

3D seismic stratigraphy and reservoir characterization of the Chalk Group in the Norwegian Central Graben, North Sea

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In memoria delle mie nonne

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Preface and acknowledgements

This thesis entitled “3D seismic stratigraphy and reservoir characterization of the Chalk Group in the Norwegian Central Graben, North Sea” has been submitted for the degree of philosophiae doctor (PhD) at the University of Bergen (UiB), Norway. The research was carried out from February 2008 to February 2011 at the Department of Earth Science (UiB) and Total E&P centre in Stavanger, Norway. The project has been funded entirely by Total E&P Norge as part of the “Carbonate Reservoir Geomodelling Programme”.

PhD studies seem inevitably connected by a common thread; they never follow the pathway initially proposed! This thesis is no different. Initial supervision on this research project was given to Professor Michael R. Talbot (UiB) and Michel C. Thomas (Total E&P Norge). The initial aim of this project was to develop a regional model of the chalk depositional system in the Norwegian Central Graben within a sequence stratigraphic framework. Apparently, history tends to repeat itself, and during the first year of the project it became evident that the initial aims were largely overwhelming the available time. Moreover, previous internal research performed by the company operating most of the chalk fields already covered large part of the initial research objectives. Consequently, the focus of the project was shifted towards a regional seismic interpretation integrated with detailed characterization of intra-reservoir heterogeneities within the largest chalk field in the study region, the Ekofisk Field.

With the premature and sad departure of Professor Michael R. Talbot in November 2009 and the coeval transfer of Michel C. Thomas to a different managerial position, an important support and driving force of the project was lost. Nonetheless, the project has been subsequently supervised jointly by Jonathan P. Wonham (Total E&P Norge), Gunnar Sælen (UiB), Wojciech Nemeč (UiB) and partly by Robert Gawthorpe (UiB), who are deeply acknowledged for the thorough manuscript reviews and commenting.

Numerous people at Total E&P Norge and UiB are thanked for the contributions, discussions and support. In particular, Jonathan P. Wonham is thanked for the excellent supervision during the work carried out in the Total E&P office in Stavanger and, along with Gunnar Sælen, is acknowledged for good and stimulating discussions. I thank Valentin Clement for the numerous discussions on the geophysics of the chalk, and for the nice time in the “Chalk Office”. Bruno Caline (Total E&P France) and Eric Lasseur (BRGM) are thanked for sharing data and interpretations as well as their sedimentological expertise on the chalk and for engaging in valuable discussions.

Family, friends, and especially my wife Sue Jin are warmly thanked for their support during the course of this study and the good times spent together.

Thesis outline

The present PhD thesis has been prepared following the Norwegian outline for doctoral dissertations in natural sciences, where the main body of the thesis consists of research articles submitted, or about to be submitted, to relevant international peer-review scientific journals. Hence, language style, reference style and use of abbreviations will vary throughout this thesis. Each manuscript represents a stand-alone contribution, but overlaps between different chapters may occur.

An overview of the scope and goals of this thesis together with a short summary of the main findings follow an authorship statement, as required by regulations for PhD thesis at the University of Bergen. The research articles that make up the bulk of this thesis are preceded by the project aims, dataset, methodology (Chapter 1) and an introduction to the regional geology of the study area, general sedimentology, depositional model and diagenesis of chalk (Chapter 2). Chapter 6 reviews the main findings, features short discussions about the results and conclusions presented in the scientific papers, and summarizes the final outcome of the research project.

Authorship statement

The supervisors mentioned were responsible for setting the project outline and its conception. The candidate is the principal investigator and author of all the articles. Below is an overview of the candidate's contribution to each paper with acknowledgements presented at the end of each paper. The candidate is the sole author of Chapters 1, 2 and 6.

Chapter 3: Seismic stratigraphy of the Chalk Group in the Norwegian Central Graben, North Sea. Submitted for publication in *Basin Research*.

Gennaro, M., Wonham, J. P., Gawthorpe, R. and Sælen, G.

The candidate was responsible for data gathering and performing interpretation. J. P. Wonham, R. Gawthorpe and G. Sælen contributed with manuscript review.

Chapter 4: Channel development in the chalk of the Tor Formation, North Sea: evidence of bottom current activity. Submitted for publication in *IAS Special Publication No. 47*.

Gennaro, M. and Wonham, J. P.

The candidate was responsible for collecting and interpreting the data. The co-author was engaged in discussions and performed manuscript review.

Chapter 5: Characterization of dense zones within the Danian chalks of the Ekofisk Field, Norwegian North Sea. *Submitted for publication in Petroleum Geoscience.*

Gennaro, M., Wonham, J. P, Walgenwitz, F., Caline, B., Sælen, G. and Faÿ-Gomord, O.

The candidate was responsible for interpreting seismic, well log and petrographic data. Petrographic data were provided and partly interpreted by F. Walgenwitz, B. Caline and O. Faÿ-Gomord. The co-authors, J. P. Wonham and G. Sælen, contributed with interpretation, writing and manuscript corrections.

Chapter 1: Introduction

1. Aim and outline of the thesis – why study the Chalk Group?

Since the first hydrocarbon discovery in 1966, intensive exploration and drilling campaigns have made the North Sea a mature petroleum province with a wealth of geological and geophysical data. Among the numerous hydrocarbon discoveries made on the Norwegian Continental Shelf, the Upper Cretaceous and Lower Paleocene chalks represent prolific reservoirs, with estimated remaining reserves of $242 \times 10^6 \text{ Sm}^3$ o.e. and accounting for 7.7% of Norway's total hydrocarbon production in 2010 (www.npd.no).

The importance of chalk as a hydrocarbon reservoir induced a vast amount of research focused on its sedimentology, diagenesis as well as petrophysical and mechanical properties. The chalk play is completely different from any other hydrocarbon plays on the Norwegian Continental Shelf. As a consequence, during the last 45 years since the first discovery, new concepts and ideas have continuously been developed in order to reduce the uncertainties related to the exploration and development of the resources within the chalk deposits. It is remarkable that, despite the North Sea chalk fields have been producing at high level for more than 40 years, the Chalk Group is relatively unexplored and underdeveloped (Megson & Tygesen, 2005). In this stratigraphic interval, the majority of hydrocarbon accumulations occur within structural traps on inversion and halokinetic structures. Relatively few stratigraphic traps have been drilled since the first discovery in 1966 and most of them have been unsuccessful. Principally because spatial prediction of facies and associated porosity variations are difficult to evaluate; the chalk depositional system is highly variable and the relationships between facies types and their spatial distribution in time and space are difficult to predict. Nonetheless, the Chalk has confirmed a great potential as hydrocarbon reservoir and the growing demand for natural resources in the present day geopolitical situation requires additional efforts to develop the remaining reserves in the North Sea petroleum province.

In chalk fields, and particularly in those located in the Norwegian sector, the reservoir geology is significantly influenced by the style of sedimentation. In this region, most of the highly porous hydrocarbon-bearing chalks consist of gravity-flow deposits. All the structural traps in the Chalk Group have been drilled by 1986, hence stratigraphic traps represent the future exploration targets and these are commonly associated with porous bodies or stratigraphic pinch-outs generated by gravity-driven resedimentation or reworking by bottom currents (Bramwell *et al.*, 1999; Surlyk *et al.*, 2008). Moreover, sedimentological characteristics, together with style of deposition, diagenesis and timing of hydrocarbon charging, directly affect porosity preservation and reservoir qualities. Therefore, it is necessary to investigate the factors which trigger and affect mass-flow resedimentation, bottom current activity and distribution of their sedimentary products, as well as changes in sediment composition, such as: (1) evolution of basin physiography in relation to tectonic and halokinetic movements; (2) topographic evolution of the sea-floor due to sediment mounding by bottom currents and large scale slumping; and (3) sea-level fluctuations.

In order to perform this task, this thesis investigates and discusses the sedimentary succession and seismic stratigraphy of the Chalk Group in the Norwegian North Sea describing the development

of its depositional system in relation to the general tectonic-stratigraphic evolution of the Central Graben; geomorphological features from seismic as well as large-scale wireline log cyclicity have been interpreted and discussed in chapter 3, while chapter 4 summarizes the geological significance and geomorphological evolution of a channel feature identified in the study area. The results and discussions presented in chapters 3 and 4 are considered of great significance for the identification of stratigraphic traps within the sedimentary successions of the Chalk Group in the Norwegian Offshore sector.

This study also focuses on the depositional setting and diagenesis of so called dense zones within the reservoir intervals of the Ekofisk Formation in the Ekofisk Field. Dense zones have a strong impact on the production performance of the Ekofisk Field since they may act as conduits for the water injected during production, or as permeability barriers that compartmentalize the reservoir. However, until now, relatively few investigations have been carried out on the dense zones. In chapter 4, the sedimentology and spatial distribution of dense zones have been interpreted using μm -scale information from SEM photos as well as cores, wireline logs and seismic acoustic impedance data.

The knowledge acquired from the study of dense zones in the Ekofisk Field implies that such layers should be an integral part of dynamic reservoir modelling, ultimately leading to higher hydrocarbon recovery.

2. Regional setting

The study area is located in the southernmost region of the Norwegian offshore sector at approximately 270 km from the coast of Norway (Fig. 1). Geologically this area belongs to the Central Graben basin, which is the southern branch of the North Sea rift system, while the Viking Graben the Moray Firth Basin represent the NE and the NW branches, respectively.

The tectonic framework of the Norwegian Central Graben consists of numerous intra-basinal lows and highs with the graben margins bounded by normal faults directed NNW–SSE. The structural highs frequently host hydrocarbon accumulations that by and large occur within the stratigraphic interval of the Chalk Group. In this region, the Ekofisk Field together with the adjacent Tor, Valhall, Tommeliten, Eldfisk and Albuskjell chalk fields form the Greater Ekofisk Area, which represent a mature hydrocarbon province on the Norwegian Continental Shelf (D’Heur, 1984; Surlyk *et al.*, 2003).

Thermal relaxation and subsidence alongside the main boundary faults characterized the Central Graben throughout the Late Cretaceous (Ziegler, 1990; Gowers *et al.*, 1993; Knott *et al.*, 1993). This period was also characterized by compressional tectonic pulses that inverted the antecedent faults and created new topographic highs such as thrust anticlines (Cartwright, 1989; Vejbæk & Andersen, 2002). Tectonic inversion was associated with halokinetic movements of the Zechstein salt that generated local domes, diapirs and salt walls (Oakman & Partington, 1998).

In the study area, the sediments of the Chalk Group reach a total thickness greater than 1000 metres and are buried at an average depth of 3000–4000 m below the bottom of the sea bed. The chalk succession was deposited over a period of 40 million years in an epicontinental and relatively deep sea that resulted from flooding of the low-lying NW European land masses during the Late Cretaceous transgression (Hancock, 1975, 1993; Hancock & Kauffman, 1979). The epicontinental sea was characterized by relatively warm temperature, normal salinity and oligotrophic nutrient levels, which were the ideal conditions for the flourishing of coccolithophorid algae. Sedimentation of the calcitic tests of the coccolithophores, and other pelagic organisms produced thick and continuous chalk successions over most of NW Europe (Surlyk *et al.*, 2003).

3. Data and methodology

Two specific datasets have been used and integrated during this thesis: (1) a regional dataset which comprises a 3D seismic survey, wireline logs and, where available, cores from more than 200 exploration and production wells; and (2) a dataset focused on the Ekofisk Field, which consists of a 3D seismic acoustic impedance seismic cube integrated with wireline logs from approximately one hundred wells and cores from twenty-six wells. The first dataset forms the backbone of chapters 3 and 4 and certain wells and cores are also part of the second dataset, which represents the foundation of chapter 5.

3.1. Regional dataset and methods

The regional seismic data consists of a 3D seismic survey called Central Graben Super Grid or TFECGSG03. This regional 3D seismic survey is composed of two pre-existing merges, the PGS MC3D-CNS-MEGA and the Statoil ST99M1 and few additional 3D seismic surveys for a total of more than 80 surveys. The PGS MC3D-CNS-MEGA merge was purchased in 2002, while the Statoil ST99M1 merge was licensed in 2003. The mega-merge between these two surveys and four smaller ones, forming the final Central Graben Super Grid, was performed by Petrodata in Stavanger during the spring of 2003. The final merge is based on time migration dataset in which amplitude scaling and time-shifting have been applied.

The output size of the Central Graben Super Grid 3D cube is $\sim 10000 \text{ km}^2 \times 4 \text{ ms}$ with spacing between inline and cross lines of 12.5 m. The dominant frequency is $\sim 26 \text{ Hz}$ and at the level of the Chalk Group the average acoustic velocity is $\sim 4000\text{--}5000 \text{ m/s}$. Based on these characteristics and on the burial depth (3000–4000 m) of the Chalk Group in the study area, the vertical and lateral resolutions of the 3D seismic cube are estimated to be $\sim 40 \text{ m}$ ($1/4$ of the dominant wave length) and $\sim 200 \text{ m}$, respectively (cf. Yilmaz, 1987). The overall quality of the final merge is good, although time shifts, lack of continuity and amplitude changes in seismic reflections often occur at the merge of seismic surveys.

The regional seismic dataset has been complemented with gamma ray, density, sonic and neutron porosity logs from two hundred exploration and production wells located across the Norwegian Central

Graben. Cores have been described and integrated with the logs in regional well-to-well correlation panels. Biostratigraphic dating covering the Chalk Group, based on nanno- and microfossils as well as fossil palynomorphs extracted from cores and ditch cuttings, were available from fifteen wells. In addition, several industrial reports of nanno- and micropalaeontological dating of the reservoir intervals were available and used during the course of this study.

Seismic and well data have been tied using synthetic seismograms produced by calculating an impedance curve from the sonic and density logs. In order to calibrate the log curves to the seismic data, each synthetic seismogram has been compared with the original seismic section across the respective well; the relationships between seismic response and petrophysical properties have also been investigated.

Seismic data have been examined using standard seismic stratigraphy interpretation techniques (Mitchum *et al.*, 1977a; Fontaine *et al.*, 1987; Brown, 1991; Macurda, 1997). Seismic interpretations and seismic-to-well ties have been carried out on a UNIX seismic workstation using the Sismage software package of Total, while well log analyses and well-to-well correlations have been performed using the Petrel software of Schlumberger.

In seismic lines, reflection terminations such as onlap, downlap, toplap and erosional truncation have been identified and mapped. These reflection terminations define key seismic horizons indicative of stratigraphic unconformities that in turn bound seismic sequences characterized by specific reflection patterns. Based on the reflection configuration and well-log signature along each key seismic horizon, the origin of the relative unconformities has been interpreted. In parallel to tracing the reflection terminations, based on the reflection configuration, amplitude, frequency and continuity seismic facies have been described and mapped (see Mitchum *et al.*, 1977b). These seismic facies have been used to distinguish pelagic chalk, which is commonly characterized by parallel and continuous reflections (Fontaine *et al.*, 1987; Andersen *et al.*, 1990; Nygaard *et al.*, 1990; Macurda, 1997; Britze *et al.*, 2000; Van der Molen *et al.*, 2005), from allochthonous chalk characterized by discontinuous and chaotic reflections (Johnson, 1987; Andersen *et al.*, 1990; Nygaard *et al.*, 1990; Britze *et al.*, 2000; Van der Molen *et al.*, 2005).

Based on previous studies on the relationship between petrophysical properties and core facies, non-cored intervals have subdivided into log facies characterized by specific log signatures and assigned to pelagic or gravity-driven deposits (see D'Heur, 1984; Hatton, 1986; Kennedy, 1987a, b; Campbell & Gravidal, 1995; Bailey *et al.*, 1999). In parallel, medium- (5–20 m thick) and large-scale (> 20 m thick) symmetrical bow trend of increasing and decreasing gamma ray values have been documented in most of the studied wells and used as a support tool for regional inter-well correlations across the study area. In each seismic sequence, log, core and seismic facies been integrated to define the regional depositional environment and the temporal and spatial evolution of pelagic and gravity-driven sedimentary processes.

3.2. Ekofisk Field dataset and methods

The dataset for the study of dense zones of the Ekofisk Formation in the Ekofisk Field consists of a 3D acoustic impedance cube in addition to gamma ray, density and calculated porosity curves from approximately one hundred wells located across the field. Twenty-six of these wells were provided with cores covering parts or the entire Ekofisk Formation. Twenty-seven core samples from wells 2/4-A8 and 2/4-X32 have been used for sedimentological, petrographic and mineralogical characterization of the dense zones present in these wells.

The 3D seismic survey, from which the 3D acoustic impedance cube derives, has been acquired during the year 1989 using a dual-source and dual-streamer configuration. The resulting frequency of the seismic survey ranges between 15 Hz and 55 Hz, while acoustic velocity ranges from 2500 m/s, for the high-porosity/low-density interval, to 4500 m/s for the low-porosity/high-density intervals. Vertical resolution is $\sim 1/4$ of the dominant wave length (Yilmaz, 1987) and at reservoir depths of 2900–3250 m corresponds to ~ 12 ms TWT (two way travel time); depending on the average velocity of the layer this resolution may vary between 15 m and 27 m.

Depth conversion of the seismic data set was performed in the years just following the acquisition by the Joint Ekofisk Reservoir Characterization Team (Clausen *et al.*, 2001) using 34 wells with sonic log plus 6 explorations wells. Wells not including checkshot or sonic log were calibrated using the base of the Ekofisk Formation since this interval is clearly represented on seismic sections and well logs. Depth conversion was followed by acoustic impedance inversion of the 3D seismic cube, which was performed using a low frequency model. This model integrates the density and sonic logs together with time-depth curves from a series of wells equally distributed across the field. Chalk shows a strong connection between density and acoustic impedance and intervals with high acoustic impedance correlate in well and cores to succession with numerous dense zones. These are commonly tens of metres thick and are therefore visible in acoustic impedance sections.

Dense zones identified in cores have been laterally traced in non-cored wells based on wireline log correlation using eight N–S and ten W–E well-to-well correlation panels. This was supported by interpretation of high acoustic impedance intervals in impedance sections directed across the same wells used in the well-to-well correlations panels.

The sedimentological, petrographic and mineralogical characteristics of the dense zone core samples from wells 2/4-A8 and 2/4-X32 have been investigated using computerized tomography scans (CT scan), mini-permeameter on core slabs, He-porosity and gas permeability on plugs, thin sections, X-Ray diffraction and X-Ray fluorescence on rock powders, scan electron microscope (SEM) in back-scattered electron (BSE) mode or rock chips, porosity estimation from image analysis of x1000 thin section in BSE mode and Energy Dispersive X-ray Spectroscopy (EDS Spectrum) on selected areas of the thin sections.

4. Summaries and main findings

The following paragraphs give a short overview of the chapters in this thesis. Detailed summaries, methods, results and conclusions can be found in chapters 3–5.

4.1. Chapter 2

Due to the importance of the chalk as a hydrocarbon reservoir, the volume of literature published on this sedimentary rock is vast. In order fully to understand the complexity behind the chalk depositional system, this study begins with a review of the depositional model and stratigraphy of the Chalk Group. To adequately introduce the geology of the Chalk Group in the study area, this chapter also includes a brief overview of the tectonic setting and evolution of the Norwegian Central Graben within existing stratigraphic schemes.

4.2. Chapter 3

This chapter discusses the influence of the tectonic evolution of the Norwegian Central Graben on the development of seismic sequences and regional distribution of facies within the Chalk Group. Chapter 3 also discusses the geomorphological and geological significance of syn-depositional features produced by the activity of bottom currents and large-scale mass-flow events. Additional considerations cover the possible causes behind large-scale cyclicity observed on wireline log curves such as the natural gamma ray log, which could signal Milankovitch cycles and relative sea-level fluctuations with associated variation in the productivity of the carbonate factory and terrigenous detrital supply.

Based on 3D seismic data and study of numerous wells, this study has distinguished three different types of seismic unconformities: (1) unconformities generated by gravity-driven erosion during tectonic uplift; (2) unconformities that are mostly related to peak of bottom current activity during periods of tectonic inversion and eustatic sea-level variations; and (3) unconformities generated by changes in climate and eustatic sea-level. A total of eight seismic unconformities have been identified, which in turn define seven seismic stratigraphic sequences characterized by different seismic facies and well log signatures. The seismic sequences can be grouped into three tectono-sedimentary sequence sets. These sequence sets reflect the general evolution, in terms of basin physiography and style of deposition, of the chalk depositional system in the Norwegian Central Graben.

4.3. Chapter 4

The fourth chapter focuses on the geological significance and geomorphological evolution of a channel-like feature present in the uppermost interval of the Tor Formation in the southern part of the Ekofisk Field. Seismic data indicate that this channel-like feature is characterized by a distinctive negative amplitude anomaly oriented WNW–ESE and developed parallel to the northern slope of the

Lindesnes Ridge. In map view, the channel is straight but has a funnel-shaped geometry widening from 1 km to nearly 5 km with a total length of ~30 km.

The funnel shape geometry and the steep wall of the southern margin of the channel indicate that it was generated by bottom currents flowing from WNW toward the SSE parallel to the palaeobathymetric contours of the Lindesnes Ridge. Wells penetrating the channel and its surrounding areas suggest a multiphase history of channel erosion and margin up-building followed by periodic infill by allochthonous chinks originating from surrounding structural highs and collapse of the channel margins. The presence of the channel strongly influenced chalk deposition in the area during the Upper Maastrichtian, creating a local erosive depression containing coarse and highly porous material.

4.4. Chapter 5

Chapter 5 focuses on the distribution of dense zones in the Ekofisk Formation of the Ekofisk Field. The Ekofisk Formation consists of fine grained allochthonous chalk sediments interbedded with several dense and less-porous intervals which have been referred to as dense zones. Commonly, reservoir chinks in the Ekofisk Field are characterized by high porosity (30–50%) but very low permeability (0.01–10 mD). Water injection is the main production mechanism; however, water imbibition in these low-permeability media progresses at a slow rate and fractures are fundamental for the distribution of water through the reservoir in order to sweep the hydrocarbons. Dense zones were originally thought of as barriers, but it is now realized that they are more prone to retain open fractures due to their brittle mechanical behaviour, making them preferential pathways for injected water.

Seismic acoustic impedance, well log and core data as well as detailed mineralogical and petrographical analyses has been used to describe the origin and lateral extent of the dense zones. Five main dense zone lithotypes have been identified: (1) argillaceous chalk; (2) flint; (3) silicified chalk; (4) incipient hardground; and (5) stylolitized chinks. These are directly controlled by various sedimentary and early and post-depositional diagenetic factors associated with reduction in the supply of chalk sediment following relative sea-level fluctuations and environmental/climatic changes.

Dense zones occur as isolated beds or as clusters in intervals of field-wide extent, which reflect periods characterized by reduced rate of sedimentation occasionally associated with stratigraphic hiatus. Six field-wide dense zone intervals have been described and interpreted as sequence boundaries defining allostratigraphic sequences dominated by allochthonous or autochthonous chinks. Correlation of the Danian successions in the Ekofisk Field with those described in Denmark suggests a eustatic and/or climatic origin for the field-wide dense zone intervals.

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Figures

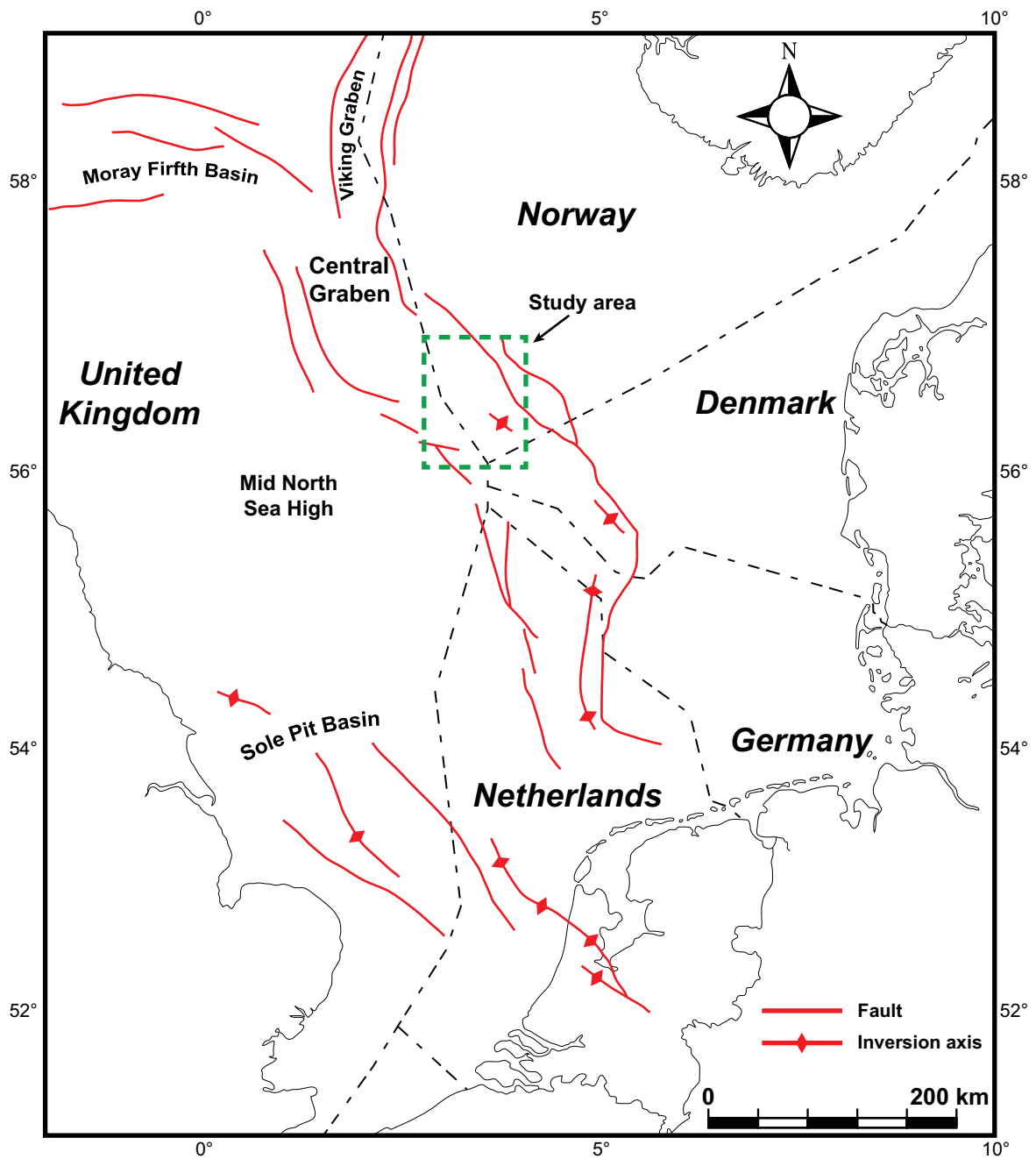


Fig.1. Cretaceous tectonic elements and major structural lineaments of the central and southern North Sea (Ziegler, 1990; Megson & Hardman, 2001).

Chapter 6: Conclusions

The importance of chalk as a hydrocarbon reservoir stems numerous research that produced a vast amount of literature focussed on the chalk sedimentology, depositional model and diagenesis (Chapter 2). However, numerous uncertainties are still present regarding the exploration potential and reservoir characterization of chalk in the North Sea. The present thesis integrates and expands the existing literature database, describing the seismic stratigraphy and the regional tectono-sedimentary of the Upper Cretaceous to Lower Paleocene Chalk Group in the Norwegian Central Graben (NCG). Additional topics addressed by the present study concern the geological significance of a channel feature present in the uppermost interval of the Tor Formation and the depositional and diagenetic model of reservoir heterogeneities in the Ekofisk Formation of the Ekofisk Field.

The chalk deposited during a peculiar period of the Earth's history conditioned by intense volcanic activity and oceanic ridge's spreading that led to warm climate, high surface-water temperatures and to one of the major sea-level rise of the Phanerozoic. This rise of the sea-level progressively inundated the existing land masses, reducing the influx of terrigenous detrital material and associated nutrients into the oceans. As a result, large part of the NW Europe was characterized by vast and relatively deep epeiric seas with clear waters, normal salinity and oligotrophic nutrient levels. These settings were the ideal conditions for the proliferation of the coccolithophorid, a type of calcite-shelled phytoplankton algae.

The primary mechanism of sedimentation of the chalk is the settlement of the calcitic tests of the coccolithophorid from suspension in the water column. Therefore, the sedimentation of chalk depends on the coccolithophorid productivity, which is consecutively affected by environmental parameters e.g. nutrient levels, water temperature, salinity and irradiance. Periodical variations of these parameters are directly reflected in pelagic chalks as changes in lithology as well as variations in the geochemical and petrophysical properties. In areas that underwent significant syndepositional tectonic activity and halokinesis, slope instability caused by oversteepening triggered downslope mass-movements. The sediment accumulations produced by these gravity-driven processes are commonly referred to as allochthonous chalk and typically comprise slide, slump, debris flow and turbidity current deposits. Chalk material was also redistributed by bottom currents, which sculpted the sea floor creating valleys, ridges, channels, drifts and mounds.

In the NCG, seismic imaging and wireline log curves provide useful insight on the tectono-sedimentary development of the Chalk Group (Chapter 3). Based on the configuration of the reflection terminations such as onlap, downlap and truncation, key seismic horizons have been mapped across the study area. In ascending order, the key seismic horizons are: (1) Base Chalk; (2) Blodøks; (3) Top Narve; (4) Top Thud; (5) Top Magne; (6) Middle Tor; (7) Top Tor; and (8) Top Ekofisk. These seismic horizons are interpreted to result from: (i) increased erosion by gravity-driven processes during tectonic uplift, e.g. Top Narve and Top Thud horizons; (ii) increase erosion due to peak in bottom current activity associated with relative fall of the sea-level, e.g. Top Magne and Middle Tor horizons; and (iii) basin-scale environmental and climatic changes, e.g. Blodøks and Top Tor horizons. The seismic horizons define seven seismic sequences: LC1–LC6 and DN, that based on thickness distribution, seismic facies, wireline log signature and interpreted style of deposition can be grouped into three tectono-

sedimentary sequence sets. In ascending order, the sequence sets are: lower sequence set (LC1 and LC2 seismic sequences; Cenomanian–Coniacian); middle sequence set (LC3 and LC4 seismic sequences; Santonian–Campanian); and upper sequence set (LC5, LC6 and DN seismic sequences; Maastrichtian–Danian).

The lower sequence set is characterized by parallel and continuous reflections interpreted as pelagic chinks interbedded with sub-seismic resedimented chinks, e.g. allochthonous bodies less than a few tens of metres thick. Similar seismic facies type characterize most of the middle sequence set. However, compared to the lower sequence set, the middle set shows more chaotic reflections, interpreted as allochthonous bodies, particularly adjacent to areas that underwent intensive syn-depositional tectonic and halokinetic movements, e.g. Albuskjell Anticline. Discontinuous to chaotic seismic facies form the majority of the upper sequence set, which indicate the occurrence of large-scale gravity flows. In the upper sequence set, gravity-driven resedimentation principally occurred from the margins of the NCG as disorganized slope apron complexes, with intrabasinal highs and halokinetic structures acting as local sources for mass-flows.

From the interpretation of seismic sections and isochron maps, it is evident that in the study area the tectono-stratigraphic development of the Chalk Group was strongly influenced by the tectonic inversion of the Central Graben lineaments during the Upper Cretaceous–Palaeogene. Uplift of the Lindesnes Ridge initiated during the Turonian, however it was until the Santonian that this feature, together with the Albuskjell Anticline, became prominent bathymetric reliefs. Coeval mobilization of deeply buried Zechstein salt along fault planes enhanced the inversion movements and created local diapirs and walls. Migration of salt from where it was previously accumulated along fault planes resulted into the formation of salt-withdrawal basins that became local depocentres for the accumulation of chalk. Although with lower intensity than during the Turonian–Santonian time, tectonic movements continued throughout the Campanian and the Maastrichtian. During this period, coeval increase in subsidence of the basinal areas allowed the accumulation of thick chalk successions. More localized subsidence continued throughout the Danian developing the marginal Ekofisk Trough alongside the northern slope of the Lindesnes Ridge. This trough acted as a catchment area for the allochthonous material originated from the surrounding structural highs and salt diapirs.

Medium-scale (5–20 m thick) intervals of increasing and decreasing values observed in the gamma ray curves of the Chalk Group have a time duration in the order of magnitude of the 40–50 ka obliquity, the 100 ka short eccentricity and the 412 ka long eccentricity Milankovitch cycles. Large-scale (>20 m thick) gamma ray trends have an estimated time duration of 1–3 Ma and are thus equivalent to second- or third-order sequences. An increasing large-scale gamma ray trend has been interpreted as a regressive sequence (R-t), while a decreasing large-scale gamma ray trend as a transgressive sequence (r-T). These large-scale gamma ray trends mostly characterize the lower and middle sequence sets, while the upper sequence set shows less-developed gamma ray trends, most probably because the frequent mass-wasting events that occurred during the Maastrichtian–Danian masked the eustatic signal.

Bottom currents have strongly influenced the sedimentation of chalk in the study area, creating sedimentary and erosive features on the seafloor and producing regional unconformities. The activity of bottom currents initiated during the Santonian and reached its acme at the Campanian–Maastrichtian boundary creating the regional Top Magne unconformity. During the Maastrichtian, the circulation of bottom currents became more focused and developed erosional and constructional sedimentary features. The stratigraphic development of the moat-drift complex within the LC5 and LC6 sequences indicates that the current system in the NCG was long-lived and significantly affected the topography of the sea floor.

During the late Maastrichtian, bottom current activity was particularly intense as suggested by the development of an erosive channel feature along the NE slope of the Lindesnes Ridge (Chapter 4). Based on: (i) channel incised based on seismic sections; (ii) funnel-shaped channel planform geometry; (iii) channel orientation parallel to the palaeobathymetric contours of the Lindesnes Ridge; and (iv) asymmetric geometry of the channel cross-section, the channel is interpreted to have been formed by an ESE-flowing contour-parallel bottom current that flowed alongside the palaeoslope of the Lindesnes Ridge. The Coriolis force deflected the bottom current towards its right-hand side, resulting in greater erosion or non-deposition on the southern channel margin and sediment deposition on the northern channel flank. As a result, the southern margin of the channel is steeper, while the northern margin is more gentle.

The wireline log signature from the channel-fill and channel-margin deposits indicate that the formation and development of the channel can be summarize in two main phases. A first phase of erosion of the substrate by the ESE-flowing bottom current accompanied by pelagic chalk deposition with sediment bypass focused along the channel thalweg zone and vertical aggradation of the channel margins. This was followed by a second phase where the channel was passively filled by allochthonous chalk deposits originated as gravity flows from the surrounding structural highs and from collapse of the channel margins. Other channels present in coeval chalk successions in the Central Graben have also been interpreted to result from the activity of contour-parallel bottom currents. This suggests that the ESE-flowing bottom that formed the studied channel may be part of a regional system of bottom currents that characterized the chalk epeiric sea throughout the late Maastrichtian.

In the Ekofisk Field, the reservoir intervals of the Ekofisk Formation consist of allochthonous chalk deposits intercalated with relatively thin beds (<10 m thick) called dense zones, which are characterized by high density and low porosity values (Chapter 5). Dense zones consist of pelagic chalk, flint, hardground, silica cemented beds and intervals showing intensive development of stylolites. Dense zones represent initial pauses or breaks in chalk sedimentation and subsequent diagenetic evolution during shallow and deep burial.

In the Ekofisk Formation, four major dense zones intervals have been identified and these are characterized in well logs by high density intervals (> 5 m thick) and on seismic acoustic impedance sections by high acoustic impedance values. The extent of major dense zone and their presence in between the resedimented chinks of the reservoir intervals suggest that throughout the Danian allochthonous sedimentation in the Ekofisk Trough was intermittent. Extensive periods of low

sedimentation rate allowed the development of large-scale dense zones, locally associated with stratigraphic hiatus. Major dense zone intervals are considered as sequence boundaries that divide the Ekofisk Formation in the Ekofisk Field into five allostratigraphic sequences. Correlation between the Danian successions in the study area and those present onshore Denmark suggest a eustatic or climatic origin rather than tectonic for the major dense zone intervals.

Across the Ekofisk Field, major dense zone intervals show an inhomogeneous distribution of the acoustic impedance values, which is interpreted to reflect lateral depositional variations that were later enhanced during burial diagenesis. In the Ekofisk Trough, the southern provenance from the Lindesnes Ridge of most of the allochthonous material favoured low rate of sedimentation and hence greater development of dense zones in the region that corresponds nowadays to the northern flank of the field. During the subsequent hydrocarbon charging, the lower permeability of dense zones led to inhomogeneous oil water contacts and higher water-saturation compared to dense zone-free intervals. The high water-saturation of dense zone-rich intervals was further enhanced by post-depositional tectonic tilt of the field, with the northern flank uplifted compared to the southern flank. The oil water contacts tilted in the same direction and, because of the low permeability of chalk, the oil water contacts cannot easily re-equilibrate. This led to higher water saturation in the northern flank of the field compared to the southern flank and hence greater porosity loss by diagenetic processes and higher acoustic impedance values.

Among the major dense zones intervals, the Ekofisk dense zone or EE geolayer is the most prominent and continuous. The EE geolayer at the base of the Ekofisk was deposited shortly after the K/T boundary and reflects a marked increase in terrigenous detrital material. The EE geolayer is interpreted to reflect the combined effects of intensive volcanic activity, sea-level lowstand, meteorite bolide impact and extreme climatic changes that occurred on the chalk depositional system across the K/T boundary.