surveys</th>
<th>Year</th>
<th>Type (Size)</th>
<th>Company</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR12_3D-D (Area D)</td>
<td>2012</td>
<td>3D P-Cable            (12km²)</td>
<td>TGS/ WGPS/ VBPR</td>
<td>HiRes 3D, Barents Sea, Hoop Fault Complex West</td>
</tr>
<tr>
<td>HR12_3D-C (Area C)</td>
<td>2012</td>
<td>3D P-Cable            (14 km²)</td>
<td>TGS/ WGPS/ VBPR</td>
<td>HiRes 3D, Barents Sea, Hoop Fault Complex West</td>
</tr>
<tr>
<td>HR15</td>
<td>2015</td>
<td>2D, P-Cable</td>
<td>TGS/ VBPR</td>
<td>HiRes 2D, Eastern Barents Sea</td>
</tr>
<tr>
<td>HR14</td>
<td>2014</td>
<td>2D, P-Cable</td>
<td>TGS/WGPS/ VBPR</td>
<td>HiRes 2D, Barents Sea South</td>
</tr>
<tr>
<td>Hoop Fault Complex 3D</td>
<td>2012</td>
<td>3D Conventional       (≈4392 km²)</td>
<td>TGS</td>
<td>Hoop Fault Complex 3D</td>
</tr>
<tr>
<td>NBR 2D lines</td>
<td></td>
<td>2D Conventional</td>
<td>TGS/Spectrum</td>
<td>Regional grid SW Barents Sea</td>
</tr>
</tbody>
</table>
3.2.1 P-Cable data and conventional seismic data

The main and unique component of the P-Cable technology, which has been developed since 2001, is the cross-cable dragged perpendicular to the streamers direction (Figure 3.2). The cross-cable is spanned by two paravanes located 150-300 m apart, and it provides power and communication for up to 24 active streamer sections. These can be connected to the cross-cable with 6.25 or 12.5 m spacing and the active sections have group spacing of typically 1.6-12.5 m (Planke and Berndt, 2007; Planke et al., 2009).

![Figure 3.2 A typical P-Cable acquisition configuration. (Planke and Berndt, 2007)](image)

The P-Cable 3D seismic acquisition provides high resolution data in a selected area (inlines and crosslines). For the 2D profile a detailed high-resolution seismic line is collected by using a wide-azimuth illumination and high-fold. This is an effective and less expensive way to collect a single survey for different target areas, and illuminate geological features and structures at different scales (P-Cable, 2017).

A dense common midpoint (CMP) line coverage with bin sizes as low as 3 m, compared to the typical 12.5/25 m bin size in conventional seismic, is a result of the short offset and dense
streamer spacing in the P-Cable technology. This, combined with a high frequency seismic source, the vertical and horizontal resolution increases. A summary of the typical system specification for P-Cable acquisition is listed in Table 3.3.

Table 3.3  Typical system specification for P-Cable acquisition with the most important difference from the conventional acquisition highlighted. Concept: P-Cable patent (Planke and Bernd, 2004).

<table>
<thead>
<tr>
<th>Typical System Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Streamers</td>
</tr>
<tr>
<td>Streamer Spacing</td>
</tr>
<tr>
<td>Bin Size</td>
</tr>
<tr>
<td>Horizontal Resolution</td>
</tr>
<tr>
<td>Vertical Resolution</td>
</tr>
<tr>
<td>Towing Depth</td>
</tr>
</tbody>
</table>

P-Cable data have a much higher resolution than the conventional seismic reflection data. Improved horizontal resolution is obtained through smaller bin size in P-Cable data compared to the conventional data, while better vertical resolution is obtained by use of higher frequency seismic waves. These differences will be documented and discussed in further detail below.

Parts of the Lower Cretaceous succession studied in the Hoop area are characterized by thin sedimentary units (Figure 3.3) with varying physical properties such as velocity and density. These closely spaced acoustic impedance boundaries cause interference depending on the wavelength of the seismic wave (Badley, 1985; Sheriff, 1985; Planke, 1994; Planke and Eldholm, 1994; Brown, 2004).

The relation between wavelength, frequency and velocity is important for the understanding of seismic resolution. The relation is defined as:

\[ \lambda = \frac{v}{f} \]  
(1)

\( \lambda \): wavelength, \( v \): velocity and \( f \): frequency.
Since the P-Cable data have significantly higher frequency range, hence shorter wavelengths, they have higher resolution than conventional seismic data. Well log data resolve more details than seismic data. The limitations of geophysical data become clear when compared to all the details that can be directly observed and measured in outcrops (field analogues). This is further studied and discussed later; here the basic principles of interference and seismic resolutions are summarized (Figures 3.3 and 3.4).

The vertical resolution (Figures 3.4 and 3.5) is determined by the minimum thickness of a bed so that reflections of the top and base can be distinguished in the seismic data (Badley, 1985; Brown, 2004). The velocity is generally increasing with burial depth due to mechanical and chemical compaction (Bjørlykke, 2015). The frequency tends to decrease with depth because higher frequencies are removed by attenuation (Brown, 2004). The combined effect of these factors is a decrease in resolution.

The limit of separability corresponds to a quarter of the wavelength ($\lambda/4$) (Brown, 2004), which is also called the tuning thickness having maximum interference (Figure 3.4). Interference can result in both constructive and destructive response. Destructive response occurs when reflections from closely spaced interfaces cancel each other out at the receiver, and constructive response is when the individual reflections add to stronger amplitudes (Figure 3.5).

The limit of visibility (Brown, 2004), or detectability, can vary depending on the seismic data quality. For data with a high signal to noise ratio, the limit of visibility can be as small as $\lambda/30$ (Brown, 2004). Here the bed thickness < tuning thickness, and no separability between top and bottom reflector of the bed will be seen in the seismic.

In Figure 3.5 synthetic seismograms based on the same geological/physical model are shown for different source frequencies. These responses and limitations are very relevant to this thesis work and will be further discussed below.
The horizontal resolution concerns how to separate two points on the same reflector that are close together. It is defined by receiver spacing and the Fresnel zone, shown in Figure 3.3. The definition of a Fresnel zone is an area down at an interface that contributes constructive to the reflected wavelet (Sheriff, 1985). Deeper the interface, the Fresnel zone increases. The width of the Fresnel zone, \( W \), is given by:

\[
W = \sqrt{2d\lambda + \frac{\lambda^2}{4}}
\]  

(2)

\( W \): width of the Fresnel zone, \( d \): depth down to the target and \( \lambda \): wavelength from formula 1.

To improve the horizontal resolution migration is a useful tool. Migration improves three distinct functions: repositions reflection out of place because of dip, focuses energy spread over a Fresnel zone and collapse diffraction patterns from points and edges (Brown, 2004).
Figure 3.4 Vertical seismic resolution for various frequencies and layer thicknesses using Ricker wavelets (redrawn from Badley, 1985). The synthetic seismograms show how various configurations of thin layers can give rise to quite different seismic responses.
Figure 3.5 Interference and seismic resolution for various frequencies using Ricker wavelets (redrawn from Badley, 1985).

Typical values for seismic resolution of P-Cable and conventional seismic data are given in Table 3.4 with typical dominant frequencies, velocity (for Lower Cretaceous units in the study area) and wavelength.
Table 3.4  Typical seismic resolutions for P-Cable and conventional seismic with characteristic frequencies and velocities, hence wavelengths, horizontal and vertical resolution $\lambda/2$ and $\lambda/4$, respectively and the width of the Fresnel zone (formula 2).

<table>
<thead>
<tr>
<th>Frequency, $f$</th>
<th>Velocity, $v$</th>
<th>Wavelength, $\lambda$</th>
<th>$\lambda/2$</th>
<th>$\lambda/4$</th>
<th>W (width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Hz</td>
<td>3 km/s</td>
<td>100 m</td>
<td>50 m</td>
<td>25 m</td>
<td>377 m</td>
</tr>
<tr>
<td>50 Hz</td>
<td>3 km/s</td>
<td>60 m</td>
<td>30 m</td>
<td>15 m</td>
<td>291 m</td>
</tr>
<tr>
<td>100 Hz</td>
<td>3 km/s</td>
<td>30 m</td>
<td>15 m</td>
<td>7.5 m</td>
<td>205 m</td>
</tr>
<tr>
<td>150 Hz</td>
<td>3 km/s</td>
<td>20 m</td>
<td>10 m</td>
<td>5 m</td>
<td>168 m</td>
</tr>
<tr>
<td>250 Hz</td>
<td>3 km/s</td>
<td>12 m</td>
<td>6 m</td>
<td>3 m</td>
<td>129 m</td>
</tr>
</tbody>
</table>

3.2.2 Interpretation methodology and strategy

The seismic interpretation was done in the Petrel software provided by Schlumberger. After doing the synthetic seismic generation (see Chapter 3.3) the horizons to interpret were picked and the interpretation in Petrel started. Before that the polarity and phase of the seismic data were identified by studying the seismic response of prominent reflections representing a sharp contrast in acoustic impedance giving rise to a reflection coefficient of known polarity (e.g. the seabed reflection).

Based on the seismic to well tie (see Chapters 3.3 and 4), four main horizons were picked and interpreted in both the P-Cable and conventional seismic data. Since the conventional 3D seismic cube covers the whole study area, the horizons were interpreted in this cube first.

The seismic horizons were first interpreted on a composite line between the Apollo and Atlantis wells. Then, every 50-100 inline and crossline in the 3D cube were interpreted with the 2D guided interpretation tool and manually picking, before the 3D auto-tracking was used to fill in the rest of the seismic horizon. This was done on horizons that were strong, continuous and easy to follow. On the more difficult horizons, a denser grid of inlines and crosslines was interpreted before using the 3D auto-tracking. By screening the 3D cube, misinterpretations were corrected with the use of the manual interpretation tool.

The interpretation of the P-Cable data was also based on a composite line between Apollo and Atlantis. All 2D P-Cable lines inside the study area were interpreted and ties were established to the two 3D P-Cable cubes located to the north of the wells. The P-Cable 3D cubes, Area D and Area C, cover just 12 km$^2$ and 14 km$^2$, respectively, making the interpretation fast. Each
10 inlines and 50 crosslines were interpreted with 2D and manual interpretation tools before using the 3D auto-tracking. Since the two 3D P-Cable cubes are narrow, it was just made surfaces (time-structure maps) of the interpreted seismic horizons in the conventional 3D data.

3.2.3 Seismic attributes analysis

Seismic attributes analysis is described in Mondol (2015) as "a quantitative measure of a seismic characteristic of interest". Attribute maps are a helpful tool to present and study information derived from, or related to, the basic seismic information of time, amplitude, frequency and/or attenuation (Brown, 2004). The goal is "to capture maximum information by quantifying the amplitude and morphological features, through a suite of deterministic calculations performed by a computer" (Mondol, 2015). It is used to present stratigraphy, structural and reservoir properties in seismic studies, based on a limited amount of basic information (Brown, 2004).

The large number of different attributes available in Petrel is divided into surface and volume attributes. When applying surface attributes the output is a surface with extraction between to levels or at an exact level (Schlumberger, 2015), while for volume attributes the input seismic is converted to virtual or realized volumes (Schlumberger, 2015). Types of attributes used in this study and their main purpose are described in Appendix 2.

Different types of attributes are used on the different seismic data sets available for this study. All attributes are run on realized 32 bit (high-quality) seismic data. Pre-processing of the seismic data with time gain and structural smoothing are used as input for the attributes in this study. Attributes that highlights both structural and stratigraphic features are used.

Another important thing with attributes analysis is the visualization of the attributes. Best use of the parameters, lightening, transparency and colours are some of the important things to have in mind (Brown, 2004). The best results are often obtained when using different attributes at the same time. This is possible with the use of transparency. With the seismic data as the base, different attributes highlighting different features are put on top with various percent of transparency.
3.3 Seismic modelling

Seismic modelling is a valuable and important tool for separation of real structures from seismic artifacts. Seismic modelling makes it possible to study the relationships between geology and seismic response, in addition to study the seismic interpretation procedure and expressions of outcrops (Johansen et al., 2013; Anell et al., 2016). With seismic modelling, challenges regarding seismic interpretation of geological features and structure, such as misinterpretations due to resolution, seismic artifacts and illumination issues, can be avoided. The key part of seismic modelling is to compare the output, synthetic seismic based on an input geological model, with real seismic data. By this we can better judge if our interpretation of the seismic data is realistic and representative. At the same time it demonstrates what we can expect to resolve in the seismic data (Lecomte et al., 2015; Anell et al., 2016).

Seismic modelling can be carried out in different ways (Lecomte et al., 2015). The simplest method of making synthetic seismic is by 1D convolution with a reflectivity log based on vertical velocity and density variations in a well or from an outcrop. Such synthetic seismograms have large uncertainties and limitations in geologically complex areas since the 1D approach does not take lateral velocity variations into account (Lecomte et al., 2016). Still, this is a standard technique used for well-to-seismic tie in interpretation tools (_workflow A) (Mondol, 2015; Lecomte et al., 2016).

A more ideal and valid approach with the potential of resolving geological details is to perform full-wavefield modelling. However, this advanced technique is time-consuming and cannot be carried out on a routine base. The ray-based seismic modelling based on 2D/3D convolution (Lecomte et al., 2015, 2016) offers an efficient and flexible intermediate option. During recent years several case studies combining this modelling technique with outcrop studies have been carried out (Anell et al., 2016; Kjoberg, 2016; Rabbel, 2016) and it will also be applied to a field analogue in this study (workflow B). A comparison between the 2D/3D and the simple 1D convolution models is illustrated in Figure 3.6 and will be briefly discussed in the next sub-chapters.
Figure 3.6 A combined figure showing the main steps for the two ray-based modelling approaches. a) Reflection coefficient used in the 1D convolution plotted on the seismic data/image, b) the wavelet the RC from a) is convolved with. c) The result of the 1D convolution of a) and b). The seismic image from a) are convolved with a point spread function, PSF, d). The results of the 2D/3D convolution are shown in h) with perfect illumination and f) 45 degree maximum illumination (Anell et al., 2016). The PSF and illumination are detailed described under Chapter 3.3.2.

3.3.1 Workflow A: From well logs to synthetic seismogram

Workflow A (Figure 3.7) shows the steps from the input, well logs, to the output resulting in synthetic seismogram. A synthetic trace can be constructed from various parameters obtained from well log information. The synthetic seismic trace "represents the seismic trace that should be observed with the seismic method at the well location" (Mondol, 2015). By comparing the synthetic trace with the real seismic at the well location improves the horizon picking and the correctness and resolution of formations of interest.
The synthetic seismogram generation was done in Petrel, and computed on the basis of the well data. The acoustic impedance was calculated based on the sonic log and the density log, and then the reflection coefficients were calculated. For missing intervals, a measured density log has to be estimated based on the sonic velocity log.

The reflection coefficient, for normal-incidence, is calculated by the difference of the two acoustic impedances from the layer above and below the interface. The formula for reflection coefficient is given by:

\[
RC = \frac{l_2 - l_1}{l_2 + l_1} = \frac{(\rho_2v_2 - (\rho_1v_1)}{(\rho_2v_2 + (\rho_1v_1)}
\]

(3)

RC: reflection coefficient, I: acoustic impedance, \(\rho\): density and \(v\): velocity.

The reflectivity log generated from reflection coefficients calculated along the well is then convolved with the wavelet that was extracted from the seismic, resulting in the output 1D synthetic seismic trace. The wavelets extracted from the different type of seismic data were tested out and made a best fit to the real seismic. Together four synthetic seismogram generations were done and these are presented in Chapter 4, one for the P-Cable data and one

**Figure 3.7** Main steps in workflow A, from well logs to synthetic seismogram.
for the conventional seismic data for the Apollo and Atlantis wells. Synthetic seismograms were also generated for a standard Ricker wavelet with different dominant frequencies to illustrate the effect on the vertical seismic resolution.

Workflow A is done in the Petrel software, and is compared to the real seismic data in the same program (last step in Figure 3.7), both for P-Cable and conventional seismic data.

### 3.3.2 Workflow B: From field analogue to synthetic seismic data

Workflow B (Figure 3.8) represents main steps from the construction of the geological model of the field analogue, to the output and result, synthetic seismic done in the NORSAR software program SeisRoX. A similar workflow has been followed in several recent studies including Anell et al. (2016), Rabbel (2016) and Kjoberg (2016). Important steps from their works comprise: (1) geological framework, (2) photogrammetry, (3) petrophysical analysis, (4) seismic modelling and (5) seismic interpretation.

![Figure 3.8 Main steps in workflow B, from field analogue to synthetic seismic.](image)
Workflow B in this study is based on 2D geological models from New Mexico building on preliminary results of field work carried out by Anna van Yperen as part of her PhD project. This depositional system is being tested as a field analogue to the Lower Cretaceous depositional system that prograded across Svalbard and southwards to the southern Barents Sea, based on its similar depositional mechanisms, as well as basin configuration and scale.

Step one in the workflow is to construct the geological model. Parameters that are important for the geological model building include geometry, architecture and lithofacies. Further, elastic parameters such as density, P-wave and S-wave velocity are assigned to the geological model based on well logs from the study area in the Barents Sea (step 3 in Figure 3.8). Each layer in the model has distinct values. The construction of the geological model is described in more detail in Chapter 6.

After the geological model with the elastic parameters is ready, it was put into SeisRoX. The principles of the seismic modelling in workflow B (Figure 3.8) is a ray-based method using the convolution principle, but it takes advantages of more ray-based information results than just the two-way time (TWT) as in the 1D convolution. It is thus possible to do 2D/3D convolution simulating Pre-stack Depth Migrated (PSDM) images for about the same cost as seismic modelling using 1D convolution (Lecomte et al., 2003, 2016).

In real cases, the PSDM image is the output result of the seismic processing of the collected seismic data. The 2D/3D convolution modelling shows that such PSDM images can be seen as a filtered version of the true earth reflectivity model (Lecomte et al., 2003; Rabbel, 2016). Unlike 1D convolution working trace by trace (Chapter 3.3.1), the 2D/3D convolution method generates a modelled image in one convolution run. For performing that 2D/3D convolution, a filter function in the wavenumber domain is first calculated. This is called a PSDM filter.

A key element of the 2D/3D convolution modelling is the illumination vector, $\mathbf{I_{SR}}$ (Figure 3.9b), which is used to form the PDSM filter mentioned above. The $\mathbf{I_{SR}}$ is defined as the difference of the incident wavefield slowness vector, $\mathbf{p_r}$, and scattered wavefield slowness vector, $\mathbf{p_s}$

$$\mathbf{I_{SR}} = \mathbf{p_r} - \mathbf{p_s} \tag{4}$$

A slowness vector, $\mathbf{p}$, is perpendicular to the wavefront
Figure 3.9c shows how a reflector near the reference point can be illuminated if it is perpendicular to an ISR at that point; the reflector will then appear on the PDSM image (Lecomte et al., 2016). The illumination vector information in seismic modelling can be provided by either source and receiver pairs making a gathering of ISR, depending on the acquisition survey and a velocity model (Figure 3.9d), or by a generic ISR set (Figure 3.9e). In the first case a background model and survey information is given, while for the last case this is not necessary. Because of the limited information available for workflow B in this study, a generic ISR is used (Lecomte et al., 2016).

**Figure 3.9** Illustrating the key element, illumination vector, with different scenarios for seismic modelling. a) The raypath towards a reference point. b) The $\text{ISR} = \text{PR} - \text{PS}$ (slowness vectors) with a source, receiver and reference point. c) One illumination reflector dip. d) Set of source-receiver pairs with the range of illuminated reflectors. e) Generic ISR which is generated when the background velocity model and survey are unknown (Lecomte et al., 2016).
The PSDM-filter corresponds to a point-spread function (PSF) in the space domain. The PSF is the impulse response of a point scatterer through the combined effect of seismic acquisition and imaging. Since the PSF is a function of, among other, an input wavelet, the velocity model and seismic survey, it includes 3D resolution illumination effects (Lecomte et al., 2015). Size and shape of the PSDM-filter and PSF thus tell us something about the resolution, and what we can see or not see (Lecomte et al., 2016). The relation between the PSDM filter and PSF is illustrated in Figure 3.10.

Figure 3.10 The relation of the PDSM filter and PSF, with 45° max-dip (a) to perfect illumination in b (Lecomte et al., 2016).

Figure 3.10 (left) shows the frequency-dependent mapping of dip-limited $I_{SR}$, in this case 45° max-dip and 90° max-dip (perfect illumination) with the associated PSF (right side of Figure 3.10). It is also depending on the velocity. Transforming the PSDM filter from wavenumber domain to space domain is done by Fourier Transform (FT) resulting into the PSF showing the impulse response of the calculated PSDM-filter (Lecomte et al., 2016).

In this study, a 45° maximum illuminated dip is used for the generic PSDM filter (as a proxy for a standard seismic illumination), with an average velocity of 3 km/s, this for the two geological models. The output of this process, i.e., synthetic PSDM seismic, is plotted out
with the associated PSF to highlight the resolution difference of the different types of seismic. These results are presented in Chapter 6, and discussed further in Chapter 7.

The PSF-based 2D/3D convolution is more realistic than the standard 1D convolution one because it takes into account model- and survey-dependent 3D resolution and illumination effects, including diffraction energy. This results in a proper modelling of complex structures, when more advanced full-wavefield modelling is not affordable. The modelling allows the geologist to better understand seismic images, analyse them and possible improve their interpretation, thus being more critical and definite in their conclusions (Anell et al., 2016; Lecomte et al., 2015).
4  Well log interpretation and seismic tie

Seismic to well tie is, as mentioned in Chapter 3, an important method for picking the right horizons, and understanding the seismic signature of the horizons and the seismic facies of the sequences. First the formation tops were interpreted for the two wells before synthetic seismograms were constructed based on the velocity and density logs. Synthetic seismic traces were constructed for different wavelet frequencies, typical for both the conventional 3D seismic and the P-Cable data. Based on this exercise, the differences in resolution between the two seismic data types can be addressed.

4.1 Well logs and formations interpretation

The formation tops as listed on the NPD FactPages (NPD, 2017b) were correlated with the gamma ray, interval transit time (sonic log), velocity, density, PEF and neutron logs. The log responses were also compared with information about each boundary from the reference and type well of the formations given on the NPD FactPages (NPD, 2017b). The well reports from the operator of Apollo and Atlantis were also helpful. To strengthen the interpretation of the formations further, correlations were made to wells in the adjacent Fingerdjupet Sub-basin (7321/7-1, 7321/8-1 and 7321/9-1) (Figure 1.2).

Figure 4.1 shows the result of the well correlation between Apollo and Atlantis, and the interpreted formation tops. Apollo is the best well for interpreting the formation tops in the Lower Cretaceous succession based on the log responses. Here, gamma ray and sonic (both P- and S-wave) logs are measured from above the Kolmule Fm, while density and neutron logs are measured from intra-Kolmule Fm. These log responses can therefore be used identifying the tops of the Kolje, Knurr and Hekkingen formations. As Figure 4.1 shows, Atlantis has gamma ray response from the sea bottom downwards, but the other logs that can be used for lithology discrimination and well-to-seismic tie are not measured before intra-Kolje Fm.
Figure 4.1 Well correlation between Apollo and Atlantis, based on interpretation of the log response measured in depth (MD).
Below the criteria for the formation interpretation in this study are described, in a geological
time order, as well as the development in lithology discrimination and depositional
environment for the Lower Cretaceous formations. The basic principles for the log
interpretation are described in Chapter 3.1 and Appendix 1.

Top Hekkingen Fm is interpreted where it is a decreasing gamma log response, decreasing
transit time and increasing density trend (NPD, 2017b). A thin sandy limestone was
discovered in the reference well, and it could be the same kind of layer that is present at this
boundary between the Jurassic Hekkingen Fm and Lower Cretaceous Knurr Fm in Apollo and
Atlantis. Perhaps this thin limestone layer is a part of the Klippfisk Fm. Further up in the
Lower Cretaceous succession a distinct low gamma ray and high-velocity unit is recognizable
in both wells (see Figure 4.1). This is interpreted as a high-velocity intra-Knurr layer,
indicating a sandier layer. This can also be seen in several other wells, e.g. 7321/7-1, 7321/8-1
and 7321/9-1 in the Fingerdjupet Sub-basin.

From Top Hekkingen Fm up to the intra-Knurr high-velocity unit, the gamma log defines a
fining upward sequence. This could be an indication of increasing fine-grained sediments and
shale volume and a more distal environment, before going more proximal in the high-velocity
layer. The positive separation in the density-neutron log responds to dolomite and shale. In
the upper part of Knurr Fm, the depositional environment becomes more distal marine with
more variation of high gamma, low density and vice versa. The density-neutron plot shows a
larger positive separation than the lower part, indicating higher shale volume.

Top Knurr Fm (Base Kolje Fm) are represented by a gradually decreasing gamma ray and
transit time, and increasing density response (NPD, 2017b). A thin layer at the base of the
Kolje Fm in Apollo has a lower gamma response but still it likely represent rather fine-
grained sediments. The Kolje Fm is characterized by variations in gamma, sonic, velocity,
density and neutron log responses in Apollo. In Atlantis there are less variations in the trend
of the well logs. The variation of the log response fits well with definition of the formation.
Top Kolje Fm (base Kolmule Fm) is represented by a decrease in gamma ray, increase in
transit time and density (NPD, 2017b).

Top Kolmule Fm, corresponding to the upper regional unconformity (URU), is difficult to
identify because of a general lack of log data in the shallow parts of the two wells. The
gamma ray log can give some indication of the lithology and shows a higher sand content than the other Lower Cretaceous formations.

The PEF log for Apollo shows a log response of average 3-4 barns/electron (Figure 4.1) indicating shale. With the results from the density and neutron logs, the PEF values are plotted in Figure 4.2, illustrating typical log responses for the respective logs to various types of lithologies. For the Lower Cretaceous formations these log responses clearly indicate shale. The high-velocity intra-Knurr unit gives a higher PEF response, about 5 barns/electron and together with the density value of ~2.7 it may represent a limestone (Figure 4.2).

![Figure 4.2](image)

**Figure 4.2** The combined neutron-density logs and litho-density (PEF-log) responses for various lithologies (Mondol, 2015). Typical density, neutron and PEF log responses for the Lower Cretaceous formations in the Apollo well are plotted indicating a shale lithology. The arrow shows PEF and density values for the high-velocity intra-Knurr unit, which may correspond to a limestone.

Lithology discrimination was also done by using a cross-plot between the Vp/Vs ratio and acoustic impedance. For this interpretation the Vp, Vs and AI were estimated from the well logs (Table 4.1), and plotted into the rock physics template (Vp/Vs vs. AI) based on the concept from Ødegaard and Avseth (2004). This is shown in Figure 4.3, and the Lower
Cretaceous formations plot in the field of shales, with various content of fine and coarser grained material.

Table 4.1  Average density ($\rho$), P-wave velocity ($V_p$) and S-wave velocity ($V_s$) for the Lower Cretaceous strata taken from the respective well logs in Apollo. $V_p/V_s$ and acoustic impedance (AI) calculated from the first parameters (density, $V_p$ and $V_s$) are also included.

<table>
<thead>
<tr>
<th>Formation</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$V_p$ (m/s)</th>
<th>$V_s$ (m/s)</th>
<th>$V_p/V_s$</th>
<th>AI ($v^*\rho$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hekkingen</td>
<td>2.47</td>
<td>2857</td>
<td>1411</td>
<td>2.02</td>
<td>7057</td>
</tr>
<tr>
<td>Knurr</td>
<td>2.60</td>
<td>2894</td>
<td>1489</td>
<td>1.94</td>
<td>7524</td>
</tr>
<tr>
<td>Kolje</td>
<td>2.52</td>
<td>2891</td>
<td>1395</td>
<td>2.07</td>
<td>7285</td>
</tr>
<tr>
<td>Kolmule</td>
<td>2.54</td>
<td>2614</td>
<td>1375</td>
<td>1.90</td>
<td>6640</td>
</tr>
</tbody>
</table>

Figure 4.3  The $V_p/V_s$ vs. AI cross-plot rock physics template (RPT) from Ødegaard and Avseth (2004), with typical $V_p/V_s$ and AI impedance calculated from the log responses (Table 4.1). Values are plotted for Hekkingen Fm (green), Knurr Fm (purple), Kolje Fm (blue) and Kolmule Fm (red), all above the clean sand line and indicating fine-grained sediments. The black arrows show various conceptual geological trends; increasing 1) shaliness, 2) cement volume, 3) porosity, 4) decreasing effective pressure and 5) in increasing gas saturation (Ødegaard and Avseth, 2004).

To sum up, the lithology discriminations done in the study indicate mostly fine-grained sediments, with some variation of shale content. The layers with the lowest gamma, indicates more coarse-grained sediments, but still not clean sands. With the interpretation of the formation tops, next step of the well calibration is the seismic to well tie presented in Chapter 4.2.
4.2 Synthetic seismograms

The basic principles for seismic to well tie are described in Chapter 3.3 as Workflow A. Four synthetic seismogram generations, two for each well and seismic data type, were performed in Petrel.

The calibrated sonic log is used for the time/depth relation (TDR) between the seismic and wells. For the synthetic seismogram generation done for both P-Cable and conventional seismic in Apollo and Atlantis the original sonic log is used. Because of the lack of density logs for the Cretaceous in Atlantis and part of the Cretaceous in Apollo, an estimated density log was made from the sonic log. To get a full density log, the original measured density log and estimated density log were merged together.

Each of the four synthetic seismogram generations had a distinct characteristic wavelet that was extracted from the seismic data. A wavelet was extracted from both P-Cable and conventional seismic data for the two wells. To get the best possible wavelet for the seismic data of interest, parameters such as wavelength, time-depth relation, following the well head or not, and converting to zero phase or rotate to zero phase were tested. At the end, alignment points were set up to make a better fit. Alignment from the well data to the seismic data can be adjusted to improve the seismic to well tie and the wavelet. By using alignment points the time variant will be shifted manually, and the applied time shifts will update the depth-time relation for the well (Schlumberger, 2015).

The wavelets were tested for the interval of interest and a bit further down into the Jurassic. Sometimes two different wavelets are needed for the seismic to well tie of a seismic data set. For Atlantis one wavelet was extracted for the shallow part and one for the deeper part and merged together for the synthetic seismic generation. Otherwise, one wavelet had to be applied for the synthetic seismogram generations in the Apollo well. The best result of the synthetic seismogram generation and seismic-to-well tie was obtained for Apollo (Figure 4.4). This is because the synthetic trace is only presented in the area with sonic and density logs, giving a bigger interval of synthetic seismograms for the Lower Cretaceous units. The synthetic seismograms for Atlantis are shown in Figure 4.5. Figures 4.4 and 4.5 contain well panels with the logs that are used for defining the formation boundaries together with seismic panel of P-Cable and conventional seismic data with its respective synthetic trace plotted on.
Figure 4.4 Synthetic seismic generated from seabed down to Top Hekkingen Fm for P-Cable and conventional seismic data in Apollo together with the important well logs in depths. From left: gamma ray log (GR), density (DEN), neutron (NEU), Vp, Vs, pseudo density log, sonic log (AC), reflection coefficient (RC) and seismic panel for P-Cable and conventional seismic data with the synthetic seismogram plotted.
Figure 4.5 Synthetic seismic generated from seabed down to Top Hekkingen Fm for P-Cable and conventional seismic data in Atlantis together with the important well logs in depths. From left: gamma ray log (GR), density (DEN), neutron(NEU), Vp, Vs, pseudo density log, sonic log (AC), reflection coefficient (RC) and seismic panel for P-Cable and conventional seismic data with the synthetic seismogram plotted.
With the well panels together with the seismic and synthetic trace, it is easier to see which horizons correspond to the interpreted formation tops. The pseudo-density log plotted with sonic log, the reflection coefficient and the two seismic panels (first P-Cable data and then conventional seismic data) with the synthetic trace plotted on top are shown in Figures 4.4 and 4.5. As explained in more detail in Chapter 3.3, the pseudo-density log gives the acoustic impedance that again calculates the reflection coefficient. The reflection coefficient convolved with the extracted wavelet gives the synthetic trace which is compared to the P-Cable and conventional seismic.

Top Hekkingen Fm to Top Kolje Fm represents the main stratigraphic interval of interest in this study. Close-ups of the seismic response within this interval are shown in Figures 4.6 and 4.7, for Apollo and Atlantis respectively. Comparing the well logs and the synthetic seismic traces plotted on top of the real seismic, illustrates large variations in seismic response and resolution between the P-Cable and conventional 3D data. Whereas the conventional seismic has 2-3 reflectors, P-Cable data shows 5-6 reflectors within the same interval (Knurr Fm).

![Figure 4.6](image)

**Figure 4.6** The synthetic seismic generations from Top Hekkingen to Top Kolje for P-Cable and conventional seismic data in Apollo together with the important well logs in depths. From left: gamma ray log (GR), density (DEN), neutron (NEU), Vp, Vs, pseudo density log, sonic log (AC), reflection coefficient (RC) and seismic panel for P-Cable and conventional seismic data with the synthetic seismogram plotted.
Figure 4.7  The synthetic seismic generations from Top Hekkingen to Top Kolje for P-Cable and conventional seismic data in Atlantis together with the important well logs in depths. From left: gamma ray log (GR), density (DEN), neutron (NEU), Vp, Vs, pseudo density log, sonic log (AC), reflection coefficient (RC) and seismic panel for P-Cable and conventional seismic data with the synthetic seismogram plotted.

In Figure 4.8, the well logs (gamma ray and Vp) are plotted on top of the P-Cable data (left) and conventional seismic data (right) through the Apollo well. This illustrates how the well response correlates to the seismic response. As mentioned above, the number of seismic reflectors can vary inside the same interval, which appears very clearly from the TWT interval 750 ms – 830 ms. The same is illustrated with synthetic traces generated for a Ricker wavelet of different frequencies in Figure 4.9 compared to the synthetic trace generated above and the available seismic data types. Figure 4.10 shows a direct tie between the P-Cable and conventional seismic data at the Apollo well location.
Figure 4.8  Gamma ray (left) and P-wave velocity (right) from Apollo, plotted on P-Cable data (left).

Figure 4.9  Synthetic seismic traces generated for Ricker wavelets with various dominant frequencies (30, 50, 100 and 150 Hz), synthetic trace generated from extracted wavelets from the seismic and the actual seismic data.
Figure 4.10 Tie between P-Cable and conventional seismic data at the location of the Apollo well measured in TWT (ms).

Typical frequencies of the Barents Sea seismic data sets (Figure 4.11) form the basis for the selection of frequencies used in the seismic modelling. The conventional seismic data have dominant frequencies between 20 and 60 Hz, while the P-Cable data have frequencies up to at least 200 Hz. The different seismic data types will be further compared in the next chapter, and the differences in seismic resolution will be discussed later in Chapter 7.

Figure 4.11 Examples of different frequencies in the P-cable and conventional seismic
5  Seismic interpretation

This chapter contains the seismic interpretation and the result of the seismic mapping. Seismic examples with different resolution, both 2D/3D P-Cable data and 2D/3D conventional seismic data will be presented throughout this chapter to illustrate important observations related to Lower Cretaceous depositional units and structures in the Hoop area. The varying seismic resolution will be discussed further in Chapter 7. Further in this chapter, the interpreted seismic horizons and sequences are presented in stratigraphic order, starting with H1. The descriptions of the main depositional and structural features will be supported by seismic examples, time-structure and time-thickness maps as well as results from seismic attribute analyses.

Given the main focus of this study, four main seismic horizons were picked and interpreted in both P-Cable and conventional seismic data (Figure 5.1). These were identified and traced based on the seismic to well tie presented in Chapter 4 and the interpretation strategy described in Chapter 3.2.2.

![Figure 5.1 Seismic to well correlation of the Apollo well. The seismic stratigraphic framework is linked to both P-Cable and conventional seismic data. URU: Upper Regional Unconformity.](image)

### Table 5.1 Seismic stratigraphy

<table>
<thead>
<tr>
<th>Seismic stratigraphy</th>
<th>Lithostratigraphy</th>
<th>Chronostratigraphy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-Cable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seabed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **S4** Quaternary
- **S3** Kolmule
  - Cenomanian
  - Albian
- **S2** Kolje
  - Aptian
  - Barremian
- **S1** Knurr
  - Hauterivian
  - Valangian
  - Berraisian
- **H1** Hekkingen
  - Volgian
Figure 5.1 shows the correlation of the Apollo well with the mapped seismic reflections. H1 is located near Top Hekkingen Fm, and represents the boundary between Late Jurassic and Early Cretaceous in the study area. H2 is located near Top Knurr Fm, hence of Hauterivian-Barremian age and H3 is located near Top Kolje Fm in the Aptian. The last interpreted horizon corresponds to the top of the Lower Cretaceous strata (Kolmule Fm) preserved in the Hoop area, and is called URU (Upper Regional Unconformity).

The interpreted seismic horizons define four sequences in the study area, S1 (bounded by H1 and H2), S2 (bounded by H2 and H3), S3 (bounded by H3 and URU) and S4 (bounded by URU and the seabed). S1, S2 and S3 are of Early Cretaceous age, while sequence S4 is of Quaternary age. This means that sediments of Late Cretaceous to Pliocene are missing in the study area due to several phases of uplift and erosion (Figure 2.2).

The polarity of each interpreted horizons with respect to seismic data types is listed in Table 5.1. Most horizons have the same polarity, peak or trough, both in the P-Cable and conventional seismic data. However this is not the case for H2, which was interpreted on negative blue (trough) in P-Cable and positive red (peak) in conventional data (Figure 5.1). This can be explained by seismic resolution and interference, which we will come back to later. A more detailed description of the interpreted horizons and sequences is given in the next sub-chapters, which are divided into the sequences starting from the oldest in geological time (sequence 1).

Table 5.1 Overview of the polarity of the interpreted seismic horizons in P-Cable and conventional seismic data.

<table>
<thead>
<tr>
<th>Seismic horizon name</th>
<th>Polarity in P-Cable data</th>
<th>Polarity in Conventional data</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Trough</td>
<td>Trough</td>
</tr>
<tr>
<td>H2</td>
<td>Trough</td>
<td>Peak</td>
</tr>
<tr>
<td>H3</td>
<td>Trough</td>
<td>Trough</td>
</tr>
<tr>
<td>URU</td>
<td>Peak</td>
<td>Peak</td>
</tr>
</tbody>
</table>

Building on the well to seismic ties described in Chapter 4, seismic tie lines between the Apollo and Atlantis wells are presented, both using composite P-Cable seismic (Figure 5.2) and conventional seismic from the 3D cube (Figure 5.3). A direct tie between P-Cable and conventional seismic data at the location of the Apollo well was shown in Figure 4.10.
Figure 5.2 Tie from Apollo to Atlantis in P-Cable data with the interpreted seismic horizons (H1, H2, H3 and URU) and the formation tops (Hekkingen Fm, Knurr Fm, Kolje Fm and Kolmule Fm described in Chapter 4). Data courtesy of TGS, WGPS and VBPR.
Figure 5.3  Tie from Apollo to Atlantis in conventional seismic data with the interpreted seismic horizons (H1, H2, H3 and URU) and the formation tops (Hekkingen Fm, Knurr Fm, Kolje Fm and Kolmule Fm described in Chapter 4). Data courtesy of TGS.
Comparing Figures 5.2 and 5.3 highlight the contrasting resolutions between the two seismic data types. The lines also give an indication of how the seismic reflections behave. The main reflections, especially the interpreted ones, are easy to trace between Apollo and Atlantis.

5.1 Sequence 1 (Knurr Fm/Klippfisk Fm)

Sequence 1, bounded by H1 and H2, corresponds to the Knurr/Klippfisk formations. The H1 and H2 horizons are parallel to each other, so when H1 first was interpreted it was easy to trace H2. In the P-Cable data both horizons were interpreted on trough (blue), and in the conventional data H1 was interpreted on trough (blue) while H2 was interpreted on a peak (red). H1 and H2 are generally well traceable in the P-Cable data, but amplitude variation, 2D line orientation changes, and faults occasionally complicates this task. The two horizons were relatively easy to follow in the conventional 3D data but their separation is close to the vertical seismic resolution of the data.

In the conventional 3D seismic cube every 50-100 inline and crossline were interpreted with the 2D auto-tracking interpretation tool, in areas with strong and continuous reflections that were easy to follow. In some areas it was more difficult to correlate the H1 and H2 horizons across faults. Here, each 1-25 inline and crossline were interpreted with the same interpretation tools. Finally, the horizon interpretation was completed by using the 3D auto-tracking tool. The 3D auto-tracking was checked systematically by scrolling through the result and manually correcting misinterpretations. Such misinterpretations in the 3D auto-tracking typically occur close to faults and erosional unconformities, and sometimes in areas with weak amplitudes. The interpreted seismic horizon was then converted to the surface shown in the H1 time-structure map in Figure 5.4. This time-structure map also represents H2 because it is parallel, follows H1 in the whole cube and is only one reflection above in the conventional 3D seismic data.

The H1 time-structure map (Figure 5.4 and Appendix 3) shows the main structural elements within the study area. It is also used in this study as an index map showing the coverage of the available seismic data. In addition, it is used as input to perform different surface attributes that are presented later in this chapter.
Figure 5.4 Time-structure map of H1 surface with location of Apollo, Atlantis and the P-Cable data in the study area. This horizon represents the data coverage of the 3D conventional data.

The H1 horizon is also applied as a flattening datum to remove the effects of younger faulting when studying the Lower Cretaceous prograding sedimentary unit. A major part of the study area was affected by extensional faulting after deposition of the prograding unit. Flattening on the H1 horizon nicely restores the characteristic clinoforms within the lowermost Cretaceous above and Upper Jurassic sequences below having rather uniform thickness (Figure 5.5). This shows that the main late Mesozoic faulting in the Hoop area occurred in the Early Cretaceous (post-Barremian) while little faulting affected the area during Late Jurassic time. The Early Cretaceous rifting will be further described below in relation to Sequence 3.
Figure 5.5  Seismic example (both flattened and unflattened) showing that the faults were mainly active in the Early Cretaceous – postdating and offsetting S2 corresponding to the Kolje Fm. Data courtesy of TGS.

S1 (equivalent to the Knurr Fm) is between 30 m and 36 m thick in the Apollo (Figure 4.6) and Atlantis (Figure 4.7) wells corresponding to 20 ms and 24 ms in the seismic using a velocity of 3000 m/s. S1 is a rather thin and uniform with the parallel base (H1) and top (H2) the two seismic surfaces will look more or less the same (as shown in Figure 5.4). The uniform thickness of Sequence 1 indicates that it was deposited during a rather quiet tectonic period.

The seismic sequence corresponding to the Knurr Fm is a good example of the seismic resolution difference between the P-Cable and conventional seismic data (Figures 4.6 and 4.7). The seismic sequence is difficult to resolve in the conventional seismic data where the interpreted horizon H2 is just one seismic reflection cycle above H1. In the P-Cable data it is possible to distinguish between the top and bottom of the sequence, as well as variation within the unit. Figures 4.6-4.7 and 5.2-5.3 show how Sequence 1 consists of 5-6 strong reflections in the P-Cable data, while the same package is represented by 2-3 reflections in the conventional seismic data. The high-velocity intra-Knurr Fm unit interpreted in the well logs
(Figures 4.6-4.7), can be distinguished from the top and bottom of the formation in the P-Cable data, but not in conventional data. It seems like this layer could be identified as a strong trough between H1 and H2 in the P-Cable data (Figure 5.2 and seismic-to-well tie in Chapter 4).

S1 becomes thinner against the platform in the north, which results in a change in the seismic response making it difficult to distinguish the top and base. The northernmost part of the profile (Figure 5.6) only shows H1 as a strong reflection. As mentioned before, S1 is equivalent with the Knurr Fm which again is time equivalent with the thin lateral Klippfisk Fm (Figure 2.3). Could this change in amplitude correspond to the boundary between Knurr Fm and Klippfisk Fm?

The Klippfisk Fm, representing a thin limestone of early Barremian age (Århus, 1990; 1991) was penetrated by a shallow IKU corehole located on the platform a short distance to the west of the seismic profile shown in Figure 5.6. The transition from the Knurr Fm to the Klippfisk Fm may be located somewhere along the seismic line in Figure 5.6, most likely associated with the faults towards the northern end of the line. The limestone of the Klippfisk Fm, representing a thin and condensed unit deposited on the platform, is expected to give rise to a strong reflection. Figure 5.7 shows a composite line from Apollo towards northeast to Atlantis and further north to the IKU corehole (composite line marked in Figure 3.1) in the conventional seismic data.

**Figure 5.6** 2D P-Cable seismic profile showing changes in thickness and amplitudes associated with sequence S1, bounded by H1(cyan) and H2 (green). These changes may be related to the transition between Knurr Fm and Klippfisk Fm. Data courtesy of TGS and VBPR.
5.2 Sequence 2 (Kolje Fm - prograding unit)

S2 is bounded by H2 at the base and H3 at the top. It corresponds to the Kolje Fm, which in the Hoop area comprises the Lower Cretaceous prograding unit being the main target of this master study. Observations made within S2 in the study area are compared both to Svalbard and the field analogue in New Mexico (Chapter 6).

Tracing H3, on top of S2, was the most challenging horizon to interpret. H3 was easy to identify and interpret close to the Apollo and Atlantis wells (Figures 5.2 and 5.3). Here it represents a strong seismic reflection of good continuity. Moving to the east into the graben structure or to the west and north towards the prograding system, it is challenging to interpret H3. To help in the interpretation of H3 at the top of the prograding unit, flattening was carried out on H1 or H2, removing the effects of younger faulting. The clinoforms of the prograding unit are thus restored. Still it was difficult to make a consistent interpretation of H3 across the entire data set. Another challenge in the interpretation of H3 is caused by the wedge-shaped units that could be interpreted as part of the prograding S2 system or they may have formed in response to the faulting that affected the area after the deposition of S2. H3 is close to or truncated by the upper regional unconformity in some areas (in north-northwest) causing an additional problem in the interpretation of this key horizon.
To improve the confidence of the H3 interpretation in western parts of the study area, a tie to the adjacent Fingerdjupet Sub-basin (Figure 1.2) was established using two of the regional conventional seismic 2D lines (Figure 3.1). H3, and the underlying H2 and H1, were identified in well 7321/7-1 and traced from the well location in the western Fingerdjupet Sub-basin to the western part of the study area covered by the 3D seismic cube (Figure 5.8). The unit corresponding to S2 in the study is thick in the Fingerdjupet Sub-basin, and the prograding system only makes up parts of sequence S2 in this area (Figure 5.8). A well constrained rift event affected the Fingerdjupet Sub-basin after deposition of the S2 (note the nomenclature from this study, marked in Figure 5.8), and this event can be tied to the Hoop area along the same regional lines (see Chapter 5.3). S2 and S3 (described in next subchapter) are coloured in blue and orange respectively along the 2D seismic profile.

Figure 5.8 Seismic tie from the Fingerdjupet Sub-basin to the Hoop area and the Bjarmeland Platform. S2 (between H2 and H3) and S3 (between H3 and URU) are coloured in blue and orange, respectively. Syn-rift sediments in the Fingerdjupet Sub-basin affected by the tectonic activity in lower S3 is marked in the black box. Location of the 2D line is given in Figure 3.1 and 5.21. Data courtesy of TGS and Spectrum.

S2 in the Fingerdjupet Sub-basin are divided into two parts, one lower part where clinoforms are observed and one upper part without. This is likely also the case in western parts of the study area.
A time-thickness map of S2 is shown in Figure 5.9. The map reflects some line effects in the northwestern part of the study area related to uncertain correlations across faults and chaotic reflections caused by the prograding unit. The thickness map reveals a significant thinning from northwest to southeast reflecting the prograding system that came in from the north-northwest.

![Time-thickness map of the S2](image)

**Figure 5.9** Time-thickness map of the S2, with corresponding colour scale in ms. Red represents the thickest parts (~250 ms). The dotted line illustrates the front of the clinoforms in S2, based on the pinch out seen on the seismic where some of these are shown in Figure 5.13. The black lines a-f, represents the location of the seismic profiles presented in Figure 5.13. Data courtesy of TGS.

The prograding delta system from Svalbard pinches out inside the study area before reaching the locations of the Apollo and Atlantis well (Figures 5.10-5.13). The pinch-out lines for Figure 5.13 are marked on the time-thickness map (Figure 5.9). S2 thickens from 37 m in Apollo to 70 m in Atlantis (Figures 4.4 and 4.5). A useful tool to interpret the prograding system and improve the understanding of the deltaic sediments is flattening of the downlap surface. By flattening H1 or H2 the clinoforms and clinothems can be studied in greater detail, as shown in Figures 5.10 and 5.11.
Both higher (blue interpretation) and lower (red interpretations) order of clinoforms can be identified in P-Cable data (Figure 5.10). Profile (unflattened and flattened) to the left shows a inline from the 3D P-Cable cube Area D, while right side of the figures shows the 2D P-Cable line crossing Atlantis. These are set up together to illustrate the tie from Atlantis up to Area D, and to see the development of the clinoforms.

Higher and lower order clinoforms are also documented in the north part of the study area (Figure 5.11) at the same profile presented for the Knurr and Klippfisk formations relations. In contrast to the profile in Figure 5.10, only one lower-order clinoform is observed, with several higher-order.
Only the lower-order clinoforms are observed in the conventional seismic data (Figure 5.12b and 5.13), because the higher-order clinoforms are below seismic resolution for this seismic data type. The visibility of clinoforms in P-Cable and conventional data is compared in Figure 5.12 in a seismic profile showing the termination before the Atlantis. A brightening event in front of the delta/prograding unit is observed in both seismic data types.

Selected examples of the tuning and front of the prograding system are shown in Figure 5.13, and are the base for making the front line marked in the time-thickness map of S2 (Figure 5.9).
Figure 5.12 Coincident 2D P-Cable data (a) and conventional 3D seismic data (b) showing pinch out of the prograding system near Atlantis. Flatten on H1 (blue). Data courtesy of TGS and VBPR.
Figure 5.13 Selected conventional 3D seismic lines (a-d) and 2D P-Cable seismic lines (e-f) showing prograding system in S2 from NNW to SSE. Flatten on H1(blue). Locations of the seismic lines a-f are shown in Figure 5.9. Data courtesy of TGS and VBPR.
3D seismic can not only give the dip as the 2D lines, but also the direction of the clinoforms. The next figures (5.14-5.18) show examples from the two narrow P-Cable 3D seismic cubes, Area D and Area C.

Once again the resolution differences of P-Cable and conventional seismic data are clearly reflected in the figures. A selected inline in Area D (Figure 5.14) and Area C (Figure 5.15) are compared to the corresponding composite line in the conventional data.

The detailed interpretation and calculation of dip is done on flattened P-Cable seismic data. Close-ups of clinoforms from selected areas, and their main characteristics and geometries, are shown in Figure 5.16. The characteristics and dip of the clinoforms in S2 are summarized in Table 5.2.

**Table 5.2** Characteristics for selected examples of clinoforms with height and dip formation. The interval velocity used in the calculation is 2900 m/s.

<table>
<thead>
<tr>
<th>Location/data type</th>
<th>Characteristic</th>
<th>Order</th>
<th>Height (ms)</th>
<th>Height (m)</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area C, 3D</td>
<td>Oblique parallel</td>
<td>Higher</td>
<td>35 ms</td>
<td>50 m</td>
<td>2.1°</td>
</tr>
<tr>
<td>Area D, 3D</td>
<td>Oblique parallel</td>
<td>Higher</td>
<td>35 ms</td>
<td>50 m</td>
<td>1.5°</td>
</tr>
<tr>
<td>Near Atlantis, 2D</td>
<td>Sigmoid</td>
<td>Higher</td>
<td>30 ms</td>
<td>44 m</td>
<td>1°</td>
</tr>
<tr>
<td>Near Atlantis, 2D</td>
<td>Sigmoid</td>
<td>Lower</td>
<td>37 ms</td>
<td>54 m</td>
<td>0.4°</td>
</tr>
</tbody>
</table>

The orientation of clinoforms is illustrated in Figure 5.17, with time-slices of the prograding units in the two 3D cubes, Area C and Area D. One time-slice for each 3D cube is taken within the clinoform interval, and one is taken at the level of H1/H2 to highlight the faults (see corresponding vertical sections in Figures 5.14 and 5.15). The blue arrows mark the clinoform orientation in the time-slices, which indicate that the prograding unit came in from the NNW of the study area. The faults in this area (penetrating S2), marked with red arrows, have a dominant W-E orientation.
Figure 5.14 Clinoforms in Area D in both P-Cable data (a-unflattened and c-flattened on H2) and conventional seismic data (c-unflattened and d-flattened on H1) in the same area. Data courtesy of TGS, VBPR and WGPS.
Figure 5.15  Clinoforms in Area C in both P-Cable data (a-unflattened and c-flattened on H2) and conventional seismic data (b-unflattened and d-flattened H1) in the same area. Data courtesy of TGS, VBPR and WGPS.
Figure 5.16 Close-up of clinoforms with measured dip and characteristic type of clinoform in top – Area C, middle – Area D and bottom 2D P-Cable data near Atlantis. Data courtesy of TGS, VBPR and WGPS.
Figure 5.17 Time-slices of Area C (left) and Area D (right) with location on the H1 surface. Dotted line illustrates the front of the prograding delta system in the study area. Data courtesy VBPR and WGPS.
Based on the observed orientation of the clinoforms the black arrows towards the front shows the direction of delta progradation northwest to the southeast. The front line of the prograding system, which has been documented earlier in Chapter 5.2, is also plotted on top of the H1 surface.

Figure 5.18 shows time-slices of P-Cable (from Figure 5.17) on top of conventional data in the same area. Looking at the time-slices gives another understanding of the resolution difference between the two types of seismic data.

Various seismic attributes have been tested to improve the imaging of the clinoforms and clinothems. This was primarily done on the P-Cable data and some attributes for the same seismic line as in Figure 5.12a through Atlantis are shown in Figure 5.19. The attributes that best highlight the clinoforms include 3D edge enhancement, the sweetness attribute and the

![Figure 5.18](image-url) Time-slices of P-Cable data on top of conventional seismic data in Area C (left) and Area D (right). See Figure 5.17 for location. Data courtesy of TGS, VBPR and WGPS.
cosine of phase. The basic principles of these were briefly described in Appendix 2 with reference to Schlumberger (2015).

**Figure 5.19** Selected seismic attributes for the same P-Cable seismic line as shown in Figure 5.12a. a) Original seismic, b) 3D edge enhancement, c) sweetness and d) cosine of phase. Data courtesy of TGS and VBPR.

A bright event is observed in front of the prograding system close to its termination (Figure 5.19). This can partly be a tuning effect associated with the pinch-out of the system, but it may alternatively represent an elongated depositional unit giving rise to the prominent high amplitude event seen in the attribute map in Figure 5.20. This is a RMS surface attribute of the H1 showing amplitudes within a window of 100 ms above (including S2). The RMS amplitude is plotted on the H1 surface in TWT and extracted values from the variance cube realized. RMS amplitude is made transparent for lower amplitude differences, which cause the high amplitudes (purple, brightening) to clearly be displayed on the H1 surface. This follows the same line as the thinning seen in the thickness map of S2 (Figure 5.9). The variance map is also done partially transparent to highlight the faults in the area. Interestingly, this anomaly is also associated with high resistivity in the EM data, shown in Figure 5.20.
Figure 5.20 Attribute map (seismic data courtesy of TGS) showing bright event along the front of the prograding system with EM data showing high resistivity along the trend of the bright event. EM data from Carstens (2015).

The bright event likely represents a channel that developed along the front (pinchout) of the prograding unit coming from north-northwest. The location and nature of this feature, and the regional implications, will be further discussed in Chapter 7.

Interpretation of the 2D P-Cable data shows that the front of the prograding system make a bend and continues southeastwards on the Bjarmeland Platform (Figure 5.9). Since the prograding delta system reaching the Hoop area from the NNW likely continued southeastwards on the Bjarmeland Platform, and there appears to be different views on this area between Dimitriou (2014) and Marin et al. (2017), this study was extended some distance into the NW Bjarmeland Platform (Figure 5.21). For this, a set of 2D (NBR) seismic lines
were selected from the regional Barents Sea database at the Department of Geosciences, University of Oslo.

The prograding system was identified on 2D lines across the area of 3D seismic data coverage and the interpretation was extended southeastwards along selected NW-SE oriented 2D lines. They all show that it was possible to follow the prograding system across parts of the Bjarmeland Platform towards SE. Elected dip lines are shown in Figure 5.22 and they all reveal clinoforms prograding towards SE. The NE-SW oriented cross-lines show different seismic signatures across the prograding system (Figure 5.22). These observations are consistent with a delta system prograding towards SE from the Hoop area across parts of the Bjarmeland Platform as Dmitriou (2014) proposed in her study. This is however in contrast to the interpretation of Marin et al. (2017) indicating a progradation from NE towards SW of their S3 unit (Figure 5.21).

![Figure 5.21](image-url) Structural map of the SW Barents Sea with interpretations for this and previous studies, outline of the 3D conventional seismic data coverage, in addition to wells. The long 2D line going from Bjarmeland Platform to Fingerdjupet Sub-basin is shown in Figure 5.8. The numbered 2D conventional seismic lines are shown in Figure 5.22 (basemap from NPD FactMap, 2017).
Figure 5.22  2D conventional seismic lines showing the prograding delta system in dip (left) and strike (right) direction. See Figure 5.21 For location of profile 1-8. Data courtesy of TGS and Spectrum.
5.3 Sequence 3 (Kolmule Fm)

S3 is bounded by H3 at the base and URU at the top, and it corresponds to the Kolmule Fm. Rifting affected the Hoop area during deposition of the lower parts of the S3 giving rise to thickness variations across the area (Figures 5.23 and 5.24). The rift structures are seen on all interpreted horizons from H1-H3. The most prominent structural feature is a segmented graben system with a NE-SW orientation, changing to N-S in the northern part of the study area (Figures 5.4 and 5.20). The faults bounding this system is cross-cut by a system of WNW-ESE fractures. The timing and nature of the faulting will be discussed in more detail in Chapter 7.

The upper regional unconformity (URU) is formed in response to Cenozoic uplift and erosion. This erosion modified the thickness distribution of the S3 and locally also the S2. On URU each 50-100 inline and crossline was interpreted with 2D auto-tracking interpretation tool, and in some places manual tool. Further the 3D auto-tracking tool was used to fill out the rest of the seismic horizon, since this seismic reflection is strong and continuous. The time-structure map of URU is shown in Appendix 3.

Figure 5.23 Rift structure in Hoop fault complex in 3D view southeast in the study area. The H1 surface is plotted in the 3D window with a crossline and inline in the conventional seismic crossing the graben. H3 is interpreted on the crossline and inline, and faults marked terminate in upper part of S3. Data courtesy TGS.
The rift basin infill shows that the faulting postdates the deposition of the prograding unit within S2. The faults in the study area terminate in the upper part of S3 before reaching URU (Figures 5.23 and 5.24). S2, which is coloured in blue, has a rather uniform thickness indicating deposition during a tectonic quiet period. The lower part of S3 shows thickening in a wedge-shaped geometry towards the fault plane, indicating that this part was deposited during the faulting. These syn-rift sediments are marked with arrows in Figure 5.24, showing the thickening towards the fault plane.

![Figure 5.24](image)

**Figure 5.24** NW-SE Seismic line showing graben structures and associated faults. S2 is coloured in blue and has a rather uniform thickness, while lower part of S3 thickens towards the fault plane (indicated with black arrows) making a wedge shaped (syn-rift) geometry. Data courtesy of TGS.

To highlight the main fault trends in the study area, various attributes were generated on the conventional 3D seismic volume (Figure 5.25). The input in the workflow was a time-gained realized 32-bit cube. Smoothening and median filter was applied to remove some of the noise, before running variance and ant tracking.

The variance and the ant tracking cubes show clearly the main fault trends. N-S and W-E faults cross-cutting each other are dominant (Figure 5.25c-d). This fault pattern has also been reported by Collanega et al. (2017) and will be discussed later.
Figure 5.25 Figure showing seismic attributes on a time-slice in conventional seismic data (data courtesy TGS), compared to the H1 surface (a). b) Result of applying smoothening and median filter on the seismic data. c) Variance added to the output b and d) ant tracking the output of c.

The fault orientation can also be studied by looking at time-slices. The combined time-slice, for both P-Cable and conventional data, in Figure 5.26 clearly pick up the faults.
Figure 5.26 Time-slice 844 ms of P-Cable seismic in Area C plotted together with the time-slice at same time-depth in conventional seismic data. Data courtesy of TGS, VBPR and WGPS.
6 Seismic modelling of field analogue

This chapter contains workflow B of the seismic modelling introduced in Chapter 3.3.2. The purpose of doing synthetic seismic from the field analogue in northeast New Mexico is to compare this to the Lower Cretaceous depositional system that prograded from Svalbard towards the Hoop area in the SW Barents Sea (Figures 2.5 and 5.9). How the different units of the New Mexico system can be imaged by seismic data with different frequency content comparable to P-Cable and conventional seismic data from the Hoop area, has been tested out in this study.

The Cretaceous fluvial to deltaic system going from Colorado down into northeast New Mexico (Figures 6.1 and 6.2) is of comparable size and style to the system that reaches from Spitsbergen, Svalbard to the Hoop area and Bjarmeland Platform in the SW Barents Sea, and has been selected specifically for this purpose. The source to sink distance for the Svalbard-SW Barents Sea depositional system is ~400 km (Figure 2.5), compared to ~350 km for the Colorado-New-Mexico system (Figure 6.1).

Figure 6.1 Maps showing the regional setting and location of areas logged during field work by Anna van Yperen (personal communication). 1) Lindsey’s Ranch, 2) Apache 3) Apache, 4) Mesa Ronda, 5) Liberty Mesa and 6) Trigg Ranch.
The outcrops on Svalbard are limited to the fluvial component of the depositional system, while the distal, and presumably marginal marine, component is visible on seismic profiles in the SW Barents Sea only. Furthermore, an erosional gap of nearly 300 km eliminates any investigation of strata between the Spitsbergen outcrops and the Bjarmeland Platform subsurface strata (Midtkandal et al., 2014). The Mesa Rica depositional system in Colorado, Oklahoma and New Mexico (Holbrook and Dunbar, 1992; Holbrook, 1996) is considered to have developed in similar conditions as the Lower Cretaceous Svalbard/Barents Sea strata (Midtkandal and Nystuen, 2009), and allows a detailed inspection of the distal termination, expressed as a series of deltaic clinothems in eastern New Mexico. A PhD student at the University of Oslo, Anna van Yperen, is looking closer into this deltaic system and field analogue, and the seismic modelling in this study is based on preliminary results from her study.

Figure 6.2 Regional dip section of the Cretaceous depositional system extending from Colorado to New Mexico (see Figure 6.1 for location). The black box indicates the main study area in northeast New Mexico, which forms the basis for the seismic modelling in this thesis. Modified from Holbrook et al. (2006) by Anna van Yperen (personal communication).

The comparison of the seismic modelling and the seismic data in the Hoop area, will explore how seismic data can image typical depositional architecture in such a prograding delta system. A range of different seismic properties will be tested. The seismic modelling results will be presented in this chapter and further discussed in Chapter 7.
A brief geological framework of the field analogue in New Mexico is presented, with focus on the Lower Cretaceous sediments here (Chapter 6.1). Subsequently, the construction of geological models from the field analogue is shown step by step (Chapter 6.2) followed by the seismic modelling and results (Chapter 6.3).

6.1 Background

The field analogue comprises Albian-Cenomanian strata representing a depositional system changing from fully fluvial (from Colorado towards Mosquero) to fully deltaic in northeast New Mexico (Tucumcari Basin) (see Figures 6.1 and 6.2). This system developed within the Western Interior Seaway (Figure 6.3; Blakey, 2014).

![Figure 6.3](image)

**Figure 6.3** Paleogeography of the Western Interior Seaway from Late Albian to Middle Cenomanian times for New Mexico and surrounding states. NM: New Mexico; Co: Colorado. Based on Blakey (2014).

The Lower Cretaceous sediments in north-eastern New Mexico were deposited during marine transgression and regression in the Late Albian-Early Cenomanian (Holbrook and Dunbar, 1992; Blakey, 2014). Three main Lower Cretaceous units (Tucumcari Shales, Mesa Rica Sandstone and Pajarito Formation) are represented in the geological model, and these are presented briefly below.
The Albian Tucumcari Shale is composed of prodeltaic marine sediments and related to the connection of the Tethys and Boreal oceans through the Western Interior Seaway (Blakey, 2014). The formation overlies the Jurassic Morrison Formation (Holbrook et al., 1987) and is the oldest marine Cretaceous formation present in east central New Mexico (Lucas et al., 1988).

The Mesa Rica Sandstone represents a changing system from fully fluvial to deltaic and is dated to be of Albian-Cenomanian age (Oboh-Ikuenobe et al., 2008; Scott et al., 2004). It represents the main prograding unit with clinoforms, and these overly the prodelta Tucumcari shales. The Mesa Rica Sandstone unit comprises distal bar, distributary-mouth bar and distributary-channel belts (Holbrook et al., 1987).

The Pajarito Formation comprises paralic strata representing a coastal plain depositional environment (e.g. Holbrook and Dunbar, 1992; Oboh-Ikuenobe et al., 2008). The Pajarito Formation overlies both fluvial and deltaic Mesa Rica Sandstone units (Holbrook and Dunbar, 1992; Lucas et al., 1988).

Two particular areas, Trigg Ranch and Apache Canyon (Figures 6.1 and 6.4), have been studied in greatest detail (van Yperen, pers. com.). The Trigg Ranch area resembles the transitional area from fully fluvial to shallow marine, unlike for the more distal and deltaic Apache Canyon area. Clinoforms are observed in both areas, which are separated by ~75 km. A question that remains unanswered, and a source of uncertainty, is which of the clinoforms were deposited first. The different scenarios have significantly different implications, e.g. retrogradation with younger delta deposits to the north, or progradation with younger strata to the south. The latter scenario forms the basis for Figure 6.4, suggesting a prograding but down-stepping clinoform succession as the result of a sea level fall (van Yperen, pers. com.). It is difficult to differentiate between the various scenarios based on the available data as of today. Detailed biostratigraphy could potentially address this issue, but is beyond the scope of this study.
A combination of limited stratigraphic control and long distances between the outcrops that exceed direct correlation is a source of uncertainty in the New Mexico analogue as well as for the Barents Sea strata, unfortunately. However, efforts are made to model realistic geologic scenarios in the following settings, despite inherent uncertainties that are of less consequence to this approach.

6.2 Construction of geological models

Two 2D geological models were constructed for the Apache Canyon and Mesa Ronda-Lindsey’s Ranch areas (see Figure 6.1 for location) based on field data, supplemented with information from Google Earth where applicable. The Apache Canyon model is mainly a depositional strike section, while the Mesa Ronda-Lindsey Ranch model is a dip-oriented section. The models will further be referred to as the "strike-model" and the "dip-model".
Important elements in the model building are the model geometry and architecture, lithofacies distribution, and elastic parameters (see also Chapter 3.3.2). The model geometry shows the lateral and vertical extent of each of the depositional units in focus, in addition to overburden and sub-stratum layers. The rather simple 2D models were constructed based on field logs and descriptions, photos and Google Earth images. The key information integrated for the Apache model is shown in Figure 6.5 and the log correlations are shown in Figure 6.6.

Figure 6.5 Location of the Apache profile (A-A’) taken from Google Earth, with photo mosaic from the field work. The log locations are also marked in the photos. This profile formed the basis for the geological strike-model.

The interpretation and correlations are divided into facies rather than lithostratigraphic units in Figure 6.6. The ~15 m thick Tucumcari Shale is fully marine prodelta shales (dark blue). The prograding Mesa Rica strata are divided into four facies; distributary channel (yellow), mouth bar facies (brown), transitional mouth bar to distal facies (grey) and completely bioturbaded distal bars (turquoise). The 9-11 m thick Pajarito Formation is described as a
marine influenced floodplain facies (green). The clinoforms observed in this area, is in the facies interpreted as completely bioturbeded distal bars (van Yperen, pers. com.).

Figure 6.6 Apache log correlation where composite log 30 and 29 is near A and log 09 is closest to A’. See Figure 6.5 for location. (van Yperen, in prep.).

The correlation panel (Figure 6.6) from Apache Canyon formed the basis for the construction of a geological model that was entered into the modelling software. The log locations was projected to the 4 km long and 52 m high A-A’ profile (Figure 6.5). By studying the photo mosaic combined with the Google Earth image, interpolation of the log data was made in the best possible way with the information available to make the full 2D geological model (Figure 6.7).

The boundary 5 in Figure 6.6 was set to be the datum in the model. This marks the boundary from the distributary channel facies (orange) to the overlying marine influenced floodplain facies. In logs 04 and 09, another type of distributary channel facies is observed and therefore the datum was set between the new distributary channel (yellow) and the marine influenced floodplain facies (Figure 6.7). For now, boundary 5 is the most reasonable datum to set, but more information from further work can change the interpretation. The distributary channel facies (yellow) is interpreted to be older than the distributary channel (orange), and are totally isolated (van Yperen, pers. com.). Under- and overburden layers are also added to the model using the Jurassic Exeter Sandstone and Cretaceous Granero Shales, respectively. The top of the marine influenced floodplain facies is not revealed in the logs, but it was measured up to
11 m and this was therefore used as a uniform thickness of the layer. For the prodelta shales (blue) the bottom of the layer was not observed, but was set to 15 m thick as a reasonable thickness based on field logs and earlier studies (van Yperen, pers. com.).

Figure 6.7 2D geological model A-A’ for the Apache Canyon area. The locations of the logs are marked with arrows in the geological model. See Figure 6.5 for location and Figure 6.6 for log correlations. Purple represent the transitional mouth bar t to distal facies, grey in Figure 6.6.

This model has some uncertainties related to 3D effects in the photo mosaic and projections of the logs (Figure 6.5). As mentioned this 2D model is mostly strike-oriented, but at (~1800 - 1850 m) a dip-oriented feature is observed due to 3D effects and topography challenges. This is between log 1 and 2, which is located in a bend within the outcrop. In the small area which is dip-oriented, the geometry of clinoforms are visible (Figure 6.7).

A more regional dip model (Figure 6.9) is made based on log correlations along a N-S profile from Mesa Ronda to Lindsey’s Ranch (see Figure 6.1 for locations). This model covers the southern part, location 4, 2 and 1, of the conceptual model of the prograding system from Trigg Ranch to Lindsey’s Ranch (Figure 6.4). The log for Location 2 in the dip-oriented model (Figure 6.8 and 6.9) is equal to log 03 in the log correlation panel for the strike-oriented model (Figure 6.6).

The geological dip-model (Figure 6.9) is 18 km long and 54 m high. The layers are divided into different facies than in the Apache model. Four different facies represents three formations of Lower Cretaceous strata (Tucumcari Shales, Mesa Rica Sandstone and Pajarito Formation). In Figures 6.8 and 6.9, the open marine strata (light blue) correlates with the Tucumcari Shales. The top of this unit is the datum for the model. The Mesa Rica Sandstone
is divided into two facies in the dip-oriented model, bioturbated distal mouth bars (grey) and fluvial sandstone (white). The marine influenced coastal plain facies (green) represents the Pajarito Formation.

Figure 6.8 Logs forming the basis for the dip model (van Yperen, in prep.). 1: Lindsey’s Ranch, 2: Apache and 4: Mesa Redonda. See Figure 6.1 for location.

The clinoforms observed in the distal part of the delta in New Mexico is located within the bioturbated distal mouth bar facies (Figure 6.8). Conceptual clinoforms are made inside this layer in the geological model marked with different scale of grey in Figure 6.9. Notice that this facies pinches out towards the south, between Apache Canyon and Lindsey’s Ranch (Figures 6.8 and 6.9).
Figure 6.9 2D geological dip model going from Mesa Redonda, location 4 – Apache Canyon, location 3, to Lindsey’s Ranch, location 1. See Figure 6.1 for location and Figure 6.8 for log correlations.

The dip-model is rather poorly constrained given the large distances between the outcrops logged in the field. It therefore represents a simple conceptual model of the most distal part of the delta system. The motivation for making this model was to do correlation to the pinch-out of the prograding system in the Hoop area (Figure 5.12).

6.3 Seismic modelling

6.3.1 Model building and input parameters

Each of the layers in the models (Figures 6.7 and 6.9) has distinctive elastic parameters listed in Table 6.1 and Table 6.2, for the strike-model and dip-model, respectively. The elastic parameters, Vp, Vs and density, are based on the Lower Cretaceous well log data from the Barents Sea presented in Chapter 4. Velocities and densities increase with burial depth, therefore the elastic properties increases with the depth in the model, but is kept uniform within the individual layers.

The strike model from Apache Canyon consists of eight layers and in addition to one undefined layer below the Exeter sandstone marked in grey (Figure 6.7). The undefined layer is needed for the step going from the geological model to the input seismic model, since the model has to be a rectangle for the MATLAB script to read and make the input model for the modelling.
Table 6.2  Elastic parameters for the Apache model based on Lower Cretaceous log data in the Barents Sea. The table is divided into facies distribution described in 6.2, colours refer to Figure 6.7, greyscale colours from the input model, Appendix 4 and elastic parameters; Vp, Vs and density.

<table>
<thead>
<tr>
<th>Facies (distribution)</th>
<th>Colour</th>
<th>Layer</th>
<th>Grey scale</th>
<th>Vp</th>
<th>Vs</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributary channel</td>
<td>Yellow</td>
<td>1</td>
<td>14</td>
<td>2800</td>
<td>1570</td>
<td>2.30</td>
</tr>
<tr>
<td>Distributary channel, different facies</td>
<td>Orange</td>
<td>2</td>
<td>42</td>
<td>2850</td>
<td>1600</td>
<td>2.32</td>
</tr>
<tr>
<td>Transitional mouth bar to distal bar facies</td>
<td>Purple (grey in logs)</td>
<td>3</td>
<td>74</td>
<td>2900</td>
<td>1630</td>
<td>2.34</td>
</tr>
<tr>
<td>Completely bioturbated distal bar facies</td>
<td>Light blue/Turquoise</td>
<td>4</td>
<td>100</td>
<td>2950</td>
<td>1660</td>
<td>2.36</td>
</tr>
<tr>
<td>Prodelta Shale</td>
<td>Dark Blue</td>
<td>5</td>
<td>134</td>
<td>3100</td>
<td>1500</td>
<td>2.60</td>
</tr>
<tr>
<td>Exeter Sandstone (Jurassic)</td>
<td>Red</td>
<td>6</td>
<td>167</td>
<td>3200</td>
<td>1800</td>
<td>2.40</td>
</tr>
<tr>
<td>Marine influenced floodplains facies</td>
<td>Green</td>
<td>7</td>
<td>190</td>
<td>2900</td>
<td>1400</td>
<td>2.55</td>
</tr>
<tr>
<td>Overburden- Graneros Shale</td>
<td>Pink</td>
<td>8</td>
<td>216</td>
<td>2700</td>
<td>1375</td>
<td>2.50</td>
</tr>
<tr>
<td>Undefined</td>
<td>Undefined</td>
<td>9</td>
<td>243</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2  Elastic parameters for the dip model based on Lower Cretaceous log data in the Barents Sea. The table is divided into facies distribution described in 6.2, colours refer to Figure 6.9, greyscale colours from the input model, Appendix 4 and elastic parameters; Vp, Vs and density.

<table>
<thead>
<tr>
<th>Facies (distribution)</th>
<th>Color</th>
<th>Layer</th>
<th>Grey scale</th>
<th>Vp</th>
<th>Vs</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesa Rica Sandstone</td>
<td>white</td>
<td>1</td>
<td>42</td>
<td>2850</td>
<td>1600</td>
<td>2.32</td>
</tr>
<tr>
<td>4a) Completely bioturbated distal bar facies</td>
<td>Grey</td>
<td>2</td>
<td>14</td>
<td>2910</td>
<td>1620</td>
<td>2.36</td>
</tr>
<tr>
<td>4b) Completely bioturbated distal bar facies</td>
<td>Grey</td>
<td>3</td>
<td>74</td>
<td>2950</td>
<td>1660</td>
<td>2.36</td>
</tr>
<tr>
<td>4c) Completely bioturbated distal bar facies</td>
<td>Grey</td>
<td>4</td>
<td>100</td>
<td>2990</td>
<td>1700</td>
<td>2.36</td>
</tr>
<tr>
<td>Open Marine</td>
<td>Light blue</td>
<td>5</td>
<td>134</td>
<td>3100</td>
<td>1500</td>
<td>2.60</td>
</tr>
<tr>
<td>Marine influenced coastal plain</td>
<td>Green</td>
<td>6</td>
<td>190</td>
<td>2900</td>
<td>1400</td>
<td>2.55</td>
</tr>
<tr>
<td>Exeter Sandstone</td>
<td>Red</td>
<td>7</td>
<td>167</td>
<td>3200</td>
<td>1800</td>
<td>2.40</td>
</tr>
<tr>
<td>Overburden-Graneros Shale</td>
<td>Pink</td>
<td>8</td>
<td>216</td>
<td>2700</td>
<td>1375</td>
<td>2.50</td>
</tr>
</tbody>
</table>
6.3.2 Modelling results

A 45 degree maximum illumination is used as PDSM filter for the seismic modelling. This is a good approximation for seismic data.

The results of the seismic modelling are shown in Figure 6.10 for the strike model and Figure 6.11 for the dip model. The input model in greyscale is compared to synthetic seismic sections for 40 Hz, 60 Hz, 100 Hz and 150 Hz Ricker wavelets. Ricker wavelets with dominant frequencies 40 Hz and 60 Hz are comparable to the conventional seismic data from the Barents Sea while Ricker wavelets for 100 Hz and 150 Hz are comparable to the P-Cable seismic data (Figure 4.9).

The synthetic seismic sections are presented together with the associated PSF. A significant improvement in seismic resolution is observed from the 60 Hz synthetic seismic to the 100 Hz synthetic seismic and further 150 Hz (Figures 6.10 and 6.11). The synthetic seismic sections will be compared to details from the Barents Sea seismic data, both conventional and P-Cable, and discussed in chapter 7.
Figure 6.10 Synthentic seismic sections for the Apache model, strike-oriented, for varying wavelets. a) original input model, b) model with Ricker wavelet 40 Hz, c) model with Ricker wavelet 60 Hz, d) model with Ricker wavelet 100 Hz and e) model with Ricker wavelet 150 Hz. The associated PSF, 45 degree maximum illumination, are plotted on the right side of the models. Positive reflection coefficient: red, negative: blue.
Figure 6.11  Synthetic seismic sections for the dip model for varying wavelets. a) original input model, b) model with Ricker wavelet 40 Hz, c) model with Ricker wavelet 60 Hz, d) model with Ricker wavelet 100 Hz and e) model with Ricker wavelet 150 Hz. The associated PSF, 45 degree maximum illumination, are plotted on the right side of the models. Positive reflection coefficient: red, negative: blue.
7 Discussion

This study has increased the understanding of the Early Cretaceous evolution of the wider Hoop area, both with respect to the regional prograding depositional system that reached the study area from Svalbard in the Barremian (Figure 7.1), and the subsequent rifting that affected the Hoop area and adjacent basins in the SW Barents Sea. It addresses how much geological detail can be resolved by different kinds of seismic reflection data – compared to what information we get from wells (e.g. workflow A, described in Chapter 3.3. and 4) and field outcrops (e.g. workflow B, described in Chapter 3.3. and 6).

Different seismic data types, both conventional 2D and 3D seismic data and 2D and 3D high-resolution P-Cable data have been integrated and compared. For each data type the seismic resolution has been quantified and modelled to determine what is possible to image by seismic data. Seismic modelling is done both by 1D convolution consisting of calibration to well data from the Hoop area and 2D/3D convolution synthetic seismic based on geological models from the field analogue in New Mexico, USA. Information on the same depositional system from Svalbard has also been integrated, and compared to the delta in New Mexico (Figure 7.1b).

In this chapter the results from Chapters 4, 5 and 6 are integrated and discussed in relation to other recent studies with focus on the Early Cretaceous geological evolution in the Hoop area (Dimitriou, 2014; Marin et al., 2017; Collanega et al., 2017). This chapter is subdivided according to the three main sequences and each of them will be discussed with special emphasis on the seismic imaging and resolution of the different seismic data types, and comparison will be made to the synthetic seismic sections based on the field analogue in New Mexico. This comparison is validated by the aforementioned similarities between the two depositional systems (Figure 7.1).
Figure 7.1 The comparable dimensions and locations for the delta systems in Svalbard-Barents Sea and New Mexico. Left: conceptual drawing of the delta from Svalbard-Barents Sea on top of a geology map (Harrison et al., 2011) with location of the study area in the SW Barents Sea marked. Right: conceptual drawing of the Colorado-New Mexico delta on a Google Map image, with field study area marked in the black box modified from van Yperen (in prep).

7.1 Lowermost Cretaceous Knurr/Klippfisk formations

In platform areas of the SW Barents Sea the Base Cretaceous horizon does not represent an unconformity but a condensed interval around the Jurassic-Cretaceous transition (Figure 7.2). The detailed work on the well data documented in Chapter 4 shows that the Knurr Fm is not only associated with acoustic impedance contrasts at it stop and base, also within this thin unit there are significant variations in acoustic impedance. At least 8 reflection coefficients are found associated with this ~30 m thick unit (Figure 4.6). The P-Cable data detect and resolve many of these while in the conventional seismic data the entire Knurr Fm corresponds to a composite peak and trough (Figures 4.6 and 4.10). As shown in Chapter 3 (Figures 3.4 and 3.5) we therefore meet resolution problems related to interference making it difficult to
determine the exact pick for a Base Cretaceous boundary (Figure 7.2). On the Bjarmeland Platform the same interval corresponds to the thin limestone unit defined as the Klippfisk Fm (Smelror et al., 1998).

**Figure 7.2** Seismic imaging and resolution of the lowermost Cretaceous Knurr Fm. A 31 m thick Knurr Fm penetrated in the Apollo well corresponds to ~15 million years and the time-thickness is 21 ms (yellow). Synthetic seismic traces for both P-Cable and conventional type of seismic are shown in the lower right. A close-up of the tie between P-Cable and conventional seismic data at the Apollo well location is shown in the upper panel. In the conventional seismic the Knurr Fm (vertical yellow bar in well) corresponds to only one peak and trough. If peak/red is used in regional mapping of the Base Cretaceous it actually corresponds to Top Knurr (horizon H2 in this thesis work).

The top of sequence S1, horizon H2, represents the downlap surface for the prograding unit that reached the Hoop area in the Barremian. In regional mapping on the SW Barents Sea platform areas, using conventional 2D seismic data, this horizon (H2) is often identified as the
BCU (Base Cretaceous Unconformity). However, the age of this boundary is close to the Hauterivian-Barremian transition (Figure 7.2). Marin et al. (2017) were therefore not able to resolve their S0 and S1 sequences, corresponding to the Knurr and Klippfisk formations, at the Bjarmeland Platform including the Hoop area.

7.2  Lower Cretaceous clinoforms

The delta prograded from Svalbard (Helvetiafjellet Formation) to the Hoop area (S2/Kolje Formation) sometimes in the Barremian. The first unit characterized by clinoforms prograded towards the Hoop area from the north-northwest (Figures 7.1 and 5.17).

The main depositional features studied here include clinoforms in a prograding system. The clinoforms have been observed in both strike and dip directions and compared to the results from the seismic modelling in Chapter 6. Examples of resolution for the seismic data, P-Cable data and conventional data, are well documented in Chapter 5. The resolution comparison of seismic data types, will be further discussed below with respect to typical geological features such as clinoforms and channels (7.3).

7.2.1 Delta system - clinoforms

Clinoforms reflect deposition by a prograding system, such as deltas, both subaerial and subaqueous (Helland-Hansen and Hampson, 2009; Figure 7.3). They are defined by a topset, foreset and a bottomset and typical shapes of clinoforms and clinothems are shown in Figure 7.3. Sigmoidal clinoforms have aggrading topsets that can be used to determine trajectories of the shelf-edge. Oblique clinoforms show little or no aggradation increasing the potential for finding coarser-grained sediments (Glørstad-Clark et al., 2010; 2011). Grain size can have some control on the shape of the deltaic clinoforms, which is used as a criteria looking for potential reservoir rocks (Glørstad-Clark, 2011; Marin et al., 2017). Different styles of deltaic subaqueous clinoforms interpreted in high-resolution seismic data can be interpreted and related to grain-size (Patruno et al., 2015). Recent advances in 3D seismic imaging and data analysis, e.g. using seismic attribute maps and time-slices, may increase...
confidence in the interpretation of depositional environments characterized by clinoforms (Bullimore et al., 2005).

![Diagram of depositional environments](image)

**Figure 7.3** Deposition of clinoforms in different scales, a) single clinoform set on the shelf or b) compound clinoform set (Helland-Hansen and Hampson, 2009). Topset, forset and bottomset are marked in a). c) Characteristic clinoform types (modified from Glørstad-Clark et al., 2010).

### 7.2.2 Hoop clinoforms – key observations

The clinoforms in the Hoop area have typical heights of 44-54 m and dips of 0.4-2 degrees (Figure 5.16 and Table 5.2). These geometries have been modified by burial and compaction, which have to be corrected for. At present, the clinoforms are found a few hundred meters below the seabed, but prior to Late Cenozoic uplift and erosion they were buried by additional 2000-2100 meters (Henriksen et al., 2011; Baig et al., 2016). The measured properties of seismic velocity (c. 2900-3000 m/s) and porosity (c. 20 %) are typical for burial depths of 2200-2500 m (Marcussen et al., 2010). Decompaction, correcting for the post-depositional burial and compaction, affects the height of the clinoforms. For the Bjarmeland Platform and adjacent Fingerdjupet Sub-basin it is assumed that actual height of the clinoforms, when they were deposited, is 32 % higher than the measured height of the clinoforms due to the decompaction and erosion (Marin et al., 2016). Taking decompaction into account the original height of the clinoform in the Hoop delta was in the order of 60-70 m at the time of deposition.
The prograding delta system, documented going NNW-SSE, consists of different order of clinoforms. Two types of clinoforms are documented in the study. Sigmoidal and parallel oblique higher-order, and sigmoidal lower-order clinoform (Figures 5.17 and 7.3) are observed according to the classification scheme in Figure 7.3. The interpretations of the clinoforms in this study are mostly done on P-Cable data. The dip and height are measured on selected examples of these geometries (Table 5.2). The dip is measured by the angles of the forset using an interval velocity 2900 m/s. Clinoform geometries in the area have already been studied (e.g. Dimitriou, 2014; Marin et al., 2017), but with high-resolution data for this area a more visible geometry is observed than looking at conventional data (Figure 7.4).

Sigmoid shaped lower and higher-order clinoforms (Figures 5.11 and 5.17) have measured dips of 0.4° and 1°, respectively. Oblique parallel clinoforms are observed in Area C and Area D, with measured dip 2° and 1.5°, respectively (Figures 5.15-5.17). The steepest clinoform, with a dip of 2°, follows more or less the direction of the progradational system (Figures 5.15-5.18), hence the dip is considered to closely match its true dip. The measured sigmoidal clinoforms are not oriented parallel to the progradational direction, so they may appear more gentle than in reality. The dips will also be affected by compaction.

**Figure 7.4** Line drawings of clinoforms with different order in S2. a) conventional seismic data going northwards from Atlantis and b) P-Cable data (same profile as in Figure 5.11). Flattened on H2 (yellow). Red: lower order clinoforms, blue: higher order clinoforms, black: parallel reflectors inside S2 close to the Atlantis well, orange: H3 and purple: reflectors in lower S3.
As Helland-Hansen and Hampson (2009) pointed out, seismic resolution can limit imaging of clinoforms which in turn limits analysis. The seismic resolution of the P-Cable data is significantly better than for conventional seismic data (Table 3.4) which allows that the clinoforms can therefore be studied in greater detail (Figure 7.4).

### 7.2.3 Seismic modelling

The differences in seismic resolution are further documented by the seismic modelling presented in Chapter 6. The height of the geological models from New Mexico are only 52 m which cause limitations of what can be resolved by the synthetic seismic sections with frequencies typical for conventional seismic data. Synthetic seismic images for the same model but with higher frequencies show greater detail, as expected. This is demonstrated for the dip model in Figure 7.5 compared to both conventional seismic and P-Cable data with clinoforms in the Hoop area. The New Mexico delta clinoform are only partly resolved in synthetic seismic data with high frequencies that simulate P-Cable data.

![Synthetic seismic for New Mexico dip model. Each synthetic model is compared to a similar feature in the P-Cable and conventional seismic data in the Barents Sea with similar frequencies as the seismic data. The synthetic seismic with Ricker wavelet with 40 Hz and 150 Hz are used for the comparison.](image)

**Figure 7.5** Synthetic seismic for New Mexico dip model. Each synthetic model is compared to a similar feature in the P-Cable and conventional seismic data in the Barents Sea with similar frequencies as the seismic data. The synthetic seismic with Ricker wavelet with 40 Hz and 150 Hz are used for the comparison.
The seismic-to-well tie in Chapter 4 also demonstrated these limitations and challenges. For thin layers with closely spaced boundaries and associated reflection coefficients, will interfere, both constructive and destructive and play an important role for what can be resolved by the seismic images. This is clearly the case for both the thin S1 sequence discussed above, and the thin higher-order clinothems seen in the P-Cable data. Pinch-out of the clinothems may give rise to tuning effects. Clinoforms appears higher and clinothems thicker in the Hoop area compared to the New Mexico analogue, and are therefore resolved both in the conventional seismic and high-resolution P-Cable data (Figure 7.4). The P-Cable data have however significantly better resolution so that higher-order, more steeply dipping, clinoforms are observed (Figure 7.4).

7.2.4 Lithologies – reservoir potential

The Lower Cretaceous strata in Apollo and Atlantis (Chapter 4) indicate fine-grained sediments, mostly mudstones. However, the Lower Cretaceous clinoforms in the Hoop area are not yet drilled, keeping the possibility open that they contain coarser-grained material than in the wells. The steeper oblique clinoforms revealed by P-Cable data are of particular interest in that respect. Their distinctly resolvable high-resolution architecture must stem from compositional variation, presumably grain-size driven. The variations in geometries between clinoforms also indicate that there are likely lithology variations between the clinothems. The steepest clinoforms are expected to have the largest potential for coarser-grained strata (Glørstad-Clark et al., 2011; Patruno et al., 2015).

7.2.5 Barents Sea – regional implications

The conventional 3D seismic data, and particularly the high-resolution P-Cable data, show that the prograding unit coming in from the NNW stopped a short distance before reaching the Atlantis well (Figures 5.10, 5.11, 5.13 and 5.14). Marin et al. (2017) identified the same progradational front and called it S3 (Figure 5.21). Dimitriou (2014) named this unit Lobe A
north and mapped it out in a regional grid of 2D seismic data to extend some distance south of the Apollo and Atlantis wells (Figure 5.21).
In this study the prograding front are set to be at maximum foreset and the transition to bottomset. The front is adjusted by finding pinch-outs of the prograding system by screening the conventional seismic data, in addition to finding good examples where P-Cable data cover the front. The front can be determined even more specific with the P-Cable data, because with the high resolution data the top and bottom reflector of the system will be differentiated longer towards pinch-out (Figure 5.13).

Lobe A_north prograded into the Hoop area in Barremian time, correlating to the Kolje Formation, based on the local stratigraphic framework calibrated to the Apollo and Atlantis wells, and from ties to the Fingerdjupet Sub-basin (Figure 5.1). This is in contrast with Marin et al. (2017) who propose an Aptian age for their unit S3 and correlate it with lower parts of the Kolmule Formation.

According to Dimitriou (2014) progradation of Lobe A_north continued across the Bjarmeland Platform towards the Nordkapp Basin. In contrast to this, Marin et al. (2017) show a prograding unit (also termed S3) crossing the Bjarmeland Platform from NE towards SW (Figure 5.22). To shed light on this the interpretation was extended some distance southeastwards based on regional 2D seismic line. Figure 5.23 shows a number of profiles documenting clinoforms prograding from NW to SE, in line with the mapping results of Dimitriou (2014). Seismic lines orthogonal to the dip direction of this system show geometries typical for the strike direction. This highlights the fact that the front of S2 in this study, and S3 in Marin et al. (2017), is a part of lobe A_north that is discussed in Dimitriou (2014).

### 7.3 Channels

Channels formed by incision are generally difficult to identify in seismic images. A possible channel feature has been interpreted in the Hoop area based on seismic observations supported by seismic attributes and an EM anomaly (Figure 7.6).

The candidate channel in the Hoop channel is located in front of the prograding unit and is oriented along strike of this front. It may therefore be younger and related to the depositional system that prograded into the area from the NE (Dmitriou, 2014; Marin et al., 2017).
The synthetic seismic data generated for the strike-oriented Apache model in New Mexico are compared to an example from strike-oriented Barents Sea data (Figure 7.7). For the P-Cable data there is only one place where it is possible to see a strike-oriented feature because of limited P-Cable data coverage. Unfortunately this was outside the coverage of conventional 3D seismic data in the study area. The channel of the size from New Mexico is only visible in the P-Cable type of synthetic seismic (Figure 7.7). Both vertical and horizontal resolution put limitations on what can be resolved by the seismic data. 3D seismic data have much better horizontal resolution which is crucial for mapping out complex channel systems.

Figure 7.6 Lower Cretaceous channel in the Hoop area. a) close-up of S2 time-thickness map (Figure 5.10) showing the pinchout of the prograding system north of the Apollo and Atlantis wells. The location of profiles 1-3 across the channel feature is also shown. b) close-up of the attribute map (Figure 5.21) showing the bright event interpreted to be associated with a channel. c) The channel feature is also associated with a positive EM anomaly (Carstens, 2015).
The vertical resolution determines how deep a channel has to be before it can be detected in seismic images. The distributary channel from New Mexico is deep enough to be seen in the synthetic seismic data for Ricker wavelets 100 and 150 Hz (Figure 7.7).

The distributary channel, marked yellow in Figure 6.6, is approximately 10 m at its thickest and is therefore above the limit of seismic resolution for P-Cable imagery, but not for conventional data. This means that sandy channel-bodies of this size cannot be detected without high-resolution data.

![Figure 7.7](image1)

**Figure 7.7** Synthetic seismic for New Mexico Apache model. Each synthetic model is compared to a similar feature in the P-Cable and conventional seismic data in the Barents Sea with similar frequencies as the seismic data. The synthetic seismic with Ricker wavelet with 40 Hz and 150 Hz are used for the comparison.

### 7.4 Early Cretaceous (Aptian) faulting

The Hoop area was affected by considerable Early Cretaceous faulting. From the flattening of a large number of seismic profiles to study the clinoforms it is clear that the main phase of faulting postdates deposition of the prograding unit (e.g. Figures 5.10 and 5.11). This is also shown in the two seismic lines in Figure 7.8 going through the Apollo and Atlantis wells. In line 1 the prograding unit within S2 (Kolje Fm) pinches out before reaching the Atlantis well. Southeast of the well the S2 and older units are down-faulted into the graben structure. Growth sequences are observed within S3, corresponding to the Kolmule Fm inside the
graben (Figures 5.24 and 5.25). Line 2 through the Apollo well (Figure 7.8) shows down-faulting into the same graben in the southeast. Northwest of Apollo a number of minor faults offset S2 and older units. These observations constrain the timing of the faulting to Aptian.

**Figure 7.8** Close-up of seismic attribute map (Figure 5.26c) showing the various fault systems in the Hoop area. See text for discussion of the main fault trends. Also shown are seismic lines through the Apollo and Atlantis wells showing that the main phase of Cretaceous faulting postdates the deposition of the prograding unit within the Kolje Formation.

This is also consistent with correlations to the adjacent Fingerdjupet Sub-basin to the west that experienced an important rift phase in the Aptian (Dahlberg, 2014). An intra-Aptian unconformity has been penetrated by a well at a structural high bounded by faults towards both the Fingerdjupet Sub-basin and the deep Bjørnøya Basin to the west (Figure 7.9). This phase of faulting was part of a regional and important rift phase within the North Atlantic rift system (Faleide et al., 1993, 2015).
Figure 7.9 Interpreted seismic lines across the NE Bjørnøya Basin and Fingerdjupet Sub-basin showing evidence of Aptian faulting (modified from Faleide et al., 1993)

During the Aptian rift phase the NE-SW to N-S trending main graben structure in the Hoop area formed (Figures 7.8 and 5.4). This structure has also been studied by Fitriyanto (2011) and Collanega et al. (2017). Collanega et al. (2017) recently published a structural analysis of the Hoop area using the same 3D conventional seismic data set as used in this thesis. They related the progressive evolution of the graben system to a change in the regional stress regime and focusing of the extension during the Aptian rift phase. Prior to that, the area was affected by more distributed deformation during Late Jurassic time. The main focus of their work was to document and discuss the main fault systems that affected the Hoop area during Late Jurassic-Early Cretaceous times. These are nicely imaged by the 3D seismic data also as part of this thesis work (Figures 5.4, 5.23 and 7.8). However, a detailed structural analysis was beyond the scope of this thesis.
8 Conclusions

This thesis presents an integrated study interpreting Lower Cretaceous delta systems on high-resolution P-Cable and conventional 2D and 3D seismic data tied to wells in the Hoop area on the NW Bjarmeland Platform, and seismic modelling from field analogues in New Mexico, USA.

The P-Cable data have significantly better resolution than the conventional seismic data. While conventional seismic data have a vertical resolution of 15-25m and horizontal resolution of 30-50 m, the P-Cable data have 5-7.5 vertical and 10-15 m horizontal resolution. With P-Cable data it is therefore possible to study the stratigraphical and structural architectures in greater detail.

The study reveals that the Base Cretaceous can be difficult to distinguish from a horizon representing the Hauterivian-Barremian transition in platform areas of the SW Barents Sea. Here, these two horizons form in conventional data a peak and a trough following each other closely. In the P-Cable data however a thin condensed unit S1, corresponding to the Knurr Formation, is well resolved with several strong reflections within this sequence. Based on well data, the basal reflector of this unit (H1) correspond to the top of the uppermost Jurassic Hekkingen Formation, and the top (H2) represents the Hauterivian-Barremian boundary corresponding to Top Knurr. A thin limestone of the Klippfisk Formation forms the lateral equivalent to the Knurr Formation on the elevated platforms.

Detailed mapping of clinoforms, both lower- and higher-order, is possible to perform with high-resolution P-Cable data, unlike for conventional data were it is not possible to see higher-order clinoforms. Sigmoidal and oblique lower and higher clinoforms are observed with typical heights of 44 - 54 m and dips in the range of 0.4-2 degrees, without taking decompaction effects into account. This study increases the confidence in interpretations of the clinoforms due to high-resolution P-Cable seismic data.

The wells drilled so far within the study area, Apollo and Atlantis, indicate fine-grained lithologies within the Lower Cretaceous strata. However, detailed mapping shows that drilling has not yet tested the prograding clinoforms and clinothems. The observation of higher- and lower-order clinoforms with different geometries, indicates that there are variations in
lithology within the study area. Coarser-grained material associated with the steepest clinoforms, can therefore not be ruled out.

The Lower Cretaceous delta system that prograded into the Hoop area from NNW, pinches out northwest of the Apollo and Atlantis wells. The high-resolution data presented here has contributed to a more detailed outline and improved time constraints of the prograding delta system compared to previous studies. The prograding direction is well documented in the 3D P-Cable cubes, confirming a NNW-SSE prograding system. In the 3D conventional seismic, in addition to high-resolution 2D seismic, termination of the clinoforms was mapped out northwest of the wells. The lateral extent of this system was mapped into adjacent areas, confirming the presence of a delta complex linked to Svalbard in the NNW.

The age of the prograding delta system, S2, is dated to Barremian time based on well data from within the Hoop area, as well as from seismic ties to wells in the adjacent Fingerdjupet Subbasin. Knowing that the Kolje Fm, corresponding to S2, is the correlation to the delta deposition at Svalbard, the Helvetiafjellet Formation, and the Top Kolje (H3) is the top of S2, the clinoformset with front before Apollo and Atlantis are dated to be Barremian in age.

Outcrop-based seismic modelling is helpful for improving constraints on what scales can be imaged in the seismic data. Thin and narrow geological features such as channels can be imaged by P-Cable data. Channels, with the size of ~10 m as in the New Mexico field analogue cannot be identified in conventional seismic data. Because of the well imaged channel in high-resolution P-Cable data, it can be easier to interpret in the conventional data knowing it is there.

The bright event observed following the interpreted frontline of the prograding delta system, seems to connect to the observed channel in 2D P-Cable line. This increases the confidence of the interpretation that this bright event observed as a nearly continuous feature in the 3D conventional seismic data represents a channel coming from NE. The incision likely occurred later along the front of the prograding system, and may be linked to a slightly younger system that prograded into the area from the NE.

The modelling also shed light on the limitation in seismic data with respect to vertical and horizontal resolution. Any kind of seismic data will have resolution limitation, but with high-resolution P-Cable data the limitation decrease significantly.
An important rift event affected the Hoop area in Aptian time. Faulting associated with this postdates the prograding system and has to be corrected for (by flattening) to restore the clinoform geometries. This faulting was part of a regional rift phase affecting the entire NE Atlantic region. Detailed 3D mapping reveal a striking fault pattern with cross-cutting relationships.
References


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van Yperen, in prep. Low-gradient delta lobe termination architecture; a case study from the Lower Cretaceous Mesa Rica sandstone in New Mexico, USA. PhD study, University of Oslo


Appendix 1

A briefly theoretical description of the selected well logs used in this study based on Mondol (2015):

The gamma ray (GR) log measures the total natural gamma radiation and the unit is API (American Petroleum Institute). The gamma ray log has a simple and high vertical resolution, and is not affected by the drilling fluids and goes through steel and cement. Gamma Ray is used for lithology discrimination, shale volume estimation and analysis of facies and depositional environments. For the purpose of this thesis the gamma ray log is used for the lithology discrimination, to describe the lithology (sand/shale), and find out where the environment changes (formation boundaries) are located (Mondol, 2015).

The gamma ray log could not alone define confident lithologies, but are valuable together with other logs to define the lithology. Because of the difference in radioactivity between sandstone/ carbonates and shale, the gamma tool can distinguish between shale and non-shale (Mondol, 2015). The highest gamma ray values correspond to shales (+ organic rich shale and volcanic ash), and the lowest to clean sandstone (+limestone, dolomite, coal +). Thin beds can be identified in the logs. The shape of the gamma ray log can give an indication of the depositional environment (Mondol, 2015).

The neutron log (NEU) gives an indication of the water content, and therefore the porosity in the rocks. It sends out radiation into the rocks, where the rays get absorbed by the rock and particularly by the water in the formations. Common units for the neutron log are p.u. (porosity unit), decimal or %. In this case the neutron is given in decimal. Two uncertainties of this log are the shale effect and gas effect. The shale effect occurs when the formation contains shale with high clay content, which will result in higher porosity estimation in the neutron log since there is also hydrogen in the clay mineral. The gas effect gives a porosity underestimation, and takes place when the pores are filled with gas because the gas contains less hydrogen per volume than water and oil.

The density log (DEN) measures the bulk density, by measuring the gamma radiation that returns to the sensors after bombarding the formation with gamma radiation. The returning gamma radiation are measured in two different energy layer, where one is measuring the high
energy gamma ray which again determine the bulk density. The second one is collecting the low energy gamma ray and is used to determine the formation lithology (Mondol, 2015).

A development of the density log is the litho-density log **photoelectric factor (PEF)**, which is one of the most valuable logs for lithology discrimination. It is therefore commonly combined with the gamma ray, density and neutron logs for assessment of lithologies. The PEF log is based on the same method as density, but with enhanced detectors decreasing the distance between long and short spacing detectors. Increase in vertical resolution is a result of this. The litho-density log is capable to count separately and recognize gamma rays with high and low energies. High energy gamma rays undergo Compton scattering (loose energy, the energy peak will both move to a lower energy level and disperse/get wider) and low energy gamma rays undergo photoelectric absorption. Pe value is a directly indication of the lithology since different materials have distinctive ways to photo-absorb gamma rays.

The photoelectric absorption, Pe, is given by

\[
Pe = \frac{1}{K} \frac{\sigma_e}{Z}
\]  

(A1.1)

\(\sigma_e = \) photoelectric cross-section, \(K=\) coefficient depending on the energy where the photoelectric absorption is observed, \(Z=\) atomic number (number of electrons).

The **sonic log**, the so-called interval transit time (\(\Delta T\)), is a measure of the slowness of the compressional and shear waves sent into the rock, with the unit \(\mu s/ft\). The compressional, P-wave, \(\Delta T\) are measured in the AC log and for the shear, S-wave, the \(\Delta T\) are measured in the ACS log. The sonic log is the inverse of the velocity (m/s) (Mondol, 2015). The P-wave velocity and the S-wave velocity are therefore calculated from the sonic logs by using these formulas for AC (A.2) and ACS (A.3), respectively

\[
Vp = \frac{1}{(AC+0.00009)}
\]  

(A1.2)

\[
Vs = \frac{1}{(ACS+0.00009)}
\]  

(A1.3)
Appendix 2

Background for the seismic attributes used in the study with reference to Schlumberger (2015).

**Time gain** is used for strengthen the trace amplitude.

A valuable attribute is the **Structural smoothening**, which increases the continuity of the reflectors, decided by local structure dip and azimuth. This attribute, in addition to time gain is used for scaling up and increase the continuity of the reflectors for the seismic data in this study.

The volume attribute, **Median Filter**, also contributes to the smoothening of the seismic data and enhance edges and boundaries. This attribute filters out rapidly changes in signal, and can therefore filter out “real”-signals in for example chaotic areas, which will affect the interpretation of the area.

**Variance (edge method)** is an attribute based on isolating edges, discontinuities, from the input data set. Using a short window for the attribute, it is good to highlight stratigraphic features. It gives a sharp result measuring the difference from a mean value. It is possible to change the inline and crossline range, which decide the number of traces that are included in the calculation, and the vertical smoothing which influence the signal to noise ratio hence improves the continuity of the vertical events.

The purpose of **Ant tracking** is to perform edge enhancement for identification of faults and linear anomalies in the data volume. “A high number of “ants” is sent into the data volume and evaluates the collective behavior of the swarm”. This is often run on a cube that has already been through other attributes, for example variance. A typical workflow ending with ant tracking is: (1) seismic conditioning, (2) edge detection (for example variance) and (3) edge enhancement (Ant tracking).

The **Sweetness** attribute is used to highlight features/structures where the overall energy signature change in the seismic data. It is defined as the ratio between the envelope (reflection strength attribute) and square root of the instantaneous frequency $\omega(t)$. 

The cut-off frequency below 1Hz, meaning $\omega(t)$ cannot be lower than 1.

The **3D edge enhancement** attribute applies its filter in a 3D environment. A rotation of the filter is applied, so that all desired directions and angels of interest get highlighted. 3D edge enhancement improves the edge detection by reducing the noise and getting better detection of edges, because it will enhance larger features and smooth away the smaller, as noise. On every pixel in the 3D cube, the attribute compares and summaries the values of the surrounding pixels along the edge detected cube and display the mean value in the output. Parameters that could be changed in this attribute are: horizontal and vertical radius, minimum and maximum on both dip and strike, and the plane half thickness.

**Cosine of instantaneous phase** (called the normalized amplitude) is based on the formula:

$$\cos(\varphi(t))$$

Cosine of phase improves the continuity of the reflector and is therefore used in poor resolution areas and also to increase structural delineation. As a result of this, faults, stratigraphic boundaries and structural features are highlighted.
Appendix 3

Appendix showing the surfaces of four of the interpreted seismic horizons.

H1 (H2 is similar)