A REVISED CHALK LITHOSTRATIGRAPHIC NOMENCLATURE

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The petroleum activity in the Noth Sea over the years revealed a need to update and revise the stratigraphic framework for the chalk units. The presence of "*time gaps"* and *redeposition* in the chalk reservoirs especially challenged the the established formal lithostratigraphic nomenclature.
Biostratigraphic analysis combined with chalk lithofacies, well log correlation and seismic studies were used to develop a revised complete lithostratigraphic nomenclature for the Upper Cretaceous and Paleocene chalks in the Central Graben. The most important change is the subdivision of the original formal Hod Formation into three new formations; Narve, Thud and Magne. This subdivision is based on the major stratigraphic breaks that were observed in the Hod Formation. These breaks represent time gaps of variable lengths in the biostratigraphic data, and are often seen as hardgrounds in cores, and especially in wells located on structural highs. Also in the seismic data, the Hod Formation was seen to embrace two significant sequence boundaries that could be tracked over large distances. On basis of international stratigraphic rules (Hedberg 1976), such major sequence boundaries are not recommended within a formation. Consequently, the split of the Hod Formation into three new formations was performed. To avoid confusion with the existing informal lithological subdivision of the Hod into lower, middle and upper Hod, unique names for the new units were suggested, following the tradition with names from the Norse mythology. The boundary definition of the Tor Formation has been revised, and the Vidar Formation overlying the Ekofisk Formation has been better defined.

INTRODUCTION

Extensive reservoir modelling and drilling activity in the chalk areas of the North Sea the last twenty years has resulted in many different ways of subdividing the chalk reservoirs. The oil companies developed their own local stratigraphic frameworks or nomenclatures in order to fit the well data from their license areas. This practice complicated communication between oil companies and the regional understanding of the chalk facies and created a need to update and revise the formal stratigraphic framework for the chalk units.

In the Joint Chalk Research (JCR) phase V, 1997 – 2000, the project “A Joint Chalk Stratigraphic Framework” was initiated in order to establish a common stratigraphic nomenclature for the Upper Cretaceous and Paleocene chalks in the Central Graben and Norwegian-Danish Basin. The work was performed by a joint work group including geologists from the companies and agencies participating in JCR Phase V. Biostratigraphic analyses comprised the majority of the project work, and the results were interpreted together with well logs, chalk depositional facies and seismic data. The resulting joint biostratigraphic and lithostratigraphic framework for the chalks in the Central Graben is presented in this publication, and a revision of the formal Hod Formation into three new formations; Narve, Thud and Magne is proposed, see **Figure 1**. The detailed documentation of the basis for the stratigraphy, including biotrat analyses and composite well log panels, can be found in the report (Fritsen *et al* 1999), available on compact disc from the Norwegian Petroleum Directorate.

The new stratigraphic nomenclature will improve the communication between the oil companies in both Norwegian and Danish areas, and ensure a standard basis for regional mapping and correlations between the various chalk fields and prospects. Since the presence of "*time gaps"* and *redeposition* in the chalk reservoirs is especially acknowledged in the proposed new lithostratigraphic nomenclature, improved understanding of deposition, erosion and redeposition of chalk, as well as better control of seismic interpretation on and between fields will result.

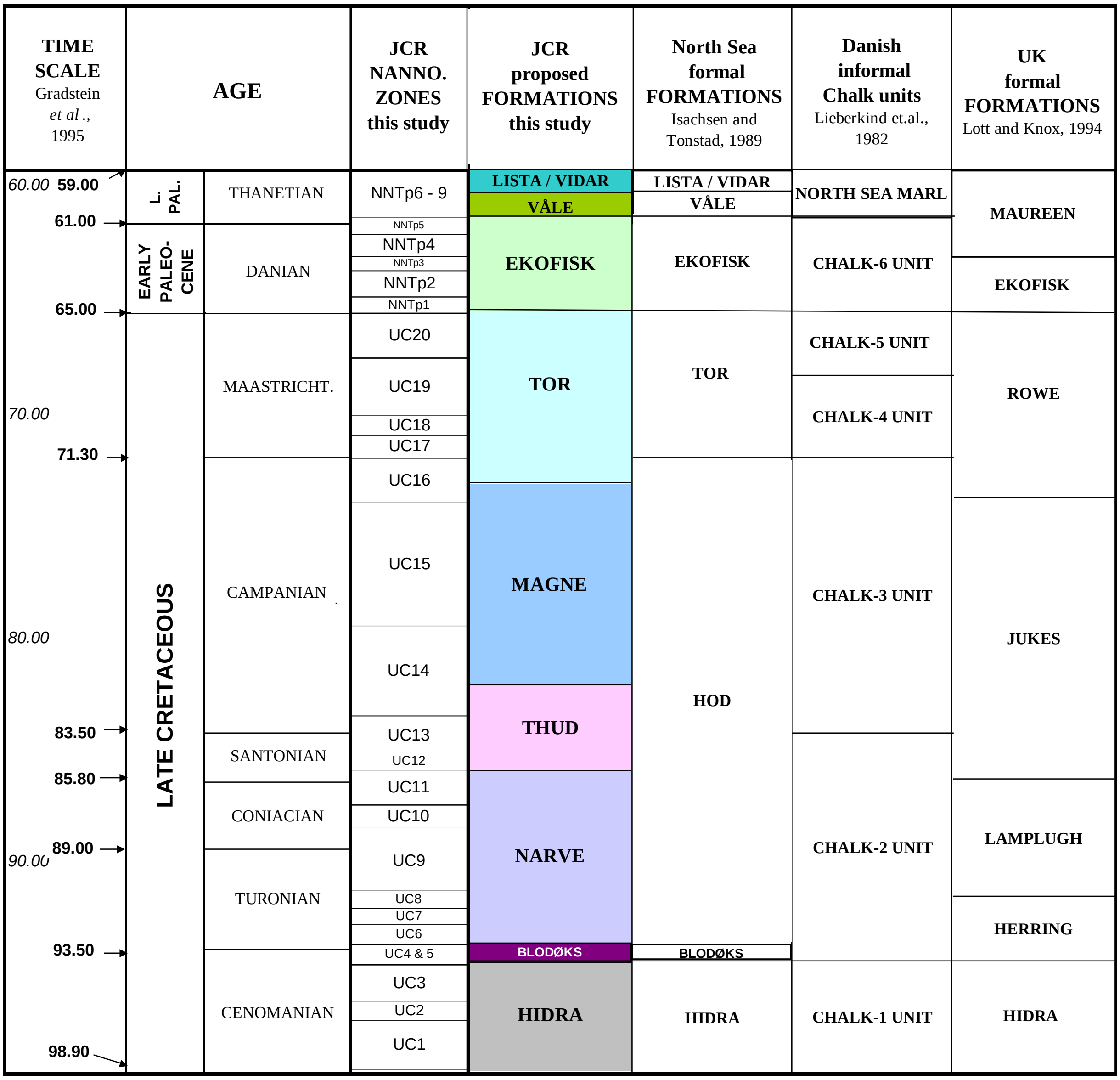

Figure 1: A revised chalk lithostratigraphic nomenclature

METHOD

A number of 35 wells from Norwegian, Danish and UK areas were chosen for the study. Biostratigraphic data, well interpretations and core descriptions from these wells were made available from the companies. Cores and wireline logs were studied by the work group, and intervals representing possible stratigraphic sequence boundaries, time gaps or redeposition were defined. In total, 1250 meters of core were described based on the previous developed JCR description system. With more than 700 new core samples collected during core descriptions, a total of more than 4000 biostratigraphic quantitative or semi-quantitative nannofossil- and micropaleontological analyses were used in the study. Regional seismic was interpreted to resolve stratigraphic surfaces between fields and key wells, and chronostratigraphic diagrams were made to identify stratigraphic time gaps and sequence boundaries in the study wells.

Selection of the study wells was based on various criteria, including the well´s position regarding basin and structural highs, and available core and biostratigraphic data. Existing stratigraphic type wells, such as 1/3-1 was also included. Wells that had core coverage across a formation boundary were considered especially important, as were wells that appeared to have been drilled across major stratigraphic time breaks.

Figure 2 shows the location of the study wells and the chalk fields in the North Sea Central Graben.

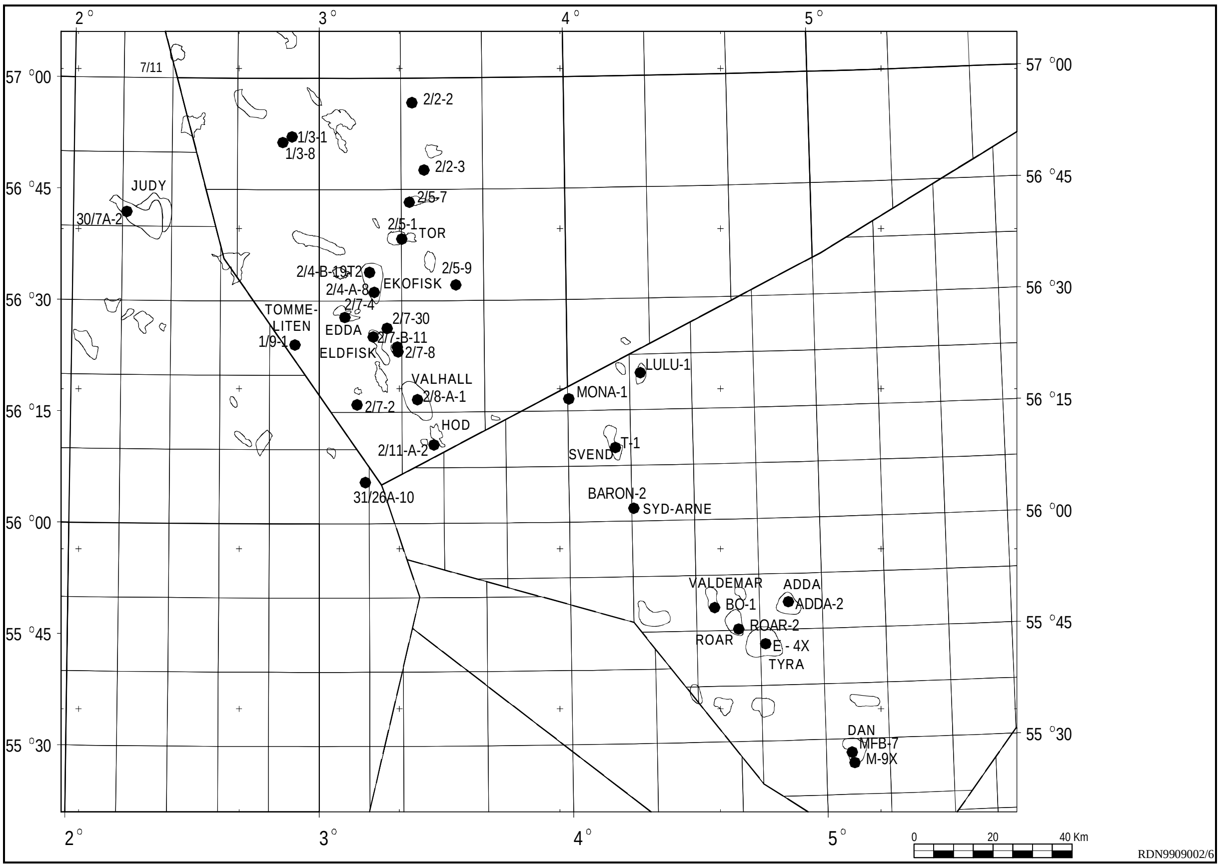

Figure 2: Location of the study wells and chalk fields

STRUCTURAL AND TECTONIC FRAMEWORK AND SEISMIC INTERPRETATION

The Central Graben was tectonically active during deposition of the chalk sequence. Graben subsidence, inversion structures and salt tectonics created a complex and changing pattern of basins and highs in the Late Cretaceous and Danian.

During chalk deposition, the Central Graben subsided along its major boundary faults towards the stable platforms. There were several episodes when the relatively uplifted platforms were eroded, and acted as source areas for redeposited chalk. Salt tectonics and inversion tectonics added to the structural complexity. Inversion highs, formed by uplift and reverse movement along pre-existing faults, were active at different occasions during and after chalk deposition, and the detailed timing of their activity may differ. They often represent a change in tectonic setting from a pre-Campanian trough to a Maastrichtian high.

Figure 3 shows the Central Graben and its main structural elements based on Anderson (1995), Britze et al. (1995) and data from the Chalk Exploration Project (CEP), which was made available for JCR by Phillips Petroleum Company.

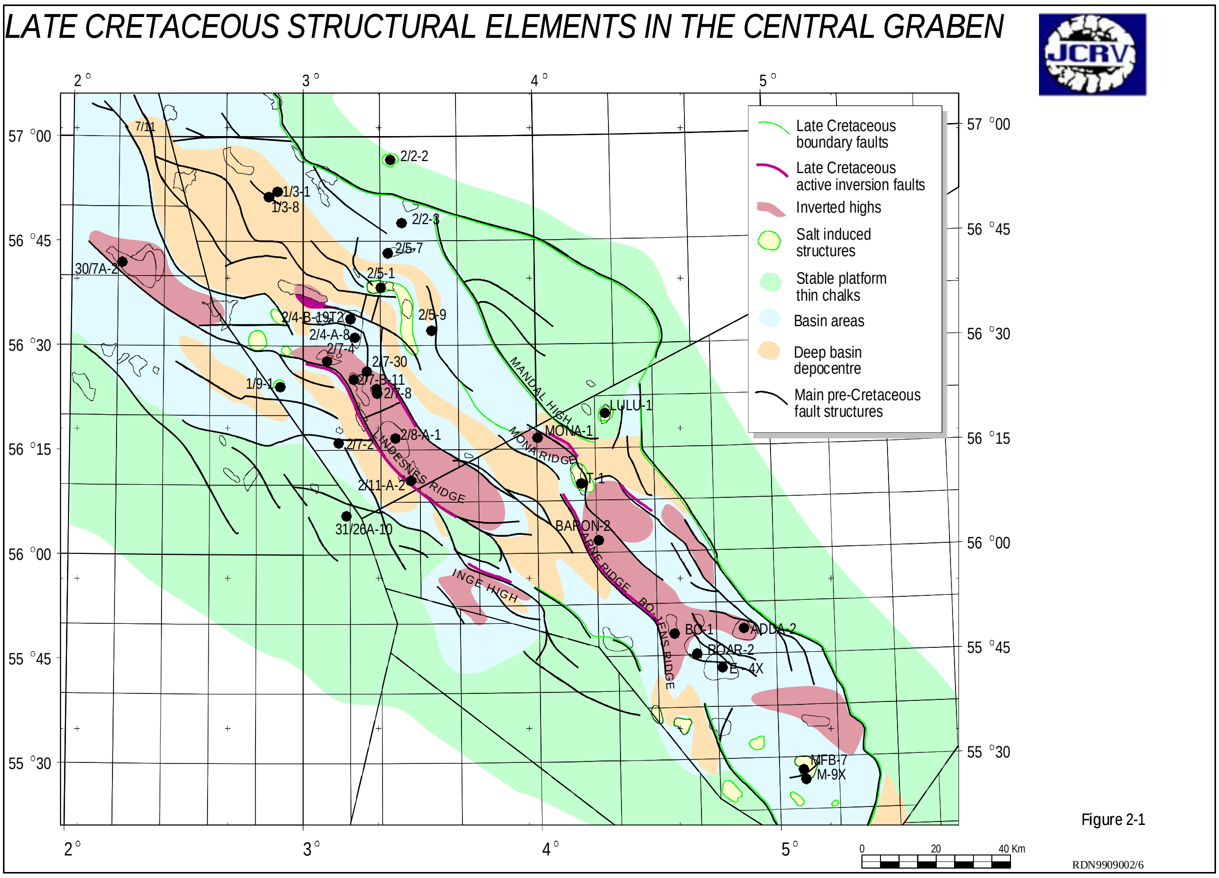

Figure 3: Central Graben main structural elements

A major depocenter for the Cretaceous chalk located in the northwestern part of the Central Graben is penetrated by wells 1/3-1 and 1/3-8. These wells have a fairly complete chalk section, and they are important reference wells. Additional depocenters with a chalk thickness exceeding 900 m were located in the deeper parts of the complex graben structure. There are few wells drilled in these depocenters, and those drilled were generally aimed at targets other than the chalk. Consequently, core and biostratigraphy data are sparse.

As part of the study, a set of regional 2D seismic lines were tied to the wells and interpreted. On the Norwegian side, about 500 km of good quality 2D seismic data was interpreted. On the Danish side, two long composite lines were provided from existing 2D and 3D surveys, in order to tie all the studied wells together. Main seismic sequences were identified and reflectors tied between the studied wells in order to support correlation based on logs and biostratigraphy. Seven sequence boundaries were interpreted to determine the important seismo-stratigraphic events in the area, these were Blodøks, Intra Middle Hod, Top Middle Hod, equivalent to an important sequence boundary in the Campanian, Top Hod, a sequence boundary at or near to the base of the Maastrichtian, Top Tor at the top of the Cretaceous, Top Ekofisk, at the top Danian, and Balder, an important near Top Palaeocene event.

In terms of the proposed lithostratigraphy, Intra Middle Hod can be correlated with top Narve in the northern part of the region. The reflectors Top Middle Hod and Top Hod correlate with top Thud and Top Magne respectively.

Top Narve (Intra middle Hod)

This event was picked on a weak peak only in the basinal areas in the north and west of the area. It represents a sequence boundary lying between the Blodøks and Top Middle

Hod reflectors (**figure 4**). There is marked onlap onto this reflector at the basin margins and on the flanks of salt domes. Towards the east, and towards structural highs, the unit pinches out.

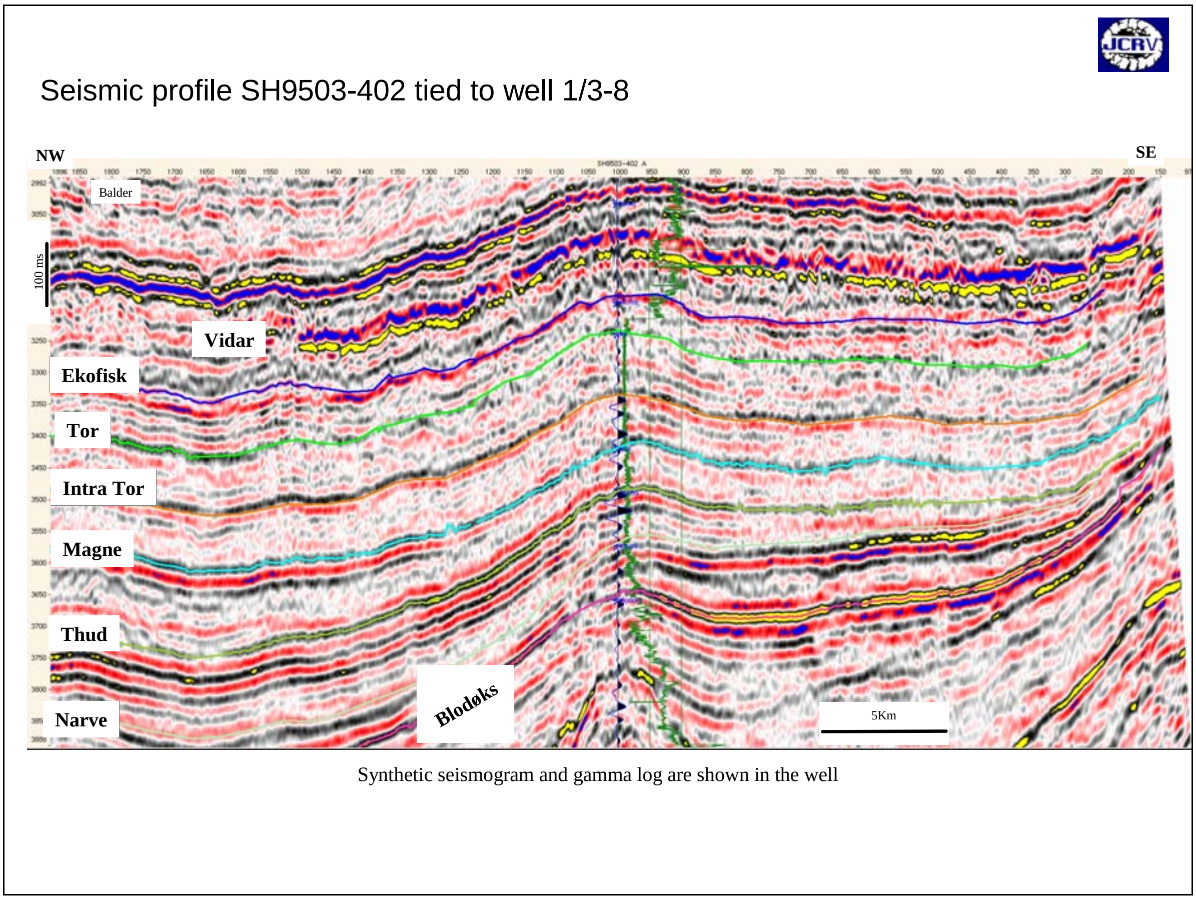

Figure 4: Seismic profile tied to reference well 1/3-1

Top Thud (Top middle Hod)

This event was generally picked on the lowest part of a poor quality peak doublet (**figure 4**). It did not have a consistent appearance throughout the area but sometimes separated a zone with stronger parallel reflectors above from a quieter zone beneath. On the platform margins and adjoining salt highs and inversion highs, marked onlap was visible onto the reflector. In more basinal areas, both onlap onto and subcrop below the reflector could be recognised, probably indicating more localised tectonic activity, perhaps associated with underlying salt movements. The overall surface of the Middle Hod was broadly undulating and not always parallel to events below or above, even in flatter areas.

Top Magne (Top Hod)

This event was generally picked as a diffuse peak at the base of the reflector separating a lower amplitude zone above from a zone below comprising stronger parallel reflectors (**figure 4**). In the structurally higher areas the reflector separates an overlying sequence of higher amplitude parallel reflectors from a lower amplitude zone below. This would imply that the Lower Tor sequence thickens considerably into the basinal areas particularly to the north and west around 1/3-1. The overlying Tor formation could be seen to onlap the reflector in places at the platform edges and on the flanks of salt induced highs (**figure 5**). However in general the Tor sequence showed a greater areal extent than the Magne, extending up onto the platform and highs albeit as a much reduced sequence.

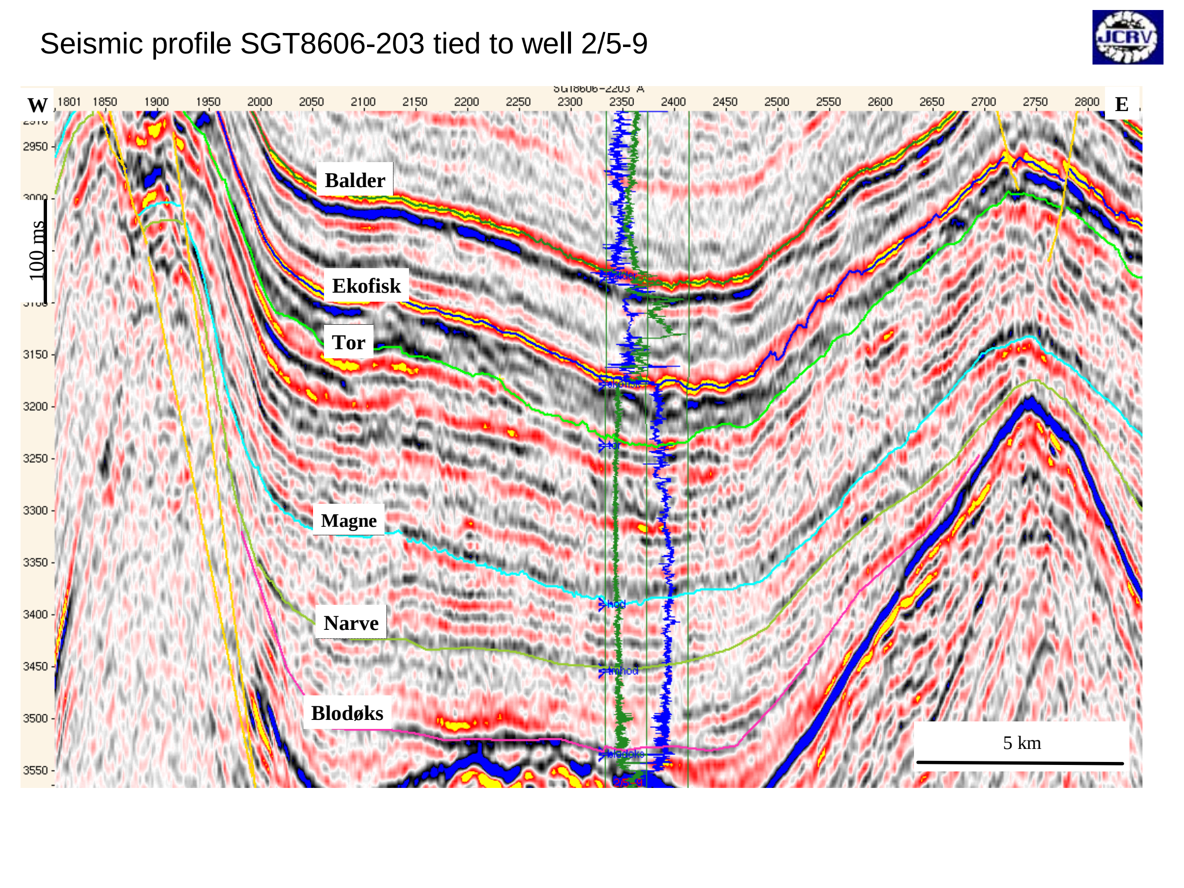

Figure 5: Seismic profile tied to reference well 2/5-9

Well data indicate that the Magne Formation is developed as a hardground at some of the highs. The representative wells are all located within gas clouds, and the hardground has not been tied to seismic lines.

NORTH SEA CENTRAL GRABEN CHALK LITHOSTRATIGRAPHIC NOMENCLATURE

The first formal lithostratigraphic nomenclature for the central and northern North Sea was published by Deegan & Scull in 1977. The Cretaceous and Tertiary for Norwegian areas were later revised by Isaksen and Tonstad (1989). Lieberkind *et al*. published an informal nomenclature for the chalks in the Danish Central Graben in 1982. For UK North Sea, Knox and Cordey published a revised lithostratigraphy in 1993.

The present study represents the most thorough stratigraphic study ever performed on the North Sea chalks. In the following section, the proposed new lithostratigraphic formations are discussed on basis of biostratigraphy, seismic data and depositional facies.

The formation boundary picks in the individual study wells are documented in the report

Figure 6 shows the JCR proposed formations in a sequence stratigraphic framework in the type/reference well 1/3-1.

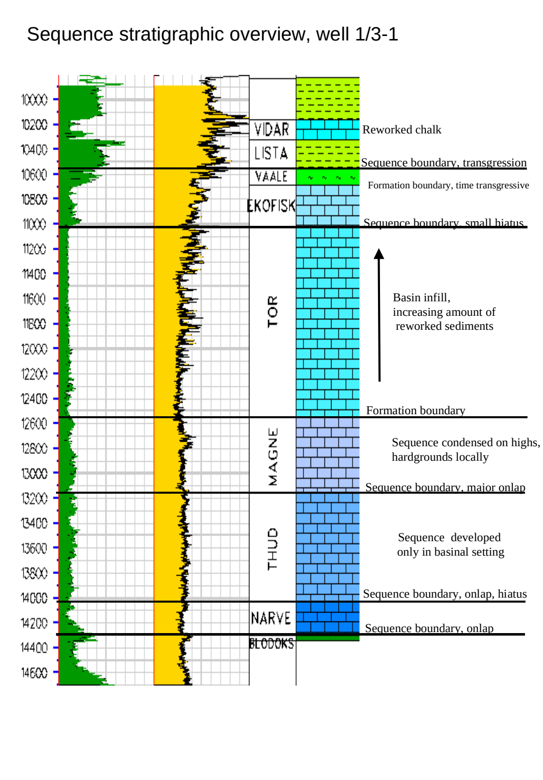

Figure 6: Well reference section 1/3-1

Turonian to Campanian chalk stratigraphic framework

The original Hod Formation (cf. Deegan and Scull, 1977) was informally split into a Lower, Middle and Upper unit (Isaksen and Tonstad, 1989). In this study, an alternative subdivision of the Turonian-Campanian section is presented, proposing three new formation names, Narve, Thud and Magne, stratigraphically placed between the Blodøks Formation and the Tor Formation. The geometrical relationships between the units are shown in **figure 7**.

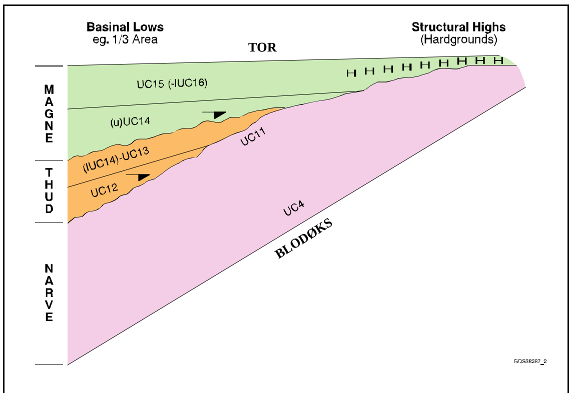

Figure 7: Schematic presentation of the sequence stratigraphic relationships between the Narve, Thud and Magne formations

The criteria for defining their boundaries on seismic, biostratigraphic and well log evidence are described below and summarised in **table 1.**

Formation/ boundary	Boundary definition		
	Seismic	Biostrat	Logs
Tor			
Tor / Magne boundary	Poorly imaged	Intra UC 16	Uphole gamma increase
Magne			
Magne / Thud boundary	Onlap surface	intraUC 14	
Thud			
Thud / Narve boundary	Onlap surface	UC 11	
Narve			
Narve / Blodøks boundary	Base chalk reflector	UC 3	Downhole gamma increase
Blodøks			

Table 1: Summary of formation boundary definitions according to the various criteria

Narve formation

Name: Narve formation (proposed). After the Norse god Narve, who was the son of Loke and Sigyn (Sturluson, 1954).

Well Type Section: 1/3-8, 4520-4337 m MD.

Well Reference section: 2/8-A-1, 2581,5 - 2501,5 m MD.

Lower Boundary Characteristics: Picked primarily on biostratigraphic and log criteria. The biostratigraphic criterion is penetration of microzone FCS13 or nannozone UC3. The log criterion is a downhole gamma increase indicating penetration of the shales of the Blodøks Formation.

Upper Boundary Characteristics: Picked primarily on seismic and biostratigraphic criteria. The seismic criterion is an onlap surface. The biostratigraphic criterion is penetration of nannozone UC11.

Thickness and Distribution throughout Study Area: The thickness of this formation ranges from zero to a few hundred metres in the study wells. It is absent in the 2/2 wells in the Norwegian Sector and in the Lulu-1 well in the Danish Sector. It is thin (typically less than 100m thick) in wells on structural highs such as Valhall-Hod and Tor in the Norwegian Sector, and thickest in wells in basinal lows such as that in the Roar area in the Danish Sector, and in the northern and western depocenters in the Norwegian sector.

Lithology, Main Depositional Facies and Environments: Lithofacies associated with the crestal biofacies on Valhall are typically (textural) mudstones and wackestones. Those associated with the "shallow water" pelagic biofacies are varied, though typically bioturbated to laminated chalks or interlaminated chalks and clays indicative of slow sedimentation. Those associated with the "deep water" pelagic biofacies are typically massive chalks. Recognition of allochthonous as against autochthonous chalks is rendered difficult by the poor bathymetric resolution afforded by the rare benthonic foraminifera. Lithofacies in core from the 2/8-A-1 well include bioturbated chalks with *Chondrites, Planolites* and *Zoophycos*, and also allochthonous debris flows and slumps with micritic matrices and polymict/non-chalk clasts, indicating affinity with the "shallow water" and "deep water" pelagic biofacies of the Valhall structure respectively. Allochthonous chalks are also observed in core from Mona-1.

Biostratigraphic Characterisation: Microzones FCS14-FCS18pp; nannozones UC4-UC11.

Log pattern: The Narve formation has been penetrated in quite many wells in the Valhall area (Lindesnes Ridge) and in the Ål basin to the west of the ridge. The gamma log patterns of these wells correlate well in this area, and a detailed correlation of different subzones is possible. A zone of clean chalk with consistently low gamma values, overlain by a gamma spike, is situated in the middle of the Narve formation. This zone (informally named Hod4 by BPAmoco) constitutes an important reservoir in the Valhall Field, and it can easily be recognised on the logs. However, its biostratigraphic age is not consistent between the wells, and it is possible that the "Hod4" subzone is diachronous.

Age: Latest Cenomanian-earliest Santonian (for practical purposes, Turonian-Coniacian).

Remarks: Eroded on crests of structures.

Thud formation

Name: Thud formation (proposed). After an alternative name for the Norse god Odin (Sturluson, 1954). Thud means "thin one".

Well Type Section: 1/3-8, 4337-4125 m MD.

Lower Boundary Characteristics: Picked primarily on seismic and biostratigraphic criteria. The seismic criterion is an onlap surface. The biostratigraphic criterion is penetration of nannozone UC11.

Upper Boundary Characteristics: Picked primarily on a seismic criterion (onlap surface), corresponding to the original informal middle Hod sequence boundary.

Thickness and Distribution throughout Study Area: The thickness of this formation ranges from zero to a few hundred metres in the study wells. It is absent in the 2/2 wells and in wells on structural highs, such as Valhall-Hod and Eldfisk in the Norwegian Sector and in the

Lulu-1 well in the Danish Sector. It is thickest in wells in basinal lows, such as those in the 1/3 area in the Norwegian Sector and the Roar area in the Danish Sector.

Lithology, Main Depositional Facies and Environments: Poorly constrained owing to the lack of core coverage. Biofacies in cuttings samples from some wells are characterised by moderately abundant and diverse planktonic foraminifera and radiolaria and generally rarer calc-agglutinated and calcareous benthonic foraminifera, indicating an affinity with the open marine platform or “shallow water” pelagic biofacies of the Valhall structure.

Biostratigraphic Characterisation: Microzones FCS18pp-FCS20pp; nannozones UC12-UC14 pp.

Log pattern: A complete Thud formation has been penetrated in few wells, because of its basinal setting. In the northern part of the region, the gamma values in 1/3-1 and 1/3-8 indicate a clay content that is higher than in the Magne Formation. The relatively argillaceous chalks seem to alternate with clean chalks, giving rise to a ”box-shaped” pattern of the gamma log. The time equivalent to the Thud Formation in the Roar-2 well in the Danish sector has developed a different log and seismic pattern.

Age: Late Early Santonian to earliest Campanian (for practical purposes, Santonian).

Remarks: Laps on to Narve formation on flanks of structures.

Magne formation

Name: Magne formation (proposed). After the Norse god Magne, who was the son of Tor, and who supported him after his great fight with the giant Hrungnir (Sturluson, 1954).

Well Type Section: 1/3-8, 4125-3952 m MD.

Well Reference section: 2/11-A-2 T2, 3486 - 3427,4 m MD.

Lower Boundary Characteristics: Picked primarily on a seismic criterion (onlap surface).

Upper Boundary Characteristics: Picked on seismic, biostratigraphic and log criteria. The seismic criterion is a reflector (which may also locally be an onlap surface) separating a lower amplitude interval below from a higher amplitude interval above, at least in structurally higher areas. The biostratigraphic criterion is penetration of microzone FCS21. The log criterion is a downhole gamma increase (the Magne is more clay-rich than the overlying Tor).

Thickness and Distribution throughout Study Area: The thickness of this formation ranges from zero to a few hundred metres in the study wells. It is absent in the 31/26A-10 well in the United Kingdom Sector, thin (typically less than 100 m thick) on structural highs such as Valhall-Hod, Eldfisk and Tor in the Norwegian Sector, and thickest in wells in basinal lows such as those in the 1/3 and, locally, 2/5 areas in the Norwegian Sector.

Lithology, Main Depositional Facies and Environments: Lithofacies associated with the crestal biofacies on the Valhall structure are typically (textural) mudstones and wackestones. Those associated with the open marine platform, high productivity upper slope and basinal biofacies are typically bioturbated argillaceous wackestones and chalks or interbedded chalks and claystones (sometimes referred to as periodites), indicative of slow sedimentation or, in the case of the basinal biofacies, incipient hardgrounds, indicative of extremely slow sedimentation (sediment starvation). Those associated with the eutrophic sub-biofacies are bioturbated, those associated with the dysoxic sub-biofacies are laminated (i.e., non-bioturbated) pyritic chalks.

Biostratigraphic Characterisation: Microzones intraFCS20pp-intraFCS22; nannozones intraUC14pp-intraUC16pp.

Age: Late Early to early Late Campanian (for practical purposes, Campanian).

Remarks: Onlaps Thud and oversteps on to Narve (?) on flanks of structures. Generally absent or thin on crests (characterised by hardground development).

Tor Formation

Name: Named by Deegan & Scull (1977) from the Tor Field in Norwegian blocks 2/4 and 2/5. Tor was a son of Odin and one of the principal Gods of Norse mythology.

Well Type Section: Norwegian well 1/3-1 from 3828 to 3354 m is the type well for the Tor Formation (Tonstad and Isaksen 1989).

Well Reference Sections: The Mona-1 well is chosen as a one of two reference sections for the Tor Formation. The stratigraphic sequence in Mona-1 is relatively complete with individual zones being represented by a significant thickness. Except for the very top the Tor Formation is cored throughout this well. Discovery well for the Tor Field, well 2/5-1, is chosen as a second reference section for the Tor Formation. Only the upper half of the Tor Formation is cored but the 2/5-1 well has all Tor zones well developed.

Age: The age of the Tor Formation has in this study been decided to encompass all of the Maastrichtian, i.e. nannofossil zones UC17 through 20 and intra microfossil zone FCS22 through FCS23. At the detailed level the top of zone UC16, which is of late Campanian age, cannot in all wells be brought to coincide with well defined log breaks. This is a problem that remains even after careful integration of all data. UC17 and 18 are Early Maastrichtian. UC19 and 20 are Late Maastrichtian.

Lower Boundary Characteristics: In general the lower Tor boundary is difficult to pick on logs. A decrease in the GR level, small or large, is common, though quite often no change of the GR level is observed. In the stratigraphically more complete wells there seems to be a regional element to the log characteristics. In the northern basin wells the sonic log shows an increase in velocity upon entering the Tor Formation from Magne below. This is associated with either no change or a slight increase in the density reading, i.e lower porosity. From the Lindesnes Ridge and southeastwards the sonic log shows a decrease in velocity crossing from Magne to Tor Formation. This is associated with either no change or a slight decrease in the density reading, i.e higher porosity. Where nannozones UC16-18 are thin or missing a change to lower porosity associated with an increase in velocity is observed at the boundary. These are observations of a general nature and exceptions can be found.

The resistivity logs to some degree mirror the sonic and density logs in water bearing chalk. Where the velocity and density go up an increased resistivity is often seen, reflecting a more dense rock, and vice versa. Exceptions are wells where the bottom part of the Tor Formation is porous and oil-bearing. Here a decrease in velocity and density is accompanied by an increase in resistivity.

The lower boundary either coincides with the boundary between biozones UC16 and 18 (UC17 is only scarcely present) or is placed midway in UC16..

Upper Boundary Characteristics:
In general the Top Tor is of the same age over the study area. The duration of the Tor/Ekofisk hiatus mostly depends on how much is missing from the Ekofisk Formation. Locally all of the Ekofisk is

missing due to later inversion as seen on the crestal parts of the Hod and Valhall Fields. Here the Tor Formation, or reworked Tor Formation, is overlain by Paleocene shales (2/8-A-1).

The GR generally shows an increase. The Top Tor pick is usually put right at the start of the increase.

In accordance with a shift to lower porosities in the bottom part of the Ekofisk Formation the velocity shows a clear increase at Top Tor. However, the uppermost part of the Tor Formation can be well cemented and as a result appear exactly like the Ekofisk on density and velocity logs. In the absence of good biostratigraphic data the usual slight increase in GR should enable an accurate log pick, though.

A relative decrease in resistivity across the Tor/Ekofisk boundary is seen. This picture is consistent even though the resistivity in the top part of the Tor Formation is affected by pore fluids (water, oil or gas).

Thickness and Distribution:
Tor thicknesses in the study wells vary from 0 m in Baron-2 to 472m in 1/3-8. The thickness variations in the study wells are however not representative of the North Sea Basin Chalk/ Tor Formation distribution as most wells are drilled on structural highs. Regional thickness maps based on seismic interpretation show a general thickening of the Upper Cretaceous package from southeast to northwest in the Central Graben system (Britze et al, 1995, Ziegler, 1990, Japsen, 1998). This general observation has an overprint of local east or west depocentres going from north to southeast along the Graben axis (This study). This pattern is confirmed by the study wells also for the Tor Formation alone.

Seismic character:
The Tor Formation seismic package is characterised by well defined continous reflectors in the upper half, while the lower half most often show less distinct reflectors. This difference is most pronounced in the northern part of the study area, where the formation is also the thickest. It is probable, that the lower half is simply better developed to the north and that these deeper layers have a very thin development southeastwards in the basin resulting in more pronounced reflectors. Neither the Base nor the Top Tor boundary are seismically distinct reflectors and would be difficult to pick without well-tie. Onto the Lindesnes Ridge a major part of the Tor package disappears. The 2/7 and 2/8 wells show that the missing part is from top down..

Lithology and Depositional Facies:
15 of the study wells are represented by core in the Tor Formation.

The Tor Formation is in general very clean with a low content of insolubles (<5%). The clean nature of the chalk is reflected in the light colour and the evidence of pressure solution in the form of dental stylolites. Dental stylolites are typical for clean chalk, while the pressure solution in the more dirty chalks appears as horsetails solution seams.

The Tor formation is composed of mixed pelagic and allochthonous chalks. There is a gradual upward increase in the amount of allochthonous material.

The distribution of sedimentary facies is driven by paleotopography, so that what is seen today is the combined result of primary deposition and secondary processes in the form of reworking and diagenesis. Therefore, to understand the depositional facies, the location of the individual wells with respect to regional structural features (basinal axis, margins and inversion ridges) and more local halokinetic structures, is critical.

Biostratigraphic Characterisation:

Biostratigraphically, the Tor Formation encompasses the upper part of nannoplankton Zone UC16 through to Zone UC20 and the two foraminiferid Zones FCS22 and FCS23, both of which have been further divided into subzones as part of the present study.

There is considerable biostratigraphic evidence for intra-formational reworking within the Tor throughout the study region. Several wells contain sections where Late Campanian and Early Maastrichtian Tor sediments have been re-deposited during the Late Maastrichtian. There is also evidence of reworking within the Late Maastrichtian. Despite the frequent presence of stacked allochthonous chalk units within the Tor, the ages of individual units can be ascertained on the basis of the characteristic nannofloral and microfaunal associations.

Many of the well sections examined include very thin and condensed Late Campanian to Early Maastrichtian intervals, suggesting active structural growth during this period. The maximum phase of allochthonous chalk deposition is during the Late Maastrichtian resulting in considerable variation in formation thickness across the region.

Subdivisions:
It has been decided not to propose any formal subdivision of the Tor Formation.

Ekofisk Formation
A schematic diagram illustrating the stratigraphic framework of the Ekofisk Formation is shown in **figure 8**. Note that the diagram is based on well data only, the internal seismic resolution of the Ekofisk Formation does not permit regional subdivision of the unit, and the exact erosional/depositional relationship is uncertain. Also, regional variations exist, and the diagram is not meant to illustrate the exact stratigraphy in a certain area, but just to give an approximate picture of the regional variations from basinal settings to structural highs.

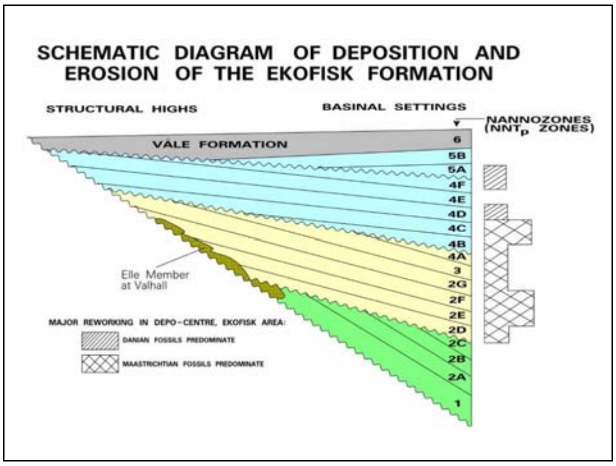

Figure 8: Schematic diagram of deposition and erosion of the Ekofisk Formation

Name: From the Ekofisk field, Norwegian Block 2/4.

Well Type Section: 2/4-5, 3164-3037 m MD (Deegan and Scull, 1977).

Well Reference Sections: 1/3-1, 3354-3257 m MD.
UK 22/1-2A, 2982.5-2935 m MD.
2/5-1, 3132-3041 m MD. (This well was added by Isaksen and Tonstad, 1989).

Age: Danian. Nannoplankton zones NNTp1-NNTp5B.

Lower contact characteristics: The lower contact of the Ekofisk Formation is defined by the distinct stratigraphic unconformity at the Cretaceous-Tertiary boundary over most of the study area. Based on lithology, the recognition of the contact may, especially in the central parts of the Danish sector, be difficult due to low contrast in physical properties between the adjacent formations, as seen for example in the Roar-2 well. In the southern and northern part of the Danish area, the lower section of the Ekofisk Formation is influenced by chert and clay in contrast to the pure chalk of the underlying Tor Formation. Most typical for the contact is, however, the erosional hardground at the top of the Tor Formation (see Chapter 5.4 and well MFB-7.

Recognition from wireline logs is less clear than for the upper contact. In the wells in the Danish sector south of the Rinkøbing-Fyn High, there is no distinct break on the Gamma Ray. The erosional hardground on the top of the Tor formation is reflected by an increase on the density log in most wells. In the Baron-2 well, where the Tor formation is absent, the contact between Ekofisk and Hod is marked by a similar break on the density log.

In the Norwegian sector, in the axial part of the Central Graben the contact is conformable, or with a minor hiatus, such as in the Ekofisk field. The lower contact is often marked by an increase of the Gamma Ray signal into a zone comprising argillaceous chalk in the lowermost Ekofisk Formation, informally known as the Ekofisk tight zone, for example in well 2/4-A-8. In some areas this zone is less well developed, and in wells in the Danish sector south of the Rinkøbing-Fyn high there is no distinct break on the Gamma Ray log.

On the flanks of the Central Graben and on the Lindesnes Ridge the contact is marked by an unconformity, and the lower part of the Ekofisk Formation is generally absent. Here the lower contact is typically marked by a basal hard ground (well 2/2-3). In some places, the Ekofisk Formation is very thin or absent, such as in the Hod and Valhall fields, where the Tor Formation is locally overlain by Paleocene shale.

The contact is in most cases easily recognized from biostratigraphy, although reworking of Maastrichtian fossils into younger deposits occasionally occur.

Upper contact characteristics: The upper contact is characterized by an upward distinct change in lithology from the pure chalk of the Ekofisk Formation to massive layered shale. In some cases, a marl-dominated layer is found in between. In some areas, both in the Danish and the Norwegian sector, there is a gradual transition into the overlying marl, which may make it difficult to pick the exact top (Baron-2).

The upper contact is observed on several of the wireline logs. It is most distinct on the Gamma Ray log, where the contact often is expressed as a very sharp break, which, however, is more gradual when marl is present at the contact. (Compare Baron-2 and MFB-7) The sonic log shows a similar response.

The density log is also showing a clear change as a consequence of the porosity contrast between the adjacent layers. The change on the neutron log is not as distinct as it is modified by the presence/absence of hydrocarbons/water in the pore spaces, but there is usually a distinct break in the neutron-density separation across the boundary (2/4-A-8).

The contact is always recognisable biostratigraphically.

Formation thickness and distribution across study area: The thickness of the Ekofisk Formation varies throughout the study area. In the southern end of the Danish sector, the thickness is some 30 to 40 meters whereas in the central area (Roar-2, Bo-1), the upper part or all of the Ekofisk Formation is absent and the thickness may be reduced significantly, down to a few meters.

Further north, the thickness increases again (61 m, Baron-2) to more than 100 meters in Mona-1 and Lulu-1. Cores from the Ekofisk formation in Lulu-1 show significant influence from turbidites and this may also be the case in Mona-1, which displays a similar log pattern.

The depositional centre for the Ekofisk Formation extends along the axis of the Central Graben from the Mona area past the Ekofisk area, with thicknesses reaching about 170 m (139 m in 2/4-A-8). Major reworking is observed in this depositional centre.

On the east and northeast flank of the Central Graben the Ekofisk Formation thins and is locally absent, as for example in well 2/2-2. On the western flank of the Central Graben, in the border area between the Norwegian and UK sectors, the thickness generally varies between 50 -100 m (e.g. 31/26a-10 and 1/9-1), reflecting an environment dominated primarily by pelagic deposition and debris flows.

Due to inversion along the Lindesnes Ridge the Ekofisk Formation thins rapidly onto the ridge and is locally absent in the Hod and Valhall fields.

Lithology, main depositional facies and environment: In general, the lowermost part (Nannofossil zones NNTp1 and NNTp2B/C) of the Ekofisk Formation is absent from the study wells in the Danish sector. This may reflect the erosion on the Tor-Ekofisk boundary continuing into the Danian. Indications of occurrence of the oldest zone (NNTp1) are reported from Lulu-1. The environment of the Ekofisk Formation in the southern part of the Danish sector is dominated by pelagic deposition of a laminated, bioturbated mudstone (MFB-7). The lower parts are often argillaceous and chert bearing. Only minor reworking of mainly Late Maastrichtian species occurs. The pelagic strata are occasionally interrupted by debris flows, in several cases marking the contact between adjacent biozones.

In the central part of the Danish sector a similar environment is found (Roar-2). However, slumps are more common compared to the southern part. In addition, the youngest part of the formation is absent. The chalk is less argillaceous and chert is rare. Continuing northwards, slumps and turbidites dominate the lower part of the Ekofisk Formation in Baron-2, whereas the upper part is dominantly pelagic laminated, bioturbated mudstone. Like in Roar-2, the youngest part of the formation is absent.

Approaching the Norwegian sector, the thickest and stratigraphically most complete Ekofisk succession in the Danish sector is found in Lulu-1. The coring of the Ekofisk Formation is, however, incomplete in this well such that the cores cover the upper and lower part but the central part (approximately 34 m) is uncored. Lulu-1 is the only of the Danish study wells where the oldest nannofossil biozone (NNTp1) is observed. The lowest part of the section is dominated by an argillaceous massive to laminated chalk mudstone. The argillaceous content shows a cyclic variation but generally the density of clay seams increase upward. The section is dominantly pelagic and slumps are rare, mainly occurring in the deepest part. The section above is dominated by massive pelagic mudstone. Clay is less common than below but stylolites are numerous. Slumps are rare and mainly present toward the top of the lower part of the cored sections. The section uncored in Lulu-1 is known from offset wells to be dominated by reworked chalk. The base of the upper part of the cored sections is dominated by pelagic massive chalk mudstones and wackestones. To the top of nannofossil biozone NNTp4D, slumps and debris flows dominate and reworked chalk thus forms a significant part of this section. In the uppermost part, white pelagic chalk becomes dominant, represented by nannofossil biozone NNTp5B. This late Danian biozone is only found in Lulu-1 and in MFB-7 in the southernmost part of the Danish sector.

The most complete Ekofisk Formation is found in the Ekofisk field area in the Norwegian sector. The lowermost part is generally formed by argillaceous, pelagic chalk belonging to nannofossil biozone NNTp1 and the lower part of NNTp2, up to NNTp2D/E (2/4-A-8). In the upper part of this “Ekofisk tight zone” some reworked layers may occur. Upwards the section is dominated by a thick, heavily reworked unit comprising predominantly Maastrichtian fossils. Dating is problematic due to the extensive reworking, but the zone seems to correspond mainly to the upper part of NNTp2 and the lower part of NNTp4. The unit consists mainly of massive, homogenous chalk and pebble floatstone interpreted as slides, slumps and debris flows, occasionally with thin pelagic layers in between. The upper part of the Ekofisk Formation is also variably reworked, but less extensively than the lower part, and generally consists of slumped, deformed chalk and debris flows with interbeds of pelagic chalk. Reworking took place especially within zone NNTp4D, but also in the uppermost part of zone NNTp4 and during NNTp5A. The uppermost part, belonging to zone NNTp5B is predominantly pelagic and grades into the overlying marl of the Våle Formation, with no sharp transition.

The source area for the reworked zones is believed to be mainly the Lindesnes Ridge to the southwest, but also with some contribution from the east and northeast. Further away from the Lindesnes Ridge, in Block 2/5, the reworking seems to be less penetrative, and the Ekofisk Formation is dominated by interbedded pelagic chalk and thin turbidites with occasional thicker debris flows (Well 2/5-1).

In the Valhall Field on the Lindesnes Ridge, the Maastrichtian chalk was reworked through shallow-water shoaling and winnowing across the central crest, feeding coarser-grained debris flows down the flank (Elle Member; Bergen and Sikora, 1999). This reworked unit seems to correlate at least in part to the lower reworked Maastrichtian deposits at the Ekofisk Field. A major flooding event at about 63 Ma BP terminated the reworking at Valhall, and younger Danian chalk is a highly condensed, stratigraphically discontinous, deep-water autochthonous deposit (Sikora et al., 1999).

On the flanks of the Norwegian part of the Central Graben, as well as in the wells from the UK sector, the lower part of the Ekofisk Formation is generally absent. Pelagic chalk with thin turbidites dominate, with occasional thicker reworked zones (i.e. 30/7a-2).

In summary, the Ekofisk Formation comprises a highly varied range of deposits, with pelagic chalk dominating in the southern and western part of the study area, but in the area around the Ekofisk field, where the thickest and most complete section is found, reworked chalk dominates. The main stratigraphic breaks appear at the base and top of the formation.

Seismic characteristics: On the type of seismic sections used in this study Top Chalk is recognised as a clear seismic trough resulting from an increase in acoustic impedance (SEG reverse polarity standard). In areas where there is a gradual transition from the Ekofisk Formation to the overlying marls the top may be difficult to pick exactly. Presence of hydrocarbons or excessive high formation porosity may result in deviations from the normally expected seismic appearance with the top of the chalk formation show dimming or even phase reversal of the seismic signal.

Where thick enough to be resolved, the internal seismic character of the Ekofisk Formation tends to be chaotic, and internal units can only be interpreted locally.

Biostratigraphic characteristics: All study wells with cores from the Ekofisk formation have been analysed to identify diagnostic nannofossil assemblages. In the present study, some 17 nannofossil zones have been identified. In the wells in the Danish sector up to seven of these were found in individual wells and four were not observed at all. As core coverage is incomplete, these are minimum numbers. However, the stratigraphic breaks seem to occur at some distinct levels, namely the lowermost zones NNTp1 to NNTp2C/D, the intermediate zones NNTp4A/B/C and the upper zones NNTp4E/F and NNTp5A/B. These zones are either sparsely represented or absent.

The wells in the southernmost part of the Danish sector (MFB-7 and M-9X) are showing the largest diversity in terms of biozones present. This is in agreement with the dominantly pelagic depositional environment as interpreted from the cores. Although the interval is cored, the oldest zones have not been identified in these wells. This may be due to absence or condensing of the zones. Also, in these wells, reworking of fossils of Maastrichtian age is observed, even in the shallowest samples. The wells in the central part of the Danish sector (Roar-2 and Baron-2) show a pattern similar to the southern part except that the upper biozones are absent. This follows generally the observations from logs.

Although the number of biozones present is low, the formation is relatively thick (30-60 m). This is at least partly caused by significant reworking of older strata especially in the lowest Ekofisk, where Maastrichtian fossils dominate. Reworking is observed continuously upwards through the formation and fossils as old as Campanian are found. The occurrence of such old fossils at this level is linked to the Tor formation being thin or absent in this area.

The thickest Ekofisk section in the Danish sector is found in the Lulu-1 and Mona-1 wells. Nevertheless, reworking seems, in the studied cores, to be insignificant. Some reworking is found in the upper part of the formation and, as mentioned above, the uncored central section is known to be dominated by reworked chalk. Note, however, that the same biozone (NNTp4D) is observed immediately below and above the uncored section. This biozone is more than 65 m thick in Lulu-1. The same zone is respectively 0 and 20 m in the central wells Roar-2 and Baron-2. It is the youngest zone in the Ekofisk Formation found in these wells, which may be due to erosion of the younger zones. However, in the pelagic-dominated MFB-7, the zone is 12 m thick. The Lulu-1 deposits are therefore likely to represent a combination of *in situ* deposits and a significant volume of redeposited (older) sediments.

In the Norwegian sector, a fairly complete stratigraphic section is found in the axial part of the Central Graben, where all 17 nannofossil zones have been identified. Up to approximately ten zones have been found in individual wells. The stratigraphic breaks that were noted in the Danish wells mentioned above can also be observed in the Norwegian wells, although somewhat shifted in position. In the depocentre in the Ekofisk area, deposition took place resulting from erosion further south, associated with some of the above mentioned stratigraphic breaks, but also here biostratigraphic breaks can be observed in individual wells.

Zone NNTp1 has been found in some wells in the axial part of the Central Graben. Zones 2A-2C is sparsely represented in the data, even in the depocentre. A significant erosional episode took place within zone NNTp2, eroding into the Maastrichtian deposits on the Lindesnes Ridge and depositing a thick reworked unit in the basin, particularly during zones 2E-F. A thin Danian unit comprising mainly reworked Maastrichtian chalk has also been described at the Valhall Field (Bergen and Sikora, 1999). The datings correspond approximately to zones NNTp1 and at least part of zone 2, and the unit probably represents the erosional remains left behind on the ridge. Zones NNTp2G/3/4A are again less frequently represented in the data, and the amount of erosional deposits is less marked. These zones, in particular zone 3, are more common in the more pelagically-dominated Danish wells. A flooding event took place on the Lindesnes Ridge at about this time, and the younger Danian chalk is represented by a thin, condensed deep-water section (Sikora et al., 1999). A new significant erosional/depositional pulse of Maastrichtian material seems to have taken place within zones NNTp4B-4C. In the wells from the areas flanking the depositional centre, both on the Norwegian and the UK sector, most of the section up through the lower part of zone NNTp4 is missing (2/2-3).

A change in deposition can be seen in the Ekofisk area in the middle part of zone NNTp4, approximately zone 4D, when there is a marked reduction in reworking, and especially in influx of Maastrichtian material. This is associated with a more widespread deposition of the Ekofisk Formation over the structurally high areas, with less erosion of the underlying Tor Formation. Significant slumping and debris flow continued, however, although less than in the section below.

Higher up in the section, pelagic deposits are more dominating, but a new episode with reworking occurred in the upper part of zone NNTp4 and lower part of zone NNTp5 (NNTp4E/F-5A), approximately coinciding with a stratigraphic break observed both in the Danish and Norwegian/UK wells**.**

Zone NNTp5B is widespread in the Norwegian study area, but has not been identified in the UK wells. It is dominated by pelagic deposits, with a gradational transition into the overlying marls.

Subdivision: In this project it was decided that no subdivisiun of the Ekofisk Formation will be performed, implying that each company continues their own nomenclature for zonation.

Late Paleocene chalk units: Vidar Formation

Reworked chalks of Early Paleocene to Late Cretaceous age are observed in the late Paleocene section. Chalk beds varying from only a few cm thick and up to beds of 70 metres thick are common. Only one formation has been named, the Vidar Formation.

Name: Vidar was a son of the Norse god Odin.

Well type section: Norwegian well 2/1-4 from 3138 to 3075 m. No cores.

Well reference section: Norwegian well 1/3-1 from 3147 to 3095 m. No cores.

Lower Boundary Characteristics: The lower boundary represents a sharp transition from the claystone of the Lista Formation or the marl of the Våle Formation to the overlying limestones of the Vidar Formation. This is marked by a distinct decrease in gamma-ray readings and an increase in velocity.

Upper Boundary Characteristics: The upper boundary represents a transition to the claystones of the Lista Formation, characterised by a dramatic increase in gamma-ray readings and a decrease in velocity. The upper boundary can be picked seismically.

Thickness and distribution throughout Study Area: The thickness varies from less than a few m to about 70 m in the study area. Where the Vidar Formation is well developed, it is easily identified on the seismic lines, as strong reflections with poor continuity, indicating an increase in acoustic impedance. Based on the seismic interpretation, the Vidar Formation is restricted to the northern part of the Central Graben, and it is found in the following of the studied wells: 1/3-1, 1/3-8, 2/2-3 and 2/5-7.

Lithology, main Depositional Facies and Environments: Homogeneous limestone is the dominant lithology. Thin shales occur within the chalk beds. The chalk beds of the Vidar Formation may occur at different levels in the Lista Formation. Presence of reworked chalk of early Palaeocene and late Cretaceous age indicates that the Vidar

Formation Chalk originates from the Shetland Group. Mass flows from each side of the Central Graben are the most probable transport mechanism for this reworked unit.

Biostratigraphic Characterisation: All chalks of the Vidar formation are reworked Danian or Late Cretaceous of age.

Age: Late Paleocene, consisting of reworked chalk mainly of Danian and Maastrichtian age.

DISCUSSION

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