# Faculty of Science and Technology

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Seismic Characterization of Lower Cretaceous Clinoform Packages in the Fingerdjupet Sub-basin, Southwestern Barents Sea

by

Camilla Husebø Hinna

MSc Thesis
Presented to the Faculty of Science and Technology
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Camilla Husebø Hinna
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29.06.2016
Abstract

Seismic Characterization of Lower Cretaceous Clinoform Packages in the Fingerdjupet Sub-basin, Southwestern Barents Sea

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The University of Stavanger, 2016

Supervisors: Alejandro Escalona, Bjørn Kåre Lotsberg Bryn and Stian Schjelderup Haaland

The three wells drilled in Fingerdjupet Sub-basin during the late 1980’s were abandoned as dry holes, resulting in little exploration interest in the sub-basin. This leaves the depositional history poorly understood, and this study aims to give a better understanding of the infill history by studying different depositional styles on new seismic data. In 2013 and 2014, these new seismic surveys with high resolution were acquired, making it possible to investigate clinoforms in detail. This data allows investigation of low relief clinoforms geometry and size, and possibility to predict lithology based on outcrop analogues, which has not been possible with the previous datasets. Estimated porosity values are included for the different types of clinoforms and lithologies, resulting in a prediction of reservoir potential.

This study is a part of a larger project, LoCrA (locra.ux.uis.no), which investigates the Lower Cretaceous basins in the Arctic. Seven sequences in the southwestern Barents
Sea were already defined in this project, however only four of them are present in Fingerdjupet Sub-basin. The four seismic sequences within the Lower Cretaceous unit are described and interpreted in the north-south trending Early Cretaceous extensional basin:

1. Latest Hauterivian - Early Barremian age, consisting of mass transport complex,
2. Late Barremian - Early Aptian age, consisting of clinoforms,
3. Aptian age, consisting of local slumps,
4. Albian age, consisting of clinoforms.

In addition, three subsequences are interpreted within the second sequence (2), which are characterized by:

(a) clinoform sets with a height of > 150 m and dip angles of around 3-6 degrees, interpreted as shelfal clinoforms,
(b) clinoform sets with a height of < 40 m and dip angles of around 12 degrees, interpreted as shallow marine deposits due to observations of shingled progradational pattern,
(c) clinoforms with a height of < 80 m and dip angles of around 10 degrees, interpreted as deltaic clinoforms.

The classification of the clinoforms indicates that the shallow water clinoforms observed in Sequence 2b, and c, have the geometry of sand-prone depositional systems, with an estimated average porosity of ~ 18% for the compacted sediments.
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1 Introduction

The Fingerdjupet Sub-basin is located in the southwestern Barents Sea and forms the shallow north-eastern part of the Bjørnøya Basin. Fig. 1.1 shows a map of the southwestern Barents Sea, where Fingerdjupet Sub-basin in addition to the three wells drilled in the area are located. Three exploration wells (7321/7-1, 7321/8-1 and 7321/9-1) were drilled in this sub-basin during the late 1980s, where well 7321/9-1 had Lower Cretaceous sandstones as a secondary target (NPD, 2016B). Clinoforms of different scales are observed on the seismic data, however, seismic interpretation reveals that the wells did not drill through the clinoforms that seem to be sandstone prone. Well 7321/7-1 was drilled through a fault in the clinoform interval, well 7321/8-1 was drilled on an eroded structural high, and well 7321/9-1 was probably drilled at a location where the foresets of the clinoforms never reached.

To date, there is little understanding of the distribution and lack of detailed internal description of the clinoforms in the Fingerdjupet Sub-basin. The presence of reservoir rocks at Lower Cretaceous level is a documented risk element of the sub-basin, since the three wells drilled in this area did not discover sandstones at this interval (NPD, 2016B). To document the distribution and presence of possibly sandy clinoforms in other parts of the sub-basin will be essential to verify a potentially new play type.

This study describes the depositional styles of the Early Cretaceous succession in the Fingerdjupet Sub-basin, and provides a seismic stratigraphic framework, which build on a regional, previous established framework by Marin et al. (accepted with revisions). Seismic data is mainly used to construct a stratigraphic framework by interpretation of key surfaces representing the unconformities and sequences. Interpretation of 3D seismic data is applied to mark the extent and distribution of clinoforms. The main focus of this study is the sequences where clinoforms are observed, although the other sequences are included and described to understand the depositional history through Lower Cretaceous times. Clinoforms in each unit are
measured to get the size and geometry, leading to prediction of lithologies based on analogues.

Fig. 1.1 Structural Elements of the Barents Sea. Modified from NPD Fact Maps (2016A).
1.1 Previous Studies

Few published studies focus on the evolution of the Fingerdjupet Sub-basin, although the LoCrA consortium (locra.ux.uis.no) is focusing on the Lower Cretaceous deposits in the Barents Sea. As this study is a part of that project the regional observations and interpretations are incorporated into this thesis, and the main previous work in the area is described below.

Marin et al. (*accepted with revisions*) defined seven third order sequences in the Barents Sea, where only four of them (S1-S4) seem to be present in the Fingerdjupet Sub-basin (Fig. 1.2). The well log interpretation in well 7321/7-1, located in the Fingerdjupet Sub-basin, shows that it is difficult to interpret any flooding surfaces, as the whole unit is consisting of shales, forcing the main correlation to be based on seismic interpretation. Clinoforms all over the Barents Sea has been defined, and lithologies from well data and predicted lithologies based on the geometry and size of the clinoforms are combined and highlighted in Fig. 1.3. It is suggested that the clinoforms observed in Fingerdjupet Sub-basin tend to be sandstone prone, and belong to Sequence 2.
Fig. 1.2 Well Correlation, Hammerfest Basin to Fingerdjupet Sub-basin. Well correlation based on regional interpretation showing the four sequences present in the Fingerdjupet Sub-basin (Marin et al., accepted with revisions). Note that the GR log response marked in the red ellipse is due to a casing shoe, and not sandstones.
Fig. 1.3 Clinoforms in the Southwestern Barents Sea. Summary map showing the maximum progradation of clinoforms for each sequence, where black arrows show the main progradation direction. S1: Sequence 1, S2: Sequence 2, S3: Sequence 3, S4: Sequence 4, S5: Sequence 5, S6: Sequence 6 (Marin et al., accepted with revisions).
The four sequences present in Fingerdjupet Sub-basin were described by Marin et al. *(accepted with revisions)* based on regional interpretations in the Barents Sea:

**Sequence 1 (S1): Latest Hauterivian - Early Barremian**

In the Hammerfest Basin this sequence shows continuous parallel reflectors, with high to medium amplitude, and a high amplitude top reflector. High-relief, sigmoidal clinoforms prograding towards the southwest is interpreted in the Nordkapp Basin.

**Sequence 2 (S2): Late Barremian - Early Aptian**

Sequence 2 consists of parallel continuous reflectors with medium amplitude in the Hammerfest Basin, and clinoforms prograding towards southeast in the Fingerdjupet Sub-basin and the western Bjarmeland Platform. The sequence top is defined as a high to medium amplitude reflector. High-relief tangential oblique to sigmoidal clinoforms with a height of approximately 280 meters are observed in the Fingerdjupet Sub-basin. The trajectory varies from flat to locally ascending. Bottomsets of the clinoforms are sometimes defined, but the lower boundary is usually relatively sharp against the base, while horizontal reflectors define the upper boundary of the clinoforms.

**Sequence 3 (S3): Aptian**

The reflectors in Sequence 3 varies from medium amplitude parallel continuous to chaotic. The top of the sequence has low amplitudes in some areas of the Hammerfest Basin, and the sequence is similar to Sequence 2, with clinoforms prograding towards southeast and southwest.

**Sequence 4 (S4): ?Albian**

Parallel continuous to chaotic reflectors with medium amplitude are defined in the Hammerfest Basin and Fingerdjupet Sub-basin. The top of the sequence has medium to high amplitude.
Suggested paleo-shorelines of the Barents Sea based on outcrop studies on Svalbard archipelago, and seismic data showing the progradation of shelf-margin clinoforms towards the basins are illustrated in Fig. 1.4 (LoCrA, work in progress). These maps are based on work done in the LoCrA consortium, and published papers from the Barents Sea. During deposition of Sequence 1 the Fingerdjupet Sub-basin was located in a deep marine area flanked by shallow shelves (Fig. 1.4). Sequence 2 is deposited in a transitional to shallow shelf zone, supported by observations of clinoforms within the sequence (Marin et al., accepted with revisions). Shallow shelf deposits seem to have dominated the study area during deposition of Sequence 3. An analysis of the sub-basin will be conducted and the depositional models will be discussed according to the observations found through detailed seismic interpretation. This study is local and will be incorporated into the previous regional studies done for the area.

Furthermore, Dahlberg (2014) states that most of the Fingerdjupet Sub-basin was filled in by aggradation except for a sequence of Late Barremian to Early Aptian age (corresponding to LoCrA Sequence 2) which was filled in by progradation. The depocenters are interpreted to be controlled by tectonic activity during Lower Cretaceous. Dimitriou (2014) concludes that there is no significant sand or coarse-grained material based on seismic facies investigations in the eastern part of the southwestern Barents Sea, and the deposition of main clinoform packages are defined as Early-Middle Barremian deposits.

As one of the main goals of this thesis is to predict possible sandstone reservoirs, the other parts of the petroleum system in the Fingerdjupet Sub-basin are essential. Hydrocarbon maturation on the Upper Jurassic succession was studied by Jamil et al. (2014) based on the three wells drilled in the Fingerdjupet Sub-basin. Measurements of hydrocarbon residuals in different reservoir units of Mesozoic age indicated that there are mature source rocks in the sub-basin. However, the drilled locations did not show any hydrocarbon filled reservoirs, which makes it interesting to map out candidate reservoir sandstones in the Lower Cretaceous section.
Fig. 1.4 Paleogeographic Maps of the Barents Sea. Interpretations of depositional environments in the Barents Sea are shown for sequences 1-3 (S1-S3). Fingerdjupet Sub-basin is located within the red square and is generally located in deep marine to shallow shelf environments (LoCrA, work in progress).
1.2 Objectives and Motivation

In this study, 2D and 3D seismic data will be combined with well data and biostratigraphic data to develop a stratigraphical understanding of the Early Cretaceous deposits of the Fingerdjupet Sub-basin in order to:

- Understand the stratigraphic development of Fingerdjupet Sub-basin by developing a detailed understanding of the depositional environments/systems in each sequence
- Quantitative classification of clinoforms and comparison to empirical data to propose whether they tend to resemble sand- or mud-dominated clinoforms
- Investigate the relationship between seismic resolution and scale of the clinoforms
- Study analogues to link the observations to other regions

This study contributes to the previous work by analysing a new high-resolution seismic dataset to do a more detailed study of the stratigraphical evolution of the Fingerdjupet Sub-basin. The clinoforms are subdivided into different types based on scales and geometries, which will provide information about deposition and distribution of sediments. As a part of the LoCrA consortium, this study will help understand the depositional environments in Fingerdjupet Sub-basin during Lower Cretaceous times.
1.3 Theoretical Background on Clinoforms

A complete clinoform is represented by topsets, foresets and bottomsets, and builds out on slopes and continental shelves. Possible location of sandstone-bodies can be determined based on the scale and geometry of the clinoforms (Anell and Midtkandal, 2015). Clinoforms are divided into three different types based on the scale: (1) delta-scale; (2) shelf-prism; and (3) continental margin clinoforms (Helland-Hansen et al., 2012; Patruno et al., 2015). The delta scale clinoforms are subdivided into subaerial and subaqueous deltas, and are characterized by the small size, only tens of metres in height (Patruno et al., 2015). A difference between these two types is that the subaerial clinoforms show a big variety in geometries, while the subaqueous are more regular. The rollover point is located approximately at the shoreline break for the subaerial, and on the shelf with water depths of up to 60 meters for the subaqueous. Shelf-prism clinoforms have a relief of ~100-500 meters, while the continental margin clinoforms have a relief of several hundreds to thousands of meters (Helland-Hansen and Hampson, 2009; Patruno et al., 2015). The main mechanism for such sediment supply to the slope and basin floor is regression of the shoreline (Fig. 1.5) (Anell and Midtkandal, 2015).

![Fig. 1.5 Clinoform Systems](image)

**Fig. 1.5 Clinoform Systems.** An idealized regional cross-section parallel to the regional depositional dip showing the three main clinoform types: delta, shelf-prism and continental-margin (Modified from Helland-Hansen et al., 2012).
To develop a prediction of the paleoshelf the classification of stacking patterns such as progradation, aggradation and retrogradation of the section is helpful (Fig. 1.6). Helland-Hansen and Martinsen (1996) subdivided shoreline trajectories into three main classes: (1) Progradation with downstepping is associated with forced regression, where the accommodation space decreases due to relative sea level fall, (2) If the sediment supply is the main controlling factor during deposition a progradational with aggradation stacking pattern will occur, with forestepping and upstepping of the shoreline, defined as normal regression, and (3) Retrogradation is associated with backstepping of the shoreline, driven by relative sea level rise. During a stillstand of relative sea level, the topsets could be replaced by toplap (Catuneanu et al., 2010).

**Fig. 1.6 Stratal Stacking Patterns Related to Shoreline Trajectories.** Forced regression, normal regression, and transgression are illustrated. The possible types of shoreline trajectory during changes in relative sea level are shown as red and blue lines. RSL - Relative Sea Level (Catuneanu et al., 2010).
There are four main types of clinoforms: (1) sigmoid; (2) oblique; (3) complex sigmoid-oblique; and (4) shingled (Fig. 1.7):

Fig. 1.7 Seismic Reflection Patterns. Progradational patterns of different types of clinoforms: (1) Sigmoid; (2) Oblique; (3) Complex sigmoid-oblique; and (4) Shingled (Modified from Mitchum et al., 1977).

Sigmoid clinoforms are by Mitchum et al. (1977) interpreted as strata with thin, gently dipping topsets and bottomsets, and thicker, more steeply dipping foresets, with an overall prograding pattern. The depositional angle is usually less than 1°, and the bottomsets are often too thin to be resolved on seismic data, making it look like downlap terminations. The topsets are usually deposited and preserved when the sediment supply is relatively low, basin subsidence relatively rapid, and/or during a rapid rise in sea level (Mitchum et al., 1977).

The oblique clinoforms can be subdivided into parallel and tangential oblique. Characteristic for this type is lack of topsets and flat to low-angle shelf-edge trajectories, which is associated with relatively high sediment supply, slow to no basin subsidence, and a stillstand of sea level (Mitchum et al., 1977). Due to the lack of topsets the relatively steep-dipping layers (up to 10°) are terminating up dip by toplap at a nearly flat upper surface, and downlap against the lower surface (Mitchum et al., 1977).

Complex sigmoid-oblique clinoforms is a combination of the two types mentioned above within a specific seismic facies unit. Some parts of the upper segment are toplapping, while some are creating the sigmoid horizontal topsets.
A shingled progradational pattern is recognized by a thin prograding seismic package with parallel upper and lower surfaces. Within this package oblique parallel clinoforms can be observed as long as the resolution of the seismic data is sufficient to resolve the thin layer. Such observations are usually associated with shallow water deposits (Mitchum et al., 1977).

Based on the work done by Patruno et al. (2015) it is possible to distinguish the shoreline deltas from the subaqueous deltas, and also the other types of clinoforms. They defined a system where the scale and geometry of the clinoforms makes them fit into a system based on the variations observed from a worldwide database. Patruno et al. (2015) has proposed a unique mathematical relationship between the dip extent and slope gradient for each type of clinoform. The bottomsets and topsets of the clinoforms are subdivided into an inner and outer part based on where they become horizontal or conformable with the underlying surface. The outer topsets (\(Th, Td\)), foresets (\(Fh, Fd\)), and inner bottomsets (\(Bh, Bd\)) height and dip extent are measured between the head point and upper rollover point, the two rollover points, and the toe points, respectively. The total height of the clinoform (\(Hh\)) is measured from the toe point to the head point (Fig. 1.8). This method is used in this thesis to help predict the lithology of the clinoforms based on these measurements.

**Fig. 1.8 Parameters for Quantitative Clinoform Analysis.** Overview of the parameters used to measure the clinoforms (Modified from Patruno et al., 2015).
2 Regional Geological Setting

The Barents Sea, located in the northwestern corner of the Eurasian continental shelf is covering an area of 1.4 million km$^2$ (Smelror et al., 2009), and developed during the Cenozoic opening of the Norwegian-Greenland Sea and the Eurasia Basin (Faleide et al., 1993). During the separation of Greenland and Eurasia the deep basins in the southwestern Barents Sea formed, and through time, basins, structural highs and platforms developed during several tectonic events (Anell et al., 2014; Faleide et al., 1993). Additionally, the sedimentation is controlled by the tectonic events along the eastern, northern and western margins, although sea level variations on both local and regional scale have influenced the depositional history of the province (Worsley, 2008).

During Triassic to Early Jurassic times the Barents Sea is considered to be a relatively tectonically quiet area (Gabrielsen et al., 1990), with deposition of the main reservoir unit in the Barents Sea, which is of Lower to Middle Jurassic age (Faleide et al., 2010). By Middle Jurassic times extensional tectonics leading to faulting commenced, and continued until the Late Jurassic and Early Cretaceous times (Gabrielsen et al., 1990). At the same times the southwestern Barents Sea experienced major transgressions and the entire Barents Shelf was flooded, leading to deposition of shallow-shelf to deep-marine sediments. During Early Cretaceous times, the northern Barents Sea area was uplifted, and formation of deep basins further south created accommodation space for the eroded sediments (Smelror et al., 2009). Three sedimentary units from Valanginian to Cenomanian age are defined in the deep southwestern Barents Sea basins. Shales and claystones, interbedded with thin layers of silt, limestone and dolomite, dominate these three units (Faleide et al., 2010). The northern Barents Sea was during this time characterized by widespread magmatism generating sills and dykes belonging to the regional Large Igneous Province (LIP) in the Arctic (Faleide et al., 2010). This has been named the High Arctic Large Igneous Province (HALIP) and covered large parts of the Barents Sea, where evidences can be
seen on Svalbard, Franz Josefs Land and the Canadian Arctic Islands (Maher Jr., 2001). This caused regional uplift in the north and east, which is supported by a regional uplift unconformity seen at Svalbard, and southward sediment progradation (Faleide et al., 2008; Grundvåg et al., 2015; Kayukova et al., 2015; Worsley, 2008).

Furthermore, the Barents Sea can be subdivided into two major provinces, the eastern, and the western, where the western province lays within Norwegian borders. This part of the Barents Sea was influenced by major post-Caledonian rifting and also later rifting episodes (Faleide et al., 1993; Smelror et al., 2009), which created many pull-apart basins and platforms in the area (Faleide et al., 1993; Worsley, 2008). These basins have been affected by tectonic and magmatic processes related to: (1) the opening of the Atlantic Ocean to the west; (2) opening of the polar Euramerican Basin to the north; (3) the compressional forces of the Ural Orogeny to the east; and (4) finally the opening of the Norwegian-Greenland Sea to the west (Faleide et al., 1993; Worsley, 2008).

Faleide et al. (1993) subdivided the western Barents Sea into three provinces based on their geological history and appearance (Fig. 2.1):

1. The Svalbard Platform, consisting of relatively horizontal sequences of Upper Paleozoic and Mesozoic age.
2. A basin province between the Svalbard Platform and the Norwegian coast characterized by a mixture of structural highs and sub-basins. The basins are mainly filled with Jurassic-Cretaceous sediments, but further west towards the Norwegian-Greenland Sea the infill sediments are also of Paleocene-Eocene age.
3. The western continental margin consisting of three main segments (a) a sheared margin along the Senja Fracture Zone; (b) a central rift complex located to the southwest of Bjørnøya associated with volcanism; and (c) a northern sheared and later rifted margin along the Hornsund Fault Zone.
Fig. 2.1 Structural Elements of the Western Barents Sea. Numbers 1-3 marks the three geological provinces described by Faleide et al. (1993). The red square highlights the Fingerdjupe Sub-basin. BB: Bjørnøya Basin, FSB: Fingerdjupe Sub-basin, HFZ: Hornsund Fault Zone LH: Loppa High, MB: Maud Basin, SFZ: Senja Fracture Zone, SH: Stappen High (Modified from Faleide et al., 2010).
Fig. 2.2 shows a litho- and chronostratigraphic chart of the Late Paleozoic, Mesozoic and Cenozoic deposits in the southwestern Barents Sea, including a column of the key tectonic events in the region (Glørstad-Clark et al., 2010; Norlex, 2012). The focus of this study is the sedimentary structures of Lower Cretaceous age, marked by a red square in Fig. 2.2. Faleide et al. (1993, 2008) combined the rift phases of Late Jurassic-Early Cretaceous into one event, as their work was more regional compared to this study. This large rift phase resulted in development of the Tromsø Basin, the Sørvestnaget Basin and the Bjørnøya Basin in the southwestern Barents Sea (Faleide et al., 1993, 2008). Later interpretations by Dahlberg (2014) suggest that the Fingerdjupet Sub-basin was a relatively tectonic quiet period during Middle to Late Jurassic, creating a distinct division between the Bjørnøya Basin, which were tectonically active, and the relatively quiet Fingerdjupet Sub-basin. Three formations are defined within the Lower Cretaceous unit: Knurr-, Kolje-, and Kolmule Formation. The descriptions of the formations are based on type well 7119/12-1, located in the Ringvassøya-Loppa Fault Complex (Dalland et al., 1988):

**Knurr Formation**

Characteristic for this formation is claystones with thin interbeds of limestone and dolomite, indicating open and generally distal marine depositional environments. The upper parts of the formation generally consist of red- to yellow-brown claystones, while the base is defined by a decrease in gamma ray response. The general pattern in the density log is an increased response towards the base, which coincides with two of the wells in Fingerdjupet Sub-basin (7321/8-1 and 321/9-1). Biostratigraphic data has suggested a Ryazanian/Valanginian to Early Barremian age, equivalent to the dark shales of Rurikfjellet Member of the Janusfjellet Formation on Svalbard (Dalland et al., 1988; Grundvåg et al., 2013; Mørk et al., 1999). The description of this formation fits well with the log responses seen in Fingerdjupet Sub-basin.
Kolje Formation

Kolje Formation is described as syn-rift deposits (Gabrielsen et al., 2013). The formation is dominated by shales and claystones, with minor interbeds of limestone and dolomite, indicating distal open marine depositional environments with good water circulation and occasionally restricted environments. Thin interbeds of siltstone and sandstone is observed in the upper part of the formation, which based on the log responses only seem to be consistent with well 7321/7-1 in the Fjordjupet Sub-basin. The age defined is Early Barremian to Late Barremian/Early Aptian, equivalent to the Helvetiafjellet Formation, which is a sand dominated unit on the Svalbard Platform (Dalland et al., 1988; Grundvåg et al., 2013).

Kolmule Formation

Kolmule Formation is mainly described as claystones and shales with some silty parts, interpreted as open marine depositional environments. Thin stringers of limestone and dolomite occur, and also traces of glauconite and pyrite. The age is defined as Aptian to mid-Cenomanian, and the lower part of the formation is equivalent to the shelf deposits of Carolinefjellet Formation on Svalbard (Dalland et al., 1988; Grundvåg et al., 2013).
Fig. 2.2 Chrono- and Lithostratigraphic Chart. Chrono- and lithostratigraphic chart of the southwestern Barents Sea including the major phases of tectonic activity. Main rift phase are marked in bold (Modified from Glørstad-Clark et al., 2010; Norlex, 2012).
Fingerdjupet Sub-basin

The Fingerdjupet Sub-basin is one of many Cretaceous and Cenozoic Basins in the southwestern Barents Sea, defined as a shallow northeastern extension of the deep Bjørnøya Basin (Faleide et al., 1993; Gabrielsen et al., 1990). It is a north-south trending Early Cretaceous extensional basin (Gabrielsen et al., 1990), which is bounded by the Leirdjupet Fault Complex towards the deeper part of the Bjørnøya Basin (west and south), and the Bjarmeland Platform and the Loppa High to the east and southeast (Fig. 2.3). Within the sub-basin, a horst and graben pattern is defined by a system of NNE-SSW trending fault blocks. Faleide et al. (1993) suggest that these faults were generated during Late Jurassic rifting, and local reactivation during the Early Cretaceous subsidence (Fig. 2.3 and Fig. 2.4) (Gabrielsen et al., 1990; Faleide et al., 1993). During Middle Triassic to Middle Jurassic times the sub-basin was part of a regional cratonic platform in the western Barents Sea (Gabrielsen et al., 1990). During Late Cenozoic at least 2000 m of the Late Cretaceous and Cenozoic sediments were eroded, leaving the history largely unknown (Henriksen et al., 2011; Gabrielsen et al., 1990).

Fig. 2.3 Regional Profile NW-SE. From NW showing Stappen High, Bjørnøya Basin, Fingerdjupet Sub-basin, Bjarmeland Platform, Loppa High, Svalis Dome, Maud Basin and Bjarmeland Platform (Modified from Gabrielsen et al., 1990).
Fig. 2.4 Regional Profile SW-NE. From SW showing Sørvestnaget Basin, Bjørnøya Basin and Fingerdjupet Sub-basin (Modified from Faleide et al., 2010).
3 Database and Methodology

3.1 Well and Seismic Data

Fig. 3.1 shows the location of the available well and seismic data used in this study.

Fig. 3.1 Database. Overview of the available well and seismic data used for the interpretation.
Well data:
The well database includes three released exploration wells (7321/7-1, 7321/8-1 and 7321/9-1) from the Norwegian Petroleum Directorate (NPD) and was provided by Centrica (Fig. 3.1). Data included for these wells were well logs, check shots, a biostratigraphic report for well 7321/7-1 (Robertson, 1989), and dipmeter data from wells 7321/8-1 and 7321/9-1 (Eriksfiord, 2014). The well tops used for well correlation were stratigraphic well tops created from seismic sequences, with ages defined from the LoCrA consortium.

Well details from NPD (2016B) of each formation are listed in Table 3.1:

<table>
<thead>
<tr>
<th>Well</th>
<th>Year of drilling</th>
<th>Knurr Fm Thickness</th>
<th>Kolje Fm Thickness</th>
<th>Kolmule Fm Thickness</th>
<th>Total Depth (MD) [m]</th>
<th>Core in Lower Cretaceous</th>
</tr>
</thead>
<tbody>
<tr>
<td>7321/7-1</td>
<td>1988</td>
<td>26 m (1918-1892)</td>
<td>747 m (1892-1145)</td>
<td>619 m (1145-526)</td>
<td>3550</td>
<td>Knurr Fm (1907-1910 m)</td>
</tr>
<tr>
<td>7321/8-1</td>
<td>1987</td>
<td>31 m (1383-1352)</td>
<td>500 m (1352-852)</td>
<td>306 m (852-546)</td>
<td>3482</td>
<td>No</td>
</tr>
<tr>
<td>7321/9-1</td>
<td>1988</td>
<td>331 m (1317-986)</td>
<td>94 m (986-892)</td>
<td>334 m (892-558)</td>
<td>1800</td>
<td>No</td>
</tr>
</tbody>
</table>

Seismic data:
This study is based on 2D and 3D seismic data provided by Centrica, covering the area of interest in the Fingerdjupet Sub-basin. The seismic data available is presented in Table 3.2 showing the type, version, quality and purpose. The density of the 2D lines is varying, and so is the quality. Due to the location of the 3D cubes the main area of interest became the southern part of the Fingerdjupet Sub-basin. Wells 7321/8-1 and 7321/9-1 are penetrating the succession within the Icebear 2 3D seismic survey, while well 7321/7-1 penetrates a super high resolution MCG1401 2D seismic line. The small-scale seismic interpretation of clinoforms has mainly been carried out on the super high resolution MCG1401 2D seismic, HR15 3D P-cable and Icebear2 3D seismic surveys due to the seismic resolution (Fig. 3.1). The HF13 and...
TGS_Hoop_HFC 3D seismic cubes, and 2D seismic lines have been used for regional mapping.

Table 3.2 Seismic Database. The seismic data used to carry out this study.

<table>
<thead>
<tr>
<th>Seismic Survey</th>
<th>Icebear2</th>
<th>HFC</th>
<th>HR15</th>
<th>HF13</th>
<th>MCG1401</th>
<th>NBR</th>
<th>Released 2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered by</td>
<td>WesternGeico</td>
<td>TGS</td>
<td>TGS</td>
<td>TGS</td>
<td>MCG/Exploro</td>
<td>Fugro/TGS</td>
<td>X</td>
</tr>
<tr>
<td>Type</td>
<td>3D Broadband</td>
<td>3D Conventional</td>
<td>3D P-cable</td>
<td>3D Conventional</td>
<td>2D Super High Resolution</td>
<td>2D Conventional</td>
<td>2D Conventional</td>
</tr>
<tr>
<td>Version</td>
<td>Full + Angle Stacks</td>
<td>Full + Angle Stacks</td>
<td>Full</td>
<td>Full + Angle Stacks</td>
<td>Full + Angle Stacks</td>
<td>Full + Angle Stacks</td>
<td>Full</td>
</tr>
<tr>
<td>Quality</td>
<td>Very good</td>
<td>Good</td>
<td>Very good</td>
<td>Good</td>
<td>Very good</td>
<td>Good</td>
<td>Varying</td>
</tr>
<tr>
<td>Purpose</td>
<td>Detailed mapping</td>
<td>Regional mapping</td>
<td>Detailed mapping</td>
<td>Detailed mapping</td>
<td>Detailed mapping</td>
<td>Regional mapping</td>
<td>Regional mapping</td>
</tr>
</tbody>
</table>

3.1.1 Data Quality

The resolution of seismic data depends on the velocity of the sediments and the frequency of the seismic signal, defining the wavelength. The seismic resolution decreases proportionally with depth as the wavelength increases due to more compacted rocks, higher velocities, attenuation, and dispersion (Brown, 1999). The resolution of the seismic data is key to differentiate what the different seismic surveys are capable of resolving, as the main goal is to study small scaled clinoforms (< 100 meters relief) in detail. A "seismic & spectrum probe" in Petrel is used to create plots showing signal strength (dB) vs frequency (Hz) for each seismic survey, to investigate the usable frequency spectrum (and peak frequency) for the interval showing clinoforms (Fig. 3.2). For the Icebear2 broadband 3D seismic survey the peak frequency is not representative alone as the concept of broadband data is that the peak frequency appears as a range in values. To simplify the calculation a mean peak frequency of 25 Hz is defined.

The velocities used in this study are varying to capture the uncertainty associated with changes in lithology and depth variations. The lithologies of most of the clinoforms are unknown as the wells did not drill through them, so to cover the uncertainty in sediment type a high and a low velocity were picked for wells 7321/7-1 and 7321/8-1,
Fig. 3.2 Frequency Spectrum. Frequency spectrum for the Lower Cretaceous unit in the different seismic surveys.

representing shaly units. In addition, candidate reservoir velocities originated from a rock physics modelling study carried out by RSI on behalf of Centrica (internal Centrica report) is included, since no sandstones have been drilled by the wells. This study has been utilised to predict P-wave velocities in two candidate reservoirs (a. clean sandstones with 28% porosity, and b. shaly sandstones with 21% porosity) at maximum burial depth, prior to the uplift, employing theoretical rock physics models. Maximum burial depth is modelled trough the net erosion map by Henriksen et al. (2011), suggesting that the average burial depth was approximately 2000 meters prior to the uplift. The seismic velocities and frequencies derived from the wells and rock physics modelling are listed in Table 3.3.

Table 3.3 Acoustic Velocities and Peak Frequencies of the Lower Cretaceous Unit. Used to calculate the resolution of the data.
**Vertical Resolution**

The top and base reflectors of a layer need to be separated by a distance of minimum $1/4$ of a wavelength to be resolved in the seismic. If the layer is thinner than this, reflectors from different layers will merge, and the true thickness of the layer cannot be determined (Sheriff and Geldart, 1995). Calculations of vertical resolution are done to get an overview of what features the different seismic surveys can resolve. The results are shown in Table 3.5.

**Horizontal Resolution**

The Fresnel zone defines the horizontal resolution of seismic data, even though other factors as signal/noise ratio are affecting the resolution (Sheriff and Geldart, 1995). This zone represents the smallest distance two reflection points must have to appear as two separate objects in the seismic (Brown, 1999). For 2D seismic lines only the x-direction (inline) can be migrated, resulting in an elliptic Fresnel zone perpendicular to the sampling direction. For 3D migrated seismic data the horizontal resolution is defined by the wavelength of the seismic, rather than the Fresnel zone, meaning that the data is migrated in all directions, resulting in a circular Fresnel zone (Fig. 3.3) (Brown, 1999).

![Fig. 3.3 Illustration of the Fresnel Zone.](image)

Showing the difference before and after migration for both 2D and 3D seismic data. The large black circle represents the data before migration and the x-line the direction of the inline. The red ellipse represents the Fresnel Zone after migration for 2D seismic data. The grey circle in the middle represents the Fresnel Zone for 3D seismic data after migration. The formula for calculation of the Fresnel zone radius is included in the figure (Modified from Brown, 1999).
Table 3.4 and Table 3.5 show the wavelengths and resolutions calculated for the different seismic surveys:

Table 3.4 Wavelengths. The wavelengths calculated by using different sediment velocities for each seismic survey.

<table>
<thead>
<tr>
<th>Seismic Survey</th>
<th>Wavelength [m]</th>
<th>Well 7321/7-1</th>
<th>Well 7321/8-1</th>
<th>Estimates by Centrica</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vp1</td>
<td>Vp2</td>
<td>Vp1</td>
<td>Vp2</td>
</tr>
<tr>
<td>Icebear2</td>
<td>-</td>
<td>-</td>
<td>110</td>
<td>134</td>
</tr>
<tr>
<td>HR15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MCG1401</td>
<td>62</td>
<td>75</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NBR</td>
<td>103</td>
<td>125</td>
<td>92</td>
<td>112</td>
</tr>
</tbody>
</table>

Table 3.5 Seismic Resolution. The vertical and horizontal resolution for each seismic survey. Note the uncertainty in the calculations of the NBR lines as these varies in quality.

<table>
<thead>
<tr>
<th>Seismic Survey</th>
<th>Seismic Resolution [m]</th>
<th>Vp1 Vertical</th>
<th>Vp1 Horizontal</th>
<th>Vp2 Vertical</th>
<th>Vp2 Horizontal</th>
<th>Vp (clean sst) Vertical</th>
<th>Vp (clean sst) Horizontal</th>
<th>Vp (shaly sst) Vertical</th>
<th>Vp (shaly sst) Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Icebear2</td>
<td></td>
<td>28</td>
<td>28</td>
<td>34</td>
<td>34</td>
<td>24</td>
<td>24</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>HR15</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>MCG1401</td>
<td>16</td>
<td>x=16/y=202</td>
<td>19 x=19/y=245</td>
<td>12</td>
<td>x=12/y=156</td>
<td>14</td>
<td>x=14/y=176</td>
<td>14</td>
<td>x=14/y=176</td>
</tr>
<tr>
<td>NBR</td>
<td>~25</td>
<td>~x=25/y=300</td>
<td>~30</td>
<td>~x=30/y=400</td>
<td>~20</td>
<td>~x=20/y=260</td>
<td>~23</td>
<td>~x=23/y=290</td>
<td></td>
</tr>
</tbody>
</table>

The HR15 P-cable survey is calculated using only the estimated velocities as the survey is located far away from the wells and it is believed that the clinoforms consist of sandstones based on the geometry and scale. The NBR 2D line calculations are a general estimate of the resolution based on an average peak frequency from different lines, as the quality of these lines are varying. The resolution is uncertain and probably varying, but calculations show that the vertical resolution should be approximately 20-30 meters. From the values listed in Table 3.5 it is clear that the high-resolution MCG1401 2D seismic lines, and HR15 P-cable should be able to resolve clinoforms with a relief larger than 20 and 14 meters, respectively. The Icebear2 3D Broadband cube will resolve clinoforms with a relief larger than 34 meters, and maybe all the way down to 24 meters, depending on the actual velocity at the exact location.
3.2 Methodology

3.2.1 Seismic to Well Ties

The synthetic seismogram was calculated using the calibrated sonic and density logs, and wavelets. Quality checks of the well logs, including the caliper log, were done to define washout zones and incorrect log responses to mark the uncertain intervals. The lithology of the wells is homogeneous in the Lower Cretaceous, which makes the reflectors weak as the changes in lithology are minor. The main focus for the well tie was to get a good tie of the unconformities that are visible in the Lower Cretaceous section. The sonic log was calibrated with the time-depth table from the check shots for the three wells. A drift curve through the check shot data was defined to correct the sonic log to the known travel time values derived from the check shots.

Prior to generating the synthetic seismogram the logs were quality checked, and replacement of poor and missing data has been carried out. The GR log has indications of a sandstone-dominated unit in wells 7321/7-1 and 7321/8-1 (at approximately 900 m), as marked in previous figures, which does not coincide with the other well logs. By investigating the log descriptions from NPD (2016B) it is clear that this correlates to a casing shoe located at a shallower depth than planned. Based on this the low GR log response is not taken into account in the study. In well 7321/7-1 the density log was missing for the shallow part where the Lower Cretaceous deposits are located, and had to be calculated from the sonic log.

The missing section of the density log for the shallow Lower Cretaceous deposits in well 7321/7-1 was predicted based on the velocities from the sonic log using Gardner's relationship,

\[ \rho = \alpha V^{1/4} \]
where $\rho$ is the density in g/cm$^3$, $\alpha$ is a constant with a value of 0.23, and $V$ is velocity in ft/s (Dey and Stewart, 1997). This was done to get the best fit to the original density log so that it could be used when doing the seismic to well tie. The log has a good tie to the original density log in the deeper parts, except for some variations in the sandy zones and large washout zones. The estimated and original density logs were combined to make a continuous log response (Fig. 3.4).

**Fig. 3.4 Estimated Density Log for Well 7321/7-1.** The original density log (DEN-red) was combined with an estimated (Estimated DEN-black), ending up with a final density log (Combined DEN-red) to be used for the seismic to well tie. Note that the incorrect GR response marked in the red ellipse is not sandstones, but due to the casing shoe.

**Seismic Wavelet**

Analytical wavelets such as Ricker and Ormsby, Statistical wavelets, and Deterministic wavelets were made to make the best fit to the seismic spectrum of the seismic datasets. The Ormsby wavelet gave the best result for all of the wells (7321/7-1, 7321/8-1 and 7321/9-1) as the frequency spectrum became similar to that of the seismic data. For wide bandwidth data an Ormsby wavelet is better because the
frequency spectrum is not represented by one peak, but a range in peak frequency. The Ormsby wavelet is constructed by looking at the frequency spectrum of the seismic data (Fig. 3.5 a) to define four corner point frequencies (1. the low cut, 2. the low pass, 3. the high pass, and 4. the high cut frequency) like shown in the model in Fig. 3.5 b. Points 2 and 3 defines the range in peak frequency.

![Frequency Spectrum and Model of Ormsby Wavelet](image)

**Fig. 3.5 Frequency Spectrum and Model of Ormsby Wavelet.** a) Frequency spectrum for the Lower Cretaceous unit in the different seismic surveys, with peak frequencies highlighted. b) Illustration showing how the Ormsby wavelet is constructed in Petrel. Numbers 1-4 shows the four input frequencies.

All frequencies lower and higher than the low cut and high cut frequencies are filtered out and not used, from point 2, the low pass frequency, all the higher frequencies will be used until point 3, the high pass frequency. Form point 3 the frequencies higher than this will be linearly tapered towards point 4.

Two different wavelets were created to get the best fit to the seismic data, one for the 7321/7-1 well that is tied to the MCG1401 2D seismic survey, and one for wells 7321/8-1 and 7321/9-1, which are tied to the Icebear2 3D seismic survey. The wavelets are calculated to have a wavelength of 128 ms, and sample interval of 4 ms for the wavelet tied to the 3D survey and 1 ms for the 2D survey (Fig. 3.6). The wavelets are zero phased and has not been modified in regards to phase manipulation or Hanning filtering. The power spectrum illustrates the difference between the two datasets, and reveals that the highest seismic frequencies for the MCG1401 2D data
are located at approximately 40-50 Hz, and approximately at 20-30 Hz for the Icebear2 3D data (Fig. 3.7). Both of the wavelets have SEG normal polarity, meaning that an increase in acoustic impedance results in a peak.

**Fig. 3.6 Seismic Wavelets.** Seismic wavelets for the three wells applied in order to create the seismic to well tie. Notice the slightly smaller sidelobes of the wavelet used to tie wells 7321/8-1 and 7321/9-1 to the Icebear2 3D seismic survey, reflecting the benefit of broadband data.

**Fig. 3.7 Power Spectrum.** Power spectrum of the two wavelets used in the seismic to well tie process.
Well 7321/7-1

This well is located outside the area covered by 3D seismic data and was tied to the MCG1401 2D data. The synthetic seismogram was computed using a zero phase Ormsby wavelet with values 1. 5 Hz, 2. 30 Hz, 3. 45 Hz, and 4. 100 Hz (see description in Fig. 3.5 b). An average shift of +6 ms was applied to the synthetic seismogram to match the real data. This well tie achieved reasonably good quality matches between synthetic and real data at the two main intervals around the Base Cretaceous Unconformity (BCU) and the Early Cretaceous Unconformity (ECU) (Fig. 3.8).

Wells 7321/8-1 and 7321/9-1

Wells 7321/8-1 and 7321/9-1 were tied to the Icebear2 3D seismic data. A zero phase Ormsby wavelet with values 1. 4 Hz, 2. 10 Hz, 3. 40 Hz, and 4. 50 Hz had the best fit to the real data. The synthetic seismogram was shifted -10 ms to match the real data for well 7321/9-1 (Fig. 3.9). Well 7321/8-1 is drilled through shallow gas and the reflectors are therefore even weaker than at other locations, making it difficult to check the tie. This well is therefore mainly tied to the BCU and Jurassic reflectors.
### 3.2.1 Seismic to Well Ties

#### Fig. 3.8 Well Tie of Well 7321/7-1 to 2D Data.
Caliper, GR, Density, Sonic and Reflectivity logs are shown with the synthetic seismogram and a NW-SE trending MCG1401 2D seismic line (courtesy of MCG), which the well is tied to. At around 850 meters depth the well logs do not have any data, and below this the GR signal is incorrect due to the casing shoe located above.
3.2.2 Seismic Interpretation Methods

Interpretation of seismic data is performed using Petrel 2014© by Schlumberger. The sequences defined by Marin et al. (*accepted with revisions*) are used in the study area to establish a stratigraphic framework, where the ages defined by the LoCrA consortium are cross-checked with a biostratigraphic report for well 7321/7-1 (Robertson, 1989). The seismic horizons represent the boundaries of each seismic sequence. Within the sequences some sub-sequences as well as some important surfaces considering the age control and observations are interpreted. The available well logs does not show any clear stacking patterns (only shale) so the reflector terminations on the seismic data were used (i.e. downlap, toplap, onlap and truncation) when interpreting the sequence boundaries.

Seismic interpretation of sequences and seismic facies analysis is based on all available 3D and 2D seismic surveys. Each sequence is described based on seismic character, but the main target of this study is the clinoform analysis, mainly observed in Sequence 2. Structural and time thickness maps between the sequences were created to investigate lateral changes.

Fault interpretation including definition of pre-, syn-, and post-rift sequences in the Fingerdjupet Sub-basin are described in detail in the collaborative thesis by Acharyya (2016), and is not focused on in this thesis.

To do the trajectory analysis, flattened seismic lines oriented in the/or close to the progradational direction was used. The lines were flattened on regional flooding surfaces (sequence tops), Base Cretaceous Unconformity (BCU) and Early Cretaceous Unconformity (ECU).
To do a quantitative classification of the clinoforms, key seismic lines were depth converted and decompacted to determine the relief and foreset angle. The uncertainties associated with decompaction are taken into consideration, and the calculations are listed in 8.1 Appendix 1 - Decomposition. A simple three-layered velocity model was built based on the available check-shot velocities of the three wells in the sub-basin. Due to the uncertainty connected to the velocity model most of the seismic sections are shown in time, while the sections used for quantitative classification are shown in depth. The estimated decompaction was calculated using the formula:

$$S_i^* = S_i (1 - \phi_i) / (1 - \phi_i^*)$$

where $S_i^*$ is the decompacted sediment thickness, $S_i$ is the thickness of the compacted sediments, $\phi_i$ is the porosity of the compacted sediments and $\phi_i^*$ is the porosity of the uncompacted sediment (Brookfield, 2008).

To be able to estimate the correct porosity a regional net erosion map was used to estimate the true burial depth (Henriksen et al., 2011), as the sediments were buried much deeper prior to the uplift (Fig. 3.10 a). An average of 2000 meters burial depth were added to the present depth and used for the prediction of porosities. The lithologies of the clinoforms are unknown as the wells did not drill through them, so to cover the uncertainty in sediment type both sandstone and shale were used as end members and the average porosities of the two lithologies are highlighted in Table 3.6. The porosities were estimated using the porosity vs depth curves for different lithologies (Avseth et al., 2005; Rodriguez, 2015), illustrated in Fig. 3.10 b and c.
The measured clinoforms were compared to a worldwide database (Patruno et al., 2015) to make more accurate predictions of facies types present in the area. Time thickness maps showing the distribution of seismic characters were created for each sequence, and are used for the paleogeographic reconstruction of the study area.

Table 3.6 Average Porosities. Sand- and mud-rich are used as end members and an average porosity for the compacted and uncompacted sediments are listed.

<table>
<thead>
<tr>
<th>Porosities, ϕ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand-rich</td>
</tr>
<tr>
<td>Compacted 23,3</td>
</tr>
<tr>
<td>Mud-rich</td>
</tr>
<tr>
<td>Compacted 12,75</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Compacted 18</td>
</tr>
</tbody>
</table>
Fig. 3.10 Net Erosion Map and Porosity vs Depth Curves. a) A regional map illustrating the estimated net erosion for the Barents Sea (Henriksen et al., 2011). b) Porosity vs depth curve where variations in clay content are presented in different colours and dashed lines indicates measurements of porosity at 2000 meters burial depth. (Modified from Avseth et al., 2005). c) Porosity vs depth for clean sandstone of three wells in the Hammerfest Basin with a trend line from the mid-Norwegian Shelf inserted for comparison (Rodriguez, 2015).
4 Observations and Interpretations

4.1 Seismic Stratigraphic Framework

The seismic stratigraphic framework of the study area, and terminology used in this study, are based on definitions of stratigraphic units made by Marin et al. \((accepted with revisions)\). As mentioned in 1.1 Previous Studies, they defined seven third order sequences by interpretation of seismic and well data in the Barents Sea. However, only four of them seem to be present in the Fingerdjupet Sub-basin when comparing the sequence tops with biostratigraphic data (Robertson, 1989). Based on this the Fingerdjupet Sub-basin holds the lowermost sequences, except for Sequence 0, which is not present in the area. Regional interpretations of key horizons in the Lower Cretaceous unit are included to be able to define the main seismic geometries within each sequence. The seismic picks of the interpreted horizons are summarized in Table 4.1. Within each sequence several seismic facies are observed, these are summarized in Table 4.2 and Table 4.3, and will be further described in each sequence in the next chapter, 4.2 Seismic Sequences.

Table 4.1 Interpreted Seismic Horizons. Showing the pick and significance of the interpreted horizons.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Pick</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Floor</td>
<td>Hard</td>
<td>Relatively flat in the area</td>
</tr>
<tr>
<td>Base Quaternary Unconformity</td>
<td>Hard</td>
<td>Early Cretaceous strata subcrop under this</td>
</tr>
<tr>
<td>Middle Albian</td>
<td>Hard</td>
<td>Strong reflector used for age control</td>
</tr>
<tr>
<td>Top Sequence 3</td>
<td>Hard</td>
<td>Flooding surface and sequence boundary</td>
</tr>
<tr>
<td>Early Cretaceous Unconformity</td>
<td>Hard</td>
<td>Post rift unconformity, reflectors are toplapping and onlapping onto it</td>
</tr>
<tr>
<td>Top Clinoforms - Sequence 2</td>
<td>Variable</td>
<td>Top reflector of the clinoforms, possibly a maximum regressive surface</td>
</tr>
<tr>
<td>Top Sequence 1</td>
<td>Hard</td>
<td>Flooding surface and sequence boundary</td>
</tr>
<tr>
<td>Base Cretaceous Unconformity</td>
<td>Hard</td>
<td>Strong amplitude reflector marking the base of the studied interval</td>
</tr>
</tbody>
</table>
The NPD formation tops follow a lithostratigraphic framework, therefore it is harder to correlate them throughout the Barents Sea. Because of this the seismic stratigraphic framework is constructed of sequences 1-4, which also provides more age control in the area. Sequence 2 is in a small area towards the southeast divided into three sub-sequences (a-c) based on observations of different depositional styles (only resolved on a few MCG1401 2D seismic lines). The seismic stratigraphic framework includes the chronostratigraphy, formations, a seismic section, well 7321/7-1 to illustrate the correlation, and sequences 1-4 previously defined in chapter 1.1 Previous Studies, and further described in chapter 4.2 Seismic Sequences. Key rift-phase (Acharyya, 2016) is illustrated as well as the main observed seismic geometries (Fig. 4.1).

<table>
<thead>
<tr>
<th>Chronostratigraphy</th>
<th>Formation</th>
<th>Seismic section</th>
<th>Well 7321/7-1</th>
<th>Sequences</th>
<th>Rifting</th>
<th>Seismic Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Cretaceous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Knurr</td>
<td></td>
<td>7321/7-1</td>
<td>S4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kolmule</td>
<td></td>
<td></td>
<td>S3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kolje</td>
<td></td>
<td></td>
<td>S1</td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aptian</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Barremian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hauterivian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valanginian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ryazanian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend**
- **Clinoforms**
- **Rifting**
- **Conformable Succession**
- **Early Cretaceous Unconformity (ECU)**
- **Base Cretaceous Unconformity (BCU)**
- **Middle Albian**
- **Top Clinoforms**
- **Top Sequence 3**
- **Top Sequence 1**

**Fig. 4.1 Seismic Stratigraphic Framework.** A seismic stratigraphic framework for the Lower Cretaceous succession in Fingerdjupet Sub-basin, created based on sequences defined by Marin et al. (accepted with revisions). Note the incorrect GR log response marked by the red ellipse.
The Lower Cretaceous unit is bounded by the strong and continuous Base Cretaceous Unconformity (BCU) at the base and the relatively horizontal Base Quaternary Unconformity eroding the Cretaceous unit at the top. There are not much sediments preserved on top of the eroded Lower Cretaceous sequence, only a thin package of Quaternary sediments. A seismic line from NW to SE, crossing the three wells, presents the four interpreted third order seismic sequences, S1-S4 (Fig. 4.2).

A well correlation from NW to SE for the three wells including main depositional structures observed on seismic data is shown in Fig. 4.3. The well correlation illustrates an overall thinning of seismic sequences 1, 2 and 3 towards the southeast, and that seismic Sequence 3 is not present at the location of well 7321/8-1.
Fig. 4.2 Seismic and Geoseismic Section. The Lower Cretaceous section is eroded on top by the Base Quaternary Unconformity. Possible syn-rift deposition can be interpreted from growth in the Aptian and Upper Barremian sections. The Early Cretaceous Unconformity (ECU) is interpreted based on seismic reflection terminations as described in the text. The vertical exaggeration is 6. Note red arrows indicating terminations of strata (courtesy of TGS).
**Fig. 4.3 Well Correlation.** The three wells drilled in Fingerdjupet Sub-basin with the interpreted seismic sequences and unconformities. Some of the GR signals are incorrect due to the location of the casing shoe (marked in red ellipses). The correlation is flattened on the Base Cretaceous Unconformity (BCU). The main observations (clinoforms, MTC (mass transport complex) and onlaps) from seismic lines are included. Dashed arrows indicate decrease/increase in GR log response. (ECU=Early Cretaceous Unconformity)
4.2 Seismic Sequences

4.2.1 Sequence 1 (S1): Latest Hauterivian - Early Barremian

Observations:
Sequence 1 is the lowermost sequence represented in the Lower Cretaceous strata in the Fingerdjupet Sub-basin. The sequence is bounded by the Base Cretaceous Unconformity (BCU), a strong and continuous reflector, and by a weak hard reflector at the top (Top Sequence 1). BCU weakens towards the deeper parts of the Bjørnøya Basin, and is truncated below the Base Quaternary Unconformity towards the Loppa High. Top Sequence 1 is not bright enough to be traced into the deep Bjørnøya Basin, due to deep burial and weakening of reflectors.

Well Character:
In the well logs this sequence is presented as a unit thinning towards the southeast. On the gamma log from well 7321/7-1 the sequence is put together by several low order coarsening and fining upwards sequences. The previously defined flooding surface marking the top of the sequence does not show a clear break in a coarsening upward sequence, rather a fining upward sequence followed by a new fining upward sequence. Well 7321/8-1 has some indications of a flooding surface at the top of the sequence. In well 7321/8-1 the sequence is divided into one fining upward sequence with a thicker coarsening upward sequence on top.

Thickness Map and Seismic Character:
The western boundary are defined by the Leirdjupet Fault Complex as the reflectors gets really weak as the depth is increasing moving into the Bjørnøya Basin. The thickness varies from 0 to approximately 300 ms, with a mean value of 125 ms, and the sequence is thinning towards the Loppa High (Fig. 4.4 a). The sequence is divided into two segments, a western and an eastern based on the seismic reflection.
patterns/defined facies. The western part is consisting of relatively horizontal reflectors (Facies 2) (Fig. 4.4 d), while the eastern has more chaotic reflection patterns (Facies 1, 3, and 4). In the thick part to the east, some slightly dipping reflectors can be observed below more chaotic and slightly wavy reflectors (Fig. 4.4 b). In some parts imbrication can be observed between nearly planar top and base reflectors, within the more chaotic unit.

**Interpretation:**

**Well Character:**
The coarsening and fining upwards sequences observed in well 7321/7-1 indicates small changes in lithology. In the wells it is evident that the sequence is deposited in a deep marine environment as the log response does not show a clear break in a coarsening upward sequence.

**Thickness Map and Seismic Character:**
The thin ellipses (marked in white and purple) in the central part of the time thickness map are due to gridding effects around faults going through the sequence. The fact that the sequence is thinning towards the Loppa High could indicate that the accommodation space towards the high was lower than in the western and central parts of the study area. The slightly dipping reflectors at the base of the sequence are interpreted as possible bottomsets of clinoforms or slope deposits, while the more chaotic reflectors (Facies 3) most likely represents a mass transport complex (MTC). The wavy reflectors observed above these dipping reflectors could be interpreted as small folds, while the observed imbrication could possibly indicate a deformed and shortened unit with internal thrust faults dipping towards the northwest. The direction of the imbrication in the interpreted MTC indicates that the depositional direction was towards the southeast, which is the same as the general trend of the clinoforms observed in Sequence 2 (Fig. 4.4 c). These imbricate structures could also possibly be injectites coming from the below laying Jurassic sediments, however, some minor faults indicating extension are interpreted on seismic data, and the dipmeter data is
indicating a dip direction towards the northwest, which is the same as the imbrication (Fig. 4.5). The chaotic deposits of facies 3 could also be storm deposits, however, based on the other observed facies, this sequence is most likely deposited during deep marine conditions. The interpreted bottomsets have a depositional direction towards the southeast.

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Fig. 4.5
Seismic Facies:

The seismic facies map for Sequence 1 in Fig. 4.6 shows the distribution of the five different seismic facies observed in this sequence, summarized in Table 4.4:

Table 4.4 Seismic Facies Table, Sequence 1

<table>
<thead>
<tr>
<th>Faceis</th>
<th>Scale</th>
<th>Reflection Pattern</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies 1</td>
<td>~ 100 ms relief</td>
<td>Imbrication</td>
<td>Moderate - Weak</td>
<td>Poor</td>
<td>Mass Transport Deposits (Slumping)</td>
</tr>
<tr>
<td>Facies 2</td>
<td>~ 200 ms relief</td>
<td>Sub-parallel - Parallel</td>
<td>Weak</td>
<td>Moderate - Strong</td>
<td>Basinal Deposition</td>
</tr>
<tr>
<td>Facies 3</td>
<td>~ 100 ms relief</td>
<td>Chaotic</td>
<td>Weak</td>
<td>Poor</td>
<td>Mass Transport Deposits</td>
</tr>
<tr>
<td>Facies 4</td>
<td>~ 70 ms relief</td>
<td>Parallel-Oblique</td>
<td>Moderate - Weak</td>
<td>Moderate</td>
<td>Clinoforms</td>
</tr>
<tr>
<td>Facies 5</td>
<td>~ 150 ms relief</td>
<td>Divergent</td>
<td>Moderate - Weak</td>
<td>Moderate - Strong</td>
<td>Wedge - Growth Strata</td>
</tr>
</tbody>
</table>
Observations:

Sequence 2 is bounded by a weak positive reflector, defined as Top Sequence 1, at the base, and the Early Cretaceous Unconformity (ECU) at the top. The base surface is characterized as a downlap surface as dipping layers are downlapping onto it. The actual top of the sequence, defined in previous work is a maximum flooding surface, but this has been eroded by the ECU in Fingerdjuret Sub-basin. The ECU is interpreted based on onlap above and erosional truncation below. In the deeper parts of the basin this unconformity becomes more conformable with the surrounding reflectors, while it is clearly unconformable in areas uplifted during the rifting. This reflector is also generally strong, and continuous throughout the Fingerdjuret Sub-basin, however it weakens towards the deeper parts of the Bjørnøya Basin, and is truncated below the Base Quaternary Unconformity towards the Loppa High.

Well Character:

In the well correlation (Fig. 4.3) it is clear that the gamma log has a peak in log response in well 7321/9-1 between the interpreted Top Clinoforms and ECU surfaces. The top of Sequence 2 is marked by a decreasing upward trend in the gamma log towards the ECU.

Thickness Map and Seismic Character:

The thickness map shows evidence of thickening towards the main faults affecting the area (Fig. 4.7 a). The thickness varies between 0 and 550 ms, with a mean value of approximately 300 ms. The clinoforms are mainly observed in the southeastern part of the study area, including the thinner part, which subcrops towards the Loppa High. High relief clinoforms are observed at the base of this sequence, as well as lower relief clinoforms higher up in the sequence (Fig. 4.7 b). On seismic sections it is evident that the sequence should be divided into two units based on observations of thickening units in the upper sequence and clinoforms in the lower. A thickness map of each unit
shows that thickening towards the faults is most evident in the upper part of the sequence (Fig. 4.8 a). In the lower unit, where all the clinoforms are observed, two clearly defined depocenters appears, where deposition of high relief clinoforms is observed (Fig. 4.8 b).
Fig. 4.8 Thickness Maps of Two Units Defined in S2. a) indicates the thickness between the ECU and the top of the clinoforms, and b) indicates the unit between top of the clinoforms and Top Sequence 1.
Based on the seismic sections it seem like bottomsets of clinoforms are penetrated by well 7321/9-1 (Fig. 4.9 a). In this well the dipmeter data states that an unconformity is present at the same location as the interpreted ECU, and in addition, an undefined unconformity or fault is interpreted just below. On seismic sections it seems like the topsets and foresets did not reach the well location.

Below the ECU a package of clinoforms of different scales prograding towards the southeast are observed. These clinoforms are shown on the seismic lines going in a NW-SE direction, together with some more chaotic reflectors located below representing the mass transport complex (MTC) of Sequence 1. In addition, terminations of strata, like downlap, onlap and truncation are observed within this unit.

Three sub-sequences, a-c, are defined within this sequence based on three intervals of clinoforms observed on the high-resolution MCG1401 2D seismic data in the southeastern corner of the study area:

Sub-sequence a:
This sub-sequence is characterized by the largest clinoforms observed within Sequence 2, with flat to ascending trajectory. The amplitudes are varying, and some topsets are observed (Fig. 4.9 b). Bottomsets are observed in some areas, although the largest parts of the foresets are down-lapping onto the base surface (Top Sequence 1). The height of the foresets varies, but an average value of approximately 200 meters is representative, although the uncertainty in both depth conversion and measurements are taken into account, giving a height between 190-300 meters. Fig. 4.10 illustrates the measurements between the two rollover points of the clinoforms, used to calculate the dip angle of the foresets, which is approximately 5-6 degrees.
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Fig. 4.9
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Sub-sequence b:
Within this unit dipping reflectors with a relief of 25-40 meters are observed. The dip of these layers is approximately 12 degrees, and there are small changes in amplitude. The extent of these layers are difficult to say since they are only resolved on a few MCG1401 2D seismic lines (Fig. 4.11).

![Figure 4.11 Seismic Section, S2, Sub-sequence b](image)

Sub-sequence c:
Sub-sequence c consists of small-scaled clinoforms. The distribution is difficult to estimate as it is only the MCG1401 and HR15 P-cable that has high enough resolution to resolve these clinoforms, however, they are visible on a few lines in the Icebear2 3D seismic cube, and are traced in the southeastern part of the study area (Fig. 4.13 b). In areas where they are not resolved, the top clinoform surface appears as a wavy horizon giving a time structure map showing the distribution (Fig. 4.12). The time structure map of Top Clinoforms show that the clinoforms have a linear shape in map view and is observed as ridges between wells 7321/8-1 and 7321/9-1. The relief of these clinoforms are < 80 meters and the gradient of the foresets are approximately 10 degrees. The trajectory seem to be relatively flat to slightly ascending (Fig. 4.13 a).
Fig. 4.12 Time Structure Map of Top Clinoforms. Top of the small scales clinoforms in the upper sub-sequence (c) have a linear shape in map view and are observed as ridges between wells 7321/8-1 and 7321/9-1.
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Interpretation:

Well Character:
The peak in gamma ray log response can be interpreted as hot shales (or possible source rocks). The top of the sequence is coarsening upward towards the ECU, and it is suggested that a flooding surface was located here, and later eroded by the Early Cretaceous Unconformity (ECU).

Thickness Map and Seismic Character:
From the time thickness map in Fig. 4.7 it is clear that there are great variations in thickness in the area. This could be related to syn-rift deposition, or variations in sediment supply and accommodation space. To establish a better understanding, the sequence was divided into an upper and lower unit. The upper unit has a thick package to the northwest, probably associated with the large fault going through the unit, although the really heavy thickening could be due to gridding problems. This unit has clear evidence of growth strata towards the smallest faults located in the middle of the thickness map, indicating that the area experienced fault activity. The two units are divided by the surface called Top Clinoforms, and the horizons on top of this surface are onlapping onto it, as seen in Fig. 4.9 b, and Fig. 4.10. The clinoforms observed in the lower unit seem to prograde towards the Loppa High (SE), and are important observations when it comes to the evolution of the Loppa High, as clinoforms would not build uphill. The uncertainty in measurements and decompaction are shown in 8.1 Appendix 1 - Decompaction.

Sub-sequence a:
The clinoforms are interpreted to have a complex sigmoid-oblique progradational pattern as some parts of the upper segments are toplapping, while some are creating sigmoid horizontal topsets. Erosion of the topsets could in some areas be the reason for interpreted flat trajectory and toplap. The variations in amplitude indicate changes in lithology, but based on the measurements of the clinoforms they are interpreted to be mud-prone shelf prisms.
Sub-sequence b:
A shingled progradational pattern is interpreted for this section as the dipping reflectors are located in between two relatively horizontal boundary reflectors. The reason why the clinoform pattern is not observed could be due to the resolution of the seismic data. As mentioned in 1.3 Theoretical Background on Clinoforms, these patterns are usually associated with shallow water deposits.

Sub-sequence c:
These clinoforms are interpreted to have a complex sigmoid-oblique progradational pattern. Sigmoid clinoforms usually have a foreset dip of less than 1 degree, but these have an angle of up to 10 degrees, indicating the complex sigmoid-oblique pattern. The bottomsets appears thin and gently dipping to not present (or resolved), which is characteristic for both sigmoid and oblique progradational patterns. Oblique clinoforms are usually associated with high sediment supply and stillstand of sea level, so these low-relief clinoforms were interpreted to be delta/shoreline deposits.

Seismic Facies:
The seismic facies map for Sequence 2 in Fig. 4.14 shows the distribution of the five different seismic facies observed within this sequence, with definitions summarized in Table 4.5

Table 4.5 Seismic Facies Table, Sequence 2

<table>
<thead>
<tr>
<th>Facies</th>
<th>Scale</th>
<th>Reflection Pattern</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies 6</td>
<td>&lt; 80 m relief</td>
<td>Complex Sigmoid-Oblique</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Sand-prone Subaqueous Delta</td>
</tr>
<tr>
<td>Facies 7</td>
<td>&gt; 150 m relief</td>
<td>Complex Sigmoid-Oblique</td>
<td>Varying</td>
<td>Moderate - Strong</td>
<td>Mud-prone Shelf Prism</td>
</tr>
<tr>
<td>Facies 8</td>
<td>&lt; 40 m relief</td>
<td>Shingled</td>
<td>Moderate</td>
<td>Poor</td>
<td>Shallow Water Deposits</td>
</tr>
<tr>
<td>Facies 9</td>
<td>~ 300 m relief</td>
<td>Parallel</td>
<td>Strong - Moderate</td>
<td>Strong - Moderate</td>
<td>Basinal Deposition</td>
</tr>
<tr>
<td>Facies 10</td>
<td>&gt; 150 m relief</td>
<td>Sigmoid</td>
<td>Weak</td>
<td>Moderate</td>
<td>Mud-prone Shelf Prism</td>
</tr>
</tbody>
</table>
4.2.3 Sequence 3 (S3): Aptian

Observations:
Sequence 3 is bounded by the strong Early Cretaceous Unconformity (ECU) reflector at the base and a relatively continuous and strong reflector at the top (Top Sequence 3). This sequence is onlapping onto the ECU towards the southeast and northwest. The southwestern boundary is stopped at the Leirdjupet Fault Complex as the reflectors get really deep and impossible to trace with the given dataset.

Well Character:
On the gamma log response in well 7321/7-1 it is clear from the other logs that this is not a sandstone unit, but artifacts in the log response (marked in red circle in Fig. 4.3). The sequence is not present at the location where well 7321/8-1 is drilled and gets really thin in well 7321/9-1, making it difficult to say anything about the well character.

Thickness Map and Seismic Character:
The thickness of Sequence 3 varies between 0 - 440 ms, with a mean value of 205 ms, and the largest accommodation space seem to be located between the two major faults in the sub-basin, as this is the thickest part (Fig. 4.15 a). Within the thick unit between the faults a layer of chaotic reflectors are observed and the whole sequence seem to be thickening towards the fault (Fig. 4.15 b). Around well 7321/8-1 the sequence is not present. Close to well 7321/7-1 a thin layer with dipping reflectors going towards each other are observed, this is localized to a small area and is only covered by the 2D seismic lines. The best example of this is highlighted in Fig. 4.15 c, and there is an up-building structure at the southeastern side.
Fig. 4.15 Time Thickness Map and Seismic Sections, S3. a) Time thickness map of Sequence 2 showing the location of different reflection patterns. The white area around well 7321/8-1 indicates that the sequence is not present here b) Seismic section illustrating chaotic reflectors, possibly related to the main fault to the NW. c) Seismic section highlighting imbrication structures going towards each other close to well 7321/7-1 (red square) (courtesy of TGS).
Interpretation:

The onlapping towards the ECU in the southeast and northwest indicates that these areas were already uplifted during deposition of this sequence. Based on this a tilt of the sub-basin is suggested to have happened between deposition of sequences 2 and 3, with clinoforms prograding towards the southeast in Sequence 2 suddenly changing to onlapping sub-parallel reflectors towards the southeast in Sequence 3. Based on these observations and interpretations, the ECU is interpreted to be a post-rift unconformity, as the main period of rifting happened during Barremian to Early Aptian times. Further understanding of the fault activity and structural evolution is explained in detail in the collaborative thesis by Acharyyya (2016).

The fact that the sequence is onlapping onto the ECU means that the study area already had a basin shape during Aptian times. That the sequence is not present around well 7321/8-1 indicates that this was already a local high at this time. The thickening against the fault could be interpreted as growth strata, with erosional sediments of the uplifted footwall being deposited as a mass transport complex (MTC) on the hanging wall. This interpretation does not coincide with a tectonically quiet period, and could be related to larger accommodation space due to subsidence. Dipping layers observed close to well 7321/7-1 are interpreted as a slump coming from the northwest, although no slump scar has been observed. The horizons dipping towards the southeast are interpreted as the extensional part of the slump, and the up-building structure is interpreted to be the forebulge of the slump.
Seismic Facies:

The different seismic facies are shown in the facies map for Sequence 3 in Fig. 4.16 where the distribution of the five different seismic facies, described in Table 4.6 is illustrated with seismic examples:

Table 4.6 Seismic Facies Table, Sequence 3

<table>
<thead>
<tr>
<th>Facies</th>
<th>Scale</th>
<th>Reflection Pattern</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>&lt; 300 ms relief</td>
<td>Parallel</td>
<td>Moderate - Strong</td>
<td>Moderate - Strong</td>
<td>Basinal Deposition</td>
</tr>
<tr>
<td>12</td>
<td>~ 100 ms relief</td>
<td>Imbrication</td>
<td>Moderate - Weak</td>
<td>Moderate - Weak</td>
<td>Slumping</td>
</tr>
<tr>
<td>13</td>
<td>150-400 ms relief</td>
<td>Chaotic</td>
<td>Moderate</td>
<td>Poor</td>
<td>Mass Transport Deposits (MTC)</td>
</tr>
<tr>
<td>14</td>
<td>&lt; 300 ms relief</td>
<td>Chaotic - Divergent</td>
<td>Moderate to weak</td>
<td>Poor</td>
<td>Mass Transport Deposits (MTC)</td>
</tr>
</tbody>
</table>
Fig. 4.16 Seismic Facies Map, Sequence 3. Seismic facies map and seismic sections showing the distribution and seismic character of four different seismic facies observed in Sequence 3.
4.2.4 Sequence 4 (S4): ?Albian

Observations:
Sequence 4 is the uppermost sequence represented in the Lower Cretaceous strata in the Fingerdjupet Sub-basin. The base of Sequence 4 is defined by the top of Sequence 3 where that is deposited, and the Early Cretaceous Unconformity (ECU) where it is not. The top of the sequence is eroded by the relatively horizontal Base Quaternary Unconformity, and because of this a time thickness map was not for any help to look at the changes within the sequence, since this unconformity has eroded large parts of the Cretaceous strata.

Well Character:
Top of Sequence 4 is eroded by the Base Quaternary Unconformity, however, wells 7321/8-1 and 7321/9-1 indicates a coarsening upward package at the top of the sequence. In well 7321/8-1 it is evident that the response indicating coarser grained sediments are not correct, rather a disturbed log response due to a washout zone observed on the caliper log.

Seismic Character:
The dipping layers are constrained to the southeastern part of the study area and have a relief of around 50-100 meters. The dip angle is approximately 2 degrees, and the layers are clearly downlapping onto the ECU, so no bottomsets are observed (Facies 16). The amplitudes are varying internally in the dipping layers, and some higher amplitudes are observed at the base of the sequence (Fig. 4.17). In the upper part of the sequence some areas of bright reflectors with poor continuity are observed (Facies 17), these were mapped out and appeared as elongated clusters in the area close to wells 7321/8-1 and 7321/9-1.
Fig. 4.17 Seismic Sections in Depth, S4. Two examples of seismic lines showing measurements of the observed clinoforms. a) NW-SE going seismic line with dip angles of approximately 2 degrees (courtesy of MCG), and b) N-S going seismic line with dip angles of approximately 1.5 degrees (courtesy of TGS). The two lines are from two different datasets and different direction showing differences in scale and geometry, indicating that the clinoforms are actually building out towards the SE as the dip angle is highest in that direction.

**Interpretation:**

The dipping layers are interpreted as clinoforms prograding towards the southeast with a downstepping trajectory. The surface on top of the clinoforms is interpreted to be a transgressive surface, and no observable bottomsets are present. Based on this, and the low dip angle the clinoforms are interpreted to be oblique. The trajectory is downstepping and interpreted to be deposited during forced regression, as the observations indicate that the shoreline prograde at the same time as the relative sea level is going down. Another explanation could be that the unit is infilling the basin and that the layers are onlapping onto the ECU, and not downlapping clinoforms. The elongate clusters of bright spots are interpreted as gas chimneys, both due to the shape, and deformation of the horizons located below.
Seismic Facies:

The seismic facies map for Sequence 4 in Fig. 4.18 shows the distribution of the three different seismic facies observed within this sequence, with definitions are summarized in Table 4.7:

Table 4.7 Seismic Facies Table, Sequence 4

<table>
<thead>
<tr>
<th>Facies</th>
<th>Scale</th>
<th>Reflection Pattern</th>
<th>Amplitude</th>
<th>Continuity</th>
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4.2.4 Sequence 4 (S4): ?Albian
5 Discussion

5.1 Depositional Evolution

In this chapter, the factors controlling the sediment infill will be discussed together with an evolutionary model, based on the observations and interpretations expressed in the previous chapters. Faleide et al. (1993) suggested that the western Barents Sea was affected by a long lasting rift phase during Late Jurassic-Early Cretaceous times, however, the observations from this study, and the collaborative study by Acharyya (2016) suggest that the main rift phase in the Fingerdjupet Sub-basin did not commence until Barremian time. This leads to a separation between the regional impression and the local observations.

Identification and interpretation of depositional units based on available seismic data established the stratigraphic framework for Fingerdjupet Sub-basin. Seismic reflection patterns was used to interpret internal characteristics of each sequence, presented in chapter 4.2 Seismic Sequences. Seismic facies for each sequence were mapped and used to propose the depositional evolution of Fingerdjupet Sub-basin.

**Sequence 1 (S1): Latest Hauterivian - Early Barremian**

The lowermost sequence in the Fingerdjupet Sub-basin has a relatively constant thickness throughout the study area, if the thinner part towards the Loppa High (SE), where the sequence subcrops under the Base Quaternary Unconformity, is not considered. A suggestion is that the sequence was eroded in the southeastern part during later erosion associated with tilting and/or uplift of the southeastern part of the sub-basin.

The main seismic facies observed are sub-parallel to parallel layers, although more chaotic reflectors are observed in the southeastern part of the study area. The sub-parallel to parallel reflectors could indicate that the sequence was deposited prior to
the event of tectonic activity, however, seismic facies 5 demonstrates that tectonic activity had already commenced along at least the main fault to the northwest. The wedge-shaped unit continues along the fault, but the thickness does not have any significant change, implying that the fault activity was not of major significance during this time period.

Based on the thickness map it is evident that the sequence was deposited prior to the main tectonic extension that created subsidence and formation of the Fingerdjupet Sub-basin. This coincides with the previous work done by Dahlberg (2014), who defined a sequence of the same age, indicating that a new phase of crustal extension had commenced during late stages of deposition in this part of the Barents Sea.

The low amplitude, continuous, sub-parallel to parallel reflectors indicates uniform, low-energy, fine-grained deposition. Facies 4, consisting of parallel-oblique clinoforms is located where the sequence is at its thickest. These reflectors could represent the lower part of bottomsets or slope deposits, interfingering with mass transport deposits represented by the chaotic reflections and imbrication. All the observed facies indicates that the relative sea level was high during deposition of Sequence 1, and that the faults did not establish major local accommodation space during this time.

**Sequence 2 (S2): Late Barremian - Early Aptian**

This sequence is divided into two units, where the lower unit is defined as an overall prograding unit, and the upper unit as syn-rift deposits. The prograding unit is further sub-divided into three sub-sequences.

*Lower Unit:*

In this prograding unit no wedge shapes are observed in relation to the faults in the Fingerdjupet Sub-basin, indicating that the small period of fault activity observed in Sequence 1 was terminated. At the base of this sequence a set of relatively high relief
prograding units coming from the northwest appears to be the main source of sediment infill in the sub-basin. Based on this it is suggested that these sediments were deposited during a relatively quiet tectonic period, and that the sequence was deposited as a post/pre-rift unit, while the Fingerdjupet Sub-basin was possibly subsiding. The reason for the subsidence is unsure as it could be due to prior rift-periods, or a regional subsidence during this time. Dahlberg (2014) suggest that it could be a result of both.

The progradation took place during three stages, and Fig. 5.3 illustrates a suggestion to how the water level changed during this time period, together with the different scales of prograding clinoforms. Marin et al. (accepted with revisions) suggest that the relative sea level did not exceed 300 meters during deposition of this sequence. However, after decompaction the observed shelf prism clinoforms height ranges between 190-300 meters indicating that the sea level must have been > 300 meters if the high estimate is representative. All the observed clinoforms are prograding towards the southeast, indicating that a high was present towards the northwest.

It is not possible to tell what the sediment source was due to the severe erosion during Quaternary time. However, it can be suggested that Greenland or Svalbard were the main sediment source as both were located closer to Fingerdjupet Sub-basin during Early Cretaceous times. Marin et al. (accepted with revisions) explains that the progradational trend towards the southeast coincides with the paleocurrent direction observed in the Helvetiafjellet Formation on Svalbard, which is time equivalent to Sequence 2, and it is suggested that a common sediment source in the northwestern Barents Sea was present (Gjelberg and Steel, 1995; Midtkandal et al., 2007). This is a representative theory based on the observations and interpretations in this study.

Sub-sequence c is compared to an analogue showing a wave dominated sandy shoreline from Spain (Hernandez-Molina et al., 2000). Based on the fact that this is the only sub-sequence that is resolved properly on seismic, and have geometries...
indicating sand-prone systems it is compared to a suggested similar depositional environment. The seismic line is combined with the conceptual depositional model, and illustrates that the clinoforms, as well as the prograding coastal plains fits well with the model (Fig. 5.1). This observation supports the idea of a sand-prone subaqueous delta, which is further described in chapter 5.2 Reservoir Potential.

![Depositional Model for the Clinoforms in Sub-sequence c (S2)](image)

**Fig. 5.1 Depositional Model for the Clinoforms in Sub-sequence c (S2).** Depositional model for a wave dominated sandy shoreline of the Spanish coast combined with a seismic line from the study area (Modified from Hernandez-Molina et al., 2000, courtesy of Centrica).

*Upper Unit:*

The upper part of the sequence is thickening towards the faults indicating syn-rift deposition. This unit is relatively thin and reflectors are onlapping towards the basin margins. Dahlberg (2014) is suggesting that the basin margins were more defined and that the basin was narrowing down to a smaller area with less extensive subsidence. The observed wedges along the faults confirm this interpretation, although major thickness changes are difficult to tell due to the Early Cretaceous Unconformity (ECU), which has eroded the top of this unit.

The fault activity observed in the upper unit, and clinoforms in the lower unit could indicate that the major period of extension had commenced during the end of the sequence and that the uplift of the Loppa High probably started after deposition of the lower unit. This is confirmed by clinoforms prograding towards the Loppa high, which would have been uphill if the high already existed. This means that the Loppa High was most likely not a structural high during deposition of Sequence 2. However,
by studying the clinoform in detail it is suggested that the tilting of the sub-basin had barely started between deposition of the high relief clinoforms in sub-sequence a, and the low relief clinoforms in sub-sequence b (Time 2.1-2.2, Fig. 5.3).

**Sequence 3 (S3): Aptian**

This sequence is clearly thickest in the fault block associated with the main fault to the northwest. Dahlberg (2014) proposes that a new period of tectonic activity may occurred during this time. The observations of a thick unit associated with the main fault could indicate that this fault was active during deposition, or that the subsidence of the sub-basin resulted in a depocenter located in the middle of the sub-basin. Based on the structural evolution proposed in the collaborative study by Acharyya (2016), this period is associated with a tectonically quiet time, defined as a post-rift sequence. These interpretations indicate that the depocenter was possibly created during the rift-period defined in Sequence 2, and later infilled by sediments of Aptian age.

At the base of this sequence, a local slump is observed in the southwestern part of the sub-basin, showing small basinward dipping listric extensional faults and linked thrust faults. This could also possibly represent clinoforms coming towards each other, however, when combining the seismic section with a depositional model from the Orange Basin in South Africa it is clearly similar to a slump (de Vera et al., 2010) (Fig. 5.2). This helps indicate the water depth during deposition of Sequence 3, as clinoforms with low relief would indicate shallower water deposits than a slump.

Sequence 3 is onlapping towards the Early Cretaceous Unconformity (ECU) towards the east, indicating that the sub-basin was narrower than the presented boundary map is showing. A possible explanation could be that the basin margins were defined towards the east, and that the subsidence rate decreased during this time. Another possibility is that the eastern part of the sub-basin was uplifted, possibly associated with the formation of the Loppa High.
Sequence 4 (S4): ?Albian

Sequence 4 does not show any evidence of tectonic activity, however, minor faults that do not connect properly to the deeper/older faults are observed. A suggestion is that these faults evolved due to more brittle lithology (Dahlberg, 2014), or that some of them are formed due to reactivation of older faults. The smallest faults, located in the upper part of the sequence (observed between wells 7321/7-1 and 7321/8-1 on the regional line in Fig. 4.2) could be interpreted as possible polygonal faults. Such faults are associated with fine-grained sediments and fluid expulsion, and are observed in the Upper Cretaceous unit in the Hammerfest Basin, which is not too far away from Fingerdjupet Sub-basin (Ostanin et al., 2012). This interpretation is also supported by the observation of gas chimney anomalies at approximately the same burial depth, and fine-grained sediments in the wells.

The interpreted clinoforms in the southeastern part of the study area could also possibly be interpreted as onlaps towards the ECU. However, observations of possible rollover points and high amplitudes at the base of the foresets indicate that these are clinoforms.
Summary of Depositional Evolution

The observations and interpretations of each sequence is summarized in map view and representative cross sections shown in Fig. 5.3 and Fig. 5.4. Fig. 5.3 is illustrating the lowermost units in Fingerdjupet Sub-basin (S1-S2), and Fig. 5.4 illustrates the upper units (S3-S4). Line A-A' is crossing the area where most of the clinoforms are observed, while the cross section illustrating Sequence 3 had to be located further east (B-B') due to no deposition at the location of line A-A'. Sequence 4 is observed as deep marine deposits at the location of A-A', so the infill cross section is moved further east, where the prograding unit is observed. The overall depositional evolution of the Fingerdjupet Sub-basin is suggested to consist of four main stages: (1) at the base of the Lower Cretaceous, deposition of distal slope/clinoforms, (2) mass transport deposits during relatively high sea level, (3) prograding clinoforms infilling the sub-basin during normal regression (aggradation), and (4) prograding clinoforms infilling the sub-basin during forced regression (downstepping trajectory).
Fig. 5.3 Depositional Evolution, S1-S2. Predicted depositional model for the lowermost unit in Fingerdjupet Sub-basin, dividing Sequence 2 into four stages (not to scale).
Fig. 5.4 Depositional Evolution, S3-S4. Predicted depositional model for the upper sequences in Fingerdjupet Sub-basin (not to scale).
5.2 Reservoir Potential

The quantitative comparison between seismic observed clinoforms and outcrop clinoforms is an important input to predict the lithology of the clinoforms (Patruno et al., 2015). Although it is not possible to build a perfect reservoir model capturing all the details of the depositional system by using this method, it has become an important input to define reservoir models (Howell et al., 2008). The comparison is presented as a plot where the open squares defines the ranges from analogues (measurements taken from Patruno et al., 2015), and the filled squares represent the uncertainties in depth conversion, compaction, and measurements of the slope extent and slope dip of the clinoforms observed in Fingerdjupet Sub-basin. The defined ranges of analogues and the ranges defined for the observed clinoforms are listed in the table in Fig. 5.5. In the figure it is clear that the foreset height and downdip extent ranges for the muddy subaerial deltas in Sequence 4, and the sand-prone deltas in Sequence 2-c, is going outside the ranges of the analogues. This could represent the uncertainties in all the parameters mentioned above.

Most of the clinoforms tend to be mudstone-prone based on the geometry, however, the low relief clinoforms observed at the top of Sequence 2 fall into a category indicating sandstones (Fig. 5.5). Based on the geometry of the analogues it is evident that there is a distinct difference between the observed sand-prone clinoforms and the analogues of mud-prone clinoforms. The resolution of the seismic data is important to be able to resolve these clinoforms, and the super-high resolution MCG1401 2D seismic survey is the only one that can be used for this purpose.

Antonsen et al. (1991) studied thin sections of sandstones of Hauterivian-Barremian age in the Olga Basin in the northern Barents Sea, giving porosities of 20-25 %. These values are slightly higher than the predicted porosity of the clinoforms of Late Barremian - Early Aptian age in the Fingerdjupet Sub-basin, which has an average porosity of ~18 %. The porosity is lower in the Fingerdjupet Sub-basin, which could be explained by the deeper burial depth prior to the uplift (Henriksen et al., 2011).
Fig. 5.5 Clinoform Classification Chart. Quantitative clinoform analysis, where open squares represent ranges from analogues (Patruno et al., 2015), and filled squares represent observed clinoforms. The measurements are shown in the tables below.
6 Conclusions

The high resolution data used in this study is essential to improve the characterization and understanding of the depositional styles and evolution of the Fingerdjupet Sub-basin, as the scale of some of the observed clinoforms have low relief (down to 15 meters prior to decompaction). Clinoform characterization has been carried out using the scale and geometry of depth converted and decompacted foresets. Analysis of the effect of seismic resolution highlights that the wavelet and overburden velocity impact the amount of details and affects the measurements of the clinoforms, as illustrated in Fig. 4.13 (4.2.2 Sequence 2 (S2): Late Barremian - Early Aptian). Comparison of seismic imaged clinoforms and outcrop analogues make it possible to predict the lithologic character of the clinoforms.

Four main third order sequences within the Lower Cretaceous unit were defined based on a well correlation to well 7321/7-1 interpreted in previous work, and stacking patterns observed on the seismic sections. Based on information from the seismic facies characterization the stratigraphical evolution of the sub-basin has been divided into seven phases:

1. Deep marine depositional phase (Latest Hauterivian - Early Barremian), defined as a tectonically relatively quiet period with local deposits of mass transport complexes, such as slumps, towards the southeastern part of the study area. Wedge-shapes are observed in relation to the main fault going through the basin in the northwest, which could be related to some minor extension of the area.

2. Prograding phase (Late Barremian - Early Aptian), defined as a partly tectonically active period, divided into four separate phases based on observations of three types of clinoforms in the southeastern part of the study area, and syn-rift wedges in the upper part of the sequence. An estimate of the porosities in sub-sequences b and c, shows that these could hold reservoirs with average porosities of approximately 18%. The source area of the
prograding sediments is not understood due to the Quaternary erosion, however, a suggestion could be that the source was a structural high created during the uplift associated with the High Arctic Large Igneous Province (HALIP).

a. The lowermost unit is defined as a system building out on the shelf, defined as mud-prone shelf prisms.

b. A system building out in shallow water conditions, on top of the lowermost unit, defined by a shingled progradational pattern.

c. A unit defined as a system building out on top of the underlying units, in shallow water. These clinoforms are defined as sand-prone subaqueous deltas.

d. Syn-rift phase, defined as a unit with growth strata towards the faults in Fingerdjupet Sub-basin.

3. Marine depositional phase (Aptian), defined as a tectonically relatively quiet period with local deposits of slump, mass transport deposits and basinal deposits. The slump is localized to the area located close to wells 7321/7-1 and 7321/9-1, and could possibly be related to the Leirdjupet Fault Complex.

4. Shallow shelf deposits (?Albian), defined as a tectonically relatively quiet period with deposits of possible mud-prone subaerial delta clinoforms towards the southeastern part of the study area.

The main progradational direction of the clinoforms, and the mass transport complexes showing imbrication were towards the southeast in the study area.
7 References


7 References


8 Appendices

8.1 Appendix 1 - Decompaction
Table 8.1. Minimum and maximum porosities. Used for calculations of decompacted sediment thickness

\[ Si^* = Si \frac{(1-\phi_i)}{(1-\phi_i^*)} \]

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