STRATIGRAPHIC GUIDE TO THE CROMER KNOLL, SHETLAND AND CHALK GROUPS OF THE NORTH SEA AND NORWEGIAN SEA

Editors and Contributors: Felix M. Gradstein and Colin N. Waters

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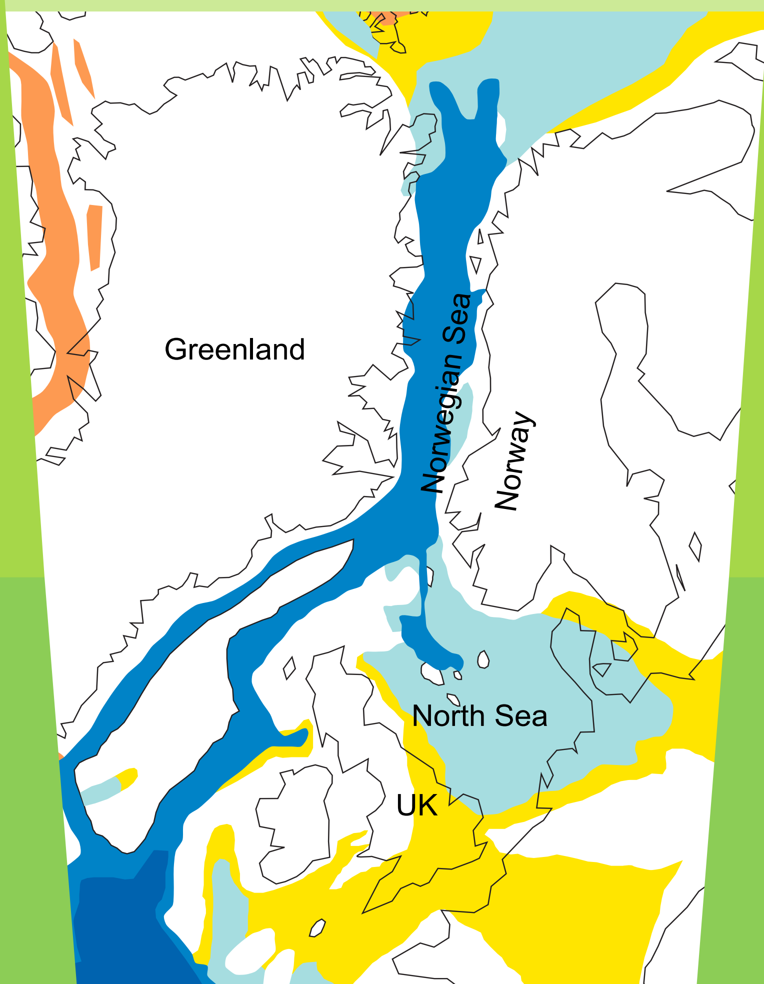
Central North Sea

Chalk Group

- Ekofisk Fm
- Tor Fm
- Mackerel Fm
- Herring Fm
- Hidra Fm

Cromer Knoll Group

- Rødby Fm
- Carrack Fm
- Valhall Fm



Norwegian Sea

Shetland Group

- Springar Fm
- Nise Fm
- Kvitnos Fm
- Blålange Fm

Cromer Knoll Group

- Langebarn Fm
- Lyr Fm

Natural History Museum
University of Oslo

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Norway

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Stratigraphic Guide to the Cromer Knoll, Shetland and Chalk Groups, North Sea and Norwegian Sea

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With 67 figures, 79 photographs, 11 tables and 1 plate

Abstract. This guide provides a major revision and update of the stratigraphy of the Cromer Knoll, Shetland and Chalk Groups for the UK and Norwegian sectors in the North Sea, and of the Cromer Knoll and Shetland Groups in the Norwegian Sea. The first chapters deal with the paleoceanographic and geologic settings and updated biostratigraphy, followed by the chapters with the new and improved lithostratigraphy.

The Cretaceous biostratigraphy calculated for the microfossil record in 37 Norwegian wells integrates over 100 foraminifer, dinoflagellate cyst, diatom and miscellaneous events in nineteen zones, numbered from NCF1 through NCF19 (North Sea Cretaceous Micro Fossil Zones 1 – 19). A literature based Dinoflagellate Cyst Zonation (DCZ), linked to the NCF zones, is also presented with eleven zones and thirty-nine subzones for Cretaceous marine strata in the North Sea. Both zonations are optimized for industrial applications with ditch cuttings samples.

The lithostratigraphy of the North Sea, unified for the UK and Norwegian sectors describes 3 groups, 30 formation units and one member. The Cretaceous lithostratigraphy for the Norwegian Sea describes 2 groups, 17 formations and 14 members.

This (long overdue) update alleviates misnaming and incidental use of unique names for reservoir units, without documentation and lack of biostratigraphic and correlative insight. The internet site *www.nhm2.uio.no/norlex* provides core archives for the lithostratigraphic units.

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1. Introduction and Geological Transects

Introduction

This study presents the first systematic review of Cretaceous lithostratigraphic units of the Norwegian North Sea and Norwegian Sea since 1988. The pioneering studies of the North Sea (Isaksen and Tonstad, eds. 1989), Norwegian and Barents Sea (Dalland *et al.*, 1988) have served the offshore petroleum industry for the past 25 years. These volumes proposed a conventional lithostratigraphic framework for the interpretation of the offshore Cretaceous sediments, but are outdated, being created from a limited well- and seismic database.

In addition, this study for the first time brings together from many sources the definitions and descriptions of Cretaceous lithostratigraphic groups and formations in the UK sector of the North Sea. These units are largely conjugate to their 'brothers and sisters' in the Norwegian North Sea sector. Thus, this volume simplifies the use of offshore Cretaceous lithostratigraphic units across political borders. This is in agreement with the request from supporting oil companies and the Norwegian Petroleum Directorate, going back to day one of the 'Norlex Project', under which the current study was conceived and executed.

The lithostratigraphy of the North Sea, unified for the UK and Norwegian sectors describes 3 groups, 30 formation units and one member. The UK offshore sector uses 18 of these formations and the Norwegian sector 17. The Cretaceous lithostratigraphy for the Norwegian Sea describes 2 groups, 17 formations and 14 members. The group subdivisions are shown in Table 1.1.

This present study formally describes 15 newly discovered lithostratigraphic bodies, surrounded and, or intertwined with massive shale units, both for the Norwegian Sea and the North Sea regions. In agreement with the standard international stratigraphic code these 15 units are assigned Member status. To quote the formal lithostratigraphic code: A Member is the formal lithostratigraphic unit next in rank below a formation. It represents a part of a Formation possessing distinctive lithostratigraphic features distinguishing it from the remainder of the Formation. Creating Members avoids the classification problem (also encountered on the NPD 'Facta Siden') of creating formations *within* formation. The latter violates the International Stratigraphic Code.

For the Cromer Knoll Group in the UK North Sea we describe the Valhall Formation, the Spilsby Sandstone Formation, the Wick Sandstone Formation, the Britannia Sandstone Formation and the Carrack Formation. For the Cromer Knoll Group in the Viking Graben, North Sea we describe the Rødby Formation and Agat Formations (updated definition), the Sola Formation with the Ran Member (new), the Mime Formation and the Åsgard Formation. For the Cromer Knoll Group of the Central Graben we describe from younger to older the Rødby Formation, the Sola Formation, the Tuxen Formation and the Asgård Formation.

The Chalk Group in the UK sector of the North Sea comprises the Hidra Formation, Svarte Formation, Herring Formation, Lamplugh Formation, Jukes Formation, Rowe Formation, Tor Formation and Ekofisk Formation. All units may be correlated with distinct biostratigraphic markers. For the Chalk Group of the Central Graben, North Sea we describe from younger to older the Ekofisk Formation, the Magne Formation (formely part of the Hod Formation), the Thud Formation (formerly part of the Hod Formation), the Narve Formation (formely part of the Hod Formation), the Blodøks Formation and the Hidra Formation.

For the Shetland Group in the UK sector of the North Sea descriptions are presented of the Macbeth Formation and the Flounder Formation. From younger to older we describe for the Shetland Group of the North Sea of the Norwegian sector (south Viking Graben) the Hardråde and Jorsalfare Formations, the Kyrre Formation, the Tryggvason Formation, the Blodøks Formation and the Svarte Formation.

From younger to older we describe for the Shetland Group (with a re-defined base) in the Norwegian Sea:

Springar Formation with Hvithval and Grindhval Members; Nise Formation with Spekkhogger and Nebbhval Members; Kvitnos Formation with Tumler and Kvitskjaeving Members and Blålange Formation (previously Upper Lange Fm) with Lysing Member (previously Lysing Formation), Tunge Member, Skolest Member, Breiflabb Member, Skrubbe Member, Sandflyndre Member and Gapeflyndre Member. For the Cromer Knoll Group (with a redefined top) in the Norwegian Sea we describe the Langebam Formation (previously Lower Lange Formation).

All new units, as far as possible, have updated colour graphics of the stratigraphy in the type-, and or reference wells, and updated well log signatures.

Regional Cretaceous subsurface lithostratigraphy to an extent depends on knowing the age of rock units, and in that sense is not an independent descriptor. Operational stratigraphers regularly use Cretaceous lithostratigraphic terms in an essentially chronostratigraphic fashion. The latter is not surprising, given the common presence in the northern North Sea and Norwegian Sea of relatively monotonous mudstone facies. Although sediments may stand out on physical well logs, biostratigraphy is an essential tool to lithostratigraphy when drilling, and when attempting well correlations at higher level of resolution. Hence, an important part of this study details the operational biostratigraphy, using multiple microfossil groups.

North Sea, Norwegian Sea and Barents Sea Lithostratigraphy at the Group level

Standard Chronostratigraphy: Ma	Ep.	Age/Stage	Base (Ma)	Southern North Sea (Revised)	Northern North Sea	Norwegian Sea (Revised)	Barents Sea
50, 55	Eocene	Ypresian	56.0				
	Paleocene	Thanetian	59.2	Rogaland Group	Rogaland Group	Rogaland Group	Sotbakken Group
60		Selandian	61.6				
65		Danian	66.0				
70	Late Cretaceous	Maastrichtian	72.1	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
75, 80		Campanian	83.6				
85		Santonian	86.3				
90		Coniacian	89.8				
		Turonian	93.9				
95, 100		Cenomanian	100.5				
105, 110	Early Cretaceous	Albian	113.0	Cromer Knoll Group	(Revised) Cromer Knoll Group	Cromer Knoll Group	Adventdalen Group
115, 120, 125		Aptian	126.3				
130		Barremian	130.8				
		Hauterivian	133.9				
135		Valanginian	139.4				
140		Berriasian	145.0				Note: no boundary
145, 150	Late Jurassic	Tithonian	152.1	Viking Group	Viking Group	Viking Group	

Table 1.1 Upper Jurassic, Lower and Upper Cretaceous and Paleocene Lithostratigraphy at the Group level.

Geological Transects

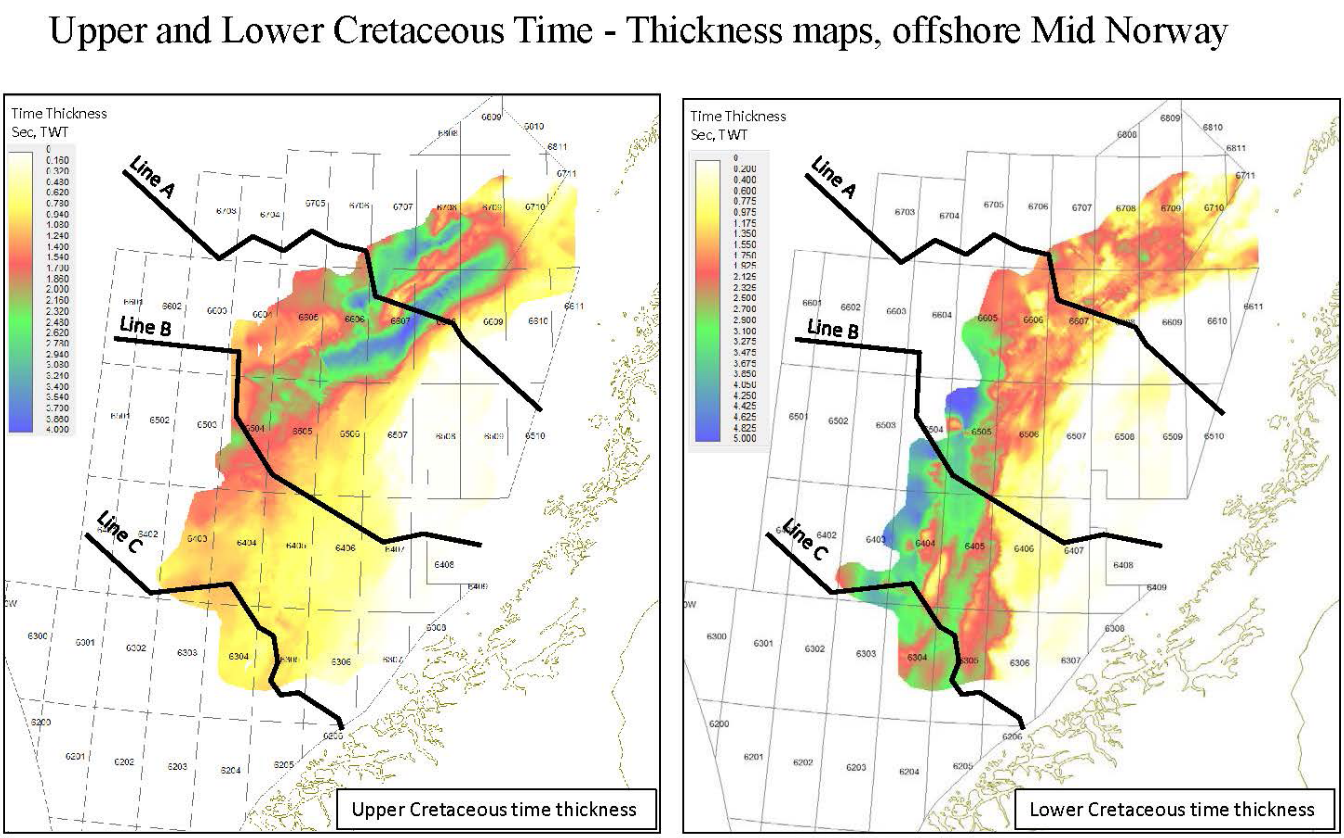
The massive sedimentary wedge that forms the continental margin off mid Norway, approximately from 62^0 to 67^0 North shows well-defined, group, formation and member packages visualized in two-way travel time figures. Geographic 'base' maps of Figures 1.1a and 1.1b show transects locations.

Figure 1.1a also provides Upper Cretaceous (to the left) and Lower Cretaceous (to the right) Time-Thicknesses, offshore Mid Norway. Figure 1.1b renders Upper Cretaceous time-depth (to the left) and Lower Cretaceous time-depth. The base maps clearly show depocentres outlined.

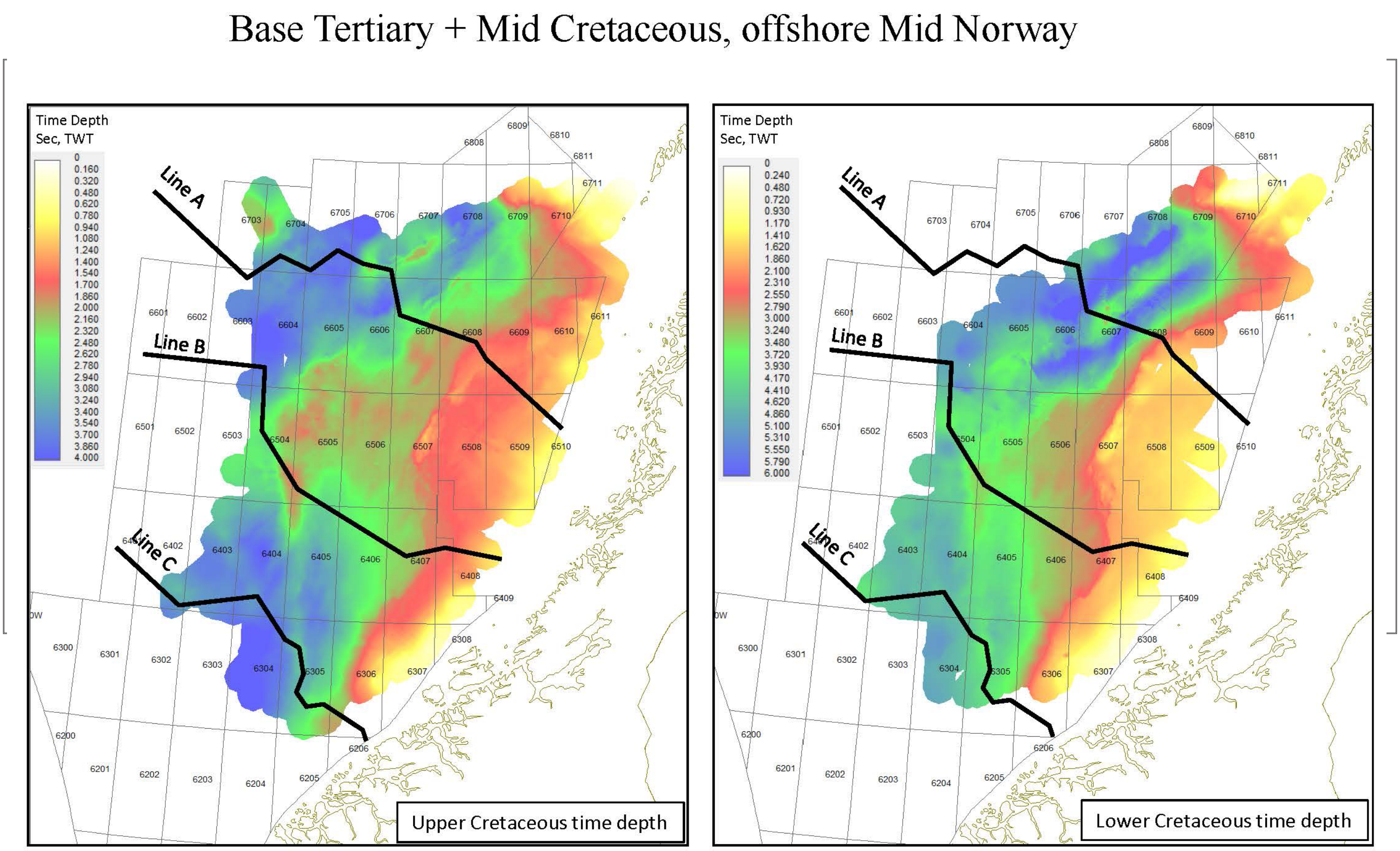
Figure 1.1c is a southeast to northwest mega transect from the Helgeland Basin through the Vøring Basin and to the Vøring Marginal High. This high uplifted prior to continental break-up around the Paleocene-Eocene transition at 55 Ma, and prior to marine magnetic anomaly C24 (see next Chapter). On this two-ways travel-time transect the BCU, top Cromer Knoll, Spekkhogger , Nise and base Paleogene are assigned.

Figure 1.1d is a southeast to northwest mega transect, a bit further south from the Halten Terrace again to the Vøring marginal High. The same units and seismic horizons are indicated.

Figure 1.1e is the southeast to northwest mega transect that runs from the Gossa High through the Møre Basin on to the Møre Marginal High. BCU level, top Cromer knoll, Spekkhogger and base Paleogene are assigned on this two- ways travel-time transect.



Figures 1.1a. Geographic 'base' maps showing the Figures 1.1a, b and c transects locations. Figure 1.1d also provides Upper Cretaceous (to the left) and Lower Cretaceous (to the right) Time-Thicknesses, offshore Mid Norway. Figure 1.1e renders Upper Cretaceous time-depth (to the left) and Lower Cretaceous time-depth. The base maps cleary outline depocentres.



Figures 1.1b. Geographic 'base' maps showing the Figures 1.1a, b and c transects locations. Figure 1.1d also provides Upper Cretaceous (to the left) and Lower Cretaceous (to the right) Time-Thicknesses, offshore Mid Norway. Figure 1.1e renders Upper Cretaceous time-depth (to the left) and Lower Cretaceous time-depth. The base maps cleary outline depocentres.

Line A

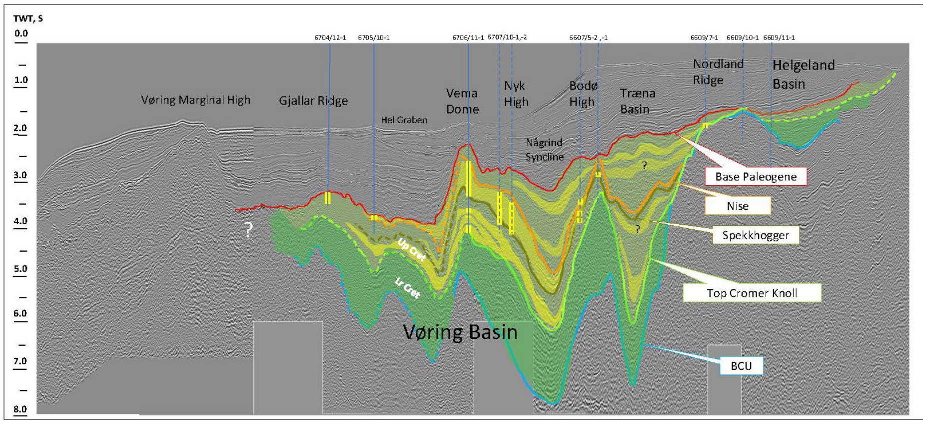


Figure 1.1c. Southeast to northwest two-way travel time transect from the Helgeland Basin through the Vøring Basin and to the Vøring Marginal High. BCU, top Cromer Knoll, Spekkhogger , Nise and base Paleogene are assigned.

Line B

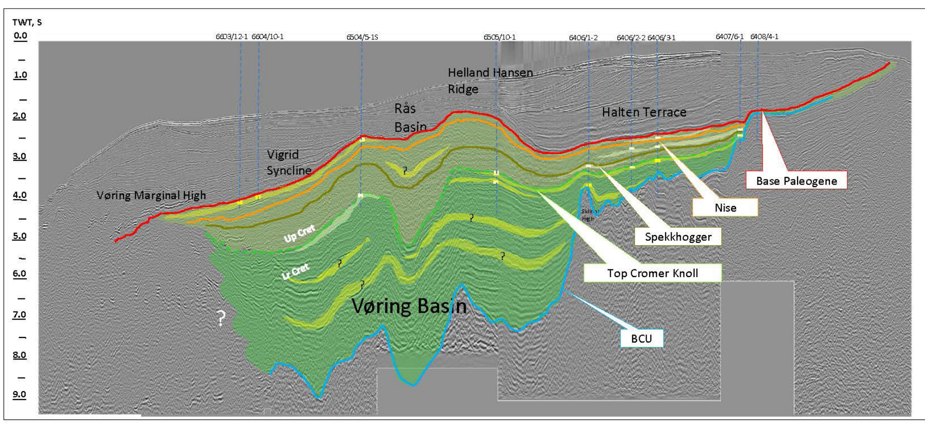


Figure 1.1d. Southeast to northwest two-way travel time transect from the Halten Terrace again to the Vøring marginal High. The same units and seismic horizons are indicated as in Figure 1.1a.

Line C

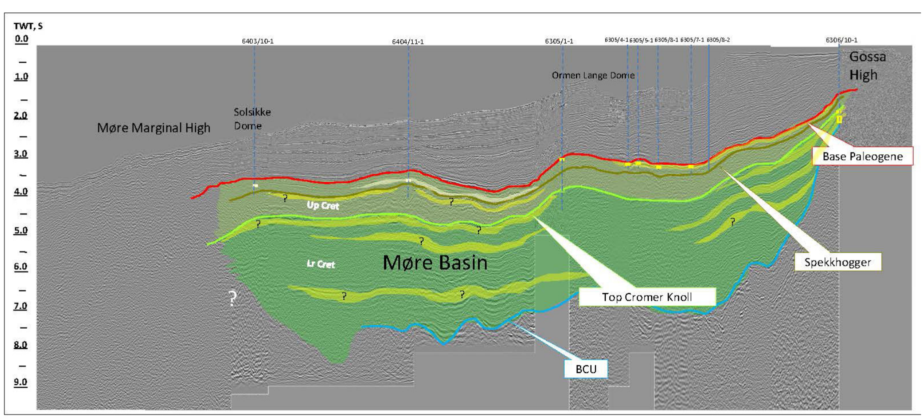


Figure 1.1e. Southeast to northwest transect in two-way travel time from the Gossa High through the Møre Basin on to the Møre Marginal High. BCU level, top Cromer knoll, Spekkhogger and base Paleogene are assigned.

2. Paleoceanography and Biostratigraphy

Paleoceanography

The Norwegian-Greenland Sea is the marine connection between the Atlantic and Arctic realms. It experienced several episodes of extensional (rifting) tectonics, grouped in late Paleozoic, late Jurassic-early Cretaceous and late Cretaceous-Paleocene phases. The latter phase of extensional tectonics finally led to Norway-Greenland continental break-up and onset of seafloor spreading at around 55 Ma. Figure 2.1 depicts the plate tectonic reconstruction and outline of structural elements of the NE Atlantic to the time of breakup (ca. 55 Ma) between Greenland and Norway, modified from Faleide *et al.,* (2010) and Tsikalas *et al.* (2012). The reconstruction provides a good sketch of the paleogeographic space occupied by the Norwegian-Greenland seaways between the North Atlantic Ocean/ North Sea and Barents Sea.

A schematic Cretaceous paleogeographic reconstruction of the North Sea and Norwegian - Greenland Sea is shown in Figure 2.2 (after Gradstein *et al.*, 1999; see also Ren *et al.*, 2003). To the left is the late Neocomian (late Hauterivian – Barremian) reconstruction, and to the right the middle Cretaceous one (approximately Cenomanian). Marine facies types are derived from micropaleontology studies and sedimentation trends.

Deep marine connections into the Barents Sea are uncertain, but Seetoyama *et al.* (2011), using micropaleontologic criteria indicates deeper bathyal, mesotrophic watermass conditions during Late Cretaceous time locally in the southwestern Barents Sea. Here, shallowing took place prior to the late Maastrichtian and early Paleocene regional uplift. This uplift is also experienced on the outer Vøring Plateau, prior to continental break-up around the Paleocene-Eocene transition (prior to Chron 24 time; Ren *et al.*, 2003; Olesen *et al.*, 2007).

Mutterlose *et al.* (2003) studying slim-line cores in IKU boreholes in the Norwegian Sea also concluded that marine connections existed from Late Jurassic into Early Cretaceous time. No biozonation was presented for this time interval, but observations on boreal nannofossils support the presence of of shallow marine Tithonian through Hauterivian strata. No study was made of the widespread basal Cretaceous hiatus in wells.

Regional highs shown on Figure 2.2 in the proto Norwegian Sea are uncertain. From Hauterivian through Cenomanian time, transgression progressed in the seaways and in the circum North Sea, in step with major (first order) global sealevel rise. Particularly since middle Albian time the Bohemian Massif and other German landmasses flooded, while land adjacent sand wedges shrank. The widespread flooding, probably combined with local fault tectonics, enhanced graben formation offshore Norway, and increased sand (reservoir) accommodation space. There are no indications for deep water connections (middle to upper bathyal) in Aptian–Cenomanian time through an easterly passage via Germany towards the Polish Carpathian Trough. Ongoing transgression during Cenomanian–Turonian time removed a wide rim of Early Cretaceous siliciclasts (yellow coloured sand-prone wedges) around the NW German Basin (J. Mutterlose, pers. comm., 1998).

The following statement is quoted verbatim from Larson *et al.* (1993), as it helps to place the Cretaceous seaway between Norway and Greenland in a wider paleoceanographic context: "The mid-Cretaceous was a time of greenhouse climates, featuring reduced temperature gradients from the equator to the poles, general absence of polar ice caps, and oceans at least 13^{0}C warmer than the present one. Oceans were elevated to extremely high-stands of sea levels, and were more susceptible to development of oxygen deficits, expressed in various ways. Not only were dark shales more widespread, but specific 'anoxic events' were recorded by condensed oil-shale sequences in widely separated parts of the world, linked by global isotope anomalies. Conditions were particularly favourable for petroleum generation: more than half of our present petroleum reserves appear to have been generated during this episode, which includes Aptian time, and

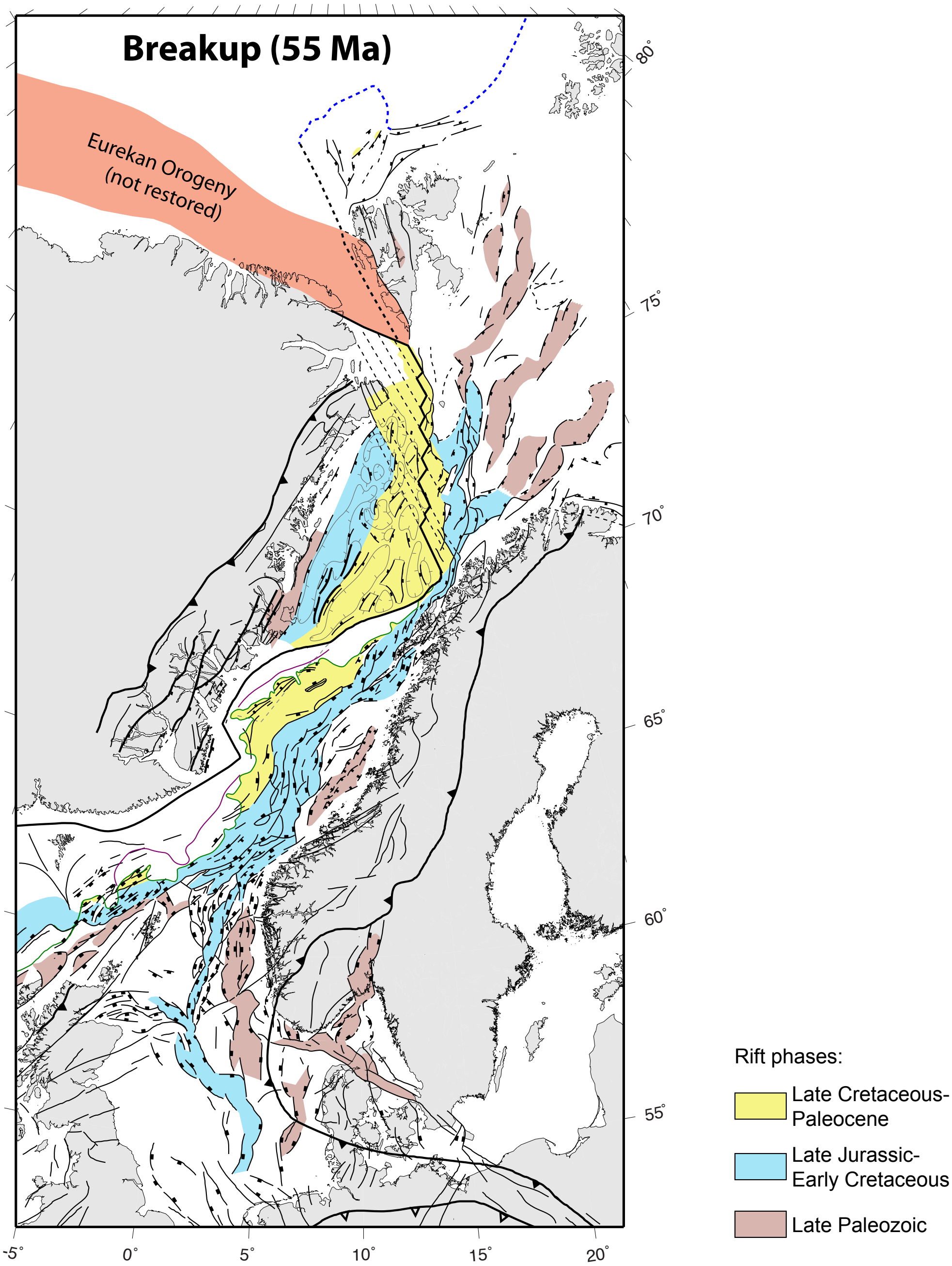
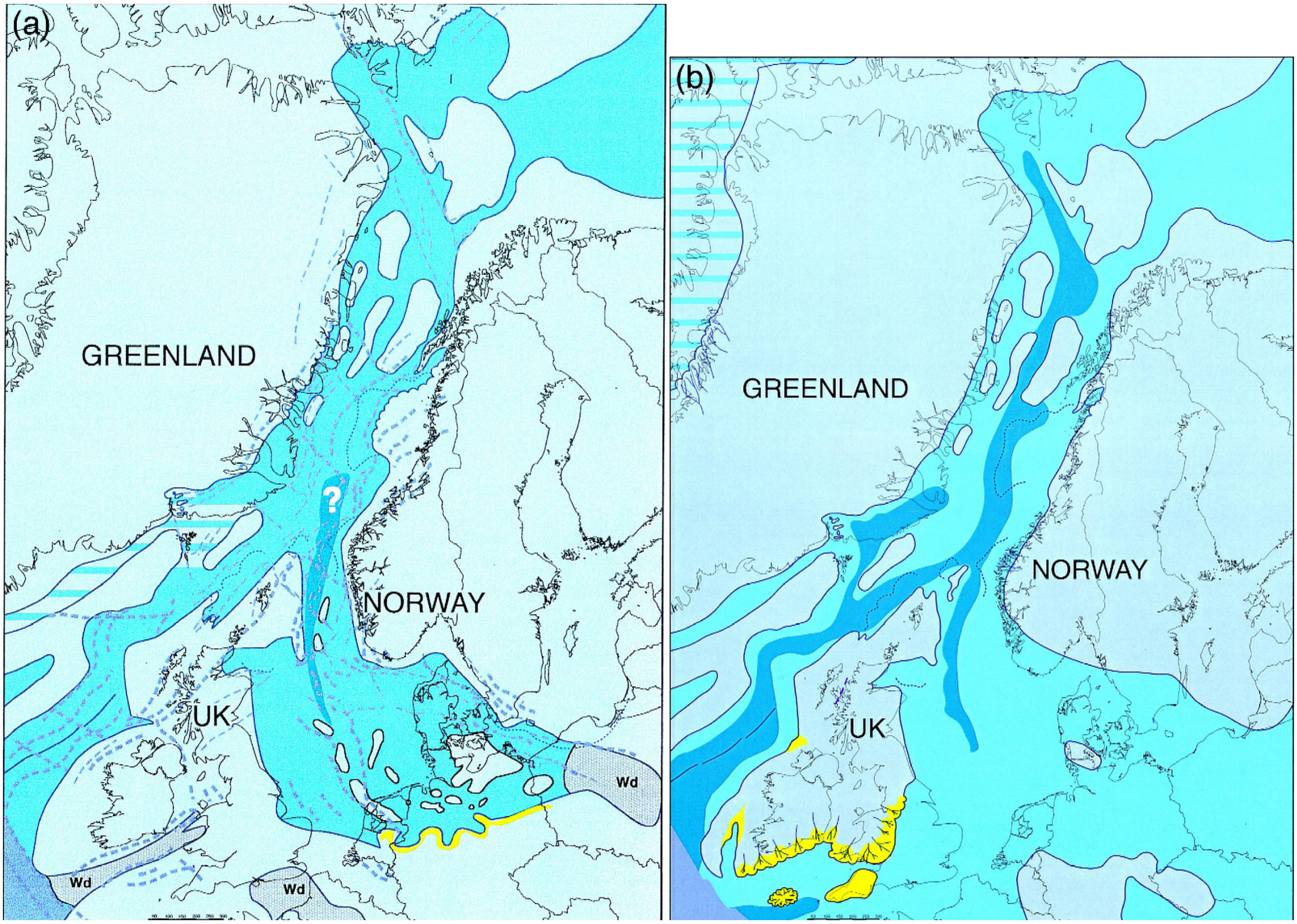


Figure 2.1. Plate tectonic reconstruction and outline of structural elements of the NE Atlantic to the time of breakup (ca. 55 Ma), (modified from Faleide *et al.*,2010 and Tsikalas *et al.*, 2012).

peaked either in the Albian, as generally believed, or in the Cenomanian. Bauxites and laterites were widespread, testifying not only to tropical climates, but also to widespread, tectonically driven uplifts and emergences."

Although the equitable climate hypothesis in Cretaceous time is under active discussion, there is abundant evidence for global anoxic events and high sealevels (Simmons, 2012). The deposition of dark shales, relatively updip, in sub-basins along the southwestern and western margins offshore Norway, clearly is related to widespread transgression along the continental margins during the high stands of mid-Cretaceous sea levels, sluggish water-mass circulation and run-off high in organics.

Whereas the extreme high-stand of Cretaceous global sealevel may be explained from volumetric changes in the oceans due to out-pouring of giant LIP's (Large Igneous Provinces), there is a growing body of evidence to support the higher-order sealevel changes in Cretaceous to be influenced directly by significant changes in polar ice volumes (Simmons, 2012). Hence, local correlation, offshore Norway may benefit from well documented sea-level changes like the Late Aptian long-lived glacio-eustatic lowstand recorded on the Arabian Plate (Maurer *et al.*, 2013).



Figures 2.2a,b. Schematic paleogeographic reconstruction of North Atlantic and Norwegian Sea in late Neocomian (late Hauterivian- Barremian) and in middle Cretaceous (approximately Cenomanian) time, showing the deep marine, bathyal passage (in dark blue) between Norway and Greenland. Purple = oceanic, abyssal (south of the Charlie Gibbs fracture zone), dark blue = middle to upper bathyal, lighter blue = marine, neritic, gray = land; Wd refers to the marginal marine Wealden facies; circum Norwegian Sea siliciclast (sand) facies is not shown. Deep marine connections into the Barents Sea are uncertain, as are various highs shown in the proto Norwegian Sea. From Barremian through Cenomanian time, transgressions progressed, and particularly since middle Albian time flooded the Bohemian Massif and other German landmasses, while land adjacent sand wedges shrank. The widespread flooding probably combined with fault tectonics enhanced graben formation offshore Norway, increasing sand accomodation space. There are no indications for deep water connections (middle to upper bathyal) in Aptian- Cenomanian time through an easterly passage via Germany towards the Polish Carpathian Trough. Ongoing transgression during Cenomanian - Turonian time removed a wide rim of Early Cretaceous siliciclasts (yellow coloured sand-prone wedges) around the NW German Basin.

Cretaceous Geologic Time Scale

There is no standard Norwegian Cretaceous biostratigraphic zonation. This is surprising in the face of well established zonations using microfossil groups suitable for Nordic offshore wells in the UK sector of the North Sea and applicable further north. Linkage of local deposits is largely achieved with reference to biostratigraphic studies in other countries of NW Europe. Hence, there are problems in interpreting most of the stages offshore Norway. In this study no attempt has been made to create a (multi order) correlation linkage to Cretaceous stage stratotypes, all of which are in the Tethyan realm.

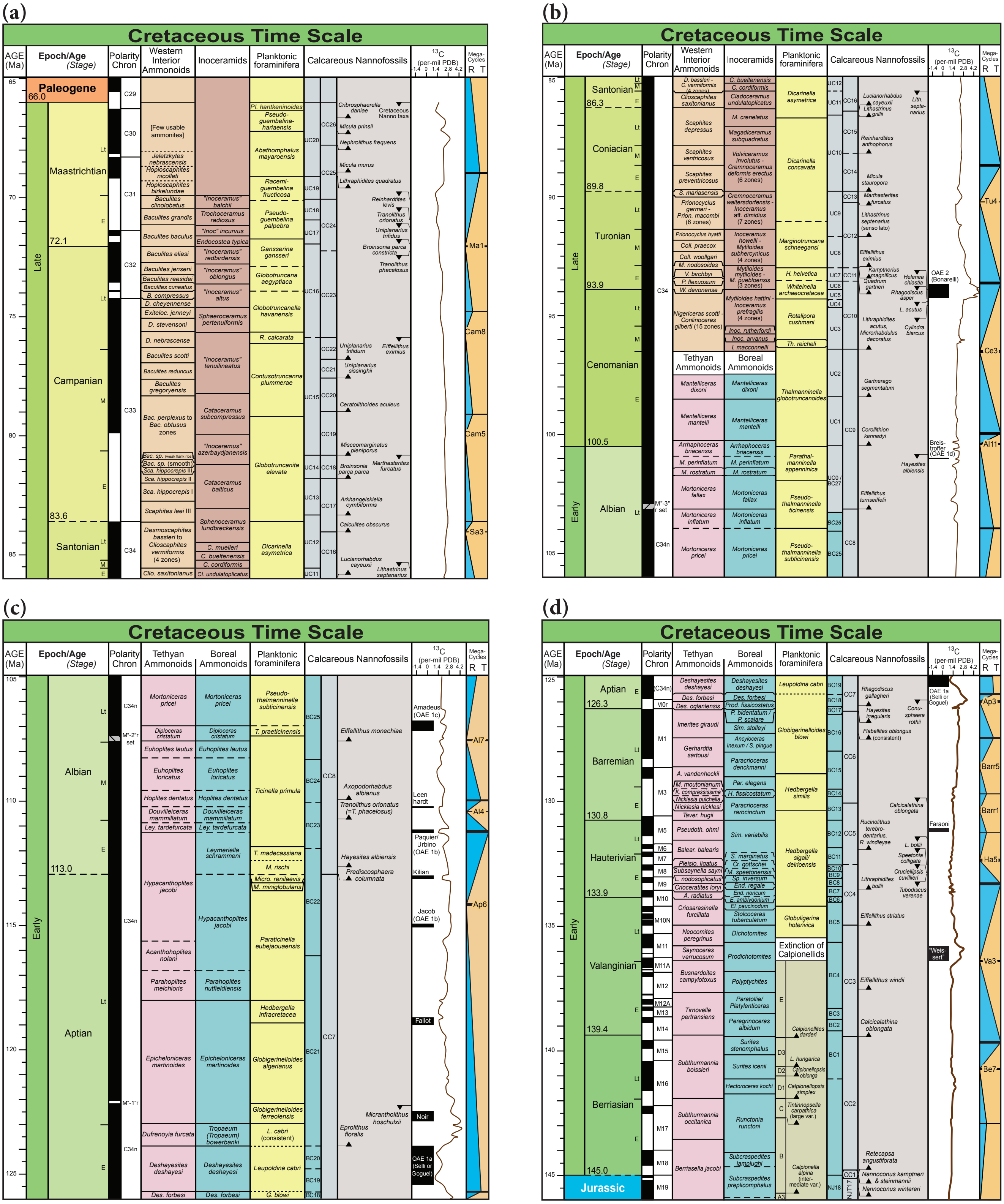
The international standard subdivisions of the Cretaceous time scale are merely a visual guide to sound stratigraphic practice, in anticipation of a detailed study of the potential (stepwise) linkage of a standard Norwegian offshore zonation to the primary Cretaceous zonal scales. For the North Sea Neogene this was recently achieved by Anthonissen (2008, 2009 and 2012).

The standard numerical time scale for the Cretaceous (Figures 2.3a-d) consists of three main "primary scales" : (1) Tethyan ammonite zones of Berriasian through Barremian are calibrated to the M-sequence age model (Geomagnetics chapter, this volume); (2) microfossil zones in Aptian-Albian are calibrated to cycle stratigraphy that is constrained by radio-isotopic dates, and (3) North American ammonite zones of Cenomanian through early Maastrichtian that have an abundance of interbedded bentonites with radio-isotopic ages are scaled with cycle stratigraphy and a spline fit. Most other Cretaceous events are assigned ages according to their calibration to these primary biostratigraphic scales or via direct calibrations to the M-sequence or C-Sequence chrons.

Also shown in Figures 2.3a-d are principle trends in carbon isotopes and sea level. The mega-cycles of sea-level trends are from Hardenbol *et al.*, (1998) in SEPM Special Publication #60. For the latter Haq (2014) provides an update, but real calibration information is still lacking. Cretaceous zonations, geochemical trends, sea-level curves, etc. are compiled in the internal datasets within TimeScale Creator (*www.tscreator.org*). For details see Ogg and Hinnov (2012).

The duration of Cretaceous stages range from over 10 myr for Aptian, Albian and Campanian to less than 3 myr for the Santonian. The differences in the age models for GTS2004 and GTS2012 are relatively minor, mainly a ~1 myr shift to older ages due to the revised Ar-Ar monitor standard. This general stability suggests that the global efforts to integrate cycle stratigraphy with high-precision radio-isotope dates and improved inter-zonal calibrations are converging on a reliable Cretaceous time scale.

However, several of the Cretaceous stages are not yet defined. Those decisions may select different horizons for global correlations than are used as the working definitions for these stages in GTS2012. The numerical age model for stratigraphic events might be relatively stable, but the future assignment of those events into chronostratigraphic stages may shift when the stage boundary definitions are eventually decided.



Figures 2.3a,b,c,d. Summary of numerical ages of epoch/series and age/stage boundaries of the Early, early Middle, Middle and Late Cretaceous with selected marine biostratigraphic zonations and principle trends in carbon isotopes and sea level. ["Age" is the term for the time equivalent of the rock-record "stage".]. The mega-cycles of sea-level trends are from Jacquin and de Graciansky (1998) and Hardenbol *et al.* (1998). Cretaceous zonations, geochemical trends, sea-level curves, etc. are compiled in the internal datasets within TimeScale Creator (*www.tscreator.org*). For details see Ogg and Hinnov (2012).

Biostratigraphy

Introduction

In the next pages two practical Cretaceous biostratigraphic zonations are outlined for the petroleum sectors of the northern North Sea and Norwegian Sea, one using mainly Foraminifera and the other dinoflagellate cysts.

The quantitative foraminiferal zonation updates Gradstein *et al.* (1999). It combines shelly and some organic walled fossil events in one interval zonation, using mostly last occurrence and last common occurrences of over 100 taxa in over 30 wells. The taxa listed are directly from the samples in the Norwegian Sea and North Sea wells on which the zonation is based. The zonation also may be consulted in the section on Biostratigraphy on *www.nhm2.uio.no/norlex*.

The separate dinoflagellate cyst zonation is a literature zonation applicable to the North Sea and Norwegian Sea. The taxa and zonation are based on available peer-reviewed palynological publications, and completed with unpublished PhD theses and collected contributions from course manuals. Note that the dinoflagellate zonation incorporates more recent literature than was used when the quantitative micropaleontology/palynology zonation was calculated; hence taxonomic details differ between both zonations but are a minor issue.

Modern biostratigraphy, particularly when well data are involved, emphasizes fossil events over fossil ranges along a depth or time scale. A biostratigraphic event is the presence of a taxon in its time context, derived from its occurrence in a rock sequence. Such events are unique and irreversible. Event positions are preferred levels (like last occurrence or last common occurrence) along the stratigraphic range of taxa. The stratigraphic ranges of taxa often change from basin to basin, with concommittant changes in event positions. The relative and/or linear positions of these events are influenced by many factors, paleoecologic, evolutionary, paleobiological and taxonomic in nature.

Subjective judgement of correlations plays an important role also. Events may change relative position from region to region, or even across any one region and also between schemes by different authors. It may not always be easy to point to clear reasons for such differences. Below, we will try to outline differences between zonal event schemes, using Foraminifera.

The biostratigraphy of Lower and Upper Cretaceous foraminifers in NW Europe has been studied by a number of authors since the 1960's. A brief review of biostratigraphic schemes developed for the NW European siliceous mudstone facies is useful in order to understand the microfossil records from the eastern sedimentary wedge of the Norwegian-Greenland Sea.

Northwest Germany - The work from H. Bartenstein and co-workers on the benthic foraminifers of the Saxon Basin has lead to the publication of a detailed biostratigraphic scheme for NW Germany (Bartenstein & Bettenstaedt, 1962). This was followed by a proposal for a general biostratigraphic zonation for the Lower Cretaceous using more cosmopolitan taxa (Bartenstein, 1978). The biostratigraphic zonation of the NW German Lower Cretaceous was based on the stratigraphic succession of 75 foraminifer, and 12 ostracod species in middle Valanginian to lowermost Cenomanian of Saxony. The stratigraphic ranges of benthic foraminifers were calibrated to the standard ammonite zones. The zonal scheme mainly uses calcareous benthic foraminiferal species more typical of shallow marine sediments, such as *Citharina*, *Epistomina*, and ornamented *Lenticulina.* Unfortunately, neither of these genera is common in the Cretaceous Norwegian Sea. Fewer than 15 of the Northwest German index species were commonly encountered in this study. Of these, the 11 taxa that do occur consistently offshore Norway, and are thus used for chronostratigraphic correlation, are listed in Table 2.1.

Northern Tethys Margin - Weidich (1990) published a zonal scheme for the Tithonian to Cenomanian based on his studies of the Northern Calcareous Alps in Bavaria and Austria. His scheme divides the Lower Cretaceous into 10 zones, based on first occurrences or acmes of nominate zonal taxa. Weidich's zonation is based primarily on calcareous benthic foraminifers, but because his studied sections were deposited in deep water, there is a greater possibility for correlation with the Norwegian Sea region. Several of the index taxa are also found in the North Sea, which verifies Weidich's selection of taxa that are largely cosmopolitan. However, Weidich's zonal scheme was only tentatively correlated to the standard chronostratigraphy, and calibration of Weidich's samples by means of planktonic microfossils is needed to refine the age of his zones. Table 2.2 gives a list of stratigraphically important cosmopolitan species from Weidich's study, which also occur in the Norwegian Sea assemblages.

Species:	Range in N.W. Germany:
Pleurostomella obtusa	lower-middle Albian
Gavelinella intermedia	lower-middle Albian
Valvulineria gracillima	upper Aptian to upper Albian (max. in upper Aptian)
Gaudryina dividens	upper Aptian to lower Albian (max. in upper Aptian)
Gavelinella barremiana	mid Barremian to lower Aptian (max. in mid Barremian)
Reophax troyeri	mid Barremian to mid Albian (max. in upper Aptian - lower Albian)
Lenticulina ouachensis ssp.	upper Hauterivian. to lower Aptian (max in middle to upper Barremian)
Textularia bettenstaedti	upper Hauterivian. to lower Albian (max. in upper. Aptian - lower Albian)
Lenticulina eichenbergi	upper Valanginian to mid Barremian (max. in Hauterivian)
Epistomina hechti	Barremian
Falsogaudryina tealbyensis	Valanginian - Barremian

Table 2.1 Benthic foraminiferal taxa found in the Lower Cretaceous, offshore mid Norway, which also occur in NW Germany.

Species:	Range in German Alps:
Caudammina crassa	Barremian to Cenomanian
Kalamopsis grzybowskii	Barremian to Cenomanian
Textularia bettenstaedti	Berriasian to Aptian
Plectorecurvoides spp	upper Albian
Trochammina quinqueloba	upper Albian
Gaudryina dividens	Aptian to Albian
Spiroplectinata spp.	Aptian to Albian
Lenticulina busnardoi	Berriasian to Hauterivian
L. eichenbergi	Valanginian to Barremian
L. wisselmanni	Barremian
Valvulineria spp.	upper Aptian to Albian
Gavelinella barremiana	Barremian to Aptian
G. intermedia/ berthelini	Aptian to Cenomanian
Patellina subcretacea	Berriasian to lower Aptian
Falsogaudryina (?) tealbyensis	Barremian - Aptian

Table 2.2 Benthic foraminiferal taxa found in the Lower Cretaceous, offshore mid Norway which also occur in the Alps in Germany and Austria.

The biozonation of Geroch and Nowak (1984), with additions by Geroch and Koszarski (1988), provide a reference frame for cosmopolitan deep-water agglutinated foraminiferal assemblages. The Lower Cretaceous portion of their scheme consists of 19 species in 7 zones, and the Upper Cretaceous of 17 species in 4 zones. All zones are based on the first occurrence of index taxa - so they are not equivalent to zones of the same name recognised in other areas, and are not directly applicable to cuttings samples in wells. Although these zones were originally developed for the Carpathian flysch deposits, parts of the Geroch and Nowak scheme apply to other deeper marine continental margins with Cretaceous flysch-type assemblages, as far away as the NW Australian margin (Kaminski *et al.* 1992), and the Pacific (Riegraf & Luterbacher, 1989).

Several of the nominal index species from this zonal scheme we have now observed also in the Norwegian seaway, including *Verneuilinoides neocomiensis, Pseudobolivina variabilis, Pseudonodosinella troyeri* (= *Reophax minutus* of Geroch & Nowak), *Haplophragmoides nonioninoides*, and *Bulbobaculites problematicus.* Other species we observed from

from Geroch & Nowak's (1984) range chart include *Ammobaculoides carpathicus, Trochammina quinqueloba, Trochammina abrupta, Thalmannamina neocomiensis, Caudammina crassa, Hippocrepina depressa, Kalamopsis grzybowskii, Gaudryina filiformis* (= ? *Gerochammina lenis*), *Caudammina ovulum, Rzekina epigona, Tritaxia dubia* (= *T. subparisiensis*), *Marsonella crassa and Dorothia oxycona*. Many of these species were not previously reported from the Norwegian and North Seas.

An interesting point is that recognition, offshore Norway of many of the middle to Upper Cretaceous taxa, known from the deep marine (bathyal to abyssal) Polish Carpathian Trough, does not mean a direct deep marine connection existed between the proto Norwegian Sea and the Carpathian Trough region. As may be seen on Figure 2.2, such a connection is not drawn, and not likely for mid-Cretaceous time given shallow marine deposits eastward into Germany. Locally in the deepest part of the NW German basin, bathyal conditions may have existed in Albian time, but such was not part of a deep passage eastward (J. Mutterlose, pers. comm, 1998). Deep marine faunal exchange most likely took place from the proto Barents Sea and Norwegian Sea into the North Atlantic oceanic realm.

Central North Sea – A foraminiferal zonal schemes for the Lower and Upper Cretaceous of the Central North Sea, developed by C. King and co-workers at the Paleoservices consulting company was published in the 'Stratigraphical Atlas of Fossil Foraminifera' (Jenkins & Murray, 1989); it links to the detailed study by Koch (1977) for the calcareous Upper Cretaceous of NW Germany. King *et al.* (1989) proposed two parallel zonations for the North Sea, subdividing the Lower Cretaceous into 12 zones and subzones, and the Upper Cretaceous in 11 zones and subzones (referred to in Figure 2.6). The "FCS" zonal scheme has applications in the shelf (chalk) facies of the southern sector of the North Sea, whereas the "FCN" zones are based on deeper-water taxa and can be used for the bathyal shale facies in the northern and central sectors. The FCN zonation scheme is most applicable to our study area, and the zonation offshore Norway resembles this scheme (referred to in Figure 2.6, and discussion below). The index taxa are widespread and common, which makes the scheme quite robust. However, little attention was paid by King *et al.* (op. cit.) to deep water agglutinated foraminifers which become more important northward. Below, we will discuss in detail similarities and differences of our NCF zonation to the FCN zonation.

Millennium Atlas - An important document for North Sea petroleum stratigraphy is the Millennium Atlas (Evans *et al.*, 2003). For the Lower Cretaceous section of this excellent compilation, Copestake *et al.* (2003) created a sequence stratigraphic model with multiple biostratigraphic event linkage (albeit no zonation). No such overview was provided for the Upper Cretaceous in the Millennium Atlas, but the study by Bailey *et al.* (2009) provides a Chalk foraminifer benthic zonation. Figure 2.4 shows the fossil events framework of Copestake *et al.* (2003) for the North Sea with linkage to the Hardenbol *et al.,* (1998) ammonite biozones, magnetostratigraphy and Lower Cretaceous stages. Unfortunately, none of the Lower Cretaceous stages have yet been formally defined. In the zonal text below reference will be made to linkages with the Copestake scheme.

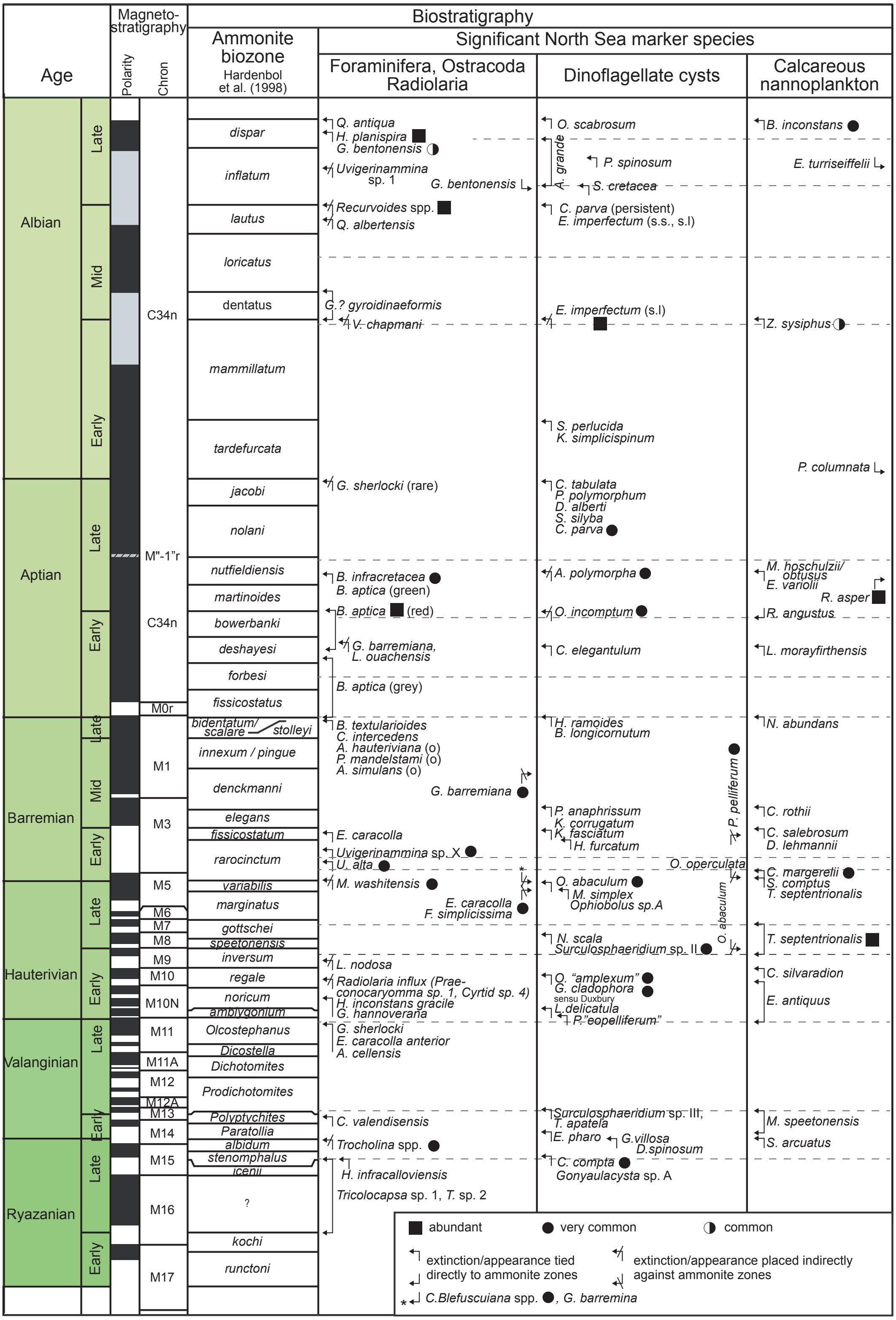


Figure 2.4. Fossil events framework of Copestake *et al.* (2003) in the Millennium Atlas for the North Sea, with linkage to the Hardenbol *et al.*, (1998) ammonite biozones, magnetostratigraphy and Lower Cretaceous stages. The regional Ryazanian Stage correlates to the upper part of the Berriasian, which is the formal lowest stage in Cretaceous.

Cretaceous foraminiferal biozonation

Our Cretaceous biostratigraphy for the North Sea and petroleum sector of the Norwegian Sea, offshore mid Norway spans almost 20 degrees latitude between 52^0 and 67^0 N. The transition from chalk and marls to siliciclastics takes place between 58^0 and 60^0 N, and modifies the biota content such that planktonic foraminifers become taxonomically much less diverse, and only *Hedbergella* taxa start dominating some levels.

The Cretaceous sedimentary succession may reach several kilometers in thickness, and basinward is buried under a Cenozoic 'mudstone blanket' of 2 - 3 km. It may be subdivided in several broad units, listed below with generalized bio-and lithostratigraphy.

(1) Thin, multicoloured, marly sediments of late Hauterivian through early Barremian age, becoming dark coloured upwards, where the paleoenvironment changed from oxic to dysaerobic. These sediments herald the broad and global transgression in Cretaceous time over continental margins and other 'highs'. The foraminiferal microfossil assemblage contains common *Falsogaudryinella* and nodosariids; ostracods also are common. It is a shallow marine, normal salinity microfossil association. The sediments belong in the Lyr Formation of the Cromer Knoll Group.

(2) Dark mudstones and minor sands, Aptian through early Cenomanian in age, with deeper water agglutinated foraminifers and monotypic (planktonic foraminfer) *Hedbergella* floods. The sediments largely belong in the Langebarn Formation of the Cromer Knoll Group, and were laid down in an upper bathyal environment, with a dysaerobic deeper watermass.

(3) Thick mudstone facies, with thin, slope-apron gravity-flow sands, with a locally impoverished benthic foraminiferal assemblage, deposited in an upper bathyal, oxic-dysaerobic facies, of late Cenomanian – Coniacian age. The sand units are classified in several lower-rank members of the Blålange Formation, including the well-known Lysing Member. Where Turonian sedimentation rates are low, a relatively rich planktonic foraminiferal assemblage may be found with *Whiteinella, Hedbergella, Preaglobotruncana, Dicarinella* and *Marginotruncana*. The AOE2 – Bonarelli (Plenus Marl) event at the Cenomanian –Turonian boundary is expressed in well logs with γ spike readings.

(4) Grayish, laminated mudstones, Santonian through Campanian in age, with locally thick sands in the distal Voering Basin have a mostly low-diversity deeper marine foraminifer assemblage, an *Inoceramus* peak, and common radiolarian/diatom taxa. The sediments belong in the Kvitnos and Nise Formations of the Shetland Group.

(5) Marly and sandy sediments of Maastrichtian age, with a low-diversity planktonic and benthic foraminiferal assemblage. Locally, and particularly southward, planktonics may occur in floods with monotypic *Rugoglobigerina* and *Globigerinelloides*. Sediments are grouped in the Springar Formation of the Shetland Group.

Organic-walled microfossil biozonations for the North Sea and Norwegian – Greenland Sea may be browsed, downloaded and printed from the Norlex website under *www.nhm2.uio.no/norlex*. Consultants frequently use proprietary zonations that borrow events from the literature. Relevant, non-proprietary charts of dinoflagelate-spore/pollen events maybe found on the Norlex website under the heading 'Biostratigraphy'.

Plate 2.1 illustrates three micro fossil taxa that are useful index taxa, and possibly are endemic to the greater North Sea region: *Uigerinammina una*, *Ammoanita globorotaliaeformis*, and *Fenestrella bellii.* The two first ones are restricted to the *Uvigerinamina una* Zone, late Middle to early Late Albian. The latter defines the *Fenestrella bellii* (total range) Zone, Early Campanian, and is an important marker in the deep Voering Basin (e.g. in the Gjallar well, 6704/12-1). Appendix 1 re-describes these taxa.

The Cretaceous biozonation documented here uses foraminiferal taxa, dinoflagelates and some miscellaneous microfossils. Rather than trying to create a zonation that maximizes stratigraphic resolution, and often is difficult to apply over a broad region, we prefer to outline reliable zonal units that are easy to correlate. Hence, use was made of the Ranking and Scaling (RASC) method (Gradstein *et al.*, 1985) to rank and scale different microfossil groups together.

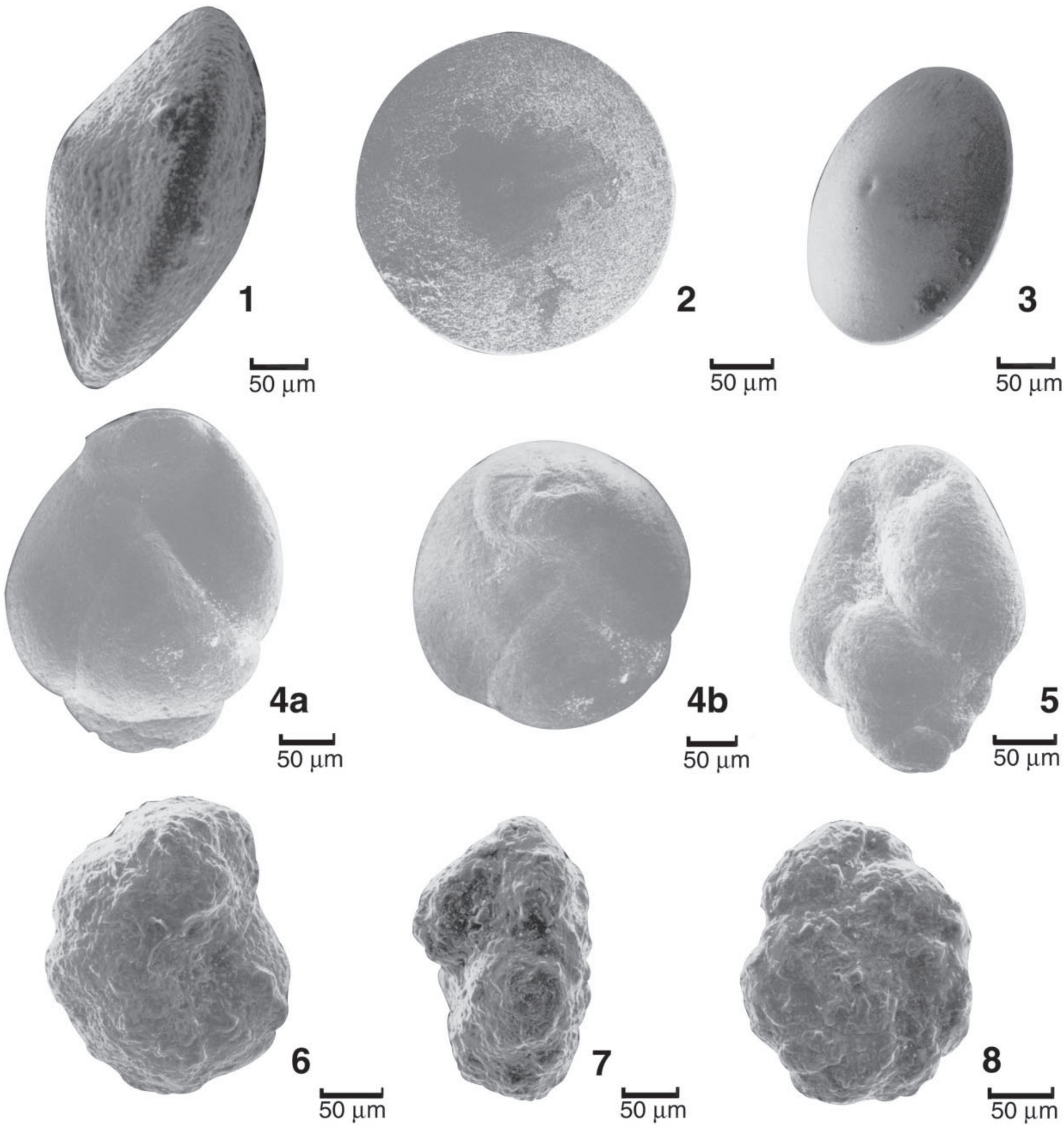


Plate 2.1

Figures 1-3. Fenestrella bellii Gradstein and Kaminski. Well 6507/6-2, Fenestrella bellii zone, cts. 2320 m, offshore mid--Norway; holotype in Fig. 1. Specimens were pyritized during burial.

Figures 4a,b, holotype. Uvigerinammina una Gradstein and Kaminski. Uvigerinammina una zone, well 6507/6-2 at cts. 3110 m, offshore mid-Norway. The specimen in Figure 5 is from cts. 3040 m in the same well.

Figures 6-8, holotype. Ammoanita globorotaliaeformis Gradstein and Kaminski. Uvigerinammina una zone, well 6507/6-2 at cts. 3110 m, offshore mid-Norway.

The lower Cretaceous, pre-Albian section is too fragmented, and well coverage insufficient to effectively apply event scaling using quantitative stratigraphic methods; that part of the stratigraphic section is ranked and zoned subjectively. Below, we first will summarize the procedure (from Gradstein *et al.*, 1985 and 1999), prior to a discussion of the successive Cretaceous zones NCF 1-21.

Initially, the data set for RASC comprised the multiple microfossil event record in 37 wells, mostly LO (Last Occurrence in a stratigraphic sense) or LCO (Last common Occurrence in a stratigraphic sense) events of 550 foraminifers, some siliceous microfossils and dinoflagellates, for a total of 1873 records.

A majority of well samples we analysed self for shelly microfossils, complemented with selected information from fossil listings in well completion reports. The organic-walled microfossil record for the wells was obtained from consultants and colleagues (ex- Saga Petroleum). After several intermediate zonations, using RASC and its normality testing functions of the event record, five erratic events, and seven wells with low sampling quality (partly due to turbo--drilling) were deleted from the data. The remaining 31 wells harbour 519 fossil events, with 1755 records. Principal wells are 6610/3-1, 6610/3-1R, 6607/5-2, 6607/5-1, 6607/12-1, 6507/2-1, 6507/2-2, 6507/2-3, 6507/6-2, 6507/7-1, 6507/7-2, 6506/12-5, 6406/2-1, 36/1-2, 35/3-1, 35/3-2, 35/3-4, 35/3-5, 35/12-1, 35/11-2, 35/11-5, 35/9-1, 35/9-2, 35/10-1, 34/7-21a, and 33/9-15.

Table 2.3 provides a summary of data properties and RASC results. Number of events in the optimum sequence with SD < ave SD, deals with the number of events that have a standard deviations below the average for the optimum sequence; the fact that 44 out of 72 optimum sequence events have a lower than average standard deviation is good. Stratigraphic coverage is relatively good, even that, as usual, only 97 out of 519 events occur in 6 or more wells, and only 72 events occur in 7 or more wells. Cretaceous dinoflagellate cysts in particular show large taxonomic diversity, but limited traceability for many taxa.

SUMMARY OF DATA PROPERTIES AND RASC RESULTS:	
NUMBER OF NAMES (TAXA) IN THE DICTIONARY	589
NUMBER OF WELLS	31
NUMBER OF DICTIONARY TAXA IN THE WELLS	519
NUMBER OF EVENT RECORDS IN THE WELLS	1755
NUMBER OF CYCLES PRIOR TO RANKING	21
NUMBER OF EVENTS IN THE OPTIMUM SEQUENCE	72
NUMBER OF EVENTS IN OPTIMUM SEQUENCE WITH SD < ave SD	44
NUMBER OF EVENTS IN THE FINAL SCALED OPTIMUM SEQUENCE (INCLUDING UNIQUE EVENTS SHOWN WITH **)	81
NUMBER OF STEPMODEL EVENTS WITH MORE THAN SIX PENALTY POINTS AFTER SCALING	14
NUMBER OF NORMALITY TEST EVENTS SHOWN WITH * OR **	78
NUMBER OF AAAA EVENTS IN SCALING SCATTERGRAMS	20

Table 2.3 Summary of data properties and RASC run results for the 31 wells data set discussed in this study, using Cretaceous microfossils. There are 519 dictionary taxa in the wells, 72 of which occur in 7 or more wells, threshold in the (scaled) optimum sequences of Figures 2.5 and 2.6. For further discussion, see text.

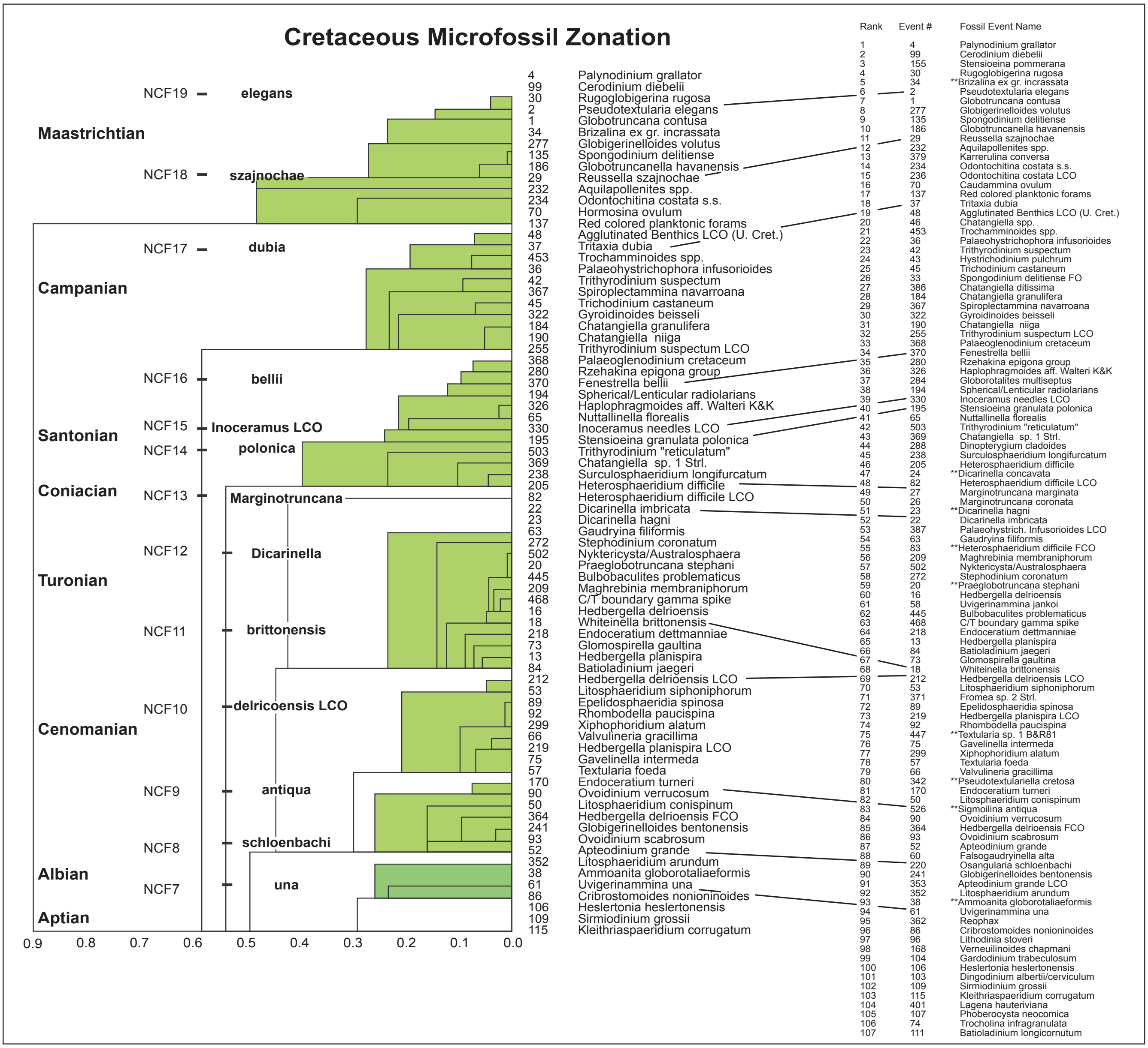


Figure 2.5 (right). Optimum sequence of Cretaceous events (foraminifera, dinoflagellates, miscellaneous microfossils and one physical log marker), offshore mid Norway, using the Ranking and Scaling (RASC) method on 1753 records in 31 wells. The arrow of time is upward. The majority of events are last occurrences (LO) in relative time; LCO stands for Last Common or Last Consistent Occurrence. Each event occurs in at least 6 out of 31 wells, leaving 97 events. The display also shows the relative stratigraphic position of nine unique events. The optimum sequence is graphically tied to the scaled optimum sequence (= RASC zonation) to the left, largely using the nominate zone markers.

Figure 2.5 (left). Scaling in relative time of the optimum sequence of Cretaceous events shown in Figure 2.5 (right). The arrow of time is upward; the inter event distances are plotted on the relative scale to the left in dendrogram display format. Each event occurs in at least 7 of the 31 wells, leaving 72 events. Sixteen stratigraphically successive interval zones are recognized, middle Albian through late Maastrichtian in age. Large breaks (at events 52, 84, 205, 255 and 137) indicate transitions between natural microfossil sequences; such breaks relate to hiatuses or facies changes, some of which are known from European sequence stratigraphy (see text for more details).

(1) The una - schloenbachi break reflects a latest Albian lithofacies change and hiatus, connected to the Octeville hiatus in NW Europe.

(2) The delrioensis LCO - brittonensis break reflects the mid-Cenomanian lithofacies change and hiatus, connected to the mid-Cenomanian non-sequence and Rouen hardground of NW European sequence stratigraphy.

(3) The Marginotruncana - polonica break, above the level of Heterosphaeridium difficile LCO, which represents a maximum flooding surface, may be the turn-around in the middle Coniacian tectono-eustatic phase, near the end of the Lysing sand phase.

(4) The bellii - dubia break, is again (near or) at a maximum flooding event, this time correlated to the LCO of T.suspectum in the early middle Campanian, above the change from marly sediments to siliciclasts at the base of the Campanian.

(5) The dubia - szajnochae break reflects the abrupt change from siliciclasts to marly sediment at the Campanian - Maastrichtian boundary, only noted in the southern part of the region.

The Cretaceous optimum sequence (Figure 2.5, right) includes 98 events ('tops') that occur in 6 or more wells, spanning Hauterivian through Maastrichtian strata. Nine events, shown with double ** in front of the name, are socalled RASC unique events, meaning they have good calibration potential, but occur in fewer than threshold (6) wells. A simple RASC routine merges these unique events in the optimum sequence. 'Range' of taxa in the optimum sequence, a measure of the number of sequence positions an event spans (= rank positions in Figure 2.5, right), is always low, except for *Fromea* sp. 2 (5 rank positions), *Dinopterigium cladoides* (6 rank positions), *Trithyrodinium,reticulatum* (5 rank positions), *Gyroidinoides beisseli* (5 rank positions), *Chatangiella niiga* (5 rank positions), and *Chatangiella* sp. (10 rank positions). The last occurrence record for these taxa is not reliable for detailed correlations in the wells examined. The optimum sequence serves as a guide to the stratigraphic order in which events in wells are expected to occur, hence it is both predictive, and serves in high-resolution correlation, as outlined below.

Figure 2.5 (left) shows the scaled optimum sequence for the Cretaceous in the 31 wells using events that occur in 7 or more wells. Nine events noted with ** occur in fewer than 7 wells, but are inserted as unique events for the purpose of zonal definition and chronostratigraphic calibration. The events listed in the optimum and scaled optimum sequences of Figure 2.5 represent average last occurrences (average 'top), unless otherwise indicated; LCO stands for last common or last consistent occurrence, and FCO means first common or first consistent occurrence (in an uphole sense).

Over a dozen stratigraphically successive RASC interval zones stand out in Figure 2.5, middle Albian through Maastrichtian in age, which guide the discussion of interval, acme, and assemblage zones below. Resolution is poor in the lowermost and uppermost parts of the scaled sequence, and reflects lack of superpositional data, and condensation of 'tops' in the uppermost and lowermost Cretaceous part of wells.

The scaled optimum sequence shows major breaks between several successive zones, including between the *una* and *schloenbachi* zones, *delrioensis LCO* and *brittonensis* zones, *Marginotruncana* and *polonica* zones, *bellii* and *dubia* zones, and particularly between *dubia* and *szajnochae* zones. The question what the meaning is of these large breaks, is best answered when we consider how RASC scaling operates. Scaling calculates the relative stratigraphic distance between successive events in the RASC optimum sequence. This relative distance is calculated from the frequency of cross-over of all possible pairs of events in the optimum sequence over all wells. Hence, large distances between successive events, corresponding to the larger RASC zonal breaks indicated above, signify strongly diminished cross-over between events that occur below and above the breaks. Reasons for these breaks thus should be thought in stratigraphic gaps, and paleoenvironmental changes. The reasons will be discussed in more detail below, but may be summarized as follows:

1. the *una - schloenbachi* break reflects a latest Albian lithofacies change and hiatus, connected to the Octeville hiatus in NW Europe.
2. the *delrioensis LCO - brittonensis* break reflects the mid-Cenomanian lithofacies change and hiatus, connected to the mid-Cenomanian non-sequence, and Rouen hardground (Hardenbol *et al.*, 1998).
3. the *Marginotruncana - polonica* break may be the turn-around in the tectono-eustatic phase of middle Coniacian, near the end of the Lysing Member sand deposition. The break occurs above the level of *Heterosphaeridium difficile* LCO, which represents a maximum flooding surface.
4. the *bellii - dubia* break occurs above the change from marly sediments to siliciclastic sediments that takes place in lowermost Campanian. The break, as the previous one, is near a maximum flooding event, i.e. the LCO of *T. suspectum* in early part of middle Campanian.
5. the *dubia - szajnochae* break reflects the abrupt change from siliciclastic to marly sediment at the Campanian - Maastrichtian boundary, noted in the southern part of the region.

An important zonal figure is in Figure 2.6. This figure displays the RASC most likely order of events calculation using a threshold of 7 instead of 6 (right side of Figure 2.5). This means that each event used in the optimum sequence calculation must occur in a minimum of 7 wells, instead of 6 wells. To the left in Figure 2.6 is the optimum sequence of Cretaceous microfossil events in 31 wells,

Cretaceous Ranked Optimum Sequence, offshore Norway

(31 wells, 1755 records)

No.		Dict.#		N	SD
1	0 1	4	Palynodinium grallator	9	1.221
2	-1 0	99	Cerodinium diebelii	7	1.709
3	0 1	30	Rugoglobigerina rugosa	14	1.289
4	-2 0	2	Pseudotextularia elegans	11	0.992
5		1	Globotruncana contusa	7	1.449
6		34	**Brizalina ex gr. incrassata		
7		277	Globigerinelloides volutus	13	1.424
8		135	Spongodinium delitiense	16	1.794
9		186	Globotruncanella havanensis	11	1.579
10		29	Reussella szajnochae	18	1.242
11		232	Aquilapollenites spp.	10	1.424
12		234	Odontochitina costata s.s.	9	1.665
13		70	Caudammina ovula	13	2.236
14		137	Red colored planktonic forams	7	1.074
15		37	Tritaxia dubia	12	1.307
16		48	Agglutinated Benthics LCO (U. Cret.)	11	1.478
17		453	Trochamminoides spp.	7	1.074
18		36	Palaeohystrichophora infusorioides	12	1.307
19		42	Trithyrodinium suspectum	11	1.478
20		45	Trichodinium castaneum	12	2.328
21		255	Trithyrodinium suspectum LCO	18	1.302
22		184	Chatangiella granulifera	7	1.753
23		367	Spiroplectammina navarroana	7	3.233
24		322	Gyroidinoides beisseli	7	2.266
25		190	Chatangiella niiga	18	2.172
26		368	Palaeoglenodinium cretaceum	14	1.501
27		370	Fenestrella bellii	13	1.376
28		280	Rzehakina epigona group	9	2.578
29	0 1	194	Spherical/Lenticular radiolarians	15	1.586
30	-1 0	326	Haplophragmoides aff. walteri K&K	9	3.279
31		330	Inoceramus needles LCO	16	1.172
32	0 1	195	Stensioeina granulata polonica	14	1.066
33	-1 0	65	Nuttallinella florealis	7	3.107
34	0 1	369	Chatangiella sp. 1 Strl.	13	1.410
35	-2 0	503	Trithyrodinium "reticulatum"	7	1.171
36		238	Surculosphaeridium longifurcatum	16	2.432
37		205	Heterosphaeridium difficile	14	1.016
38		82	Heterosphaeridium difficile LCO	20	1.403
39	0 2	445	Bulbobaculites problematicus	7	3.868
40	-2 0	63	Gaudryina filiformis	11	2.295
41		22	**Dicarinella imbricata		
42		209	Maghrebinia membraniphorum	10	3.116
43		23	**Dicarinella hagni		
44		502	Nyktericysta/Australosphaera	9	2.161
45		272	Stephodinium coronatum	18	1.909
46		16	Hedbergella delrioensis	17	1.883
47		20	**Praeglobotruncana stephani		
48		468	C/T boundary gamma spike	11	2.108
49		218	Endoceratium dettmanniae	14	2.125
50		13	Hedbergella planispira	15	2.432
51		84	Batioladinium jaegeri	10	2.319
52		73	Glomospirella gaultina	9	3.156
53		18	Whiteinella brittonensis	8	2.933
54		212	Hedbergella delrioensis LCO	14	1.243
55		53	Litosphaeridium siphoniphorum	19	2.122
56		89	Epelidosphaeridia spinosa	13	2.615
57		219	Hedbergella planispira LCO	7	1.539
58		92	Rhombodella paucispina	9	1.672
59		66	Valvulineria gracillima	11	2.291
60	0 1	75	Gavelinella intermeda	11	1.778
61	-1 0	299	Xiphophoridium alatum	9	3.216
62		57	Textularia foeda	9	2.837
63		170	Endoceratium turneri	10	1.631
64		90	Ovoidinium verrucosum	7	1.736
65		50	Litosphaeridium conispinum	7	1.386
66		364	Hedbergella delrioensis FCO	8	1.242
67		93	Ovoidinium scabrosum	11	1.256
68		241	Globigerinelloides bentonensis	7	2.117
69		353	Apteodinium grande	12	0.989
70	0 2	352	Litosphaeridium arundum	7	2.276
71		38	**Ammoanita globorotaliaeformis		
72	-1 0	61	Uvigerinammina una	12	1.792
73		86	Cribrostomoides nonioninoides	8	0.519
74		106	Heslertonia heslertonensis	7	0.895
75		109	Sirmiodinium grossii	7	0.703
76		115	Kleithriaspaeridium corrugatum	8	1.813

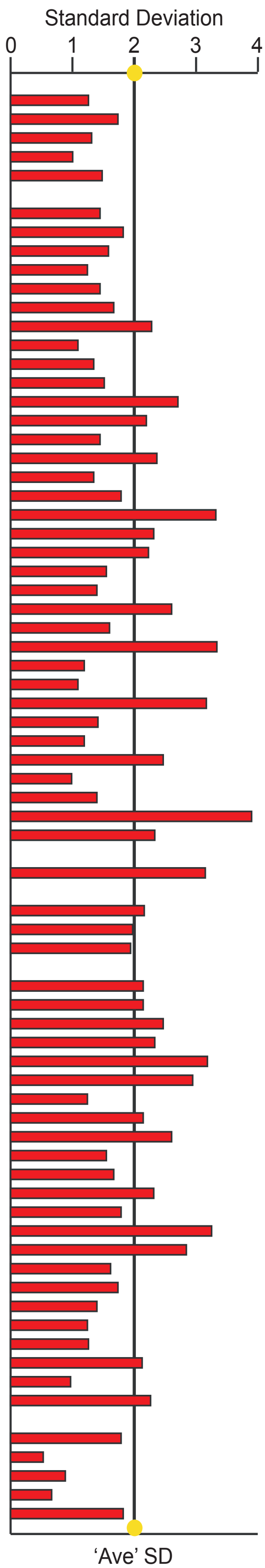


Figure 2.6. Summary of event variance analysis results for the Cretaceous optimum sequence of Figure 2.5, but using a threshold of 7 instead of 6. This means that each event used for Ranking and Scaling (RASC) analysis must occur in a minimum of 7 wells, instead of 6 wells (as shown in Figure 2.5, right side). To the left in Figure 2.6 is the optimum sequence of Cretaceous microfossil events in 31 wells, offshore mid-Norway, where each of the 76 events occurs in at least 7 out of 31 wells. The paired numbers in the column between the column (extreme left) of the event position level and the column with the event dictionary event number (Dict.#) indicate that the event could have been placed 1 or 2 position higher or lower (uncertainty due to cycling). N is the number of wells sampled to calculate the s.d. per event (N > or = 7), and s.d. is the standardized deviation from the line of correlation in each well. The average standard deviation of 1.8903 is the sum of all s.d.'s, divided by the total number of events (= 72) in the optimum sequence. The asterisk behind events indicates a s.d. that is smaller than the average s.d. From event s.d. theory it follows that events with a below average s.d. correlate the same relative stratigraphic level more faithfully from well to well than events with a higher s.d.

offshore mid-Norway. N is the number of wells sampled to calculate the s.d. per event (N > or = 7), and s.d. is the standardized deviation from the line of correlation in each well. The average standard deviation of 1.8903 is the sum of all s.d.'s, divided by the total number of events (= 72) in the optimum sequence. The asterisk behind events indicates a s.d. that is smaller than the average s.d. From event s.d. theory it follows that events with a below average s.d. correlate the same relative stratigraphic level more faithfully from well to well than events with a higher s.d.

Within the major units, smaller zonal subdivisions may be recognized, using a combination of subjective judgement from individual well study, and objective subdivision from ranking and scaling analysis. Hence, the final zonation takes advantage of both subjective, and more objective analysis, and integrates the two into one framework for a nineteen fold NCF (North Sea Cretaceous MicroFossil) Zonation (Figures 2.7a,b). The numbering makes it easy to use for geologists and non-foraminifer biostratigraphers. As mentioned earlier, integration, using the RASC method, with dinoflagellate events, improves the applicability of both types of microfossils for regional biostratigraphy.

Besides the zonal numbers, the zones are also named after prominent foraminiferal taxa, which are easily recognized in the wells, and are relatively widespread. Some of the foraminiferal index taxa (like *Trocholina, Blefusciuana, Globigerinelloides gyroidinaeformis, Hedbergella brittonenesis, Marginotruncana coronata* and *Dicarinella concavata*) are rare due to the high-latitude setting of the study region, or poor preservation of carbonate tests in the siliceous mudstones.

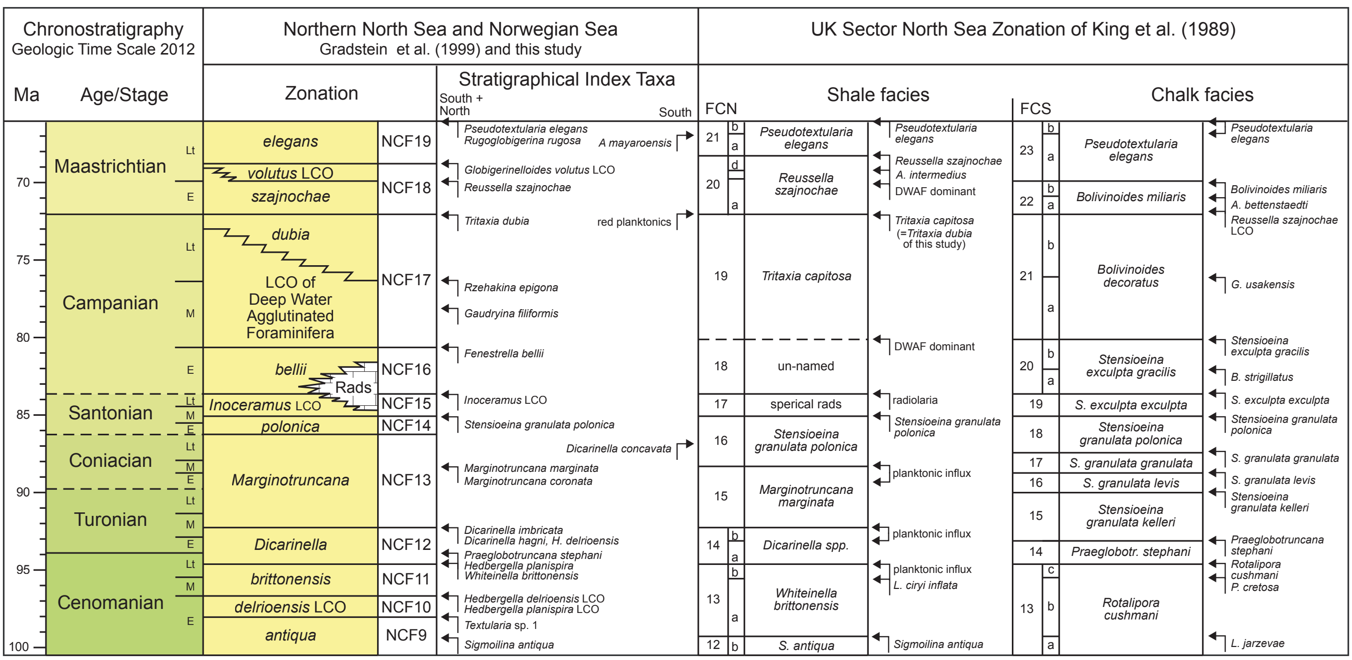


Figure 2.7a. Lower Cretaceous zonation, offshore mid- Norway with stratigraphical index taxa for shaly facies (more predominant northward), and for marly facies (more predominant southward). The zonation compares with the North Sea zonation for shaly (north) and for marly (south) facies of King *et al.* (1989), with which it shown taxa and zones in common. Seemingly, stratigraphic resolution decreases northward, but this is partly a bias from a more limited data set than available to King et al (op.cit.) in the North Sea.

Chronostratigraphic assignments are tentative, hampered among others by the absence, or scarcity of keeled planktonic foraminifers, including *Rotalipora* and the majority of *Dicarinella, Marginotruncana*, and *Globotruncana* taxa. Zones of relative short stratigraphic duration, like the *Sigmoilina antiqua* Zone, assigned to lower Cenomanian may be difficult to observe in ditch cuttings, particularly when the lithology is sandy. Zone definitions are bound to be refined with additional data, and further assessment of taxonomy, for example in the condensed Hauterivan - Barremian, and hiatus-riddled Aptian-middle Albian sections. Another zonal challenge is the thick, siliciclast interval in the inner Voering Basin, assigned to Campanian. The latter represents a poorly sampled section, probably laid down on a deeper marine, basin floor.

Stratigraphic range charts of principal taxa in the zonation of Figures 2.7a, b are in Figure 2.7a, b and in Figure 2.8. Taxon names followed by FO or FCO are events that help to define the lower level of the zones; similarly, taxon names followed by LCO or LO are events that assist with deliniation of the upper level of zones.

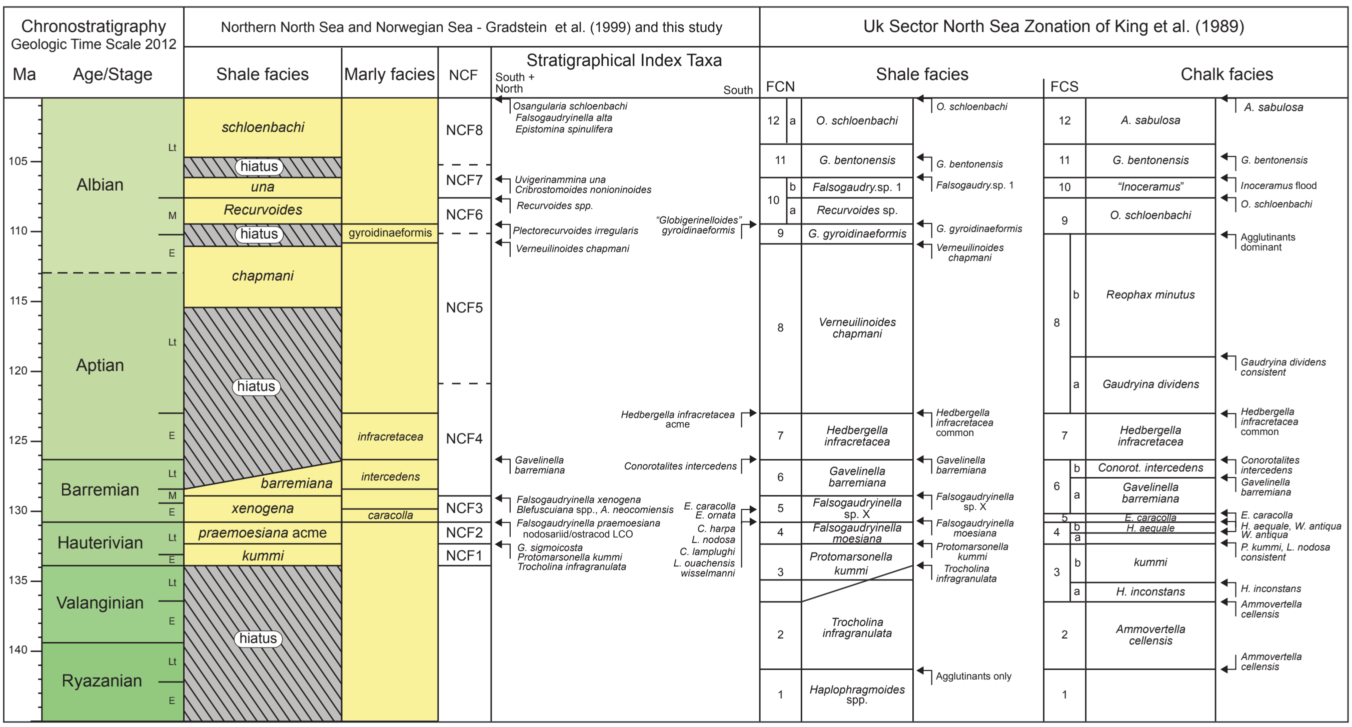


Figure 2.7b. Upper Cretaceous zonation for the Norwegian Sea, offshore mid-Norway, with stratigraphical index taxa for the region under study and taxa observed in its southern part only. The zonation is compared to the RASC model zonation using foraminifera and dinoflagellates (Fig. 5). The zonation compares well with the North Sea zonation for shaly facies by King et al (1989), and is slightly more detailed in part. As expected, the chalk facies zonation of the North Sea does not compare or apply.

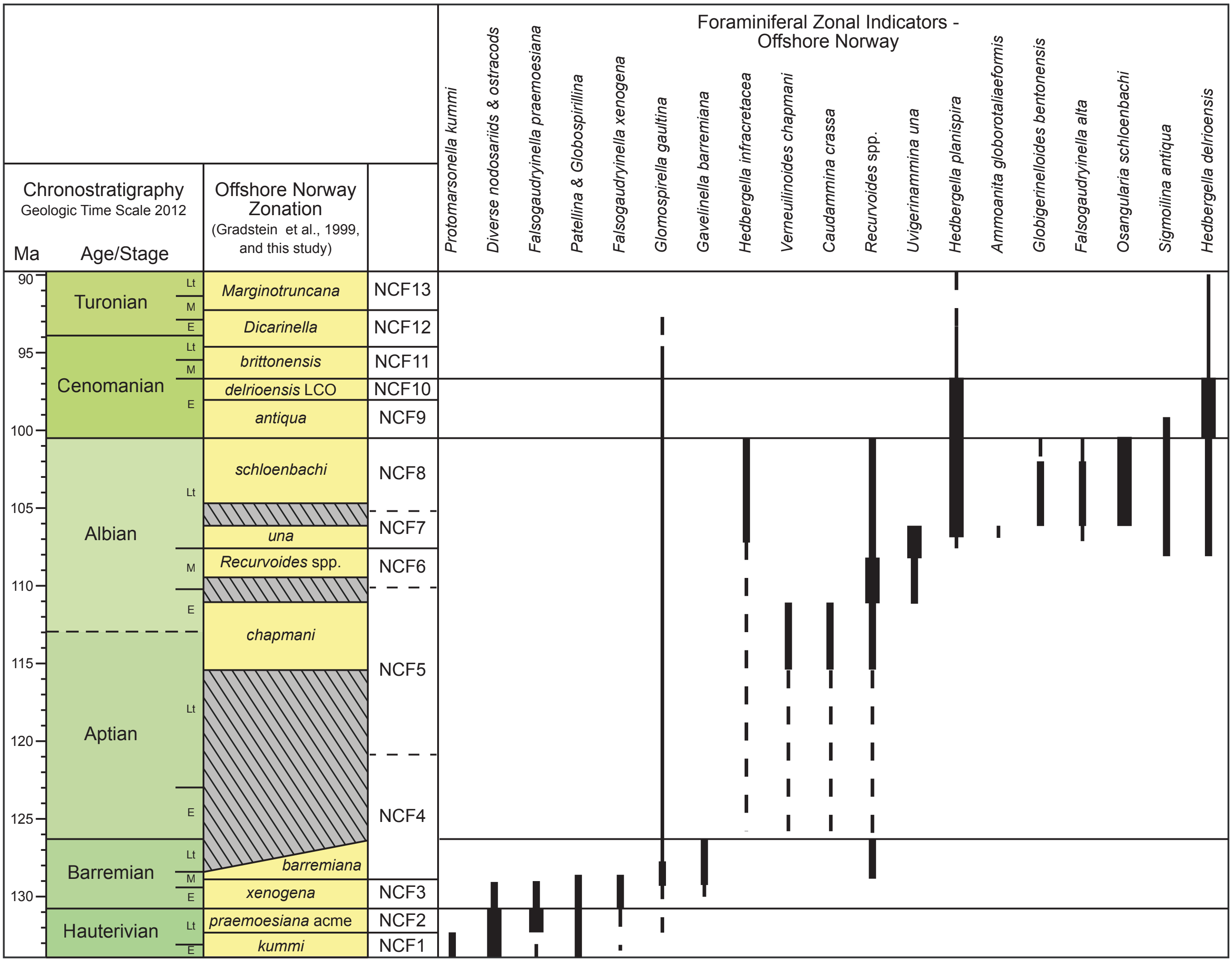


Figure 2.8a. Stratigraphic ranges of Lower Cretaceous index taxa, offshore mid-Norway, with the foraminiferal zonation established in this study.

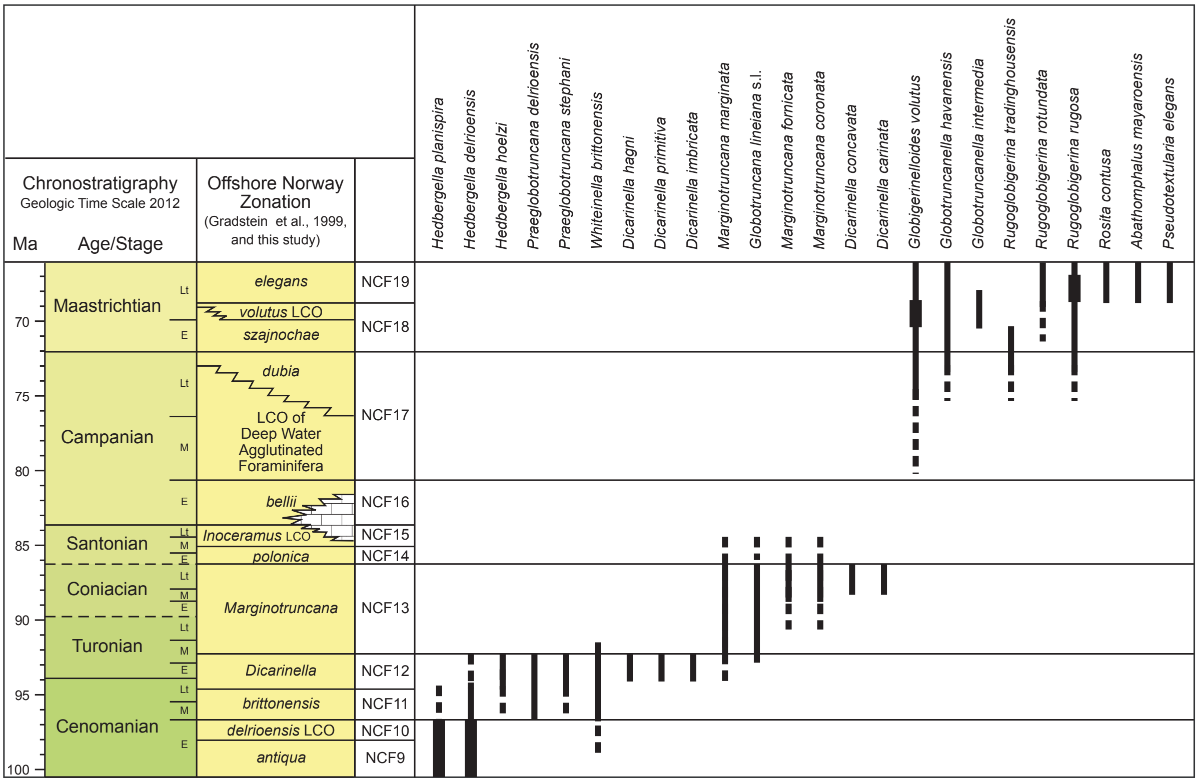


Figure 2.8b. Stratigraphic ranges of Upper Cretaceous planktonic foraminifera index taxa, offshore mid-Norway, with the foraminiferal zonation established in this study.

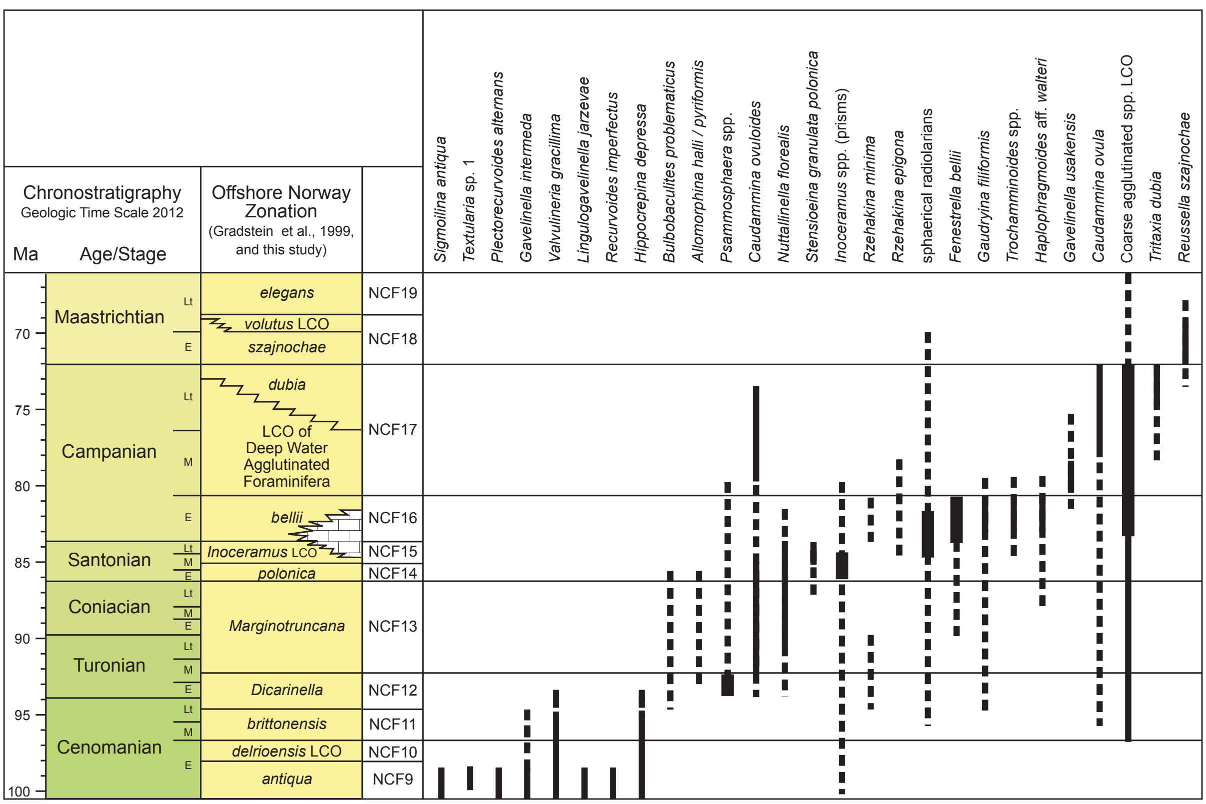


Figure 2.8c. Stratigraphic ranges of Upper Cretaceous benthic foraminifera, and miscellaneous index taxa, offshore mid-Norway, with the foraminiferal zonation established in this study.

Protomarssonella kummi Zone = NCF1 Zone

This zone is defined on the upper range of *Protomarsonella kummi*, prior to the acme of *Falsogaudryinella praemoesiana* (Figure 2.7a). As described above, NCF stands for Norwegian Cretaceous (micro-) Fossil. The following taxa were observed in assemblages assigned to the zone:

Protomarssonella kummi LO
nodosariids and ostracods (common to abundant)
Falsogaudryinellapraemoesiana FO (rare)
Patellina subcretacea
Trocholina infracretacea
Globospirillina neocomiana
Spirillina spp.
Lagena hauteriviana
Lenticulina aff. subalata
Lenticulina cf. busnardoi LO
Lenticulina munsteri (common)
Lenticulina heiermanni
Epistomina tenuicostata

Age: Hauterivian, probably early to mid Hauterivian.

Environment: Neritic, carbonate substrate; higher numbers of attached forms such as *Patellina subcretacea* Cushman & Alexander, *Trocholina infragranulata* Noth, *Globospirillina neocomiana* (Moullade), and *Spirillina* spp., indicate shallow neritic conditions.

Remarks: This assemblage displays high species diversity and high numbers of specimens. Preservation is good, colour is reddish.

Occurrence: Found in the 33/9-15 well between 2731.7 and 2733 m, and observed in numerous other wells in the Viking Graben. The foraminiferal assemblage at the base of the studied section in well 33/9-15 is dominated by *Globospirillina neocomiana* and *Patellina subcretacea*. At 2731.7 m, *Falsogaudryinella praemoesiana* is still common, but in the lower sample (2733 m) it is only represented by a single specimen. Accessory species include *Lenticulina munsteri*, ammodiscids, and nodosariids. A single occurrence of a species of *Protomarssonella* that resembles *M. kummi* is present at 2733 m.

This type of assemblage has not been observed offshore mid-Norway, where the lower part of the Lower Cretaceous interval (between the Upper Jurassic Spekk Formation and the Lower Cretaceous Lyr Formation) is missing.

Correlation: The assemblage probably corresponds to the *Marssonella kummi* (= FCN 3) zone of King *et al.* (1989) in the Viking Graben. The species *M. kummi* has been subsequently transferred to the genus *Protomarssonella* Banner & Desai (1987). This zone can be difficult to recognise, because the nominate species may be rare or absent.

The *Trocholina infragranulata* (=FCN 2) zone of King *et al.* (op.cit) was not utilized in this study, because its occurrence is facies-related, and clearly diachronous. King *et al.* regarded it as Valanginian, corresponding to the "basal Valhall limestone" facies of the Viking Graben. However, the species also occurs in limestones as young as Barremian in condensed facies deposited in shallower parts of the Viking Graben. Offshore mid Norway specimens were observed in the lower Barremian. Neagu (1975) also reported it from the Barremian of Romania.

None of the (more tethyan) shelly microfossil taxa reported for Hauterivian listed in the Millennium Atlas (Figure 2.4) were observed in Zone NCF1.

Falsogaudryinella praemoesiana Zone = NCF2 Zone

This zone contains a distinctive assemblage, defined on the concurrence of abundant Falsogaudryinella praemoesiana, abundant nodosariids and ostracods, and rare to common *Patellina* and *Globospirillina* (Figure 2.7a). In the study area, the zone corresponds to the basal part of the Lyr Formation. The following taxa were observed:

Falsogaudryinella praemoesiana LCO (abundant)
Falsogaudryinella tealbyensis (rare)
Falsogaudryinella xenogena (rare)
Recurvoides spp.
Glomospira spp. (rare)
Trocholina infracretacea (rare)
Patellina subcretacea
Globospirillina neocomiana
common to abundant nodosariids, and ostracods LCO
Lingulina semiornata LO
Lenticulina aff. subalata
Lenticulina cf. busnardoi LO
Lenticulina munsteri (common)
Lenticulina heiermanni LO
Lanticulina ouachensis wisselmanni LO (rare)
Citharina harpa (rare)
Planularia crepidularis (rare)

Epistomina tenuicostata LO (rare)
Epistomina hechti
Epistomina caracolla
Conorboides lamplughi LO
Lagena hauteriviana LO
Gavelinella sigmoicostata LO (rare)
small planktonics, including *Blefusciana* spp. (rare)

Age: Generally late Hauterivian, though locally persisting in early Barremian

Environment: Shallow to deep neritic.

Remarks: The upper boundary of the zone is recognised based on the LCO of *Falsogaudryinella praemoesiana*. The nominate species is abundant within the zone (as much as 50% of the assemblage), but it also persists in low numbers into the overlying zone. The assemblage is characterised by high species diversity, but also high dominance. It is often dominated by the species *Falsogaudryinella praemoesiana*, but *Recurvoides* and/or *Glomospira* may also be present in large numbers. The proportion of agglutinated taxa is higher compared with the underlying zone.

Direct comparisons with the type specimens of *Falsogaudryinella moesiana* Neagu described from the middle Albian of Romania revealed that the nominate species of this acme zone in the North Sea is indeed a different species. Because it has characters that are considered to be more primitive, Kaminski, Neagu and Platon (1995) erected the new species *Falsogaudryinella praemoesiana.*

Occurrence: The NCF2 Zone is readily observed in wells, offshore mid Norway. In the 33/9-15 well a single core sample collected from 2729 m contains an assemblage that is completely dominated by *Falsogaudryinella praemoesiana* and *Protomarssonella subtrochus.* Additional taxa include common ammodiscids *(Ammodiscus tenuissimus, Glomospira charoides, G. gordialis)*, *Lenticulina munsteri,* and *Globospirillina neocomiana*. Rare planktonic foraminifers are represented by *Blefuscuiana* spp.

Correlation: This assemblage corresponds to the *Falsogaudryinella moesiana* (= FCN 4) zone of King *et al.* (1989). King equated the top of this zone to the top of the Hauterivian. However, identification of the top of acme zones is subjective. In the Viking Graben, the maximum number of Falsogaudryinella praemoesiana, on average are found below the Munk Marl horizon, which is assigned to lower Barremian, but in some well sections, the acme of this species probably persists into Barremian. The species *Falsogaudryinella praemoesiana* also occurs in the upper Hauterivian of Romania (Dambovicioara Valley).

Falsogaudryinella xenogena Zone = NCF3 Zone

This zone is defined on the upper part of the ranges of *Falsogaudryinella xenogena, F. praemoesiana, Patellina, and Globospirillina* (Figure 2.7a). Assemblages assigned to the zone typically contain the following taxa:

Falsogaudryinella praemoesiana LO (rare)
Falsogaudryinella xenogena LO (rare)
Recurvoides spp.
Glomospira spp. (rare)
Textularia bettenstaedti
Ammobaculoides carpathicus LO (rare)
Trocholina infracretacea LO (rare)
Patellina subcretacea LO
Globospirillina neocomiana LO
common to abundant nodosariids and ostracods
Gavelinella barremiana FO
Lenticulina munsteri (common)
Lenticulina aff. subalata
Lenticulina guttata
Lenticulina saxonica LO
Saracenaria spp.
several unilocular taxa
Epistomina hechti LO
Epistomina ornata LO
Epistomina caracolla LO
Conorotalites bartensteini LO (rare)
small planktonics (*Blefuscuiana* spp.) (rare)

Age: Early Barremian

Environment: Neritic

Remarks: The assemblage assigned to this zone is easily distinguished from the overlying non-calcareous (agglutinated) foraminiferal assemblages by the presence of diverse, red-stained lenticulinids and nodosariids. The nominate species, *Falsogaudryinella xenogena* is never common; it co-occurs with *F. praemoesiana.*

Occurrence: Found widespread offshore mid Norway, where it is characteristic of the reddish, calcareous sediments of the Lyr Formation.

Correlation: Corresponds to the "Falsogaudryinella sp. X" (= FCN 5) zone of King *et al.* (1989)

The species illustrated by King *et al.* (op. cit.) was named *Falsogaudryinella xenogena* by Kaminski, Neagu and Platon (1995), partly because the authors wished to preserve the letter "x" in the name. The name also refers to the fact that is it "foreign", (i.e. not observed in the Tethys region). In the Viking Graben, the nominate species mostly occurs in the lower to middle Barremian. It generally occurs below the Munk Marl horizon, though it is occasionally observed in or above it, partially overlapping in range with *Gavelinella barremiana*, the nominate species of the overlying zone.

In the absence of the nominate taxon, the LO of diverse, reddish lenticulinids can be used to recognize the top of the zone. Offshore mid Norway, the sediments immediately overlying this zone are non-calcareous claystones, and its benthic foraminiferal assemblage is stained green. At localities in the Viking Graben (UKCS Blocks 21 and 22) where the Barremian section is more complete, the first downhole occurrence of diverse lenticulinids, and a peak in their relative abundance correlates to a level just below the Munk Marl (ca. 20 - 40 m below).

Offshore mid - Norway, the lateral equivalent of the Munk Marl horizon was not observed in the logs, possibly owing to the presence of a hiatus. This horizon represents a regional dysaerobic facies in the North Sea, and contains a distinctive, white-stained benthic foraminiferal assemblage, with common *Glomospira*. The species *Glomospira gaultina* is well represented in the Munk Marl.

Several taxa of this and the previous zone are listed for Hautervian-Barremian strata in the Millennium Atlas (Figure 4).

Gavelinella barremiana Zone = NCF4 Zone

This zone is defined on the upper part of the range of *Gavelinella barremiana* (Figure 2.7a). Assemblages assigned to this zone typically contain the following taxa:

Gavelinella barremiana LO
Glomospira spp. (common)
Recurvoides spp. (common)
small specimens of *Gyroidinoides* aff. *infracretaceus*

Age: Barremian
Environment: Deep neritic

Remarks: The assemblage consists of small-size, reddish-stained specimens. An accessory zonal species, tentatively identified as *Gyroidinoides* aff. *infracretaceus*, differs from the typical Albian form in its much smaller size and in possessing fewer chambers.

Occurrence: The zone is rarely observed offshore mid-Norway, due to the common presence of a hiatus. A single core sample collected at 2725 m in well 33/9-15 in the northern Viking Graben, recovered a rich foraminiferal assemblage assigned to this zone. The sample consists almost entirely of red-coloured calcareous benthic foraminifers, dominated by the Barremian index species *Gavelinella barremiana* Bettenstaedt. This species is the index taxon of the upper Barremian *G. barremiana* zone (= FCN 6 of King *et al.*, 1989). The sample also includes diverse nodosariids, and single specimens of *Gyroidinoides* and *Ammodiscus.*

Correlation: *Gavelinella barremiana* Bettenstaedt is a cosmopolitan species, known from the upper middle Barremian to upper Barremian of the northern North Sea, and from the upper Barremian to lower Aptian of northwest Germany, and offshore Canada. This zone is equivalent to the *G. barremiana* (= FCN 6) zone of King *et al.* (1989). In the Millennium Atlas the nominate taxon is listed from middle Barremian and Early Aptian.

Verneuilinoides chapmani Zone= NCF5 Zone

This zone is defined on the upper part of the ranges of *Verneuilinoides chapmani*, and *Caudammina crassa* (Figure 2.7a). Assemblages assigned to this zone consist mostly of green-stained, deeper water agglutinated foraminifers. However, in some wells, calcareous taxa may also be present with few specimens, especially at the base of the zone. The following agglutinated taxa have been observed:

Verneuilinoides chapmani LO
Caudammina crassa
Recurvoides spp. (common)
Glomospira sp. (common)
Cribrostomoides nonioninoides LCO (frequent)
Kalamopsis grzybowskii (rare)
Glomospira gaultina (rare)
Bathysiphon sp. (rare)
Rhabdammina, Rhizammina (few)

Age: Late Aptian – early Albian

Environment: Outer neritic – upper bathyal

Remarks: Taxonomic diversity is relatively high, and some deeper water taxa are present, including *Kalamopsis grzybowskii, Bathysiphon* sp., and *Caudammina crassa*. *Glomospira gordialis* is more common in the lower part of the zone. Increased number of tubular agglutinated forms such as *Rhabdammina, Rhizammina*, and *Bathysiphon* is interpreted as indicating deposition in deeper water. Dinoflagellate events present in this zone include the LO of *Lithodinia stoveri.*

Occurrence: Observed widespread, offshore mid Norway.

Correlation: The NCF5 Zone is equivalent to the *Verneuilinoides chapmani* (= FCN 8) zone of King *et al.* (1989). In the lower part of the zone, the ratio of *Glomospira gordialis* to *Glomospira charoides* increases considerably. This feature is often observed in the lower Albian of the Viking Graben, and probably denotes a more dysoxic environment. In the lowermost part of the zone, pyritized specimens of *Lenticulina*, and other calcareous benthics are occasionally observed. This is consistent with the observation by King *et al.* (1989), that calcareous benthic foraminifers sometimes "re-appear down section in the lowest part of the [*V. chapmani*] zone". King *et al.* (op.cit.) correlated the lowest part of zone FCN 8 with the uppermost Aptian. In the wells studied, the base of this zone lies disconformably upon the Barremian (mostly lower Barremian) Lyr Formation. Therefore, a regional hiatus that encompasses most of the Barremian and Aptian is deemed to be present. The hiatus corresponds to a change in lithology from reddish marls and limestones below, to greenish non-calcareous claystones above.

Recurvoides/Glomospira Zone= NCF6 Zone

This assemblage zone contains the following characteristic species:

Recurvoides spp. (acme)
Plectorecurvoides irregularis
Glomospira charoides (abundant)
Glomospira gordialis
Ammodiscus spp.
Uvigerinammina una (rare)
Cribrostomoides nonioninoides (rare)
Textularia spp. (rare)
Pseudobolivina variabilis
Gyroidinoides infracretaceus
Gavelinella intermedia

Age: Middle Albian

Environment: Upper bathyal Remarks: The assemblage is strongly dominated by *Recurvoides* spp., and *Glomospira* spp. Other agglutinated taxa listed above often occur as single specimens. Calcareous benthic and planktonic forms are rare in this zonal interval, and may represent caving.

Occurrence: The zone is missing in many wells due to a widespread hiatus of Aptian through early middle Albian age; it occurs condensed in well 6406/2-2.

Correlation: This zone corresponds to the *Recurvoides* sp. (= FCN 10a) zone of King *et al.* (1989). The species *"Globigerinelloides" gyroidinaeformis* has not been observed offshore mid-Norway. It is, however, known from the northern Viking Graben in well 33/9-15 at 2723 m, dated latest early Albian. The core sample collected at 2723 m in that well contains an assemblage comprised mainly of calcareous benthic species and *Hedbergella*. The dominant (and most distinctive) taxon is *"Globigerinelloides" gyroidinaeformis* Moullade, a species that is probably a benthic form because of slight streptospiral coiling, a feature unusual for planktonics. Moreover, it is often found in assemblages where other well-known planktonic forms are absent. This distinctive species is often observed in acmes (floods), and defines the latest early Albian *"Globigerinelloides" gyroidinaeformis* (FCN 9) zone in the Viking Graben of King *et al.* (1989). The species is also known from the Grand Banks, offshore eastern Canada, and from the Vocontian Basin, France. This stratigraphic level has not been observed offshore mid Norway; either the species is ecologically excluded from the area or a late Early Albian hiatus is present in the offshore mid-Norway area.

Uvigerinammina una Zone - NCF7 Zone

This zone is defined on the upper part of the range of *Uvigerinammina una*, together with *Ammoanita globorotaliaeformis* (Plate 2.1). Assemblages assigned to this zone generally consist of diverse, green-stained deep-water agglutinated foraminifers, with few calcareous benthics present, and common to frequent planktonics, belonging to few species. The following taxa have been observed in the zone:

Uvigerinammina una LO (common)
Falsogaudryinella alta
Textularia bettenstaedti (rare)
Haplophragmoides spp.
Reophax troyeri LO
Ammoanita globorotaliaeformis LO
Cribrostomoides nonioninoides LO
Trochammina abrupta
Gyroidinoides infracretaceus
Gavelinella intermedia
Pleurostomella barrowsi LO
Glomospira charoides
Glomospira gordialis
Hedbergella planispira FCO
Hedbergella infracretacea (common)
Hedbergella delrioensis (rare)
Globigerinelloides bentonensis (rare)

Age: Late middle to early late Albian

Environment: Upper bathyal

Remarks: Assemblages assigned to this zone, typically are comprised of agglutinated, and few calcareous benthic taxa, and often common to frequent planktonics, mostly *Hedbergella planispira*. The nominate taxon, *Uvigerinammina una*, apparently is a boreal species restricted to the Norwegian Sea and North Sea region. It appears not to possess calcareous cement, hence it cannot be assigned to the genus *Falsogaudryinella*. Most likely it belongs in the genus *Uvigerinammina*, as originally reported by Burnhill & Ramsay (1981).

It has not been found in the Albian of the Kirchrode-1 Borehole (Jaroslaw Tyszka, personal communication), or in North Atlantic oceanic deposits. The acme of *Uvigerinammina una* itself often forms a narrow zone, but it is also found in low numbers in both the overlying and underlying zones. Additionally, the LO of *Pseudonodosinella troyeri* (= *Reophax minuta* of other authors) and the LO of *Textularia bettenstaedti* have been observed in this zone. Both events are reported to occur within the early Albian *"R. minuta* zone" (zone FCS 8), of King *et al.* in the southern North Sea.

According to our observations, *Ammoanita* (*Trochammina*) *globorotaliaeformis* has a tighter coil than the Paleocene *A. ingerlisae* Gradstein & Kaminski and, on average more (not fewer) chambers in the last whorl. In local well completion reports such specimens are referred to as *Trochamina 'globorotaliaformis'*, and constitute a useful mid-upper Albian index species.

Dinoflagellate events present in his zone include *Apteodinium grande* LCO, and *Lithosphaeridium arundum* LO; *Ovoidinium scabrosum* and *Endoceratium turneri* range upwards through this zone.

The number of planktonic foraminifers locally increases stratigraphically upwards in Zone NCF7, reflecting a change from more restricted marine (dysaerobic) to more oxygenated, open marine conditions. A similar change was reported by King *et al.*, (1989) from the northern North Sea, as reflected in a change from non-calcareous to calcareous claystone (top of Sola Formation).

Occurrence: Found in a majority of wells studied, offshore mid-Norway.

Correlation: This zone corresponds to the *Falsogaudryinella* sp 1 (FCN 10b) zone of King *et al.* (1989). In the Kirchrode-1 Borehole in the Lower Saxony Basin, the change from dominant *Hedbergella planispira* (below) to *Hedbergella delrioensis* (above) is observed within the early late Albian *P. columnata* calcareous nannofossil zone, and the *Ticinella raynaudi* planktonic foraminiferal zone of Randrianasolo and Anglada (1989; Weiss, 1997). The zone probably correlates to the *inflatum* ammonite zone.

Osangularia schloenbachi Zone = NCF8 Zone

This zone is defined on the upper part of the stratigraphic range of *Osangularia schloenbachi. Sigmoilina antiqua, Falsogaudryinella alta,* and *Globigerinelloides bentonensis* co-occur (Figure 2.7). Assemblages assigned to this zone typically contain the following taxa:

Osangularia schloenbachi LO (rare to common)
Gavelinella intermedia
Gyroidinoides infracretaceus
Sigmoilina antiqua
Lenticulina muensteri
Epistomina spinulifera LO
Valvulineria gracillima (rare)
Falsogaudryinella alta LO (rare)
Clavulina gaultina
Glomospira charoides (often common)
Ammodiscus tenuissimus
Hedbergella infracretacea LO (common)

Hedbergella infracretacea LO (common)
Hedbergella delrioensis FCO
Hedbergella planispira (rare)
Globigerinelloides bentonensis FO
pink coloured *Inoceramus* prisms
Age: Late Albian
Environment: Upper bathyal

Remarks: This is a diverse assemblage, comprised of calcareous and agglutinated taxa, stained green. The species *Osangularia schloenbachi* occurs as an acme, and rare specimens are often found in the underlying zone. The species is known from the upper Albian of Romania, Poland, Germany and France, andprobably originated in Tethys (Price, 1976). In addition to the nominate taxon, *Gavelinella intermedia, Gyroidinoides infracretaceus,* and lenticulinids are also common, as well as *Glomospira charoides*. Planktonic foraminifers are often abundant, and are strongly dominated by small specimens of *Hedbergella delrioensis*, probably the stratigraphic onset (FCO) of a regional bloom that ends in the *H. delrioensis* LCO zone, as discussed below.

Dinoflagellate taxa present in the zone include *Lithosphaeridium conispinum* LO, *Lithodinium arundum* LO, *Ovoidinium scabrosum* LCO and *Apteodinium grande* LO, marker taxa for upper Albian (Costa and Davey, 1989; E. Monteil, pers. comm., 1997).

In the RASC scaled optimum sequence of Figure 2.5 this zone is represented by a tight cluster of 5 events, and in the corresponding optimum sequence of Figure 2.5 by taxa at rank positions 85 - 90.

Occurrence: Found in several of the wells, offshore mid-Norway. Where *O. schloenbachi* is rare, recognition of the zone may be hampered by cavings from overlying, fossiliferous strata assigned to lower Cenomanian. An uppermost Albian hiatus in some of the wells, may truncate part of this zone, possibly related to the pronounced eustatic offlap cited by Hardenbol *et al.* (1993), and by Rohl & Ogg (1996) at the base of the *inflatum* zone. The hiatus is visualized by the large interfossil distance below *A. grande*, at the base of the RASC interval zone in Figure 2.5.

Correlation: This zone corresponds to the *Osangularia schloenbachi* (= FCN 12a) zone of King *et al.* (1989; see also Crittenden, 1983). King *et al.* (1989) reported that the stratigraphical range of this species is diachronous from south to north, occurring in the mid-Albian in the southern sector of the North Sea, but persisting to the upper Albian in the Viking Graben. The underlying *Globigerinelloides bentonensis* (=FCN 11) zone of King *et al.* (1989) is not recognised in the study area owing to the rarity of this species. In the Kirchrode-1 Borehole in the Lower Saxony Basin, NW Germany, the level with abundant *Globigerinelloides bentonensis* correlates to the late Albian *E. turriseiffelii* calcareous nannofossil zone (Weiss, 1997). The zone probably correlates to the *dispar* ammonite zone.

Sigmoilina antiqua Zone = NCF9 Zone

This zone is defined on the upper part of the stratigraphic range of *Sigmoiliona antiqua. Textularia* sp. 1 Burnhill&Ramsay, *Pseudotextularia cretosa, Recurvoides imperfectus* and *Plectorecurvoides alternans* also occur in this zone. Assemblages assigned to this zone typically contain the following taxa:

Sigmoilina antiqua LO
Pseudotextulariella cretosa LO
Spiroplectinata annectens LO
Arenobulimina advena
Marssonella ozawai
Textularia sp. 1 Burnhill&Ramsay (1981) LO
Textularia chapmani
Textularia foeda
Plectorecurvoides alternans LO
Recurvoides imperfectus LO
Hippocrepina depressa
Valvulineria gracillima
Hedbergella delrioensis FCO
Hedbergella planispira
Gavelinella sp. X (unpublished) LO
Gavelinella intermedia
Lingulogavelinella jarzevae
pink coloured *Inoceramus* prisms
Age: Early Cenomanian
Environment: Upper bathyal

Remarks: *Sigmoilina antiqua*, the nominate taxon is rare. Its stratigraphic range extends from the two underlying zones, *Uvigerinammina una* Zone and *O. schloenbachi* Zone, into this zone. Average LO events that co-occur in this zone are *Pseudotextulariella cretosa, Marsonella ozawai, Arenobulimina advena,* and other taxa listed above. *Gavelinella* sp. X, with its steep last chamber is probably a new form, and together with *Textularia* sp. 1 may be restricted to the northern North Sea and Norwegian Sea. When and where found with sufficient number of specimens, offshore Norway, both taxa might be formally described as new taxa. The planktonic foraminifers *Hedbergella delrioensis* and *H. planispira* locally are common in this zone; *Globigerinelloides bentonensis* occurs with few specimens, and is only common in the immediately underlying zone.

The dinoflagellates *Ovoidinium verrucosum* and *Endoceratium turneri* on average top in this zone, and in fact form the constituent zonal cluster in the scaled optimum sequence (Figure 2.5), which correlates to the optimum sequence (Figure 2.5) at rank positions 80 to 84.

According to King *et al.*, (1989), the LO events of foraminifers in this zone are indicative of lower Cenomanian strata, in agreement with the upper part of the stratigraphic range of the dinoflagellate taxon *Ovoidinium verrucosum* (see Costa and Davey, 1992).

Occurrence: Widespread offshore mid-Norway. In sandy lithology (for example in gravity flows assigned to the Blålange Formation), this zone may be difficult to detect. The lack of clustering of events assigned to this zone in the scaled optimum sequence (Figure 2.5) indicates considerable 'noise', including missing data, in the wells that penetrate this stratigraphic level. The zone may be identified in well 6507/2-3 near 3350 m, and in well 35/3-4 near 3370 m.

Correlation: This zone corresponds to the *Sigmoilina antiqua* (= FCN 12b) zone of King *et al.* (1989), and to the upper part of the deep marine assemblage zone with *Plectorecurvoides alternans* (Geroch & Nowak, 1984). The zone probably correlates to the lower part of the *mantelli/cantianum* ammonite zone.

Hedbergella delrioensis LCO Zone = NCF10 Zone

This distinctive zone is defined on the LCO of *Hedbergella delrioensis*; it may occur in floods, accompanied by the LCO of *H. planispira* (Figures 2.5 and 2.9). The following taxa have been observed in assemblages assigned to this zone:

Hedbergella delrioensis LCO (common to abundant)

Hedbergella planispira LCO (common to frequent)

Hedbergella sigali (rare)

Whiteinella brittonensis FO (isolated occurrence, rare)

Praeglobotruncana praehelvetica FO (isolated occurrence, rare)

Gavelinella intermedia (rare)

Gavelinella cenomanica (rare)

Valvulineria gracillima (rare)

Lingulogavelinella jarzevae LO (rare)

Arenobulimina spp. (rare)

Glomospirella gaultina

Recurvoides imperfectus LO

Hippocrepina depressa LO

Plectorecurvoides spp. LO

Textularia sp. 1 LO (rare)

Textularia foeda (rare)

Age: Late early Cenomanian, possibly extending into early middle Cenomanian

Environment: Upper bathyal

Remarks: In many wells, including 35/3-5 between 3035 and 2930 m, 6507/2-3 between 3300 and 3200 m, and 6507/6-2 near 2950 m, a distinctive assemblage is observed with *Hedbergella delrioensis* LCO (last common and last consistent occurrence, as observed uphole), in association with *Gavelinella intermedia, G. cenomanica, Valvulinera gracillima, Lingulogavelinella jarzevae, Plectorecurvoides alternans, Recurvoides imperfectus, Hippocrepina depressa, Glomospirella gaultina, Ammophaeroidina* sp 1 (RRI), *Eggerellina mariei, Textularia foeda,* and *Tritaxia pyramidata*. The majority of benthic taxa assigned to this zone are rare. Among planktonics *Hedbergella planispira* LCO occurs slightly down in this zone; *H. sigali, Whiteinella brittonensis* and *Praeglobotruncana praehelvetica* occur at few localities only in this zone, and are rare; in two wells (35/3-5 and 36/1-2) single specimens of *Rotalipora* cf. *greenhornensis* were reported.

Among dinoflagellates occur (average LO) *Rhombodella paucispina, Fromea* sp. 2, *Epelidosphaeridia spinosa, Xiphophoridium alatum* and *Litosphaeridium siphoniphorum.* The latter two taxa may extend in the overlying zone. The first (up well) occurrence of *Heterosphaeridium difficile* is in this zone (e.g. in well 6507/7-1 at 3506 m), as reported by Bell & Selnes (1997). These authors regard this event to be close to the boundary of lower and middle Cenomanian, in good agreement with stratigraphic evidence cited below.

The dinoflagellate assemblage with *E. spinosa, R. paucispina, X. alatum* and *L. siphoniphorum* overlap ranges in lower Cenomanian strata (Costa and Davey, 1992). The benthic foraminifer *L. jarvzevae* in the southern North Sea ranges upwards into the lower Cenomanian (King *et al.*, 1989). The possible presence in this zone of the planktonic foraminifer *Rotalipora greenhornensis* would indicate an early to middle Cenomanian age. *Recurvoides imperfectus* and *Plectorecurvoides irregularis* commonly occur in the older zones described above, and occasionally range upwards into this zone, together with *Hippocrepina depressa*. The upper range of these taxa Geroch and Nowak (1984) assigned to the *Plectorecurvoides alternans* Zone in the Carpathians extends into the lower part of Cenomanian. According to Prokoph (1997), the upper part of the LCO of *H. planispira* and *H. delrioensis* in NW Germany corresponds to the *dixoni* ammonite zone of late early Cenomanian age. We adhere to this correlation for offshore Norway.

From the age of the underlying and immediately overlying zones, and the evidence cited above, we assign the *Hedbergella delrioensis* LCO zone to the upper part of the lower Cenomanian, possibly extending into middle Cenomanian (see below).

Occurrence: Widespread and distinctive, offshore mid-Norway.

Correlation: The zone overlaps with the lower part of the northern North Sea zone of *H. brittonensis* (= FCN 13) of King *et al.*, (1989) containing abundant hedbergellids, assigned broadly to the middle part of Cenomanian. Offshore mid-Norway, the top of the zone is below or in sand of the basal Lysing Member. Since recognition of the zone is dependent on suitable, shaly lithology (the widespread gravity flow sands are not fossiliferous), the full stratigraphic extent of the zone remains to be determined

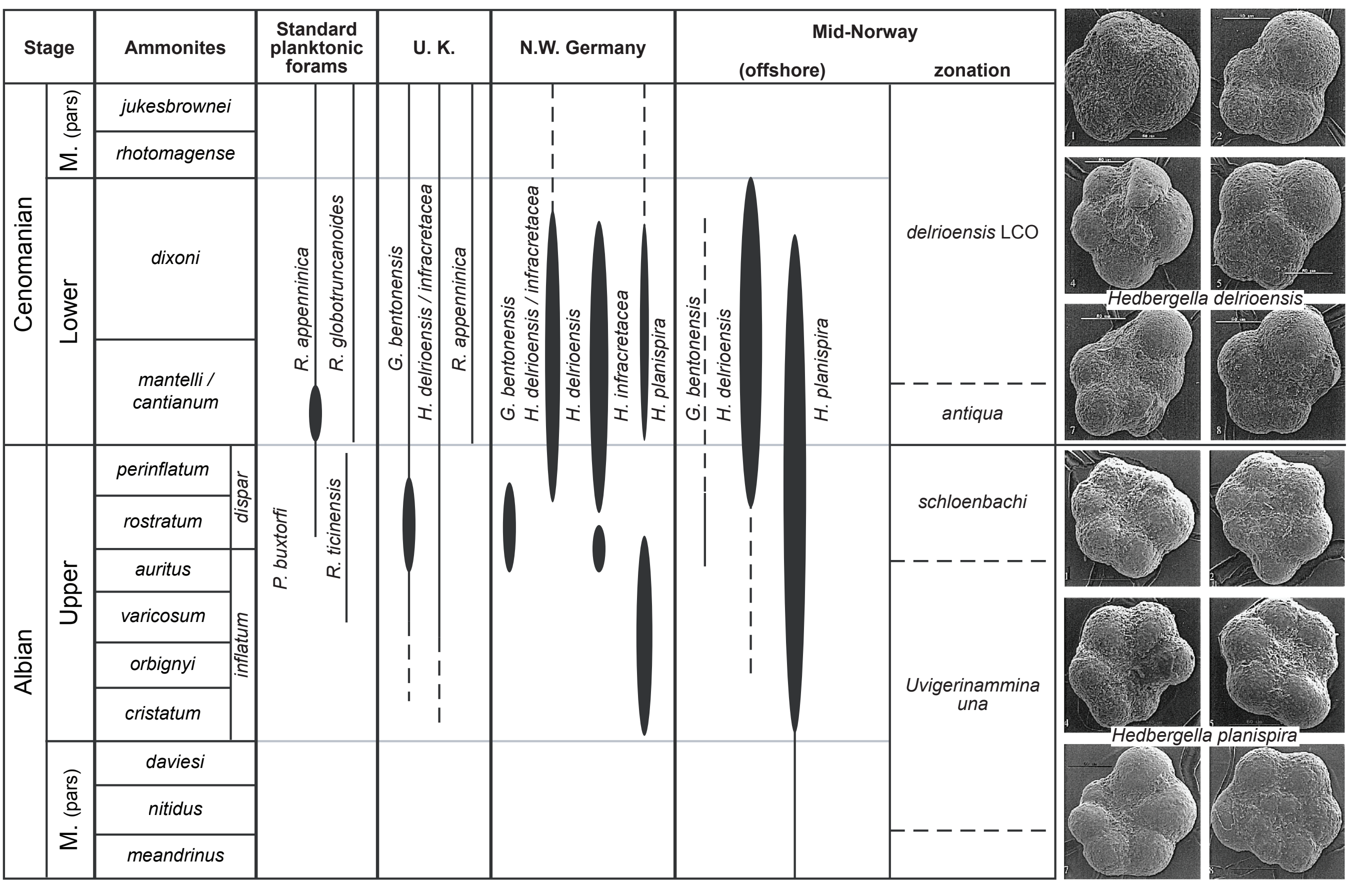


Figure 2.9. Boreal planktonic foraminifera acmes, offshore mid-Norway, correlated to similar acmes in NW Germany and U.K. (Prokoph, 1997; Hart 1993). Also shown are the standard ammonite and planktonic foraminifer zonations for the interval, and the regional RASC zonation. The prominent *Globigerinelloides bentonensis* acme in NW Europe is barely recognizable offshore Norway, which region is peripheral to its distribution. Reasons for the acmes are discussed in the text.

It probably incorporates a flooding horizon in the upper part of the lower Cenomanian, truncated by the mid-Cenomanian non-sequence (like the Rouen hardground of northern France), discussed below.

Whiteinella brittonensis Zone = NCF11 Zone

This zone is defined on the lower part of the range of *Whiteinella brittonensis*, with rare *Hedbergella* spp. and *Praeglobotrunacana* spp. Also present may be *Gavelinella intermedia*, *Valvulineria gracillima*, and *Glomospirella gaultina*. *Dicarinella* and *Marginotruncana* taxa are not present in this zonal interval. The following taxa have been observed in assemblages assigned to this zone:

Hedbergella delrioensis (rare)
Hedbergella planispira (rare)
Clavihedbergella simplex LO (rare)
Whiteinella brittonensis FO
*Gavelinella cenomanic*a LO (rare)
Gavelinella intermedia LO (rare)
Lingulogavelinella spp.
Valvulineria gracillima LO (rare)
Bulbobaculites problematicus
Glomospirella gaultina LCO
Uvigerinammina (pre-) jankoi
Ammosphaeroidina sp.
Eggerellina mariei LO

Age: Late middle to early late Cenomanian

Enviroment: Upper bathyal

Remarks: The interval from the level of the dinoflagelates *Batioladinium jaegeri* LO upwards to *Heterosphaeridium difficile* LCO, between optimum sequence positions 68 and 47, groups relatively tightly (Figure 2.5). This tight clustering in the scaled optimum sequence is the result of frequent cross-overs of the events in the wells.

A tight, lower subgroup in this interval, corresponding to rank positions 68 to 64 in the optimum sequence of Figure 2.5 is assigned to the *W.brittonensis* Zone, with the events listed above, some of which are scarce, or absent in the northern part of the region under study. The depth interval in wells that might be expected to contain this zone is often impoverished in fossils due to poor sample recovery from turbine drilling, widespread paleo watermass dysaerobia, stratigraphic hiatusess, or gravity flow sands. This zone and the immediately overlying one may be difficult to separate.

As far as may be determined, this zone contains rare *Hedbergella delrioensis, H. planispira, Uvigerinammina (prae-) jankoi, Glomospirella gaultina, Gavelinella intermedia, G. cenomanica, Ammosphaeroidina* sp.*, Eggerellina mariei,* and *Whiteinella brittonensis*. Occasional events are *Clavihedbergella simplex*, and a specimen of *Rotalipora* cf. *greenhornensis* in southern well 36/1-2 at 2660 m. The age assigned to the zone is late middle to early late Cenomanian.

Among dinoflagellate occur *Batioladinium jaegeri* LO, *Endoceratium dettmaniae* LO, *E. ludbrookii* LO, *Dorocysta litotes*, and *Lithosphaeridium siphoniphorum* LO (southern wells only). These events together are assigned a late middle to early late Cenomanian age (Costa and Davey, 1992), in agreement with the age assigned to the *W. brittonensis* Zone.

Occurrence: The zone is widespread, offshore Norway, but not easy to recognize, due to sandy facies.

Correlation: The *W. brittonensis* zone corresponds to the zone of the same name for the shale facies of the northern North Sea (King *et al.*, 1989). It is possible that the upper part of the zone includes part of the unfossiliferous beds that occur as a result of widespread dysaerobia, or anoxia near the Cenomanian/Turonian boundary (see below).

Dicarinella Zone = NCF12 Zone

This zone is defined on the presence of *Dicarinella hagni-indica, D. imbricata*, or *D. primitiva*. Other key taxa that may be present include *Whiteinella inornata, W. paradubia, Praeglobotrunaca stephani* LO, and *Hedbergella hoelzi* LO. The following taxa have been observed in assemblages assigned to this zone:

Dicarinella hagni - indica LO
Dicarinella imbricata LO
Dicarinella primitiva LO
Gaudryina filiformis (= *Gerochammina lenis*)
Hedbergella delrioensis LO (isolated specimens)
H.planispira LO (isolated specimens)
Hedbergella hoelzi LO
Praeglobotruncana stephani LO
Whiteinella brittonensis LO
Whiteinella inornata
Whiteinella paradubia
Marginotruncana marginata FO
Heterohelix globulosa (rare)

Bulbobaculites problematicus LO
Stensioeina humilis LO (rare)
Lingulogavelinella spp. (rare)
Gavelinella balthica (rare)
Rzehakina spp FO (incl. *R. minima*)
Caudammina ovuloides
Uvigerinammina jankoi (rare)
Psammosphaera spp. (frequent)
Allomorphina pyriformis LO
Allomorphina halli LO
C/T boundary gamma spike (more than one spike may be present)
pyritized small diatoms (frequent)
pyritized spumellarian radiolarians (rare)

Age: Latest Cenomanian - middle Turonian

Enviroment: Upper bathyal

Remarks: For the reasons, mentioned also with the immediately underlying zone, this zone maybe difficult to separate from the underlying one. Where siliciclastic sedimentation rates are high, with predominant gravity - flow sands, a typical *Psammophaera*/small pyritized diatom biofacies occurs, sprinkled with isolated *H. delrioensis, H. planispira* or *Dicarinella.* In few wells, particularly in the south where sand is less common, planktonic foraminifers are more diverse than in the immediately underlying or overlying zones, and include *Praeglobotruncana stephani, P. delrioensis, Dicarinella hagni - indica, Dicarinella imbricata, Marginotruncana marginata* FO, *Dicarinella primitiva, Hedbergella hoelzi, H. delrioensis* (rare), *Whiteinella archeocretacea, W. inornata, W.paradubia*, and *W. brittonensis. Marginotruncana* is mostly rare and only represented by *M. marginata.* From the overlap of planktonic foraminiferal ranges, the zone may be assigned a late Cenomanian through early middle Turonian age (Robaszynski *et al.*, 1983; Stainforth, 1981). *Marginotruncana marginata* and *Dicarinella* are restricted to post Cenomanian strata and assist with constraining the age of the upper part of the zone.

It is likely that rare last occurrence in this zone of *Uvigerinammina jankoi* is in situ, since this taxon is known from the Turonian through Santonian (see e.g. Geroch and Nowak, 1984).

The assignment of an event labelled Cenomanian/Turonian (C/T) boundary gamma spike reflects our hypothesis that a distinct and narrow (less than a few meters thick) gamma ray high on physical well logs, near the base of this zone, corresponds to the well--known, global oceanic, 'anoxic', Event -2 (Bonarelli), reported widely in latest Cenomanian through earliest Turonian strata. The exact reason for the spike in the wells is unclear, but it is assumed to be high thorium concentration, associated with organic rich levels. We have no reason to believe that the spike is a local feature; in few wells more than one spike occurs over a short interval in this zone. From cuttings it cannot be ascertained that the spike is actually associated with an interval barren of microfossils, but in cores in well 6507/2-3 a distinct reduction to virtually no microfossils at and below the C/T boundary gamma spike at 2972 m is observed. A peculiar, monotypic *Nyktericysta / Australosphaera* dinocyst assemblage maybe more or less associated with this 'Bonarelli' type interval (G. Bell, pers. comm., 1996), although RASC does not link the two events closely on average (Figure 2.5). Reason for the latter may be high variance in the average stratigraphic position of both events.

Considerable confusion exists over the identity of triserial to twisted biserial agglutinated benthic foraminifer specimens commonly found in the middle to upper Cretaceous of wells. Caved (?) *Karrerulina conversa* may be mislabelled as *Gaudryina filiformis*, and be difficult to distinguish from it. A detailed taxonomic study of such morphotypes in the wells is warranted.

In core sample 2885.5 m in well 6507/2-3, assigned to this zone, *Rzehakina minima* has its first stratigraphic occurrence. Such would agree with the report by Kaiho and Hasegawa (1994) that in Japan *Rzehakina* (*R. epigona*) appears in Turonian strata. *Bulbobaculites problematicus* commonly occurs in this zone, and rarely in the immediately underlying one, which agrees with broad age assignment for this taxon in Kuhnt & Kaminski (1990).

Among dinocyst events occur *Maghrebinia membraniphorum* LO, *Palaeohystrichosphera infusorioides acme* and LCO, *Heterosphaeridium difficile* FCO, *Stephodinium coronatum* LO, and *Spiniferites porosus.* According to Costa and Davey (1992) these taxa are associated with Turonian strata. *Dorocysta litotes* LO alo may be present, but was omitted from RASC input data due to erratic stratigraphic occurrence.

The age of the *Dicarinella* zone is Turonian in its

its upper part, while the lower part may extend downward into Cenomanian, hence the zone is bracketed to occur across the C/T boundary. High sedimentation rates, a sandy, dysaerobic facies with occasionally much pyrite, and turbo drilling in many wells prevent satisfactory stratigraphic resolution across this interval.

Occurrence: This zone is widespread and relatively thick, offshore Norway.

Correlation: The *Dicarinella* zone corresponds to the zone of the same name in the northern North Sea, characterised by a downhole influx of abundant planktonic foraminifers, dominantly hedbergellids and *Dicarinella* spp. (King *et al.*, 1989). The lower part of the zone contains strata coeval to the organic- rich Plenus marls and the Blødoks shales of the North Sea and England.

Marginotruncana Zone = NCF13

This zone is defined on the presence of *Marginotruncana marginata, M. coronata, Globotruncana linneiana* gr.*,* and *G. fornicata* (primitive morphotype). The following taxa have been observed in assemblages assigned to this zone:

Margintruncana marginata

Marginotruncana fornicata (primitive morphotype)

Marginotruncana coronata

Globotruncana linneiana gr.

Dicarinella concavata (isolated specimens)

Dicarinella carinata (isolated specimens)

Whiteinella archeocretacea

Conorbina supracretacea

Lingulogavelinella sp.

Nuttalina florealis

Globorotalites spp.

Gaudryina filiformis

Uvigerina jankoi

Haplophragmoides aff. *walteri* (*sensu* Kuhnt & Kaminski, 1990)

Inoceramus needles

Age: Late Turonian - Coniacian

Enviroment: Upper bathyal

Remarks: This zone is recognized in few wells in the southern part of the study region, where it constitutes a downhole influx of *Marginotruncana, Globotruncana* and *Whiteinella*. A distinct influx of *Marginotruncana,* together with *Whiteinella* was for example observed in the 35/3-4 well, together with isolated specimens of *Dicarinella concavata* and *D. carinata*. The overlap of ranges of the latter two taxa is indicative of Coniacian strata (Robaszynski *et al.*, 1983).

The zone constitutes the upper part of high sedimentation rate interval and sandy facies in northern wells, where globotruncaniid planktonic foraminifers are mostly absent; hence recognition of the zone may be difficult. The large interfossil zone limit in Figure 2.5 (left) at *H. difficile* LCO reflects this important stratigraphic facies change; in the optimum sequence of Figure 2.5 (right) the zone is recognized at rank positions 47 - 50.

The (local) relative abundance of *Marginotruncana*, together with *H. difficile* probably is the result of a condensed sedimentary sequence under open marine and relatively warm water conditition. Unfortunately, the dinoflagellate cyst *Heterosphaeridium difficile* may display more than one LCO or acme, hence this event may not be unique. The acme ccurrence of *H. difficile*, according to Costa and Davey (1992) suggests a Turonian age, with the taxon ranging into the Coniacian. Among dinoflagellate cyst that range through the upper part of the zone, and may extend slightly in the overlying foraminiferal *S. granulata polonica* zone, are *Chatangiella* sp. 1 Stratlab, *Trithyrodinium 'reticulatum,' Surculosphaeridium longifurcatum* and *Heterosphaeridium difficile.*

Occurrence: This zone is clearly recognized in southern well 35/3-4 from 2425 - 2460 m. Where globotruncaniid foraminifers are missing, as in many northern wells, recognition of the zone may be difficult.

Correlation: A *M. marginata* zone is defined by King *et al.*, (1989) for the northern North Sea, and was assigned a late Turonian through early Coniacian age. These authors extend the overlying *S. granulata polonica* interval zone beyond the Santonian range of the nominate taxon down into the upper Coniacian. We restrict the *S. granulata polonica* zone to the Santonian.

Stensioeina polonica Zone = NCF14

This distinctive zone is defined on *Stensioeina (granulata) polonica* LO. The following taxa have been observed in assemblages assigned to this zone:

Stensioeina (granulata) polonica LO
Globorotalites multiseptus
Nuttalina florealis
Gavelinella beccariiformis FO
Epistomina supracretacea
Globotruncana marginata (rare)
Globotruncana linneiana group (rare)
Globotruncana fornicata (rare)
Heterohelix sp.
Inoceramus needles (common)
Archeoglobigerina spp.
Allomorphina sp.
Tritaxia spp.

Age: Early to middle Santonian

Enviroment: Upper bathyal

Remarks: The nominate zone marker is the key taxon in this easily recognizable zone, with the last stratigraphic occurrence of the nominate species delimiting its upper boundary. The zonal interval also contains various other calcareous taxa, listed above. Planktonic foraminifers decrease stratigraphically upwards in this zone, and are much more typical for the immediately underlying zone. Deep marine agglutinated benthics mostly are scarce, but less so offshore mid-Norway. *Uvigerinammina jankoi* only was observed in few southern wells. Lenticular radiolarians also occur. In some wells the immediately overlying *Inoceramus* LCO zone and this zone are merged (see below).

Occurrence: This zone occurs widespread, offshore Norway, and in some wells where the *Inoceramus* LCO zone merges with this zone, constitutes the first downhole carbonate rich interval, below the thick siliciclast interval assigned a Campanian age.

Correlation: This zone correlates to the *Stensioeina granulata polonica* zone of Koch (1977) of early and early middle Santonian age in NW Germany. This is the only *Stensioeina* taxon from the evolutionary plexus of *Stensioeina* that is widespread, offshore Norway, and also is observed in the Voering Basin. Elsewhere in NW Europe six or more successive *Stensioeina* zones are recognized from Turonian to Campanian age. King *et al.* (1989) also recognizes the *polonica* zone (FCS18), but these authors extend the zone below the range of the nominate species down into the Coniacian.

Inoceramus LCO Zone = NCF15

This zone contains the following characteristic event:

Inoceramus LCO

This zone is recognized from a relative abundance of *Inoceramus* needles that constitute the first carbonate rich interval downhole following a thick, siliciclastic Campanian section, with pyritized diatoms, deep water agglutinated foraminifers, and locally radiolarians. In a few wells, such as 35/3-4 this zone merges with the immediately underlying *S. granulata polonica* zone, but on average the two events are clearly superpositional (Figure 2.5), possess low variances, and are assigned to successive and separate zones. Spherical and lenticular radiolarians may be common in this zone, but are more so in the overlying *Fenestrella bellii* zone. In the southern part of the study area (34 and 35 blocks), the lower stratigraphic ranges of *Tritaxia dubia, Globotruncana bulloides* and *Whiteinella baltica* are in this zone, and *Archaeoglobigerina* may also be present.

The sudden disappearance of common *Inoceramus* needles, stratigraphically upwards suggests a regional hiatus to span a part of upper Santonian and lower Campanian.

Age: Late Santonian

Enviroment: bathyal

Occurrence: The *Inoceramus* LCO zone is widespread, offshore Norway, and easily recognizable.

Correlation: This zone correlates to the 'radiolaria' zone, or part of it, in the North Sea (King *et al.*, 1989) which zone according to these authors may have a somewhat spotty distribution northward. The latter might be the result of local dissolution of silica. The distribution of the *Inoceramus* zone north of the North Sea reflects a temporal increase of carbonate productivity during a time of limited terrigenous sedimentation.

Fenestrella bellii Zone = NCF16

This distinctive zone is defined on the presence of a small, pillbox diatom with an oval cross-section, a sharp periphery and sometimes a small dimple, named *Fenestrella bellii* (Appendix 1 and Plate 1). It may occur in floods, accompanied by rare to common deep water agglutinated foraminifers, and rare to common spherical/lenticular radiolarians. The following taxa have been observed in assemblages assigned to this zone:

Fenestrella bellii LO

spherical/lenticular radiolarians (rare to common)

Rzehakina epigona LO

Haplophragmoides aff. *walteri* LO (*sensu* Kaminski&Kuhnt, 1990), (rare)

Spiroplectammina navarroana

Trochamminoides spp.

Deep water agglutinated foraminifers, undifferentiated

Remarks: Above the *Inoceramus* LCO zone, an interval occurs in many wells with a small, morphologically distinctive, pyritized diatom, informally named Diatom sp. H in well reports, and here assigned to *Fenestrella bellii* (see Appendix 1). Spherical/lenticular radiolarians may be common, and so are coarse agglutinated benthic foraminifers with organic cemented tests. The latter include *Karrerulina conversa, Haplophragmoides* aff. *walteri* (sensu Kaminski & Kuhnt, 1990), S*piroplectammina navarroana, Paratrochamminoides olszewska, P. mitratus, Trochamminoides subcoronatus,* and *Rzehakina epigona*, all of which may extend slightly higher in the section, above this zone. *Rzehakina epigona* has a high variance, and is not a reliable correlation event; although offshore Norway it disappears on average in *the F. bellii* zone.

Various taxa of *Trochamminoides*, listed above, in the North Atlantic underwent an evolutionary radiation in the early Campanian, an 'event' clearly recorded offfshore Norway in flysch-type, bathyal strata. In exploration well reports, the distinct *Trochamminoides* taxa are commonly lumped under *Paratrochamminoides irregularis*. The appearance and local disappearance (or probably more correctly, the part of the stratigraphic range of the genus where its taxa become rare) is in Campanian strata. In deeper bathyal settings, like in the Voering Basin, *Gaudryina filiformis* occurs in this zone (cf. Geroch & Nowak, 1984), but maybe difficult to separate from the younger ranging *Gerochammina lenis* Neagu. In Figure 2.5 (left) *the F. bellii* assemblage forms a distinct interval zone, separated with a large interfossil distance from the immediately overlying zone of *Tritaxia dubia* that includes the dinoflagellate *Trithyrodinium suspectum* LCO at its base.

Other dinoflagellate cyst taxa that have their average last occurrence in this zone include *Paleoglenodinium cretaceum*, while *Chatangiella niiga, C. granulifera, Xenascus ceratoides* and *Trithyrodinium suspectum* LCO on average disappear in the lowermost part of the immediately overlying zone (Figure 2.5).

Age: Early Campanian

Enviroment: Dysaerobic, middle to upper bathyal

Occurrence: Widespread offshore Norway, including the Voering Basin.

Correlation: This zone probably largely correlates to the 'Unnamed' zone FCN18 of King *et al.* (1989) with exclusively non-calcareous agglutinated foraminifers in the northern North Sea, assigned to lower Campanian, in agreement with our superpositional zone data and the upper range of the dinoflagellate cyst *P. cretaceum* in Costa and Davey (1992). In the southern North Sea, in UK and in NW Germany this stratigraphic interval is probably shallow marine, and hence dominated by carbonates. There it is zoned with *Stensoeina* taxa and planktonic foraminifers.

The lower Campanian *Goesella rugosa* zone of Geroch & Nowak (1984), first recognized in the Carpathian Trough, and based on the lower range of *G. rugosa,* is not recognized offshore Norway. The taxon is present in North Atlantic DSDP Sites and in Zumaia, Spain (Kuhnt and Kaminski, 1997).

The diatom, and locally radiolarian-rich interval in the Norwegian Sea wells, assigned to the *F. bellii* zone may correspond to the bio-silicious event in western Tethys and North Atlantic, observed in the upper part of magnetic anomaly 34 reversed (near the Santonian-Campanian boundary). This paleoceanographic event is a faunal change at a number of localities in the Atlantic and western Tethys (Kuhnt *et al.,* 1989) coeval with a change from well-oxygenated reddish claystones below, to greenish, radiolarian-rich sediments above. This event has been termed Ocean Anoxic Event 3 (OAE 3), although there is no evidence for truly anoxic conditions at the seafloor. It reflects a time when surface productivity (and hence seafloor organic flux) was comparatively high.

Tritaxia dubia Zone = NCF17

This zone is defined on the presence of *Tritaxia dubia* LO, widely reported under a variety of names (see below). The following taxa have been observed in *assemblages assigned to this zone:*

Tritaxia dubia LO
Pseudogaudryina pyramidata LO (rare)
Marsonella crassa
Trochamminoides spp. LCO
Spiroplectammina dentata (rare)
Spiroplectammina navarroana (rare)
Spiroplectammina spectabilis
Arenoturrispirrilina sp.
Caudammina ovulum
Caudammina ovuloides
Remesella varians
Glomospira spp.
Coarse agglutinated benthic foraminifers LCO
Epistomina supracretacea
Globorotalites michelinianus
Gyroidinoides beisseli LO
Gavelinella usakensis LO
Red coloured planktonic foraminifers including *Hedbergella, Rugoglobigerina, Marginotruncana,* and *Archeoglobigerina*

Remarks: In the southern part of the region studied, calcareous foraminifers may include abundant planktonics, as listed above, often stained red. Northward, calcareous foraminifers become rare, and the zone is more difficult to define, particularly when overlying Paleocene and Maastrichtian strata also contain coarse agglutinated foraminifers that may be caving. On average though, the latter disappear stratigraphically upward together with other taxa listed above, one of the most typical which is *Tritaxia dubia*. This taxon likely is a junior synonym of *Tritaxia subparisiensis* (Grzybowski) and in well reports may hide under junior synonyms like *Pseudogaudryina capitosa, Tritaxia tricarinata* and *T. capitosa.* Typically, several *Spiroplectammina* taxa may be present, including *S. spectabilis*, which regionally re-appears in the upper Paleocene, and *Arenoturrispirillina.*

The assemblage, together with the dinoflagellates listed below forms a distinctive interval zone in Figure 2.5 (left), which is assigned a middle to late Campanian age, based on the upper stratigraphic range of *T. dubia* (= *T. subparisiensis*) in Geroch and Nowak (1984).

Dinoflagellates are abundantly present, and include the average last occurrences of *Trithyroidinium suspectum* LCO, *T. suspectum, T. castaneum, Chatangiella niiga, C. granulifera, C. ditissima, Spongodinium delitiense* FO and *Palaeohystrichophora infusorioides,* which together belong in middle and upper Campanian (Costa and Davey, 1992). Using dinoflagellates, the LCO of *T. suspectum* and *Chatangiella niiga* LO may be used to distinguish a lower part of the *T. dubia* zone, middle Campanian.

Age: Middle to late Campanian

Enviroment: Upper bathyal

Occurrence: Widespread and relatively thick, offshore Norway.

Correlation: After early Campanian, North Atlantic low diversity agglutinated foraminifer assemblages with *Glomospira* increase in diversity. New species belonging to the genera *Caudammina, Haplophragmoides, Paratrochamminoides,* and *Rzehakina* are observed for the first time, as are calcareous-cemented agglutinated forms belonging to the genera *Arenobulimina, Clavulinoides, Dorothia, Goessella, Marsonella, Remesella,* and *Spiroplectinata.* The latter assemblage change marks an Atlantic-wide drop in the level of the Carbonate Compensation depth (CCD) to a depth of below 5000 m, resulting in the deposition of the marly Crescent Peaks member of the Plantagenet Formation (Jansa *et al.*, 1979). At this time, the distinctive 'flysch-type' and calcareous-cemented agglutinated taxa become common, and their overall diversity increase in the North Atlantic and also in the Norwegian Sea, reflected in the composition of the *Tritaxia dubia* zone. This faunal turnover coincides with major changes in watermass properties, owing to increased deep-water productivity from high-latitude sources, cooling and increased ventilation of deep waters, and higher upwelling rates. Active watermass communication through the Scotland-Greenland gateway (Figure 2.2) existed between the proto Norwegian Sea and the North Atlantic Ocean.

The *Tritaxia dubia* zone correlates to the *Tritaxia capitosa* zone, FCN19 of King *et al.* (1989), also assigned to (middle to) upper Campanian. King *et al.* (op cit.) also refers to the red claystones, assigned to the upper part of the zone, that stain the foraminifers red. The claystone corresponds to the 'Upper Red Unit' of the Flounder Formation in Moray Firth and 'Pink Chalk' in the central North Sea.

Reussella szajnochae Zone = NCF18

This zone is defined on the LCO of *Reussella szajnochae.* Other key events include *Rugoglobigerina* spp., *Globigerinelloides volutus*, and *Globotruncanella havanensis*. The following taxa have been observed in assemblages assigned to this zone:

Reussella szajnochae LO
Caudammina ovulum
Globotruncanella havanensis
Rugoglobigerina tradinghousensis (southern area only)
Rugoglobigerina rotundata
Rugoglobigerina spp.
Globotruncana arca (south only)
Globotruncana mariei (south only)
Globotruncanella intermedia
Globigerinelloides volutus
Hedbergella spp., including *H. holmdelensis*
Bolivinoides draco miliaris (southern area only)
Deep water agglutinated foraminifers (more commonly found northward)
Brizalina ex gr. incrasssata
Anomalinoides velascoensis
Stensioeina pommerana
Gavelinella beccariiformis

Remarks: The zone of *Reussella szajnochae* is easily recognizable from the average LO of its distinctive, nominate species, which generally is present with few specimens only in the wells samples examined, but occurs widespread. Associated calcareous benthic taxa and planktonics are listed above. In southern wells many more taxa occur, that require study. In a few of these southern wells, isolated specimens of the nominate taxon range in the overlying zone of *Pseudotextularia elegans*. It is not clear if *R. szajnochae* is in fact reworked or extends stratigraphically upward. A similar pattern was observed also by King *et al.* (1989), suggesting the taxon is in fact time transgressive southward.

In few wells, the upper part of the R.szajnochae zone shows a bloom of *Globigerinelloides volutus* which may constitute a stratigraphically useful subzone.

Dinocysts that have their average last occurrence in this zone include *Odontochitina costata* and *Aquilapollenites* spp (Figure 2.5), typical for lower Maastrichtian (Costa and Davey, 1992).

Age: Probably mostly early Maastrichtian.
Enviroment: Deep neritic to upper bathyal
Occurrence: Widespread, offshore Norway.
Correlation: The *R. szajnochae* zone correlates to the lower part of zone of the same name (FCN20 p.p.) in the northern North Sea (King *et al.*, 1989). In the Carpathian belt, sediments of the same age contain *Caudammina ovulum gigantea*, a middle bathyal to abyssal taxon not observed offshore Norway. The taxon is known from the North Atlantic (Kaminski & Kuhnt, 1990), and the Faeroer Basin (D. van den Akker, pers. comm., 1997).

Pseudotextularia elegans Zone = NCF19

This distinctive zone is defined on presence of *Pseudotextularia elegans* LO (Figure 2.5); other key taxa that may be present include *Rosita contusa, Rugoglobigerina* spp., *Racemiguembelina varians,* and *Brizalina* ex. gr. *incrassata.* The following taxa have been observed in assemblages assigned to this zone:

Pseudotextularia elegans
Abathomphalus mayaroensis
Rosita (Globotruncana) contusa
Rugoglobigerina rugosa (includes acme)
Globigerinelloides volutus (includes acme)
Pseudoguembelina excolata
Racemiguembelina varians
Stensioeina pommerana
Brizalina ex gr. *incrassata*
Heterohelix spp.
Hedbergella spp., include. *H. monmouthensis*

Remarks: As far as can be determined, this zone is largely missing in northern wells (together with Danian, lower Paleocene). Where it is present, it is rich in calcareous taxa, predominantly planktonics. The lower part of the zone harbours acmes or LCO levels of *Rugoglobigerina rugosa* and/or *Globigerinelloides volutus* which may constitute 50-90% of specimens observed. More study, particularly of cores is desirable to understand the successive records of events in this zone.

Abathomphalus mayaroensis, where observed does not seem to occur at the top of the zone, but rather at its base or even lower. It is not clear from the data if such occurrences are due to caving, or indeed represent an older record.

Dinoflagellate cysts present in the zone include

Cerodinium diebeli and *Palynodinium grallator* LO, indicative of upper Maastrichtian (Costa & Davey, 1992).

Age: Late Maastrichtian

Enviroment: Deep neritic to upper bathyal.

Occurrence: The *P. elegans* zone is largely recognized in the southern part of the area studied. We postulate that this hiatus is due to shoulder uplift during 'break-up', prior to the onset of Paleogene seafloor spreading in the Norwegian Sea.

Correlation: The *P. elegans* zone correlates to the North Sea wide *P. elegans* zone of King *et al.* (1989), and the *Gavelinella danica* and *P. elegans* zones of Koch (1977) in NW Germany, correlative to the *junior* and *casimirovensis* belemnite zones (Late Maastrichtian).

Planktonic Foraminifera Acmes

In the zonal description mention was made of last common occurrence events, acmes or blooms and possible 'flooding horizons' of selected non-keeled planktonic foraminifers like *Hedbergella planispira*, *H.delrioensis, Globigerinelloides volutus* and *Rugoglobigerina rugosa*. Such levels may have good correlation potential. What is insightful is to compare planktonic foraminifer ranges in the UK and NW Germany with offshore Norway (Figure 2.9).

The boreal acmes offshore Norway of mid Cretaceous taxa compare to similar acmes in NW Germany and UK (Prokoff, 1997; Hart, 1993). Also shown on Figure 2.9 are the standard ammonite and planktonic foraminiferal zonations, and the regional RASC zones.

The prominent *Globigerinelloides bentonensis* acme in NW Europe is barely recognizable offshore Norway, which area is likely peripheral to its distribution. On the other hand, the offshore Norway acmes of *Hedbergella delrioensis* and *H.planispira* correlate well, albeit with lower stratigraphic resolution due to lower resolution sampling in wells. Why hedbergellids dramatically decline abundance near the boundary of lower and middle Cenomanian is not well understood, but some lines of evidence bear on the issue.

Firstly, in the Norwegian 35 block area the abrupt reduction in hedbergellids, the *H.delrioensis* LCO event, is followed by a level with abundant, sideritic concretions. The latter suggest that a local hiatus or condensed interval is present above that level, probably of early Middle Cenomanian age. Although a regional sequence stratigraphic analysis is lacking, we postulate that the *H.delrioensis* LCO event is indicative of the top of a transgressive or highstand sequence interval, and that the subsequent hiatus or lag represents a relative sealevel rise after a sudden lowstand. Hence, we propose that this hiatus is coeval with the Rouen hardground complex in France, the mid-Cenomanian non-sequence in southern UK and the large hiatus at the boundary of lower and middle Cenomanian in NW Germany, e.g. in the Baddeckenstedt area (Hardenbol *et al.*,1993; Mutterlose *et al.*, 1997).

The hiatus may be linked to a tectonic uplift, and or tilt of basin margins across the early to middle Cenomanian boundary, followed by (renewed) gravity flow sand deposition, offshore mid-Norway from middle Cenomanian time onward. Detailed coring would be required to detail the paleobiotic transition and paleoceanography. Not until early to middle Turonian time do rich and more diverse planktonic foraminiferal assemblages re-appear, offshore Norway.

Cretaceous dinoflagellate cyst zonation

In this chapter we present a regional dinocyst zones (DCZ) with eleven zones and thirty-nine subzones for Cretaceous marine strata in the North Sea. HO stands for Highest (Stratigraphic) Occurrence and HCO for Highest Common (Stratigraphic) Occurrence, hence the zonation is optimized for industrial applications with ditch cuttings samples.

To increase utility of the operational micropaleontological (discussed before; see also Figures 2.5 through 2.8) and the literature dinoflagellate zonations we have placed them side by side in Figures 2.10a-d, using their independent chronostratigraphic calibrations.

The chronostratigraphic interpretation of the dinoflagellate cyst events is mainly based on available peer-reviewed palynological publications. It also builds on results of unpublished PhD theses and collected contributions from the manuals of the "Advanced courses in Organic-Walled Dinoflagellate Cysts" organized from 1994 through 2012 in Utrecht, Haarlem, Bremen, Tubingen, Urbino and other locations. Use was made also of in-house (RGD, LPP and TNO) reports from 1980 - 2015 (e.g. TNO compilation report "Ranges and zonation of Cretaceous dinoflagellates in NW Europe, 2002" (see remarks below and reference list).

The international geologic timescale of Gradstein *et al.* (2012) is used for chronostratigraphic calibration.

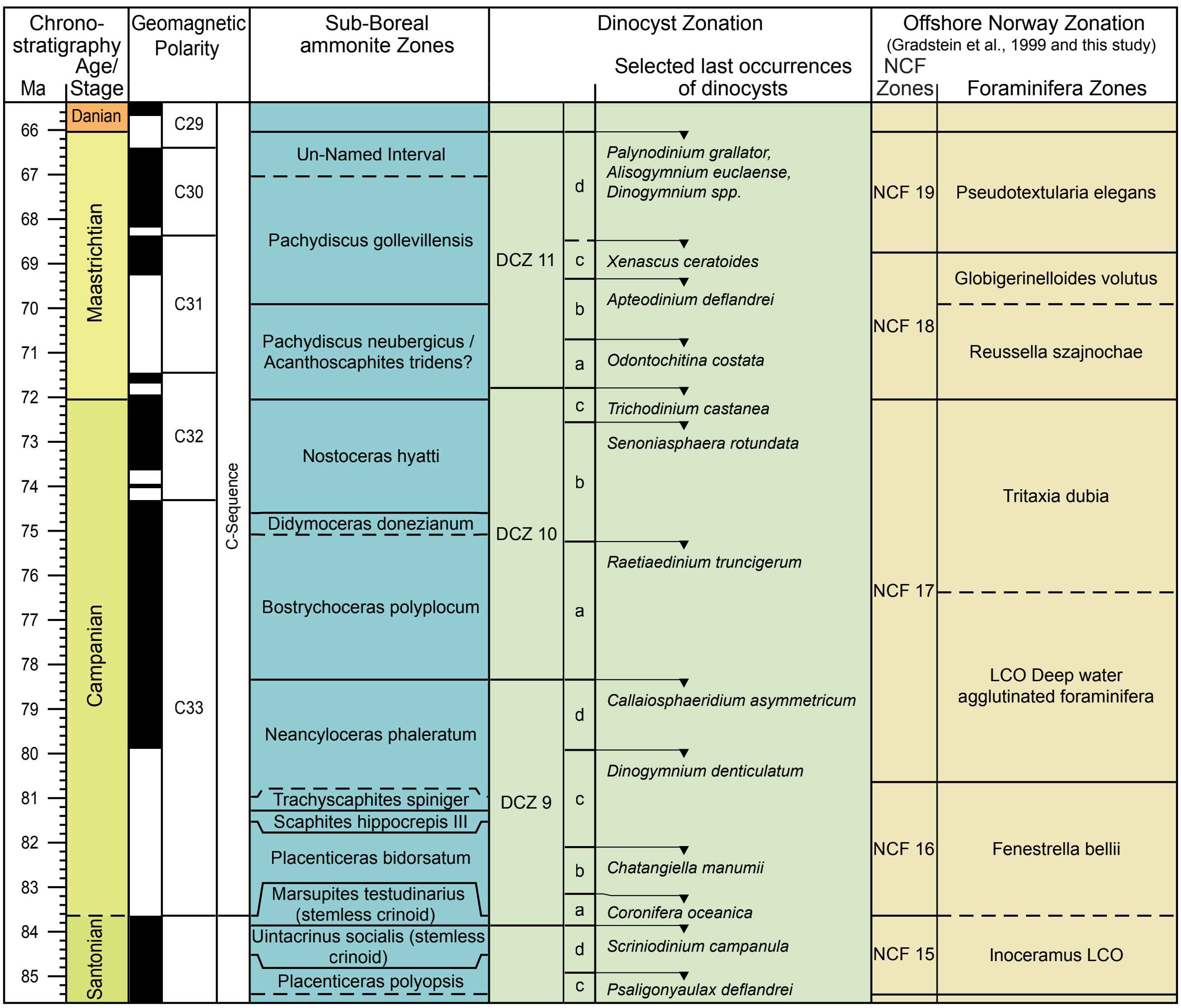


Fig. 2.10.a

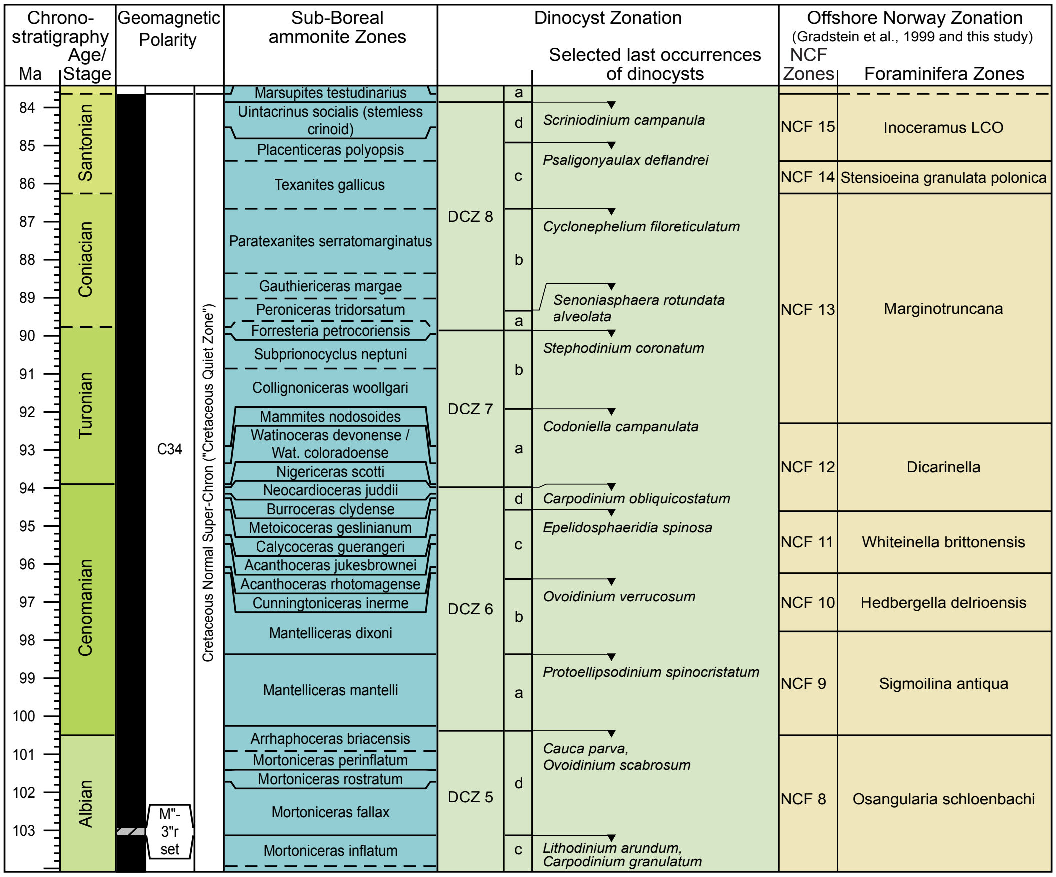


Fig. 2.10.b

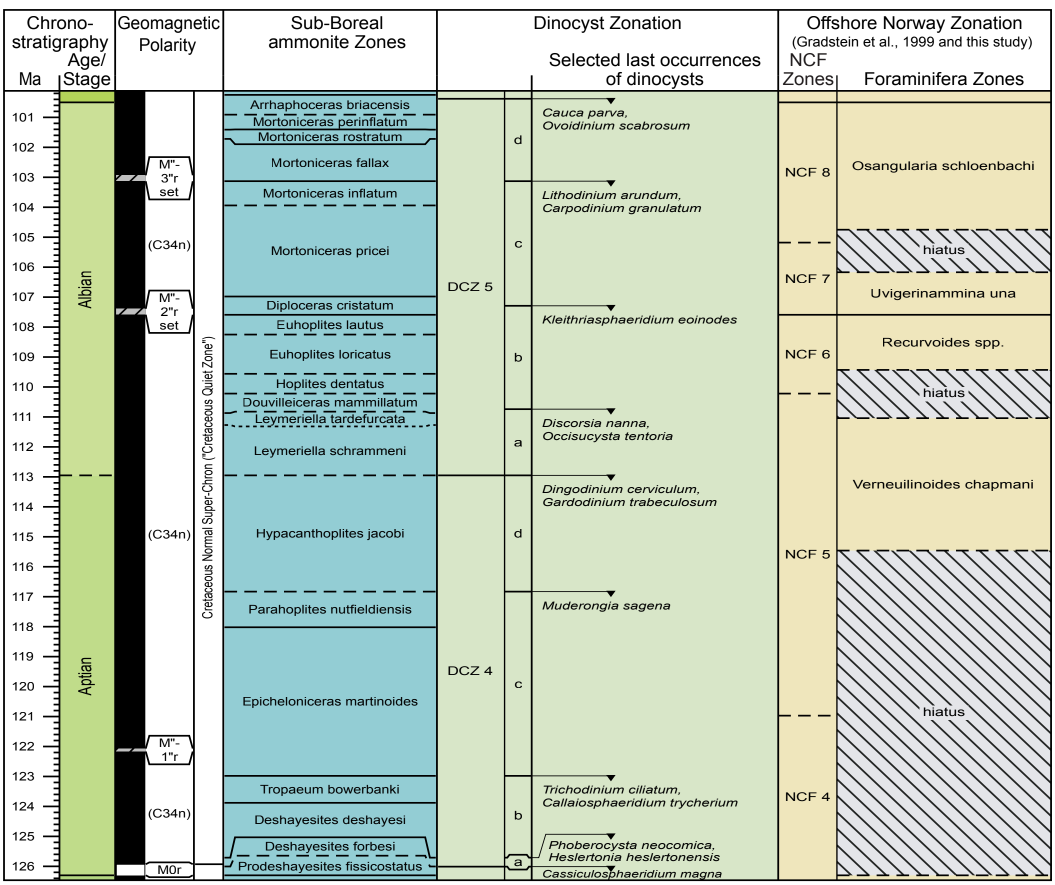


Fig. 2.10.c

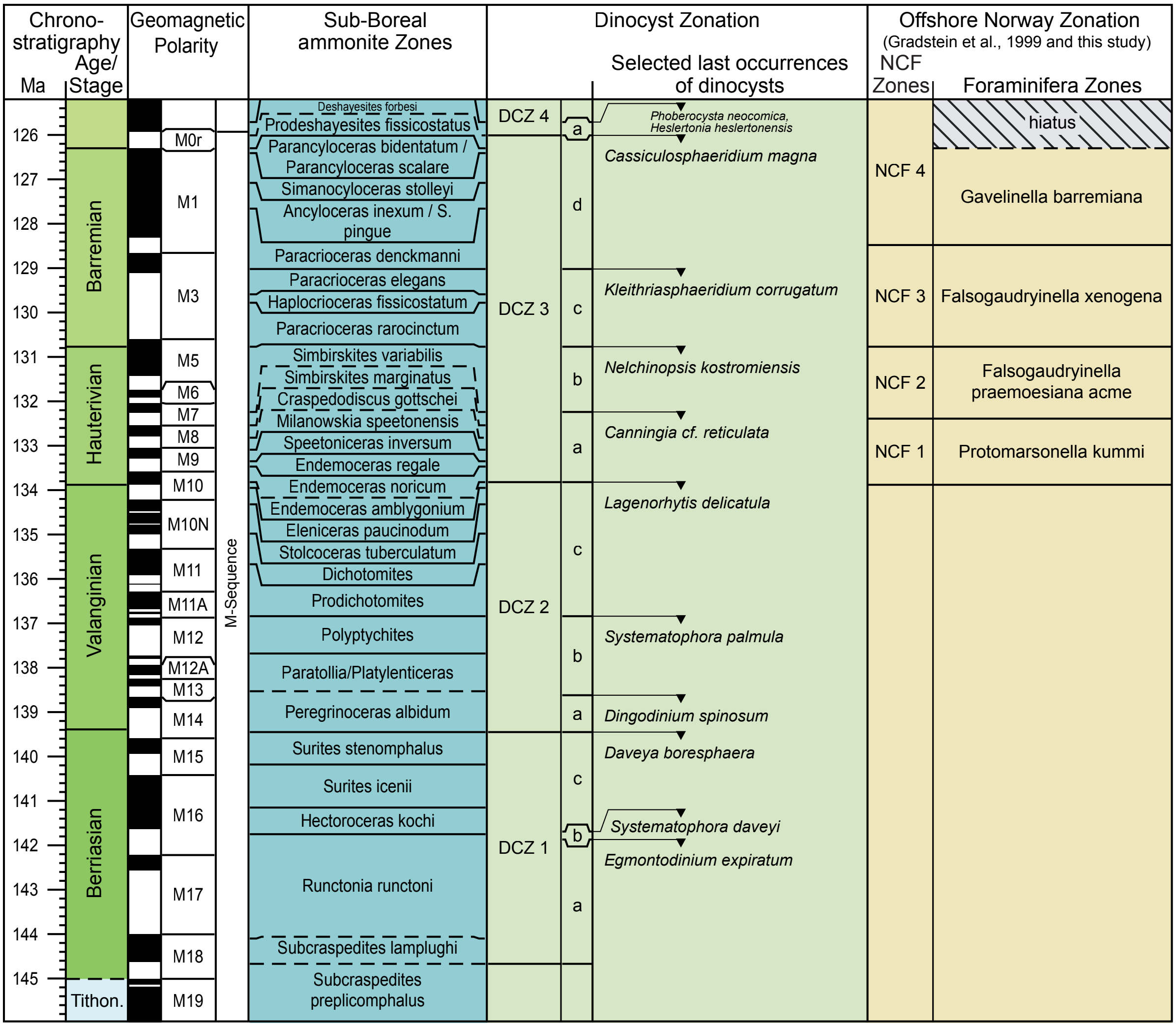


Fig. 2.10.d

Figures 2.10a,b,c,d. Eleven dinoflagelate cyst zones (DCZ) and thirty-nine subzones for Cretaceous marine strata in the North Sea. To increase utility of the operational micropaleontological zonation in Figures 2.7 and 2.8 and the literature dinoflagellate zonation we have placed them side by side in Figures 2.10a-d, using their independent chronostratigraphic calibrations. The chronostratigraphic interpretation of the dinoflagellate cyst events is mainly based on available peer-reviewed palynological publications. It also builds on results of unpublished PhD theses and collected contributions from the manuals of the "Advanced courses in Organic-Walled Dinoflagellate Cysts" organized from 1994 through 2012 in Utrecht, Haarlem, Bremen, Tubingen, Urbino and other locations. Use was made also of in-house (RGD, LPP and TNO) reports from 1980-2015 (e.g. TNO compilation report "Ranges and zonation of Cretaceous dinoflagellates in NW Europe, 2002" (see remarks below and reference list). The international geologic timescale of Gradstein *et al.* (2012) is used for chronostratigraphic calibration.

DCZ 1 Zone

Definition: The interval from the HCO of *Cribroperidinium hansenii* (*preplicomphalus* Ammonite Zone) to the HO of *Daveya boresphaera* (*stenomphalus* Ammonite Zone).

Age: Latest Volgian (latest Tithonian)-Berriasian

Remarks: *Egmontodininium polyplacophorum* has a HO in the *oppressus* Ammonite Zone (Partington *et al*., 1993) and the HO's of *Glossodiniium dimorphum* (Riding and Thomas, 1992 and Partington *et al*., 1993) and *Senoniasphaera jurassica* (Riding and Thomas, 1992, Partington *et al*., 1993 and Poulsen, 1996) are in the *anguiformis* Ammonite Zone.

DCZ 1a subzone

Definition: The interval from the HCO of *Cribroperidinium hansenii* (*preplicomphalus* Ammonite Zone) to the HO of *Egmontodinium expiratum* (*runctoni* Ammonite Zone).

Age: Latest Volgian (latest Tithonian)-early Berriasian

Remarks: Davey (1982) reports the HO of *Egmontodinium expiratum* in the *runctoni* Ammonite Zone.

DCZ 1b subzone

Definition: The interval from HO of *Egmontodinium expiratum* (*runctoni* Ammonite Zone) to the HO of *Systematophora daveyi* (*kochi* Ammonite Zone).

Age: Middle Berriasian

Remarks: The HO of *Systematophora daveyi* is reported in the *kochi* Ammonite Zone by Davey (1992) and Poulsen (1996).

DCZ 1c subzone

Definition: The interval from HO of *Systematophora daveyi* (*kochi* Ammonite Zone) to the HO of *Daveya boresphaera* (*stenomphalus* Ammonite Zone).

Age: Late Berriasian

Remarks: The HO of *Daveya boresphaera* is defined by Davey (1979) and Birkelund *et al.* (1983). This taxon was better known as *Gonyaulacysta* sp. A and B *sensu* Davey (1979, 1982).

DCZ 2 Zone

Definition: The interval from the HO of *Daveya boresphaera* (*stenomphalus* Ammonite Zone) to the HO of *Lagenorhytis delicatula* (*amblygonium* Ammonite Zone).

Age: Valanginian

DCZ 2a subzone

Definition: The interval from the HO of *Daveya boresphaera* (*stenomphalus* Ammonite Zone) to the HO of *Dingodinium spinosum* (*albidum* Ammonite Zone).

Age: Earliest Valanginian

Remarks: The HO of *Dingodinium spinosum* in the *albidum* Ammonite Zone is published by the work of Duxbury (1977), Costa and Davey (1992) and Partington *et al.* (1993).

DCZ 2b subzone

Definition: The interval from the HO of *Dingodinium spinosum* (*albidum* Ammonite Zone) to the HO of *Systematophora palmula* (*Polyptychites* Ammonite Zone).

Age: Early Valanginian

Remarks: Reference for the HO of *Systematophora palmula* in the *Polyptychites* Ammonite Zone is Davey (1982) and Costa and Davey (1992).

DCZ 2c subzone

Definition: The interval from the HO of *Systematophora palmula* (*Polyptychites* Ammonite Zone) to the HO of *Lagenorhytis delicatula* (*amblygonium* Ammonite Zone).

Age: Late Valanginian

Remarks: The HO of *Lagenorhytis delicatula* in the *amblygonium* Ammonite Zone is reported in the compilation works of Heilmann-Clausen (1987) and Costa and Davey (1992).

DCZ 3 Zone

Definition: The interval from the HO of *Lagenorhytis delicatula* (*amblygonium* Ammonite Zone) to the HO of *Cassiculosphaeridium magna* (*fissicostatum* Ammonite Zone).

Age: Hauterivian-earliest Aptian

DCZ 3a subzone

Definition: The interval from the HO of *Lagenorhytis delicatula* (*amblygonium* Ammonite Zone) to the HO of *Canningia* cf. *reticulata* (lowermost variabilis Ammonite Zone).

Age: Early-middle Hauterivian

Remarks: The HO of Canningia cf. reticulata in lowermost *variabilis* Ammonite Zone is known from e.g. Duxbury (1977), Davey (1979), Costa & Davey (1992) and Heilmann-Clausen (1987).

DCZ 3b subzone

Definition: The interval from the HO of *Canningia* cf. *reticulata* (lowermost variabilis Ammonite Zone) to the HO of *Nelchinopsis kostromiensis* (variabilis Ammonite Zone).

Age: Late Hauterivian

Remarks: The HO of *Nelchinopsis kostromiensis* in the *variabilis* Ammonite Zone is referred to by Duxbury (1977; 2001) and Harding (1990).

DCZ 3c subzone

Definition: The interval from the HO of *Nelchinopsis kostromiensis* (*variabilis* Ammonite Zone) to the *Kleithriasphaeridium corrugatum* (*elegans* Ammonite Zone).

Age: Early Barremian

Remarks: The HO of *Kleithriasphaeridium corrugatum* in the *elegans* Ammonite Zone is reported in Duxbury (2001). Harding (1990) indicates the last occurrence in the *fissicostatum* Ammonite Zone of Speeton, UK, and in the *Aulacoteuthis* (belemnite) Zone of the Gott quarry in Germany. However, for the same quarry Heilmann-Clausen & Thomsen (1995) mention regular finds in the Upper Barremian brunsvicensis to lowermost *germanica* zones.

DCZ 3d subzone

Definition: The interval from the HO of *Kleithriasphaeridium corrugatum* (*elegans* Ammonite Zone) to the HO of *Cassiculosphaeridium magna* (*fissicostatum* Ammonite Zone).

Age: Late Barremian-earliest Aptian

Remarks: In the Speeton Clay this taxon is rare to fair up to bed LB2A, *fissicostatum* Zone. It is not recorded by Harding (1990) between LB1F (top *fissicostatum* Zone) and the basal part of the Upper B beds. Finds from this interval, which mainly includes the Middle B Beds, as mentioned by Davey (1974) and Duxbury (1980), are very rare. For the present study the HO of *Cassiculosphaeridium magna* is taken at the top of the *fissicostatum* Zone. Younger occurrences are rare and may (in part) be due to reworking; see also Mutterlose & Harding (1987), Heilmann-Clausen & Thomsen (1995), Lister & Batten (1995) and Below & Kirsch (1997).

DCZ 4 Zone

Definition: The interval from the HO of *Cassiculosphaeridium magna* (*fissicostatum* Ammonite Zone) *to the HO of Dingodinium cerviculum* (*jacobi* Ammonite Zone).

***Age:** Aptian*

DCZ 4a subzone

Definition: The interval from the HO of *Cassiculosphaeridium magna* (*fissicostatum* Ammonite Zone) to the HO of *Phoberocysta neocomica* (*forbesi* Ammonite Zone).

Age: Earliest Aptian

Remarks: Duxbury (1983) shows a HO of *Phoberocysta neocomica* in the *forbesi* Ammonite Zone. In addition, the HO of *Heslertonia heslertonensis* is recorded in the *forbesi* Ammonite Zone by Duxbury (1983) and Lister & Batten (1988).

DCZ 4b subzone

Definition: The interval from the HO of *Phoberocysta neocomica* (*forbesi* Ammonite Zone) to the HO of *Trichodinium ciliatum* (*bowerbanki* Ammonite Zone).

Age: Early Aptian

Remarks: In England Lister & Batten recorded the taxon in the *deshayesi* and *bowerbanki* Zone. The HO of *Callaiosphaeridium trycherium* also verifies the top of the current subzone 4b (Duxbury, 1983).

DCZ 4c subzone

Definition: The interval from the HO of *Trichodinium ciliatum* (*bowerbanki* Ammonite Zone) to the HO of *Muderongia sagena* (*nutfieldiensis* Ammonite Zone).

Age: Middle Aptian

Remarks: The HO of *Muderongia sagena* in the *nutfieldiensis* Ammonite Zone is recorded by Lister & Batten (1988).

DCZ 4d subzone

Definition: The interval from the HO of *Muderongia sagena* (*nutfieldiensis* Ammonite Zone) to the HO of *Dingodinium cerviculum* (*jacobi* Ammonite Zone).

Age: Late Aptian

Remarks: The HO of *Dingodinium cerviculum* is uppermost *jacobi* Ammonite Zone (Duxbury, 1983). The top of the Dinocyst Zone 4 could also be ascertained by the HO of *Gardodinium trabeculosum* (Davey, 1982b).

DCZ 5 Zone

Definition: The interval from the HO of *Dingodinium cerviculum* (*jacobi* Ammonite Zone) to the HO of *Cauca parva* (*dispar* Ammonite Zone).

Age: Albian

DCZ 5a subzone

Definition: The interval from the HO of *Cauca parva* (*dispar* Ammonite Zone) to the HO of *Discorsia nanna* (*tardefurcata* Ammonite Zone).

Age: Earliest Albian

Remarks: According to Duxbury (1983) *Discorsia nanna* shows rare occurrences in the Upper Aptian and it becomes scarce in the *tardefurcata* Ammonite Zone. This last zone is also recorded by Costa & Davey (1992). In addition *Occisucysta tentoria* has its HO in the *tardefurcata* Ammonite Zone (Davey, 1982b and Duxbury, 1983).

DCZ 5b subzone

Definition: The interval from the HO of *Discorsia nanna* (*tardefurcata* Ammonite Zone) to the HO of *Kleithriasphaeridium eoinodes* (*lautus* Ammonite Zone).

Age: Early Albian

Remarks: The youngest occurrences of *Kleithriasphaeridium eoinodes* are mentioned by Verdier (1975) in the *lautus* Ammonite Zone. Davey (1982) shows the HO in the *tardefurcata* Ammonite Zone.

DCZ 5c subzone

Definition: The interval from the HO of *Kleithriasphaeridium eoinodes* (*lautus* Ammonite Zone) to the HO of *Lithodinium arundum* (*inflatum* Ammonite Zone).

Age: Middle-late Albian

Remarks: *Lithodinium arundum* has a HO in the *inflatum* Ammonite Zone (Davey & Verdier 1971, Fauconnier, 1975, Chateauneuf & Fauconnier, 1979, Foucher 1984) with a single occurrence in the topmost part of the dispar Zone (Tocher & Jarvis, 1996). *Carpodinium granulatum* could also be used for the top of the present subzone 5c (Verdier, 1975 and Foucher, 1983).

DCZ 5d subzone

Definition: The interval from the HO of *Lithodinium arundum* (*inflatum* Ammonite Zone) to the HO of *Cauca parva* (*dispar* Ammonite Zone).

Age: Late Albian

Remarks: *Cauca parva* is recorded in rare frequency in the uppermost Albian by Davey & Verdier 1973, Fauconnier, 1979 and Tocher & Jarvis, 1996. Younger Cenomanian occurrences (e.g. Foucher, 1984 and Prössl, 1990) are probably reworked (see discussion in Heilmann-Clausen, 1987).

The last consistent occurrence of *Ovoidinium scabrosum* is traditionally used for the top of the Albian (Gradstein, 2012). *Ovoidinium scabrosum* has an acme in the upper(most) Albian (TNO-NITG internal reports, Prössl, 1990). The LOD is lowermost Cenomanian (*cantianum* Zone, Foucher 1984, basal part varians Zone, Cookson & Hughes 1964, Davey 1970 and undifferentiated, Prössl 1990).

DCZ 6 Zone

Definition: The interval from the HO of *Cauca parva* (*dispar* Ammonite Zone) to the HO of *Carpodinium obliquicostatum* (*judii* Ammonite Zone).

Age: Cenomanian

DCZ 6a subzone

Definition: The interval from the HO of *Cauca parva* (*dispar* Ammonite Zone) to the HO of *Protoellipsodinium spinocristatum* (*mantelli* Ammonite Zone).

Age: Earliest Cenomanian

Remarks: Tocher & Jarvis (1996) mentioned the HO of *Protoellipsodinium spinocristatum* in the basal most part of the Lower Cenomanian, *mantelli* Ammonite Zone.

DCZ 6b subzone

Definition: The interval from the HO of *Protoellipsodinium spinocristatum* (*mantelli* Ammonite Zone) to the HO of *Ovoidinium verrucosum* (*dixoni* Ammonite Zone).

Age: Early Cenomanian

Remarks: Costa and Davey (1992) show a HO of *Ovoidinium verrucosum* in the *dixoni* Ammonite Zone. The top occurrence is confirmed by unpublished data of the Utrecht Knowledge Centre (LPP, TNO, RGD).

DCZ 6c subzone

Definition: The interval from the HO of *Ovoidinium verrucosum* (*dixoni* Ammonite Zone) to the HO of *Epelidosphaera spinosa* (*guerangeri* Ammonite Zone).

Age: Late Cenomanian

Remarks: The HO of *Epelidosphaera spinosa* is published by Tocher and Jarvis (1995) in the *guerangeri* Ammonite Zone. This age determination agrees with observations by Prössl (1990), who recorded the present taxon in regular to common values in the non-calibrated, basal Upper Cenomanian. Foucher (1979), Marschall (1983) and Costa & Davey (1992) show that last occurrence one ammonite zone older in the *jukesbrownei* Ammonite Zone.

DCZ 6d subzone

Definition: The interval from the HO of *Epelidosphaera spinosa* (*guerangeri* Ammonite Zone) to the HO of *Carpodinium obliquicostatum* (*judii* Ammonite Zone).

Age: Latest Cenomanian

Remarks: Regularly recorded up into the Plenus Marl (e.g. Clarke & Verdier, 1967, Davey, 1969, Foucher, 1979, 1980, 1983, Marshall 1983 and Dodsworth, 2000). Dodsworth (2000) reports the HO of *Carpodinium obliquicostatum* in the *judii* Ammonite Zone.

DCZ 7 Zone

Definition: The interval from the HO of *Carpodinium obliquicostatum* (*judii* Ammonite Zone) to the HO of *Stephodinium coronatum* (*petrocoriensis* Ammonite Zone).

Age: Turonian

DCZ 7a subzone

Definition: The interval from the HO of *Carpodinium obliquicostatum* (*judii* Ammonite Zone) to the HO of *Codoniella campanulata* (*woollgari* Ammonite Zone).

Age: Early Turonian

Remarks: The HO of *Codoniella campanulata* is reported by Pearce (PhD 2001) and may be associated with the *woollgari* Ammonite Zone.

DCZ 7b subzone

Definition: The interval from the HO of *Codoniella campanulata* (*woollgari* Ammonite Zone) to the HO of *Stephodinium coronatum* (*petrocoriensis* Ammonite Zone).

Age: Late Turonian

Remarks: The HO of *Stephodinium coronatum* in the *petrocoriensis* Ammonite Zone refers to Marschall (1983) and Schioler (1992).

DCZ 8 Zone

Definition: The interval from the HO of *Stephodinium coronatum* (*petrocoriensis* Ammonite Zone) to the HO of *Scriniodinium campanula* (*socialis* Zone)

Age: Coniacian-Santonian

DCZ 8a subzone

Definition: The interval from the HO of *Stephodinium coronatum* (*petrocoriensis* Ammonite Zone) to the HO (consistent) of *Senoniasphaera rotunda alveolata* (*tridorsatum* Ammonite Zone)

Age: Early Coniacian

Remarks: The interpretation of the HO (consistent) of *Senoniasphaera rotunda alveolata* in the *tridorsatum* Ammonite Zone is based on Pearce (2001) and Pearce *et al.* (2003).

DCZ 8b subzone

Definition: The interval from the HO of *Senoniasphaera rotunda alveolata* (*tridorsatum* Ammonite Zone) to the HO of *Cyclonephelium filoreticulatum* (*serratomarginatus* Ammonite Zone).

Age: Late Coniacian

Remarks: The interpretation of the HO (consistent) of *Cyclonephelium filoreticulatum* in the *serratomarginatus* Ammonite Zone is based on Prince *et al.* (1999) and Pearce (2001).

DCZ 8c subzone

Definition: The interval from the HO of *Cyclonephelium filoreticulatum* (*serratomarginatus* Ammonite Zone) to the HO of *Psaligonyaulacysta deflandrei* (*polyopsis* Ammonite Zone).

Age: Early Santonian

Remarks: The HO (consistent) of *Psaligonyaulacysta deflandrei* is in the Coniacian (Schioler 1992). In rare occurrences the taxon shows a HO in the early Santonian, *polyopsis* Ammonite Zone (Pearce, 2001).

DCZ 8d subzone

Definition: The interval from the HO of *Psaligonyaulacysta deflandrei* (*polyopsis* Ammonite Zone) to the HO of of *Scriniodinium campanula* (*socialis* Zone).

Age: Late Santonian

Remarks: The HO of *Scriniodinium campanula* is late Santonian, *Uintacrinus socialis* Zone according Prince *et al.* (1999).

DCZ 9 Zone

Definition: The interval from the HO of S*criniodinium campanula* (*socialis* Zone) to the HO of *Callaiosphaeridium asymmetricum* (*phaleratum* Ammonite Zone).

Age: Early Campanian

DCZ 9a subzone

Definition: The interval from the HO of *Scriniodinium campanula* (*socialis* Zone) to the HO (consistent) of *Coronifera oceanica* (basal *bidorsatum* Ammonite Zone).

Age: Earliest Campanian

Remarks: Regular and common occurrence of *Coronifera oceanica* is recorded up to the basal part of the Lower Campanian (*O. pilula*, Prince *et al.*, 1999; and Pearce, 2001).

DCZ 9b subzone

Definition: The interval from the HO (consistent) of *Coronifera oceanica* (basal *bidorsatum* Ammonite Zone) to the HO of *Chatangiella manumii* (*bidorsatum* Ammonite Zone).

Age: Early Campanian

Remarks: The HO of *Chatangiella manumii* is shown in the *bidorsatum* Ammonite Zone by Pearce, 2001 and in unpublished compilations hereafter (e.g. "Advanced course in organic-walled dinoflagellate cysts, 2012; HO at 82.2 Ma").

DCZ 9c subzone

Definition: The interval from the HO of *Chatangiella manumii* (*bidorsatum* Ammonite Zone) to the HO (consistent) of *Dinogymnium denticulatum* ("mid" *phaleratum* Ammonite Zone).

Age: Early Campanian

Remarks: Pearce (2001,and in more recent unpublished compilations, see above) shows a HO (consistent) of *Dinogymnium denticulatum* in the "mid" *phaleratum* Ammonite Zone. Slightly older HO in the Santonian is given by Prince *et al.*, 1999 and Clarke & Verdier, 1967). Irregular younger occurrences in the Maastrichtian, are mentioned by Wilson, 1974; Herngreen *et al.*, 1986 and Kirsch, 1991).

DCZ 9d subzone

Definition: The interval from the HO (consistent) of *Dinogymnium denticulatum* ("mid" *phaleratum* Ammonite Zone) to the HO of *Callaiosphaeridium asymmetricum* (top of *phaleratum* Ammonite Zone).

Age: Early-mid Campanian

Remarks: The HO of *Callaiosphaeridium asymmetricum* at the top of *phaleratum* Ammonite Zone is interpreted from records in the Lower Campanian Vaals Formation and in the succeeding Zeven Wegen Member (Foucher 1983b) and fairly regular records up to the Lower- basal Middle Campanian elevata Zone and an isolated occurrence in the Middle Campanian ventricosa Zone (Kirsch, 1991). These data confirm the top at the boundary "Lower/Upper" Campanian in the compilation of Costa & Davey (1992) and Van

Adrichem Boogaert & Kouwe, 1993-1997.

DCZ 10 Zone

Definition: The interval from the HO *Callaiosphaeridium asymmetricum* (*phaleratum* Ammonite Zone) to the HO of *Trichodinium castanea* (basal *P. neubergicus/A.tridens* Ammonite Zone).

Age: Late Campanian-earliest Maastrichtian

DCZ 10a subzone

Definition: The interval from the HO of *Callaiosphaeridium asymmetricum* (*phaleratum* Ammonite Zone) to the HO of *Raetiaedinium truncigerum* (*polyplocum* Ammonite Zone).

Age: Late Campanian

Remarks: The HO of *Raetiaedinium truncigerum* is recorded in the polyplocum Ammonite Zone by Pearce, 2001 and in unpublished compilations hereafter (e.g. Advanced course in organic-walled dinoflagellate cysts, 2012).

DCZ 10b subzone

Definition: The interval from the HO of *Raetiaedinium truncigerum* (*polyplocum* Ammonite Zone) to the HO of *Senoniasphaera rotunda* (*hyatti* Ammonite Zone).

Age: Late Campanian

Remarks: *Senoniasphaera rotunda* is (very) common in the upper Turonian (FitzPatrick, 1995), and Santonian to Lower Campanian (Clarke & Verdier, 1967; Prince *et al.*, 1999) and has a consistent HO in the late Campanian (Pearce, 2001 and later unpublished compilations, see above). Scarce occurrences are reported from the Maastrichtian (Wilson, 1974, Foucher, 1983 and Schioler *et al.,* 1997).

DCZ 10c subzone

Definition: The interval from the HO of *Senoniasphaera rotunda* (*hyatti* Ammonite Zone) to the HO of *Trichodinium castanea* (basal *P. neubergicus/A.tridens* Ammonite Zone).

Age: Latest Campanian-earliest Maastrichtian

Remarks: The HO of *Trichodinium castanea* in the transitional latest Campanian/earliest Maastrichtian is based on Foucher, 1983b, 1985; Kirsch, 1991 and Herngreen, 1996).

DCZ 11 Zone

Definition: The interval from the HO of *Trichodinium castanea* (basal *P. neubergicus/A.tridens* Ammonite Zone) to the HO of *Dinogymnium* spp. (un-named interval).

Age: Maastrichtian

DCZ 11a subzone

Definition: The interval from the HO of *Trichodinium castanea* (basal *P. neubergicus/ A.tridens* Ammonite Zone) to the HO of *Odontochitina costata* (*P. neubergicus/ A.tridens* Ammonite Zone).

Age: Early Maastrichtian

Remarks: The HO of *Odontochitina costata* in the *P. neubergicus/A.tridens* Ammonite Zone is based on Wilson, 1974, Foucher, 1983b, 1985, Herngreen, 1998 and Van Adrichem Boogaert & Kouwe, 1993-1997.

DCZ 11b subzone

Definition: The interval from the HO of *Odontochitina costata* (*P. neubergicus/A.tridens* Ammonite Zone) to the HO of *Apteodinium deflandrei* (basal *gollevillensis* Ammonite Zone).

Age: Early Maastrichtian

Remarks: The HO of *Apteodinium deflandrei* in the basal *gollevillensis* Ammonite Zone is shown by Van Adrichem Boogaert & Kouwe, 1993-1997 and by unpublished dinoflagellate cyst stratigraphy from the Utrecht dinocyst course manual, 2012). Several authors record a HO in the Campanian (Wilson, 1974, Foucher, 1983a and 1983b, Neumann & Patel, 1983). Marheinecke (1992) and Brinkhuis & Schioler (1996) confirm occurrences in the Maastrichtian.

DCZ 11c subzone

Definition: The interval from the HO of *Apteodinium deflandrei* (basal *gollevillensis* Ammonite Zone) to the HO of *Xenascus ceratoides* (*gollevillensis* Ammonite Zone).

Age: Middle - Late Maastrichtian

Remarks: In their compilation Costa & Davey (1992) indicate occurrences up to the lowermost Upper Maastrichtian. Van Adrichem Boogaert & Kouwe (1993-1997) show the HO of *Xenascus ceratoides* in the late Maastrichtian (*junior* belemnite Zone).

DCZ 11d subzone

Definition: The interval from the HO of *Xenascus ceratoides* (*gollevillensis* Ammonite Zone) to the HO of *Dinogymnium* spp.

Age: Late Maastrichtian

Remarks: The HO of *Dinogymnium* spp. on top of the Maastrichtian is deduced from Marheinecke (1992), Brinkhuis & Schioler (1996), Schioler *et al.* (1997), Herngreen *et al.* (1986), Wilson (1974), Kirsch (1991) and Van Adrichem Boogaert & Kouwe (1993-1997).

3. Lithostratigraphy

Cromer Knoll and Shetland Groups of the Norwegian Sea

Geographic and Stratigraphic overview

The Norwegian Sea region dealt with in this chapter extends from 62⁰ N to 67⁰ N along the Norwegian continent. A considerable local topographic jargon is utilized by petroleum industry, and an effort has been made to assemble these names in the northern half of Figure 3.1.

Tables 3.1 and 3.2 show the complete overview of the Norwegian Sea Cretaceous lithostratigraphic units dealt with in this chapter. As mentioned already previously, regional Norwegian Cretaceous subsurface lithostratigraphy to an extent depends on knowing the age of rock units, and in that sense is not an independent descriptor. Hence, biostratigraphic asignments of the units are listed, where available. The user should note that the chronostratigraphic placement of the formation and member units in Table 3.2 is

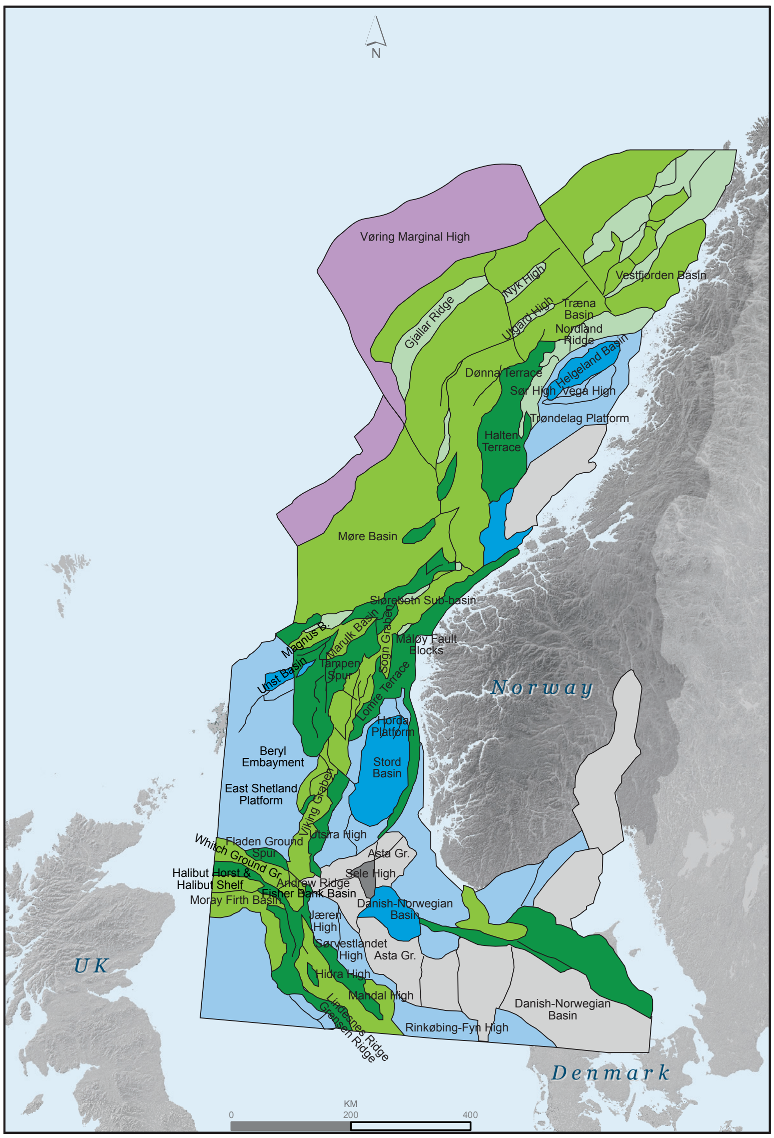


Figure 3.1. Geographic nomenclature used for the Norwegian- and North Seas.

highly schematic. Virtual none of the units have isochronous boundaries in subsurface space. No effort has been made to visualize the complex and incompletely understood extent of the units (in space) and time; such is left to more detailed regional studies that should build on the current litho-and biostratigraphic compilation. For one, detailed seismic and isopach contour maps are required, not released at this time.

From younger to older we describe for the Shetland Group (with a re-defined base) in the Norwegian Sea: Springar Formation with Hvithval and Grindhval Members; Nise Formation with Spekkhogger and Nebbhval Members; Kvitnos Formation with Tumler and Kvitskjaeving Members and Blålange Formation (previously Upper Lange Fm) with Lysing Member (previously Lysing Formation), Tunge Member, Skolest Member, Breiflabb Member, Skrubbe Member, Sandflyndre Member and Gapeflyndre Member.

For the Cromer Knoll Group (with a redefined top) in the Norwegian Sea we describe the Langebarn Formation (previously Lower Lange Formation).

All new units, as far as possible, have updated colour graphics of the stratigraphy in the type-, and or reference wells, and updated well log signatures.

The type and reference wells of all units are shown in Figure 3.2.

North Sea, Norwegian Sea and Barents Sea Lithostratigraphy at the Group level

Standard Chronostratigraphy (Gradstein et al., 2012) Ep.	Age/Stage	Base (Ma)	Southern North Sea (Revised)	Northern North Sea	Norwegian Sea (Revised)	Barents Sea
Eocene	Ypresian	56.0				
Paleocene	Thanetian	59.2	Rogaland Group	Rogaland Group	Rogaland Group	Sotbakken Group
Paleocene	Selandian	61.6	Rogaland Group	Rogaland Group	Rogaland Group	Sotbakken Group
Paleocene	Danian	66.0	Rogaland Group	Rogaland Group	Rogaland Group	Sotbakken Group
Late Cretaceous	Maastrichtian	72.1	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
Late Cretaceous	Campanian	83.6	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
Late Cretaceous	Santonian	86.3	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
Late Cretaceous	Coniacian	89.8	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
Late Cretaceous	Turonian	93.9	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
Late Cretaceous	Cenomanian	100.5	Chalk Group (Re-instated)	Shetland Group	Shetland Group (Revised)	Nygrunnen Group
Early Cretaceous	Albian	113.0	Cromer Knoll Group	Cromer Knoll Group (Revised)	Cromer Knoll Group	Adventdalen Group
Early Cretaceous	Aptian	126.3	Cromer Knoll Group	Cromer Knoll Group (Revised)	Cromer Knoll Group	Adventdalen Group
Early Cretaceous	Barremian	130.8	Cromer Knoll Group	Cromer Knoll Group (Revised)	Cromer Knoll Group	Adventdalen Group
Early Cretaceous	Hauterivian	133.9	Cromer Knoll Group	Cromer Knoll Group (Revised)	Cromer Knoll Group	Adventdalen Group
Early Cretaceous	Valanginian	139.4	Cromer Knoll Group	Cromer Knoll Group (Revised)	Cromer Knoll Group	Adventdalen Group
Early Cretaceous	Berriasian	145.0	Cromer Knoll Group	Cromer Knoll Group (Revised)	Cromer Knoll Group	Adventdalen Group (Note: no boundary)
Late Jurassic	Tithonian	152.1	Viking Group	Viking Group	Viking Group	Adventdalen Group

Table 3.1 North Sea, Norwegian Sea and Barents Sea Cretaceous lithostratigraphy at the group level.

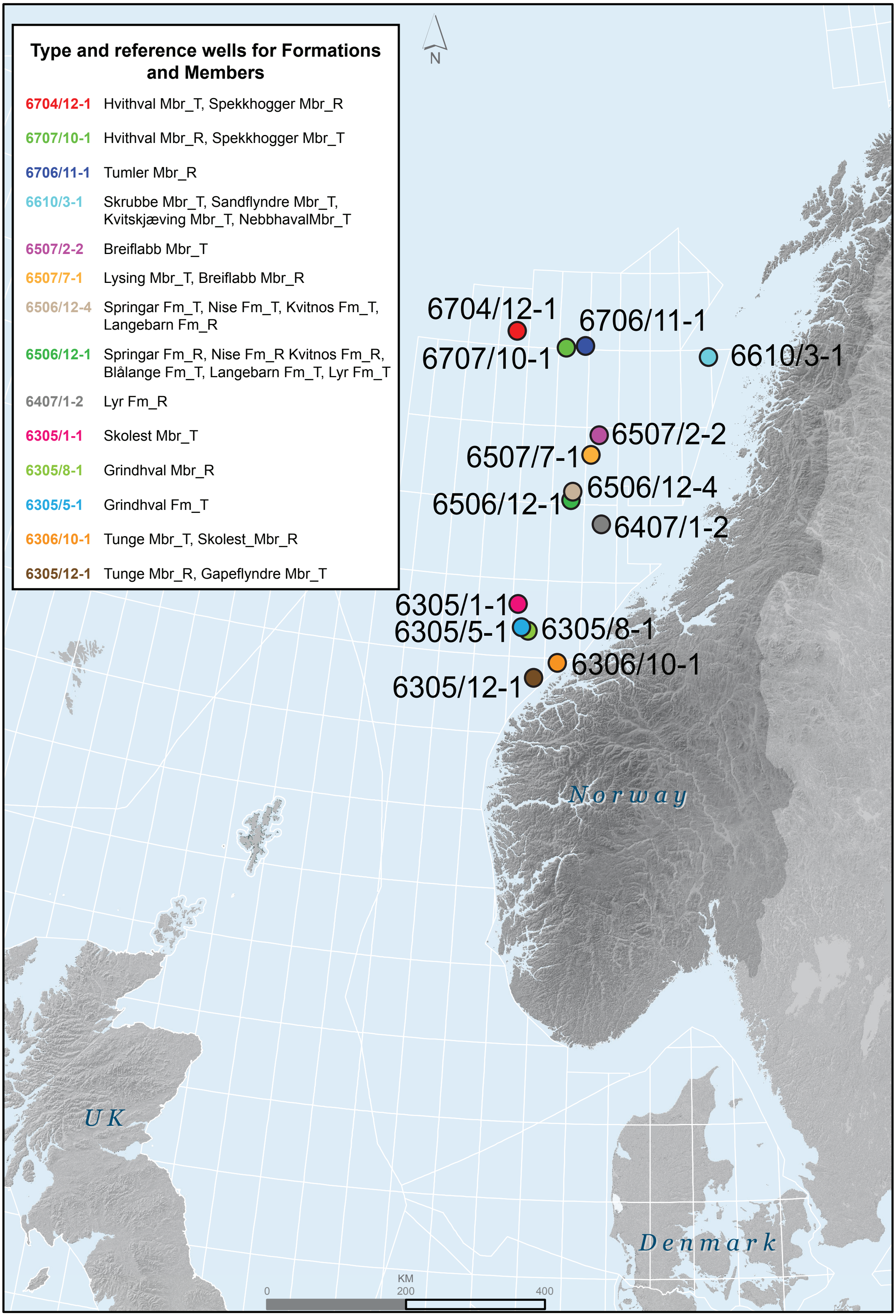


Figure 3.2. Type and reference wells for Cretaceous formations and members, Norwegian Sea

Cromer Knoll Group (Updated) (Cromer Knollgruppen)

The original definition of the Cromer Knoll Group is in Isaksen and Tonstad (1989). In the Norwegian Sea the group originally included the Lyr, Lange and Lysing Formations, and extended across the Lower/Upper Cretaceous boundary. Thus, it was of greater stratigraphic extent than the Cromer Knoll Group in the North Sea, where it essentially is a Lower Cretaceous argillaceous unit. We have redefined the stratigraphic extent of the Group such that the Norwegian and North Sea definitions agree more closely.

Name

From the Cromer Knoll buoy in the southern North Sea. Named by Deegan & Scull (1977). Norlex lithostratigraphy at the Group level is shown in Table 3.1.

Cretaceous Lithostratigraphy, Norwegian Sea						Standard Chronostratigraphy (Gradstein et al. 2012)	
Group	Formation	Members					
		Vøring Basin	Dønna & Halten Terraces	Vestfjorden Basin	Møre Basin	66.0	
Shetland Group (redefined base)	Springar Fm	Hvithval Mbr			Grindhval Mbr	Maastrichtian 72.1	Late Cretaceous
	Nise Fm	Spekkhogger Mbr		Nebbhval Mbr		Campanian 83.6	
	Kvitnos Fm	Tumler Mbr		Kvitskjæving Mbr		Santonian 86.3; Coniacian 89.8	
	Blålange Fm (previously 'upper' Lange)	Lysing Mbr	Lysing Mbr		Tunge Mbr	Turonian	
			Informal minor sst		Skolest Mbr	Turonian 93.9	
			Breiflabb Mbr	Skrubbe Mbr	Gapeflyndre Mbr	Cenomanian	
				Sandflyndre Mbr		Cenomanian 100.5	
Cromer Knoll Group (redefined base)	Langebarn Fm (previously 'lower' Lange)		Informal minor sst			Albian 113.0; Aptian 126.3	Early Cretaceous
	Lyr Fm					Barremian 130.8; Hauterivian 133.9; Valanginian 139.4; Berriasian 145.0	

Table 3.2 Cretaceous formations and members of the Norwegian Sea.

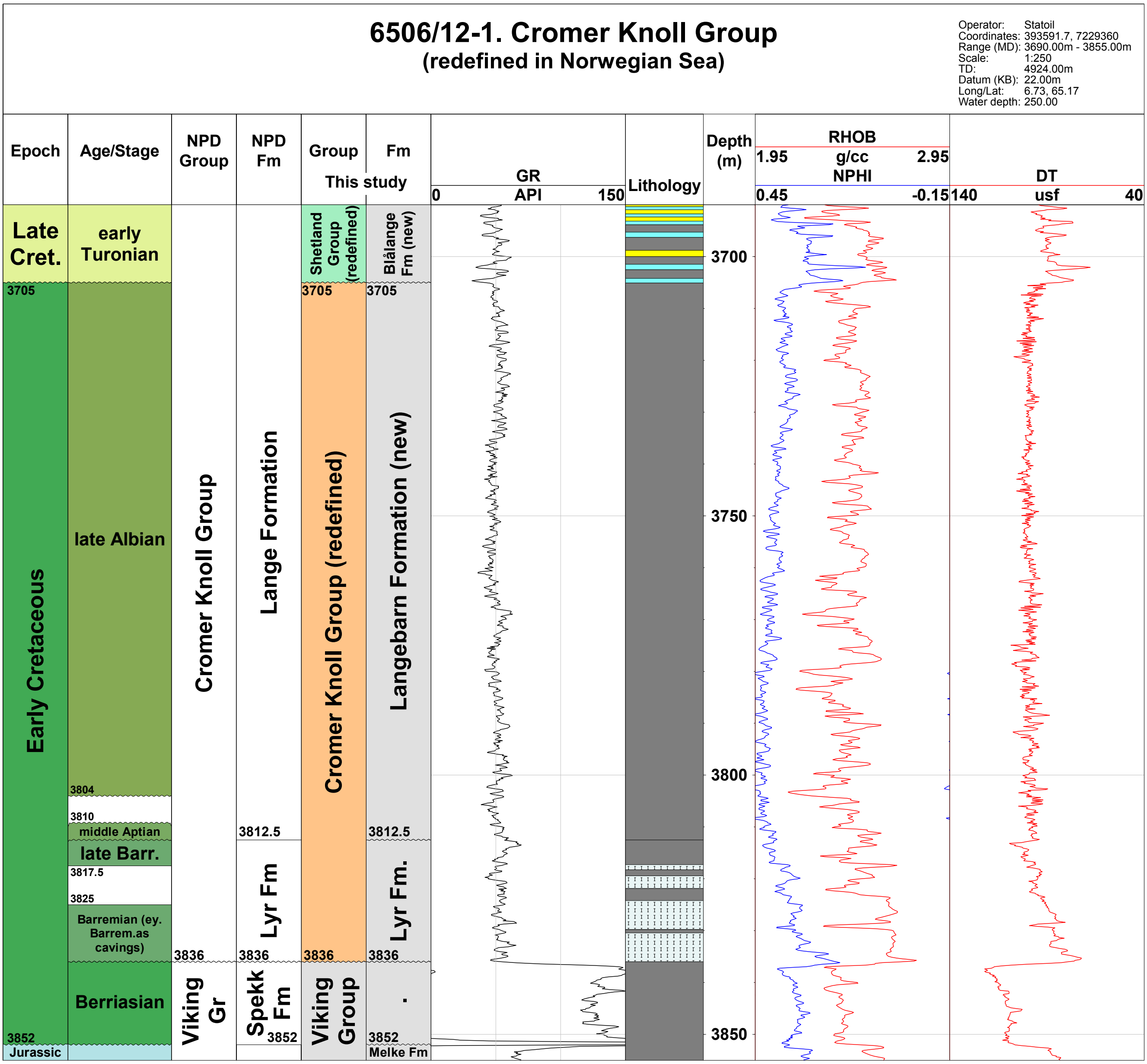


Figure 3.3. Well log and lithology for the re-defined (in the Norwegian Sea) Cromer Knoll Group and its formations in reference well 6506/12-1.

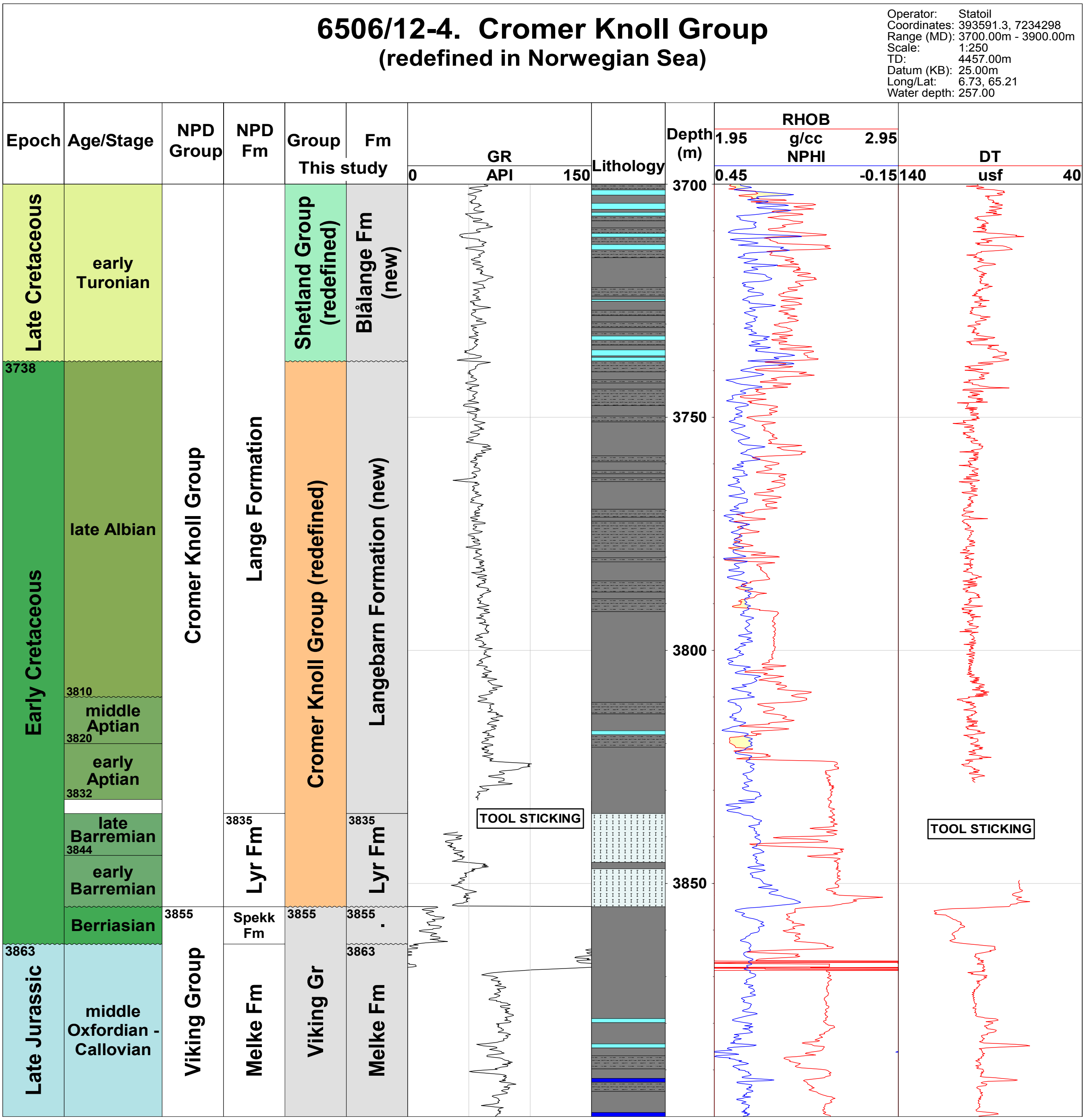


Figure 3.4. Well log and lithology for the re-defined (in the Norwegian Sea) Cromer Knoll Group and its formations in reference well 6505/12-4.

Type area

The type area for the Cromer Knoll Group is in the southern North Sea. Rhys (1974) used UK well 48/22-2 to illustrate a typical section of the group, and Deegan & Scull (1977) used UK wells 29/25-1, 22/1-2A and 3/29-1, and Norwegian well 2/11-1. The emphasis in this paper is on the Norwegian sector, and for this purpose wells 6506/12-1 and 12-4 (locations in Figure 3.2) are used to illustrate local developments of the group. Other wells useful to study the Group are 2/6-2, 2/7-15, 2/11-1, 7/3-1, 17/11-2, 34/10-18, 35/3-4, 35/3-5, 31/6-3, 24/12-2 and 17/4-1; the Danish well DK1-1 has also been used (see hyperlinks in the Norlex website under this group).

In well 6506/12-1 the Cromer Knoll was previously defined from 3175 m to 3836 m (NPD definition). This is corrected in this study from the clear log break at 3705 m and the top of *Apteodinium grande* and *Osangularia schloenbachi* to the log break at 3836 m, top of Viking Group (Figure 3.3). In well 6506/12-4, the Cromer Knoll Group was previously defined from 3132.5 - 3855 m (NPD definition). This broad usage is corrected in this study in well 6506/12-4 from the clear log break at 3708 m, just above the LO of *A.grande*, to 3855 m, to encompass the Lyr and redefined Lange Formations (Figure 3.4).

Thickness

The thickness of the group varies considerably. In the Viking Graben, the Asta Graben and locally in the Central Trough the thickness is often more than 600 m, gradually thinning towards the basin margins. The group is 667 m thick in Norwegian well 2/11-1 and 643 m thick in Norwegian well 17/11-1. Seismic data indicate that the group is thickest in the Sogn Graben, where it probably reaches up to 1400 m in thickness.

Figure 3.5 shows depth to the base of the Cromer Knoll Group (revised definition) in the Norwegian Sea based on released well data. The wells displayed are those that penetrated the base of the group.

Figure 3.6 shows depth to the top of the Cromer Knoll Group (revised definition) in the Norwegian Sea based on released well data. This follows the revised definition that corresponds to the top Lower Cretaceous, and coincides with the level applied in the North Sea. The wells displayed are those that penetrated the group.

Lithology

The Cromer Knoll Group consists mainly of fine-grained, argillaceous, marine sediments with a varying content of calcareous material. Calcareous claystones, siltstones and marlstones dominate, but subordinate layers of limestone and sandstone occur. The claystones are generally light to dark grey, olive-grey, greenish and brownish, often becoming light grey, light greenish-grey and light olive-grey marlstones. Mica, pyrite and glauconite are common. Generally, marlstones become the more dominant lithology in both the upper and lower parts of the group.

Basal stratotype

The lower boundary is usually well defined and is recognised by a distinct decrease in gamma-ray response and an increase in velocity when passing upward from the generally more organic-rich shales of the underlying Upper Jurassic formations (see Figures 12-14 and 22 in Isaksen and Tonstad, 1989).

Characteristics of the upper boundary

South of approximately 59° N, the upper boundary is the base of the chalk facies of the Shetland Group, defined by the onset of a decrease in gamma-ray response and an increase in velocity into the overlying carbonates. The uppermost Rødby Formation of the Cromer Knoll Group often appears on logs as a transition between the overlying carbonates of the Shetland Group and the more argillaceous parts of the Cromer Knoll Group. Further north, the upper boundary is the base of the siliclastic facies of the Shetland Group. This boundary is normally also shown by a decrease in gamma-ray response and an increase in velocity when passing into the overlying, generally more calcareous, Svarte Formation of the Shetland Group.

Distribution

The group is widely distributed in the Norwegian sector of the North Sea. It is absent from the highest parts of the Mandal High, Jæren High, Utsira High and Lomre Terrace in the Troll area and locally from the Tampen Spur. The Norlex internet website under Cromer Knoll *www.nhm2.uio.no/norges/litho/cromer.php* has a link for 'Occurrences of Group tops in wells'.

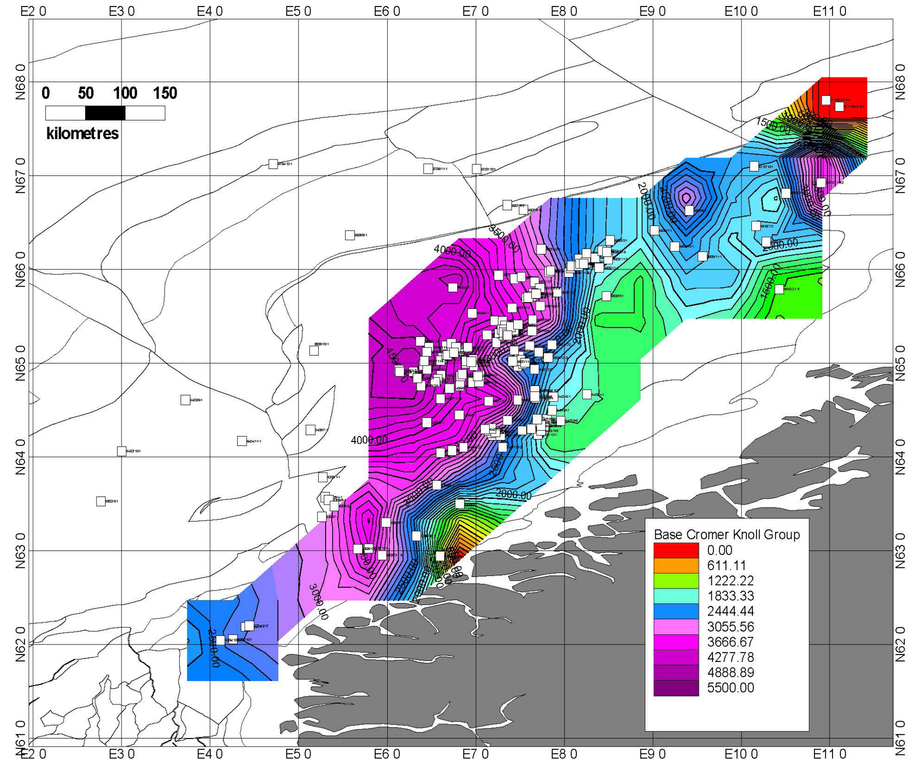


Figure 3.5. shows depth to the base of the Cromer Knoll Group (revised definition) in the Norwegian Sea based on released well data. The wells displayed are those that penetrated the base of the group.

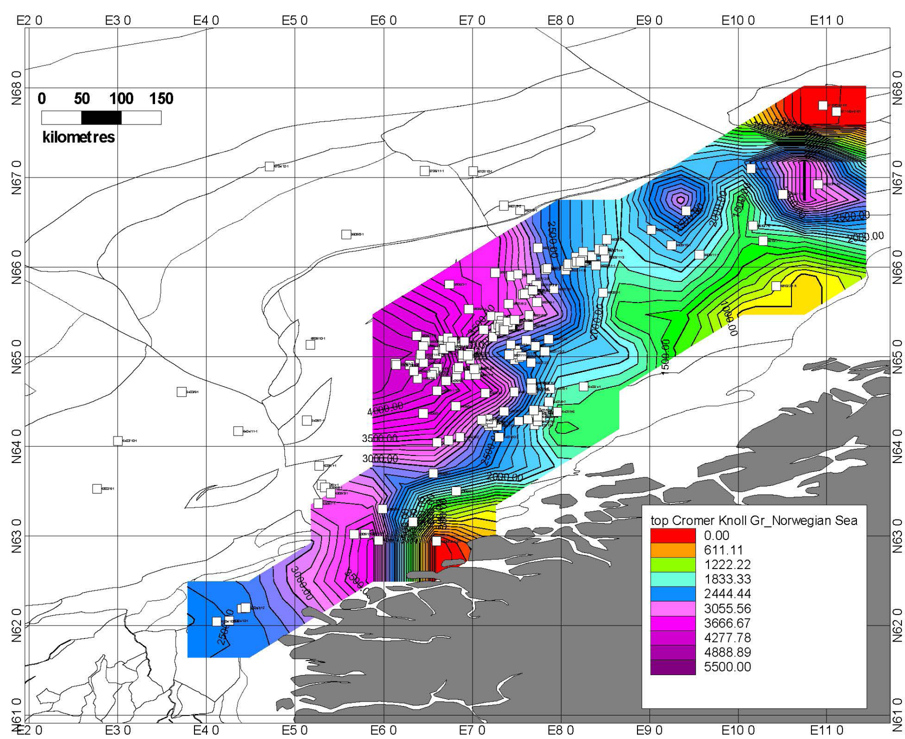


Figure 3.6. shows depth to the top of the Cromer Knoll Group (revised definition) in the Norwegian Sea based on released well data. This follows the revised definition that corresponds to the top Lower Cretaceous, and coincides with the level applied in the North Sea. The wells displayed are those that penetrated the group.

Age

Early Cretaceous.

Depositional environment

Open marine, with generally low energy.

Subdivision

Several formations and members are recognized within the group (Tables 3.2 and 3.3). In the Norwegian Sea this includes the Langebarn and Lyr Formations. In the northern North Sea the Cromer Knoll Group includes the Rødby, Agat, Sola, Tuxen, Åsgard and Mime Formations, and Ran Member.

Remarks

The group was erected by Rhys (1974) to embrace three marine, arenaceous, argillaceous to marly formations of mainly Early Cretaceous age recognisable onshore and offshore. Deegan & Scull (1977) formally defined the group to include the sediments between the underlying Humber Group and Bream Formation and the overlying Shetland and Chalk Groups. Vollset & Dorset (1984) replaced the Humber Group of the northern North Sea by the Viking Group, and the Bream Formation in the Central Trough and the Norwegian-Danish Basin by the Tyne and Boknfjorden Groups, respectively. The tops of the Draupne Formation of the Viking Group, the Mandal Formation of the Tyne Group and the Flekkefjord Formation of the Boknfjorden Group define the base of the Cromer Knoll Group.

The Cromer Knoll Group is partly equivalent to the Dutch sector (NAM & RGD 1980, Crittenden 1982) and the Speeton Clay Formation together with the Red Chalk Formation of the UK sector (Rhys 1974).

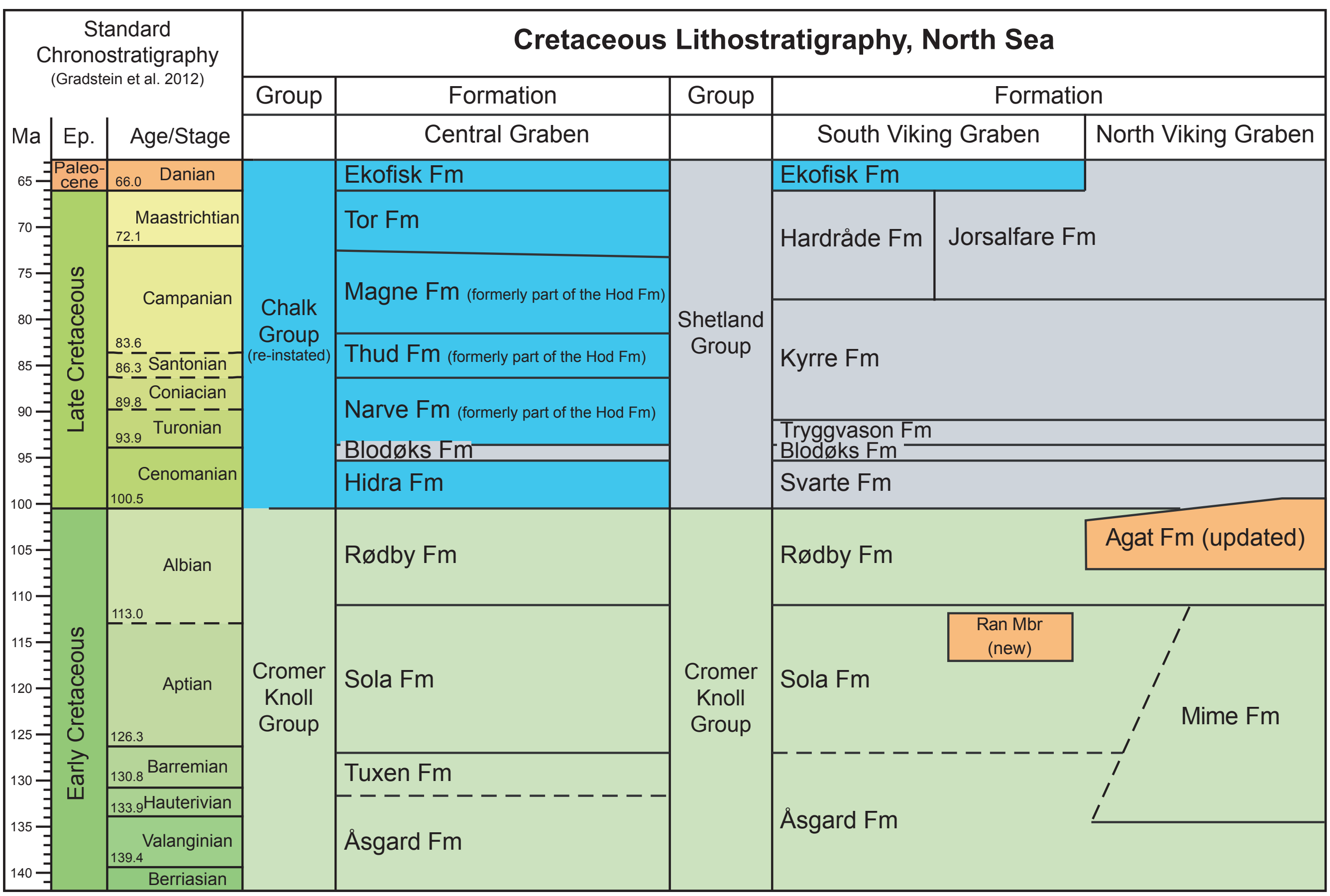


Table 3.3 Cretaceous lithostratigraphy of the Norwegian North Sea.

Lyr Formation

Cromer Knoll Group, Norwegian Sea (Table 3.2)

Introduction

The term Lyr Formation was introduced by Dalland *et al.* (1988) for a unit of calcareous mudstones and marls.

Sandstone members have not been formally defined in the Lyr Formation, although rare, isolated, sand units have been identified at Barremian and Hauterivian stratigraphic levels, and are predicted to be more widespread in the un-drilled deeper sections of the Vøring Basin. The following account concentrates on providing some useful additional information on the stratigraphic and geographic distribution of the formation.

Name

English/ Norwegian and any previous names: Informally as "Basal Cretaceous Marl" (Hastings 1987).

Derivatio nominis: From the Norwegian word for the fish species *Pollachius pallachius* or Pollack (Dalland *et al.,* 1988).

Lithology

The Lyr Formation consists of interbedded marls, calcareous mudstones and mudstones with occasional stringers of limestone. The mudstones are calcareous, grading to marls, and are medium dark grey to light grey or white-light grey, green-grey or red-brown, soft to firm, occasionally moderately hard, blocky to sub-fissile, plastic, amorphous, partly silty and micromicaceous. Non- calcareous mudstones may also be present (particularly towards the top of the formation) and these are grey, red brown, firm and blocky. The limestones form subordinate stringers and are white to light grey and hard.

Sample depository

Palynological preparations (organic matter depository)

Type well 6506/12-1: Four slides from ditch cuttings samples covering the interval 3815 - 3830 m (Stratlab, RRI and NPD preparations) deposited at the Norwegian Petroleum Directorate.

Reference well 6407/1-2: Three slides covering the interval 3520 - 3526 m including two slides from swc samples at 3520.5 m and 3526 m (Stratlab and LAP preparations) deposited at the Norwegian Petroleum Directorate.

Core photographs

Type well 6506/12-1: No cores taken in this formation.
Reference well 6407/1-2: No cores taken in this formation.

Thickness

The Lyr Formation ranges in thickness from 0.5 m to 444 m.

Geographical distribution

The Lyr Formation is regionally extensive but generally less than 100 m thick. It locally reaches a maximum in well 6510/2-1 (444 m) located on the Vega High on the Trøndelags Platform. It also forms a local thick in well 6407/8-1 (272 m) on the Halten Terrace and in block 6608/10 on the Dønna Terrace e.g. 6608/10-9 (226.5 m) The Lyr Formation is either absent or extremely condensed in wells on the Nordland Ridge e.g.in well 6608/11-2 (0.5 m); it has not been penetrated in deep water wells in the Vøring Basin.

Dalland *et al.* (1988) suggested that the carbonate content is expected to decrease to the west in the Møre and Vøring Basins. The formation consists of very thin limestones with intra-formational conglomerates on the eastern part of the Trøndelag Platform (Bugge *et al.* 1984). Dalland *et al.* (1988) noted a thin sequence of claystones of Hauterivian to Barremian age subcrop along the eastern part of the Trøndelag Platform. Red-brown oxidized silty claystone found there is also commonly encountered in wells further offshore. Similar sequences are exposed on Andøya and on East Greenland. The Lyr Formation description on the Norlex website has a function to generate occurrences of formation tops in wells.

Type well

Well name: 6506/12-1
WGS84 coordinates: N 65°10'07.58, E 06°43'44.07
UTM coordinates: 7229359.52 N 393591.68 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)

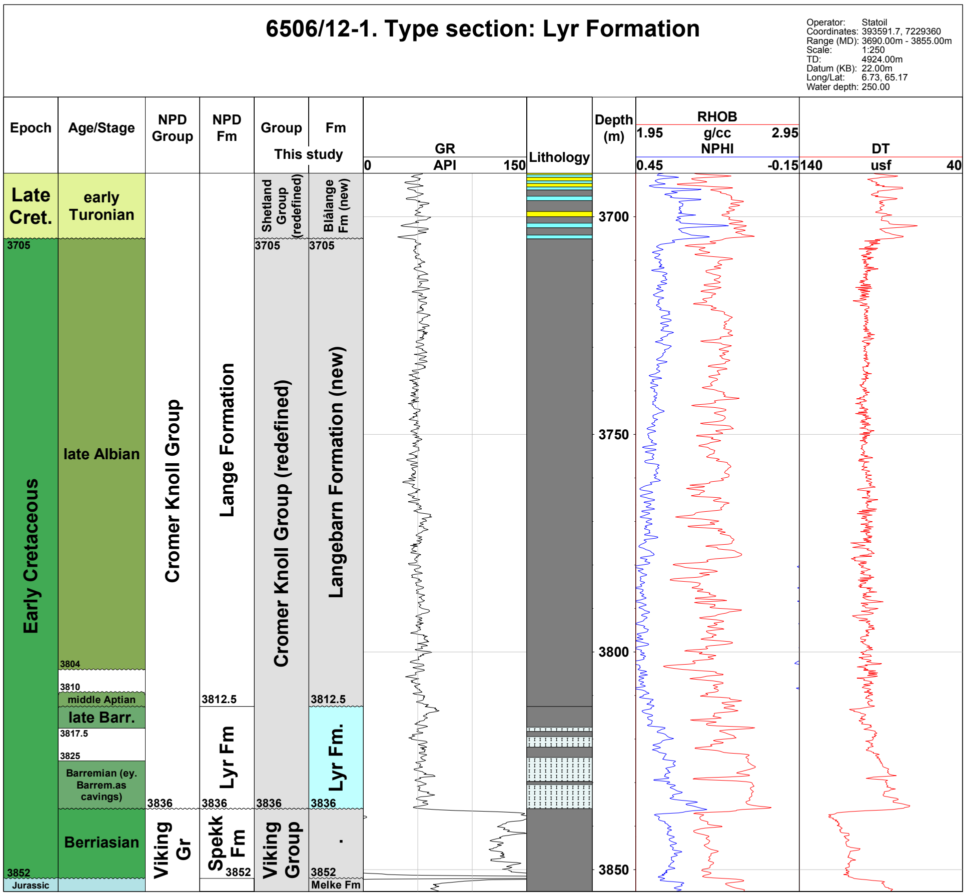


Figure 3.7. Well logs and lithology for the Lyr Formation in type well 6505/12-1, Norwegian Sea.

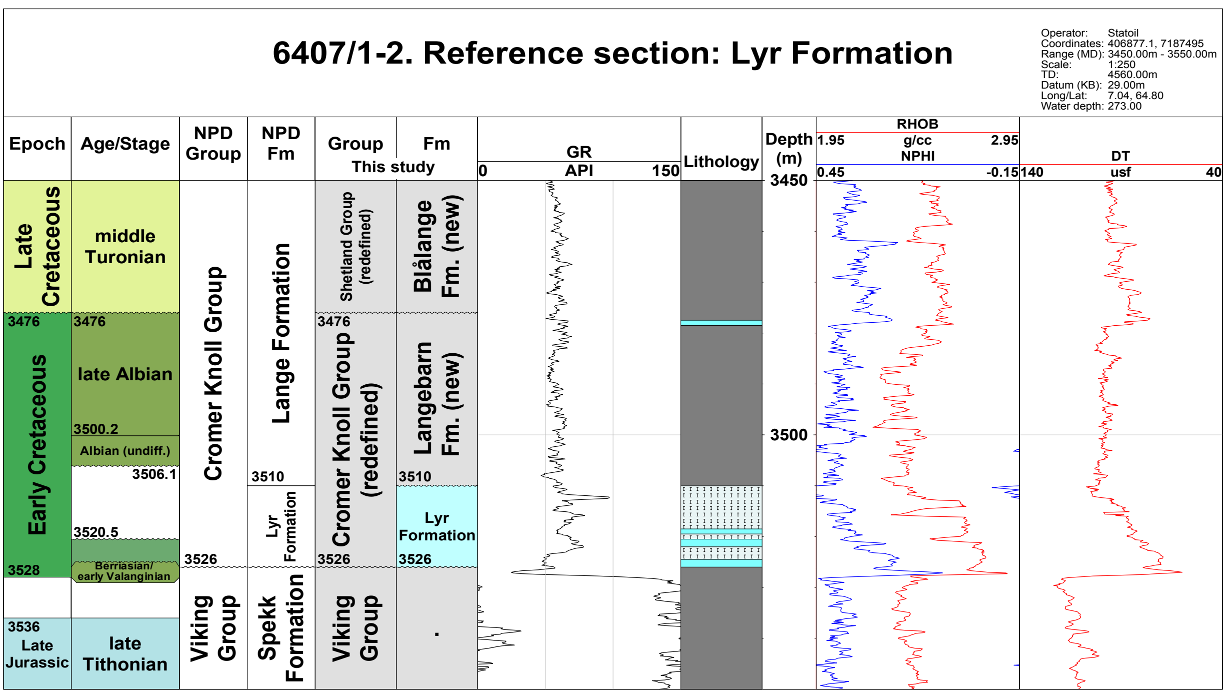


Figure 3.8. Well logs and lithology for the Lyr Formation in reference well 6407/1-2, Norwegian Sea.

Completion date: 15.05.1983
Status: P & A
Interval of type section & thickness in reference well: 3526 - 3510 m, 16 m thickness. Figure 3.8 provides the well log and lithology column for the reference well.

Upper and lower boundaries

Upper boundary

The upper boundary of the Lyr Formation is normally defined by a downward change from non-calcareous mudstones of the Langebarn Formation to grey or red--brown mudstones, calcareous mudstones or marls of the Lyr Formation. In both the type and reference wells, Dalland *et al.* (1988) indicated that this boundary corresponds on wireline logs to a downward increase in gamma ray values and decrease in sonic velocities. This a-typical wireline log response is taken to reflect a thin regional interval of early Aptian-late Barremian organic-rich mudstones developed in the upper part of this formation. There is an increase in average sonic velocities in the lower part of the formation, providing potential to subdivide the formation into two units.

Lower boundary

The base of the Lyr Formation is normally taken at a sharp downward change from marls or calcareous mudstones to dark grey or brown-grey, non-calcareous, organic-rich, mudstones of the Draupne Formation. The base is usually well defined on wireline logs and characterised by a marked downward increase in gamma-ray values and decrease in sonic velocities.

Well log characteristics

The log response is generally variable. An informal two-fold subdivision of the Lyr Formation is possible in many wells. At the base, the Lyr unit 1 (L1) is a thin unit with higher sonic velocities and variable gamma ray values that is characterised by calcareous mudstones and marls. The overlying Lyr unit 2 (L2) is characterised by mudstones with a less calcareous content and has lower average sonic velocities. On some operator completion logs, it is this intra-Lyr L1/L2 boundary that was used to define the top of the formation.

Biostratigraphy

Zones NC1 through 4 decribed in Part 1 of this study have been locally found in the Lyr Formation. In deeper parts of the Vøring Basin the formation is not penetrated by wells and in the type area around blocks 6506/12 and 6407/1 located on the Halten Terrace the Lyr Formation is truncated and bounded both above and below by unconformities. In these wells, the age is based primarily on the benthonic foraminiferal species, LO *G. barremiana*, LO *Marssonella trochus*, LO *Patellina subcretacea* and (in the case of the type well 6506/12-1) the common occurrence of *Falsogaudryinella praemoesiana* as cavings within the underlying Viking Group. This is confirmed by the co-occurring Barremian dinocyst marker LO *Valensiella magna.*

More extensive sections of the Lyr Formation are developed in the Gimsan Basin e.g. 6407/8-1 where the base of the Cromer Knoll Group and Lyr Formation is conformable with the underlying Viking Group. In this well the Lyr Formation is over 450 m thick and contains a relatively complete sequence of Hauterivian and Valanginian dinoflagellate cysts. The base of the Lyr Formation is Early Cretaceous, latest Berriasian - earliest Valanginan in age and the oldest markers recorded are the LO *S. palmula* and LO *Endoscrinium pharo* associated with an influx of pyritised radiolarians.

Age (revised)

Early Cretaceous, late Berriasian - early Aptian. The revised age differs only slightly from the Valanginian - early Aptian age recorded by Dalland *et al.* (1988).

Correlation

The only Cretaceous sediments present onshore Norway crop out on the east coast of Andøya, and have been described in detail by Dalland (1975, 1979 and 1981). These form an approx. 400 m thick, but truncated and condensed, overall transgressive sequence of shallow marine sandstones and deeper offshore mudstones of the Nybua and overlying Skarstein Formations Formations of Valanginian to Aptian age (Løfaldi and Thusu, 1979; Smelror *et al.*, 2001). These strata are time equivalent to the deeper offshore mudstones of the Lyr Formation.

In addition, Smelror *et al.* (2001) described some shallow cores of Middle Jurassic- Early Cretaceous age from the Troms III (Harstad Basin) and Nordland

VII offshore areas, northern Norway, and correlated these with the Andøya section. Using the lithostratigraphic scheme devised for the Tromsøflaket, western Barents Sea by Worsley *et al.* (1988), these authors assigned the Valanginian - Albian cored sediments to the Klippfisk and Kolje Formations. They noted the condensed calcareous siltstones and nodular limestones of the Klippfisk Formation (Valanginian - Hauterivian age) in core 6814/04-U-02 resemble those of the Lyr Formation. These were interpreted as being deposited over a long time span in a marine environment below wave base. The overlying restricted marine dark-grey pyritic claystones of the Kolje Formation (middle Hauterivian - early Albian age) penetrated in the 7018/07-U-01 and 7018/05-U-01 shallow cores (Troms III) are equivalent to the Skarstein Formation of Andøya and the Lyr and 'lowermost' Langebarn Formation of the deeper Norwegian Sea.

Dalland *et al.* (1988) correlated the Lyr Formation regionally with the Valhall Formation in the North Sea. Biostratigraphic calibrations in this study suggest that it is equivalent to the Åsgard, Mime and (lower) Sola Formations in the Viking Graben, northern North Sea and Knurr and Kolje Formations in the Barents Sea area.

Depositional environment

The formation was deposited under open marine conditions (Gradstein *et al.*, 1999).

Remarks

The Lyr Formation represents deposition with the K1 sequence of Swieciciki *et al.* (1998), K10 to K30 sequences of Vergara *et al.* (2001), and the K10 sequence of Færseth and Lien (2002).

Langebarn Formation [new]

Cromer Knoll Group, Norwegian Sea (Table 3.2)

Introduction

The Langebarn Formation is a new formation representing the lower part of the original Lange Formation of Dalland *et al.* (1988). It represents a relatively uniform sequence of Lower Cretaceous (Albian--Aptian) marine mudstones with sporadic limestone stringers. The upper part of the original Lange Formation is defined as a new formation also, the Blålange Formation. In the type area of the Halten Terrace, the Langebarn and Blålange Formations are separated by a significant stratigraphic break that corresponds to the Lower/Upper Cretaceous boundary. With this new definition, it is now practical to redefine the Cromer Knoll Group in the Norwegian Sea with a similar stratigraphic extent to that in the North Sea. The Langebarn Formation being time-equivalent to the Rødby and Sola Formations in the North Sea area.

Sandstones within the redefined Lange Formation are generally rare, although a sandstone unit is discussed informally that was penetrated in well 6507/7-12. This unit was informally described as 'Aptian Sands' by the Operator in a Lower Cretaceous mini-basin drilled in the hanging wall of the Revfallet Fault complex separating the Dønna Terrace from the Nordland Ridge/Trøndelags Platform. Thus, sandstones may be developed in this formation in the deeper, undrilled parts of the Vøring Basin.

Name

English/ Norwegian and any previous names: This is equivalent to the informal 'Middle' and 'Lower' Lange Formations of Swiecicki *et al.* (1998) and 'lower' Lange Formation of Færseth and Lien (2002).

Derivatio nominis: The name Langebarn is derived from the Norwegian for the fish species *Lumpenus lumpretaeformis*, or more correctly, the Langhalet Langebarn or Snakeblenny. This fish is found along the entire Norwegian coast, and is usually associated with muddy bottoms at 30 - 200 m water depths.

Lithology

The Langebarn Formation consists predominantly of mudstones containing occasional stringers of limestone and rare sandstones. The mudstones are similar to those of the overlying Blålange Formation, but are generally more uniform with fewer limestone and sandstone interbeds. The mudstones are light to medium grey, grey brown, occasionally green-brown, soft, plastic, amorphous, non- to moderately calcareous, blocky, firm, locally subfissile, micromicaceous and slightly silty in part.

An informal sandstone unit in the well 6507/7-12 (3670 - 3703.5 m MD and 33.5 m thickness) consists of sandstones and interbedded siltstones and mudstones. Sandstones are medium grey to dark grey in colour, white to light yellowish grey, clear quartz grains, very fine to coarse, predominantly fine to medium, becoming very silty, grading to siltstone, subangular to subrounded, occasionally angular in coarse fraction, moderately sorted, friable, argillaceous matrix, common silica cement or locally moderate calcareous cement, locally trace of *coal*, mica and pyrite, rare glauconite, no visible porosity.

The siltstones are dark grey, blocky, firm, slightly calcareous, argillaceous grading to mudstones in part, locally very fine sandy, grading to silty sandstones, carbonaceous.

The mudstones are grey, black to olive black, blocky, sub-fissile, moderately hard to hard, non calcareous becoming locally very silty, carbonaceous to very carbonaceous.

Sample depository

Palynological preparations (organic matter depository)

Type well 6506/12-1: Twenty-one slides from dc samples and two swc samples at 3724 m and 3804 m covering the interval 3710 - 3810 m, deposited with the Norwegian Petroleum Directorate.

Reference well 6506/12-4: Eleven slides from dc samples covering the interval 3757 - 3835 m, deposited with the Norwegian Petroleum Directorate.

Core photographs

No cores were taken in the designated type 6506/12-1 and reference 6506/12-4 wells.

Thickness

The Langebarn Formation ranges in thickness from 3 m to 467 m. Under *www.nhm2.uio.no/norges/litho*

/langebarn.php is the regional isochore of the Langebarn Formation thickness in the Norwegian Sea, based on released well data. The isochore map is generated from Norlex data using thin plate splines (thickness constrained to original range). Thicknesses are in metres. Circled wells contain both top and base horizons. The red wells have Norlex biostratigraphy. On this Norlex website an interactive and larger version may be uploaded, hence users can generate more specific, local area isochore maps interactively.

Geographical distribution

The (new) Langebarn Formation is generally regionally extensive, and is only absent from parts of the Nordland Ridge and on local highs along the western flank of the Trøndelag Platform. However it has generally not been penetrated in the deep wells of the Vøring Basin, so data from this area is lacking. It reaches a maximum thickness of 467 m in well 6507/7-12. This well was drilled in an Early Cretaceous mini basin, developed in the hanging wall of the Revfallet Fault complex separating the Dønna Terrace from the Nordland Ridge to the east, and contains rare interbedded sandstones and mudstones (informal unit).

The formation is generally thicker in wells on the Dønna Terrace e.g. 6507/2-3 (432 m). Elsewhere, on the Halten Terrace it is generally between 50 - 150 m thick although it may reach 300 m in some wells, e.g. 6406/3-2. In the Helgeland Basin, it locally reaches over 150 m, e.g. in well 6610/7-1.

The interactive decription of the Langebarn Formation on the Norlex website has a function to generate formation tops in wells.

Type well (revised)

Well name: 6506/12-1
WGS84 coordinates: N 65°10'07.58", E 06°43'44.07"
UTM coordinates: 7229359.52 N 393591.68 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 06.02.1985
Status: P & A
Interval of type section and thickness in type well: 3812.5 - 3705 m, 107.5 m thickness. Figure 3.9 provides the well log and lithology column for the type well. The lower boundary follows the original definition of Dalland *et al.* (1988). Previously, the original Lange Formation extended from 3190 m. The interval 3705 m to 3190 m is now assigned as the new Blålange Formation, described furtheron in this study.

Reference well (revised)

The top of the reference well is revised from 3150 m to 3755.5 m to accommodate the new Blålange Formation, described later in this study.
Reference well (revised)
The top of the reference well is revised from 3150 m to 3755.5 m to accommodate the new Blålange Formation, described later in this study.

Well name: 6506/12-4
WGS84 coordinates: N 65°12'46.97 ", E 06°43'30.37"
UTM coordinates: 7234298.14 N 393591.29 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 13.08.1985
Status: P & A
Interval of type section and thickness in reference well: 3835 m to 3738 m, 97 m thickness. The lower boundary follows the original definition for the Lange Formation of Dalland *et al.* (1988). The upper boundary of the Langebarn Formation is with the new Blålange Formation.

It is unfortunate that Dalland *et al.* (1988) defined the 6506/12-4 as the reference section for the Lange Formation since the base of the formation with the underlying Lyr Formation has an incomplete log profile (on both gamma ray and sonic logs). This is due to the tool sticking during wireline logging (see Figure 3.10).

Upper and lower boundaries

Upper boundary

In the type area of the Halten and Dønna Terraces, the boundary between the Langebarn Formation and overlying Blålange Formation is characterised by a down-section decrease in sonic velocities representing a stratigraphic break corresponding to the Lower/Upper Cretaceous boundary.

Lower boundary

The base of the Langebarn Formation is typically with

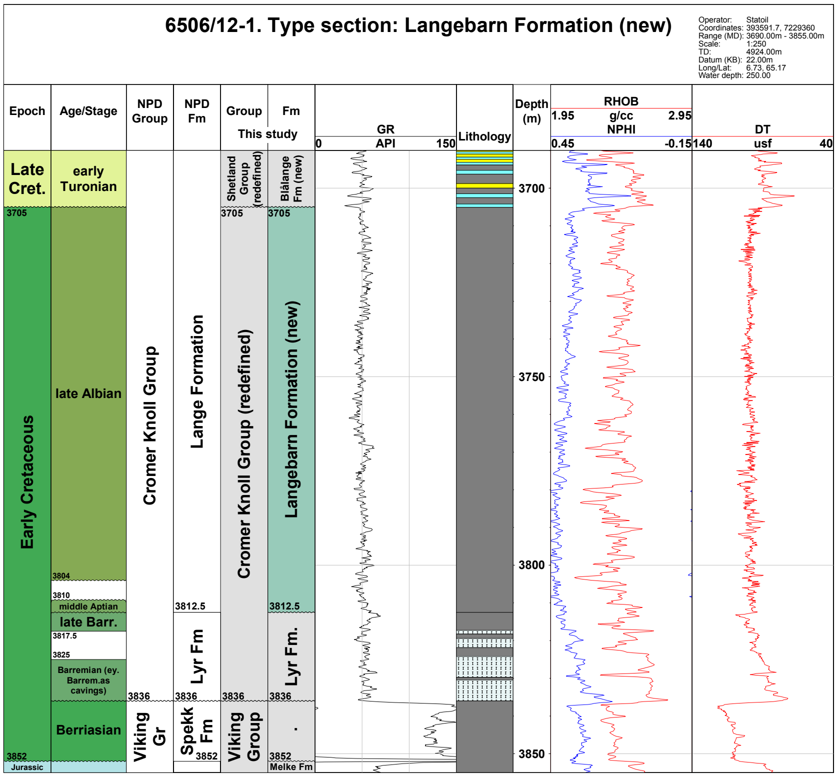


Figure 3.9. Well logs and lithology for the Langebarn Formation in type well 6506/12-1, Norwegian Sea.

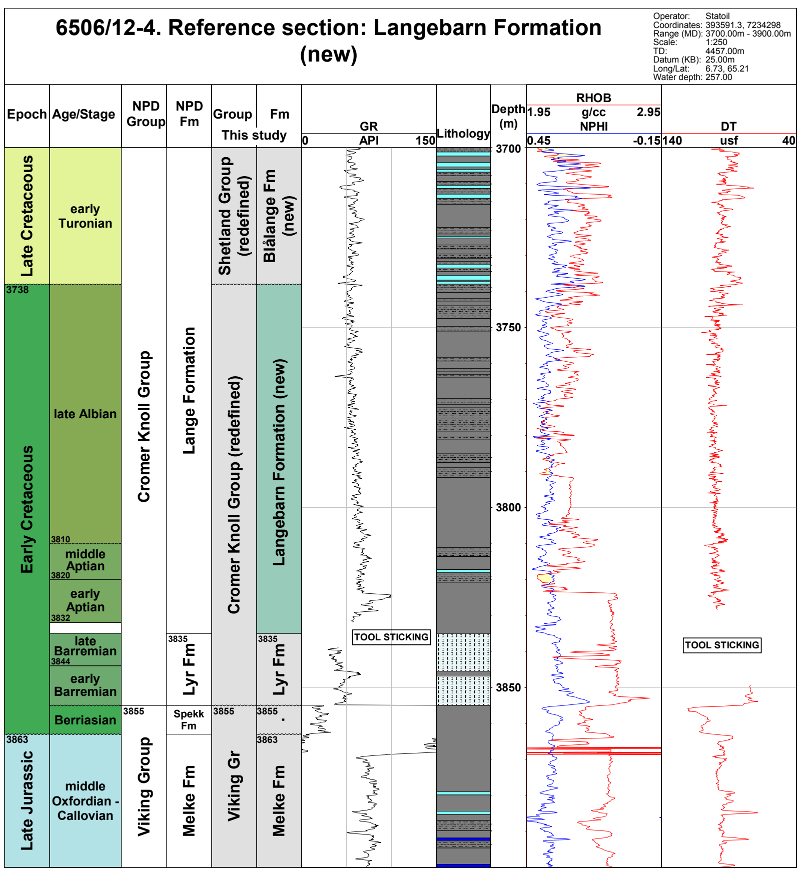


Figure 3.10. Well logs and lithology for the Langebarn Formation in reference well 6506/12-4, Norwegian Sea.

the underlying Lyr Formation and is characterised by an increase in gamma-ray values and decrease in velocity. The boundary has been sampled in shallow cores from the eastern part of the Trøndelag Platform (Bugge *et al.*, 1984).

Well log characteristics

The Langebarn Formation is generally characterised by a relatively uniform gamma ray and sonic velocity response, reflecting the monotonous nature of the mudstone sequence.

Biostratigraphy

In the type well 6506/12-1 the Langebarn Formation is middle Aptian to late Albian in age, and has unconformable lower and upper boundaries with the Lyr and Blålange Formations respectively. In the type well the lower boundary of the Langebarn Formation lies between the LO *Gardodinium trabeculosum*, LO *Cerbia tabulata* and LO *Aptea polymorpha* dinocyst markers and downhole increase in *Hedbergella* spp. defining a middle Aptian age, and above the LO *Valensiella magma* typical of late Barremian.

In the type well, sediments of early Aptian age are absent at the base of the formation. In other wells, including the reference well 6506/12-4, the lower boundary with the underlying Lyr Formation is complete and a thin early Aptian interval characterised by LO *Sirmiodinium grossii* is developed at the base of the Langebarn Formation.

In the type and reference wells, the upper boundary with that of the overlying Blålange Formation is associated with the late Albian dinocyst LO A*pteodinium grande* and the planktonic foraminiferal event LAO *Hedbergella planispira*. In these wells Cenomanian sediments of the basal Blålange Formation are absent.

In the 6507/7-12 well, an informal unit of interbedded sandstones and mudstones developed between 3670 - 3703.5 m MD and informally referred to as 'Aptian Sands' by Conoco (operator) is dated between the LO *Achmosphaera neptuni* (3600 m) of middle Aptian age and LO *Sirmodinium grossii* (3750 m) of early Aptian age, establishing firmly that the member is middle Aptian in age.

Type well (revised)

Early Cretaceous, early Aptian to late Albian.

Dalland *et al.* (1988) had the oldest extent of their Lange Formation as ranging into the Ryazanian Boreal stage, and as a partial time equivalent of the Lyr Formation which they considered to be Valanginian to early Aptian. This interpretation is not followed in this study with the oldest extent of the Langebarn Formation being stratigraphically younger than the Lyr Formation.

Correlation

Our biostratigraphy indicates that the re-defined Langebarn Formation is correlative to the Cromer Knoll Group, Rødby and Sola Formations of the northern North Sea.

Depositional environment

The Langebarn Formation was deposited in a relatively deep marine bathyal paleoenvironment with variable oxic or dysoxic bottom conditions (Gradstein *et al.*, 1999).

Remarks

The Langebarn Formation represents deposition with the K2 sequence of Swiecki *et al.* (1998), K35 to K40 sequences of Vergara *et al.* (2001), and the K20 - K30 sequences of Færseth and Lien (2002).

It is noteworthy that Lower Cretaceous sandstones of the Langebarn and Lyr Formations do not represent any appreciable thickness and are exceptionally rare in the Norwegian Sea based on the available released well coverage. This may be due to the Lower Cretaceous interval being generally not reached in wells drilled in the Vøring Basin. In addition, the wells drilled at the margins of the Trøndelags Platform are typically on structurally high Cretaceous locations in the quest for deeper lying Jurassic prospects. The frequency and distribution of Lower Cretaceous sandstones analogous to the North Sea Agat Member is therefore considered to be underestimated, based on the available well data. The (informally retained) sandstones penetrated in well 6507/7-12 represent the best example drilled to date of these potentially more extensive Lower Cretaceous sandstones.

Shetland Group (Updated) (Shetlandsgruppen)

The original definitions are in Dalland *et al.* (1988) and Isaksen and Tonstad (1989). Here the original definition is updated. The Shetland Group has been extended in the Norwegian Sea such that it has a similar stratigraphic duraton and boundaries to the original definition in the North Sea by Deegan & Scull (1977), (Table 3.1).

Name

Named after the Shetland Islands off the north coast of Scotland (Deegan & Scull 1977). The group was expanded in Isaksen and Tonstad (1989) to include the formational units of the former Chalk Group.

Type area

The group is typically developed in the central and Northern North Sea. A chalk facies is developed in the central North Sea, and a siliclastic facies in the northern North Sea. A typical section of the chalk facies in the central area is represented by Norwegian well 1/3-1 (Figure 24 in Isaksen and Tonstad, 1989), while Norwegian well 25/1-1 (Figure 33 in Isaksen and Tonstad, 1989) provides a typical section of the siliciclastic facies in the northern area. UK well 22/1-2A illustrates a section in the transition zone between the two facies (Figures 5 and 25 in Isaksen and Tonstad, 1989).

Thickness

In well 1/3-1 the group is 1183 m thick, and in well 25/1-1 it measures 1284 m. Seismic interpretation and well data indicate that the thickness of the group ranges between 1000 m and 2000 m in graben areas. The group shows considerable thinning towards and in the platform areas.

Figure 3.11 shows the depth to top of the Shetland Group in the Norwegian Sea based on released well data. A regional isopach of the Shetland Group thickness in the Norwegian Sea based on released well data is in the Norlex website. The isochore map is generated from Norlex data using thin plate splines (thickness constrained to original range). Thicknesses in metres. Circled well contain both top and base horizons. In the case of the Shetland Group this includes wells with a well TD within the group. The red wells have Norlex biostratigraphy. Note that this map is only a regional interpretation and the user can generate more specific, local area isochore maps interactively within the Norlex website, using a dedicated link.

Lithology

The group consists of the chalk facies of chalky limestones, limestones, marls, and calcareous shales and mudstones. Chert (flint) occurs throughout the facies. The siliciclastic facies consists of mudstones and shales, partly interbedded with limestones. Minor amounts of sandstones are present in the lower part in the Agat Field area (block 35/3). The shales and sandstones are slightly calcareous to very calcareous. In the Maastrichtian age part of the unit the quantity of limestones is generally higher on the Horda Platform than in the Viking Graben.

Figure 3.12 is the well log and lithology section of our reference well 6506/12-1, where the Shetland Group extends from the clear log break at 2279 m with lower Maastrichtian fossil taxa to the log break at 3705 m, just above the top of Albian index taxa (see below) in the Cromer Knoll Group.

Figure 3.13 is the well log and lithology section of our reference well 6506/12-4, where the Shetland group extends from the clear log break at 2211 m with upper Maastrichtian fossil taxa to the log break at 3738 m, just above the top of Albian index taxa (see below) in the Cromer Knoll Group.

Characteristics of the lower boundary

Typically the lower boundary is the contact to the calcareous mudstones or marlstones of the Cromer Knoll Group. On structural highs like the Horda Platform, Tampen Spur, Sørvestlandet and Mandal Highs the lower part of the group is occasionally absent, and the remainder rests unconformably on the Cromer Knoll Group, Jurassic or even older rocks.

Characteristics of the upper boundary

The group is overlain by Paleocene mudstones, marls or sandstones of the Rogaland Group.

Distribution

The group is present throughout the Norwegian North Sea, being absent only locally on highs (e.g. in the 16/5-1 and 31/2-9 wells) and a few salt diapirs

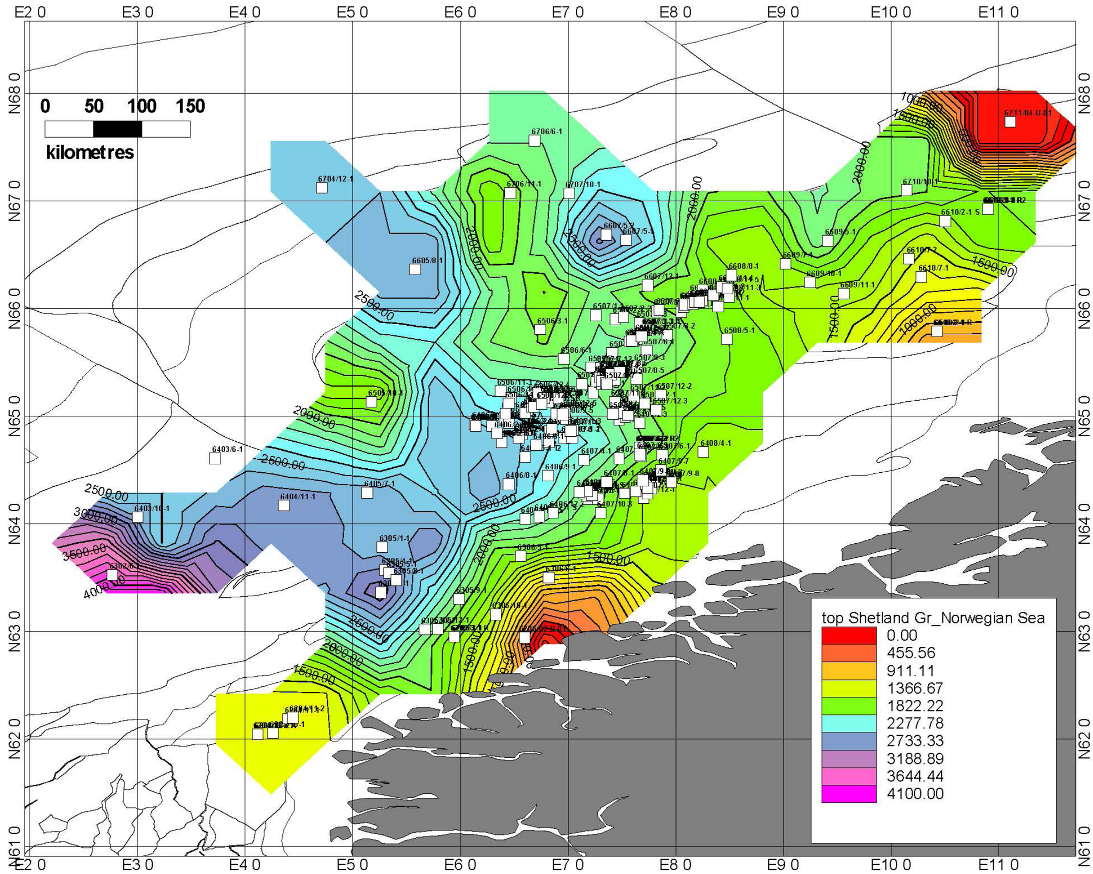


Figure 3.11. Depth to top of the Shetland Group in the Norwegian Sea based on released well data.

(e.g. in well 2/7-12). A transition between the chalk and siliciclastic facies of the group occurs relatively abruptly in the Norwegian sector along the Utsira High and more gradually in the graben areas. The interactive decription of the Shetland Group on the Norlex website has a function to generate formation tops in wells.

Biostratigraphy and Age

The Shetland Group ranges in age from Cenomanian to Danian. The siliciclastic facies is restricted in age to the Late Cretaceous.

In well 6506/12-1, the upper part of the Shetland Group just below 2279 m contains *G.michelinianus, O.costata, O.operculata, L.cooksonia* and *S.delitiense,* belonging in Zone NCF18 of an Early Maastrichtian age. Just below the base of the group in this well near 3710 m, in the uppermost Cromer Knoll Group, occur *A.grande*, common *H.planispira* and *O.schloenbachi* of our Zone NCF8, Late Albian (see Figure 2.7b).

In well 6506/12-4, the upper part of the Shetland Group at 2220 m contains *T.utinensis* of Late Maastrichtian age, and just below the base at 3738 m common *H.planispira* and *A.grande* of Zone NCF8, Late Albian.

Depositional environment

The Upper Cretaceous sequence was deposited in an open marine environment during a general rise in sea level (Hancock & Kauffman 1979). The siliciclastic facies in the Norwegian Sea is less well studied than its counterpart in the North Sea. The influx of siliciclastic mud was higher, and carbonate production lower than in the North Sea area with chalk facies.

Subdivision

The Shetland Group in the Norwegian Sea is subdivided from older to younger in the Blålange Formation (new) and Kvitnos, Nise and Springar Formations (Table 3.2).

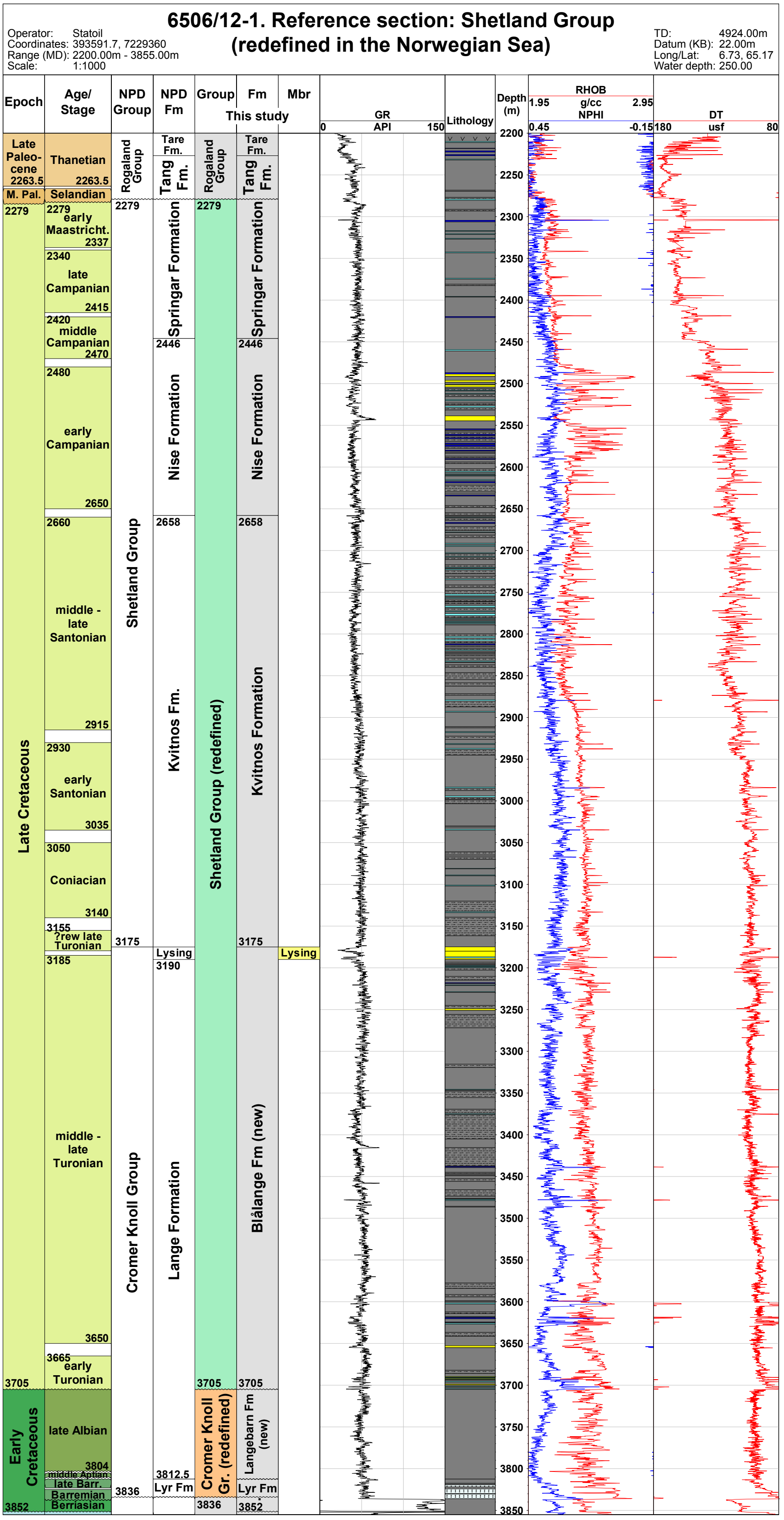


Figure 3.12. Well logs and lithology section for the Shetland Group in reference well 6506/12-1, Norwegian Sea.

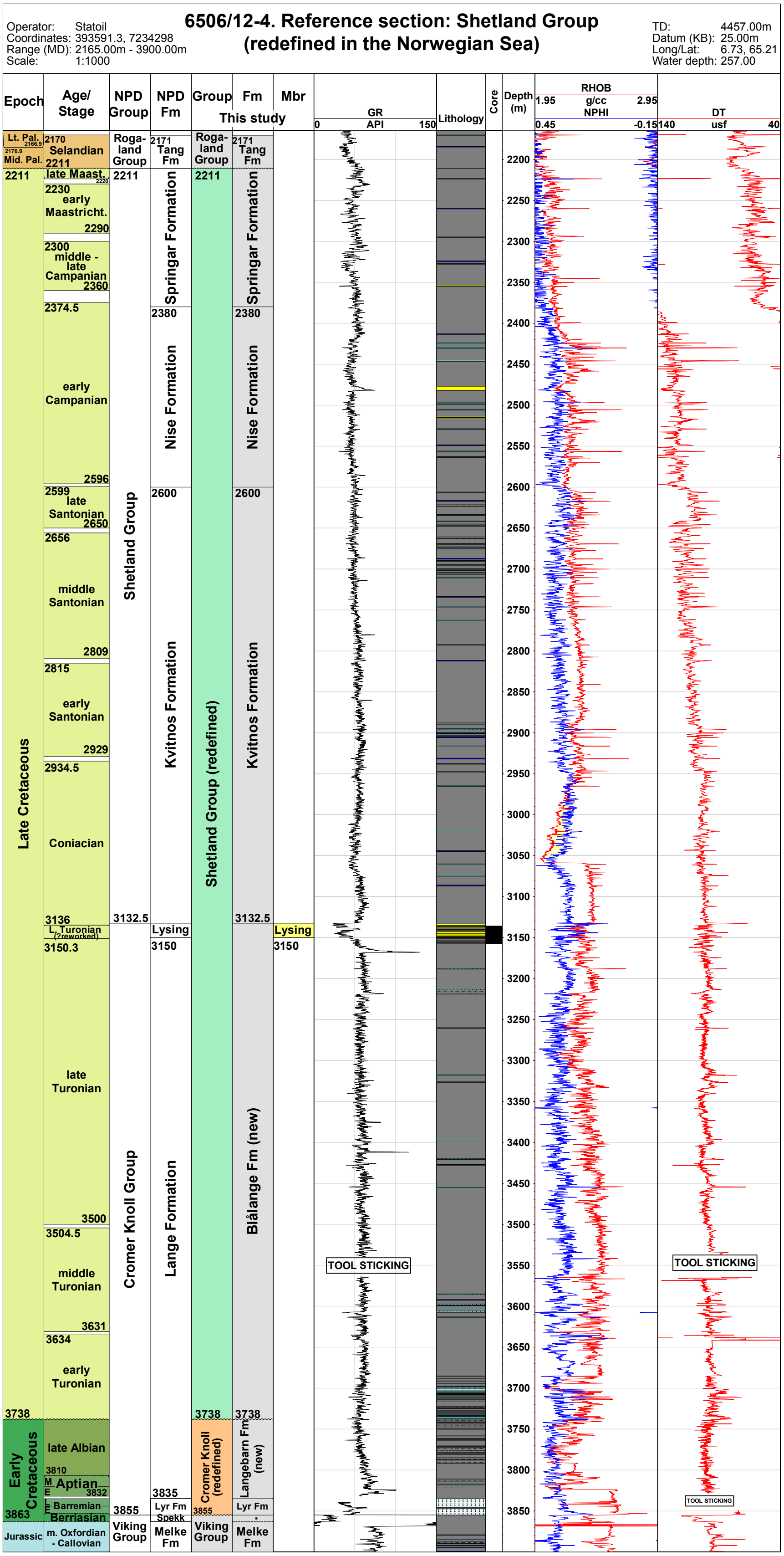


Figure 3.13. Well logs and lithology section for the Shetland Group in reference well 6506/12-4, Norwegian Sea.

Blålange Formation [new]

Shetland Group, Norwegian Sea (Table 3.2)

Introduction

The original and highly unfortunate Lange Formation of Dalland *et al.* (1988) has been replaced by two new formations: The Langebarn Formation and the Blålange Formation. Unfortunate, because the stratigraphically long and thick unit encompasses several sands that were not properly named, leading to considerable confusion when drilling and in well completion reports.The Blålange Formation is a new formation that is equivalent to the upper part of the original Lange Formation as defined by Dalland *et al.* (1988). The new underlying Langebarn Formation is proposed for the lower part of the original Lange Formation.

A two fold distinction was necessary since in many wells on the Halten and Dønna Terrace the two units are separated by an unconformity that is regionally identifiable on wireline logs. The definition of the Blålange Formation follows the main criteria used by Dalland *et al.* (op.cit) to recognise the original mudstone dominated formations and is primarily based on a change in average sonic velocity. This new sub-division also provides an opportunity to re-define the Shetland/ Cromer Knoll Group boundary in the Norwegian Sea at a similar stratigraphic level to that of the North Sea.

The Blålange Formation typically comprises a thick, relatively uniform sequence of Upper Cretaceous (Coniacian - Cenomanian) mudstones with sporadic limestone stringers and interpreted tuffaceous horizons. The Blålange Formation is of Late Cretaceous age. The formation contains of a series of local sandstones units, defined as members in this study. These members are locally developed on the Halten-Dønna Terrace area, in the Vøring Basin and along the Møre margin.

In total seven detached sandstone members are defined within the Blålange Formation in three distinct geographical areas: Skolest, Gapeflyndre and Tunge Members (Møre margin), Breiflabb, Lysing Member (Halten and Dønna Terrace areas), Sandflyndre and Skrubbe Members (Vestfjorden basin area).

These seven members are described in the following sections:

- Sandflyndre Member (Vestfjorden Basin)
- Gapeflyndre Member (south-east Møre margin)
- Skrubbe Member (Vestfjorden basin)
- Breiflabb Member (Halten and Dønna Terraces)
- Skolest Member (south-east Møre margin)
- Tunge Member (south-east Møre margin)
- Lysing Member (Halten and Dønna Terraces)

The new members range in age from Cenomanian through Coniacian. In addition to these seven new members, two intervals of sandstones are retained with informal status only (Table 3.2), due to a lack of information or isolated occurrences. In the deeper water of the Vøring Basin (e.g. in well 6505/10-1), an interval of interbedded sandstones and mudstones developed sporadically below the Turonian/Coniacian boundary (and below the Coniacian Lysing Member). The strata currently may only be distinguished on the basis of biostratigraphy, rather than independent log or lithological data.

Isolated thin bedded sandstones within the upper part of the Blålange Formation of 'mid' Turonian age are commonly developed in Quadrant 6507, e.g. 6507/5-2. These sandstones have not been cored and do not reach any significant thickness although there is potential for these to be more extensively developed in deeper, undrilled locations.

Name

English/ Norwegian and any previous names: The Blålange Formation is equivalent to the informal 'upper' Lange Formation of Swiecicki *et al.* (1998) and 'upper' Lange Formation of Færseth and Lien (2002).

Derivatio nominis: The name Blålange is derived from the Norwegian name for the fish species *Molva dypterygia*. The Blålange or blue Ling is appropriately a close relative of the Lange fish (cod family) and lives in deep waters along the Norwegian coast and fjords. It is therefore considered an appropriate name for a lithostratigraphic unit formerly part of the Lange Formation.

Lithology

The Blålange Formation mainly consists of mudstones with subordinate beds of sandstones and stringers of limestones, dolomites and marls. The mudstones are medium dark grey to medium brown grey, blocky, occasionally sub-fissile to fissile, predominantly firm, occasionally moderately hard, generally non calcareous or occasionally slightly calcareous. The formation contains subordinate sandstones as beds or members, siltstones and stringers of dolomite, limestones and marls. The siltstones are light brown-light brown grey, argillaceous and slightly calcareous. The calcareous stringers are white to light brown or red brown, moderately hard to hard.

Sample depository

Palynological preparations (organic matter depository)

Type well 6506/12-1: 102 slides including 5 swc samples covering the interval 3179.5 m swc - 3705 m dc deposited at the Norwegian Petroleum Directorate.
Reference well 6506/12-4: 94 slides including 20 core and 5 swc samples covering the interval 3129.1 m core (3135 m corrected depth) - 3754 m dc deposited at the Norwegian Petroleum Directorate.
Reference well 6610/3-1R: 67 samples including 6 core and 29 swc samples covering the interval 2670 m dc - 3411 m dc deposited at the Norwegian Petroleum Directorate.

Type well 6506/12-1: no cores taken in this formation
Reference well 6506/12-4: core #1 interval 3129 - 3150.9 m (Core Photographs CP1-5); (uncorrected m MD RKB core depths). Note there is a +5.9 m core correction to this core. The core was cut in the lower part of the Lysing Member and across the lower boundary.
Reference well 6610/3-1R: core #2 interval 3315 - 3324.25 m (Core Photographs CP6-8); (uncorrected mMD RKB core depths). The core was cut within the middle part of the Sandflyndre Member.

Thickness and Geographical distribution

The Blålange Formation ranges in thickness from 13 m to 1573 m. An interactive ischore map of the formation is available on the Norlex website under Blålange Formation. Depth distribution of formation tops in wells is also available via this link.

The Blålange Formation reaches a maximum thickness of 1573 m in the Helland Hansen well 6505/10-1, where it did not penetrate the base of the formation at TD (5031 m). It generally reaches in excess of 1000 m in wells in quadrants 6406 and 6506 on the Dønna Terrace e.g. 6506/6-1 (1114 m). Thicknesses in the Vøring Basin are difficult to establish since many wells have a TD within this formation but in well 6606/5-1 located on the Utgard High, 849 m of Blålange Formation was penetrated prior to the well TD at 3817 m. The Blålange Formation is generally thinner on the Trøndelags Platform, and in the Halten and Dønna Terrace areas it is between 300 m and 900 m thick.

Type well (revised)

Well name: 6506/12-1 (Figure 3.14)
WGS84 coordinates: N 65°10’07.58”, E 06°43’44.07”
UTM coordinates: 7229359.52 N 393591.68 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s (Statoil a.s.)
Completion date: 06.02.1985
Status: P & A
Interval of type section and thickness in type well: 3705 - 3175 m, 530 m thickness.

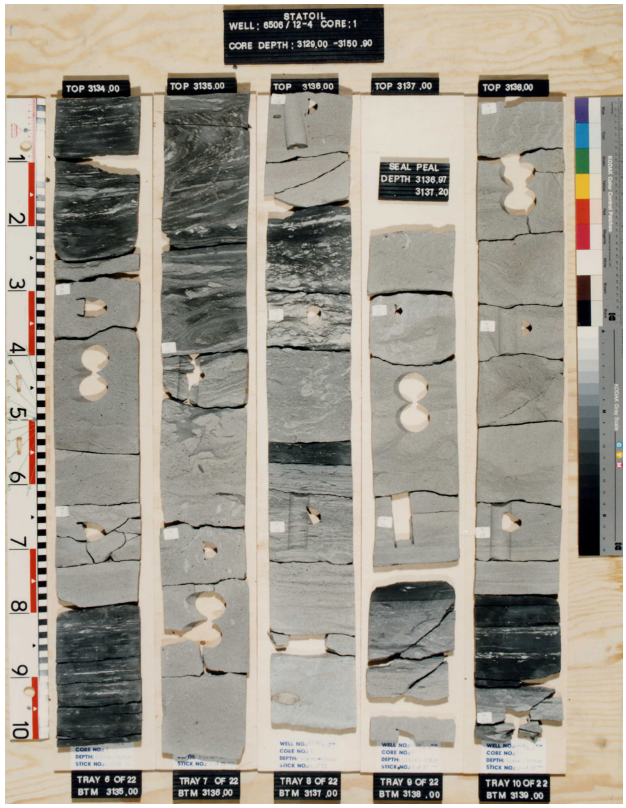
Reference wells

Two reference wells are designated, namely 6506/12-4 (Figure 3.15), the original reference well used by Dalland *et al.* (1988) to illustrate their Lange Formation (replaced herein) and in the upper part illustrating the (new) Blålange Formation, and well 6610/3-1R (Figure 3.16) to show variation in the formation in the Norwegian Sea.

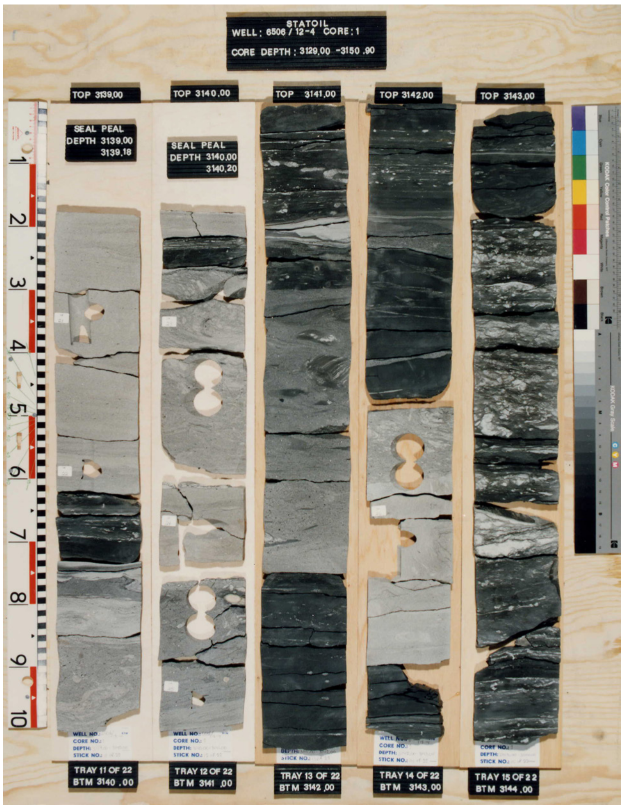
Well name: 6506/12-4
WGS84 coordinates: N 65°12’46.97”, E 06°43’30.37”
UTM coordinates: 7234298.14 N 393591.29 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 13.08.1985
Status: P & A

Well name: 6610/3-1R
WGS84 coordinates: N 66°55’29.70”, E 10°54’06.28”
UTM coordinates: 7424470.29 N 583170.04 E
UTM zone: 32

CP1. Core 1, 3129-3133m, Blålange Fm., reference well 6506/12-4.



CP2. Core 1, 3134-3138m, Blålange Fm, reference well 6506/12-4.

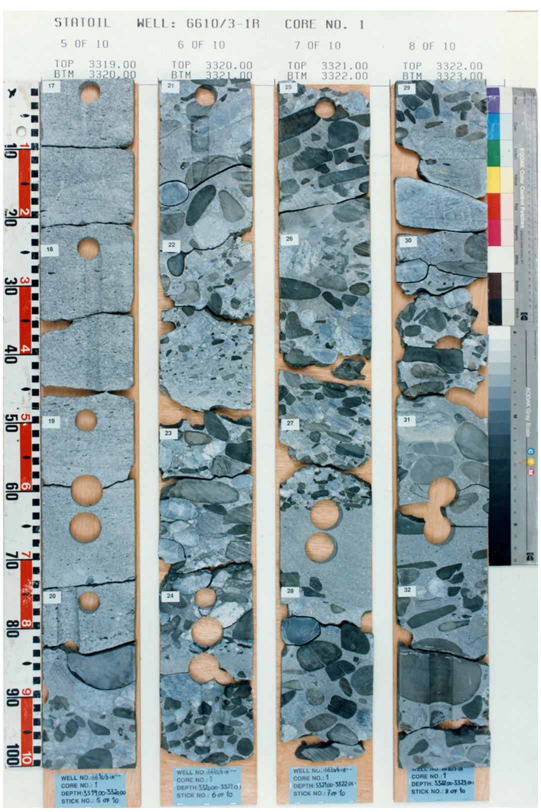


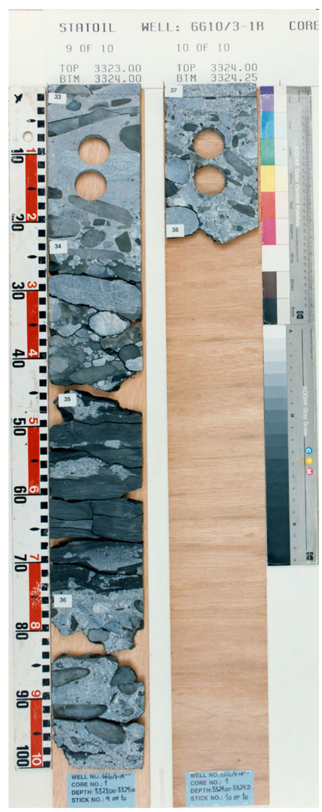
CP3. Core 1, 3139-3143m, Blålange Fm, reference well 6506/12-4.

CP4. Core 1, 3144-3148m, Blålange Fm, reference well 6506/12-4.

CP5. Core 1, 3149-3150m, Blålange Fm, reference well 6506/12-4.

CP6. Core 2, 3315-3319m, Blålange Fm, reference well 6610/3-1R.





CP7. Core 2, 3319-3323m, Blålange Fm, reference well 6610/3-1R.

CP8. Core 2, 3323- 3324m, Blålange Fm, reference well 6610/3-1R.

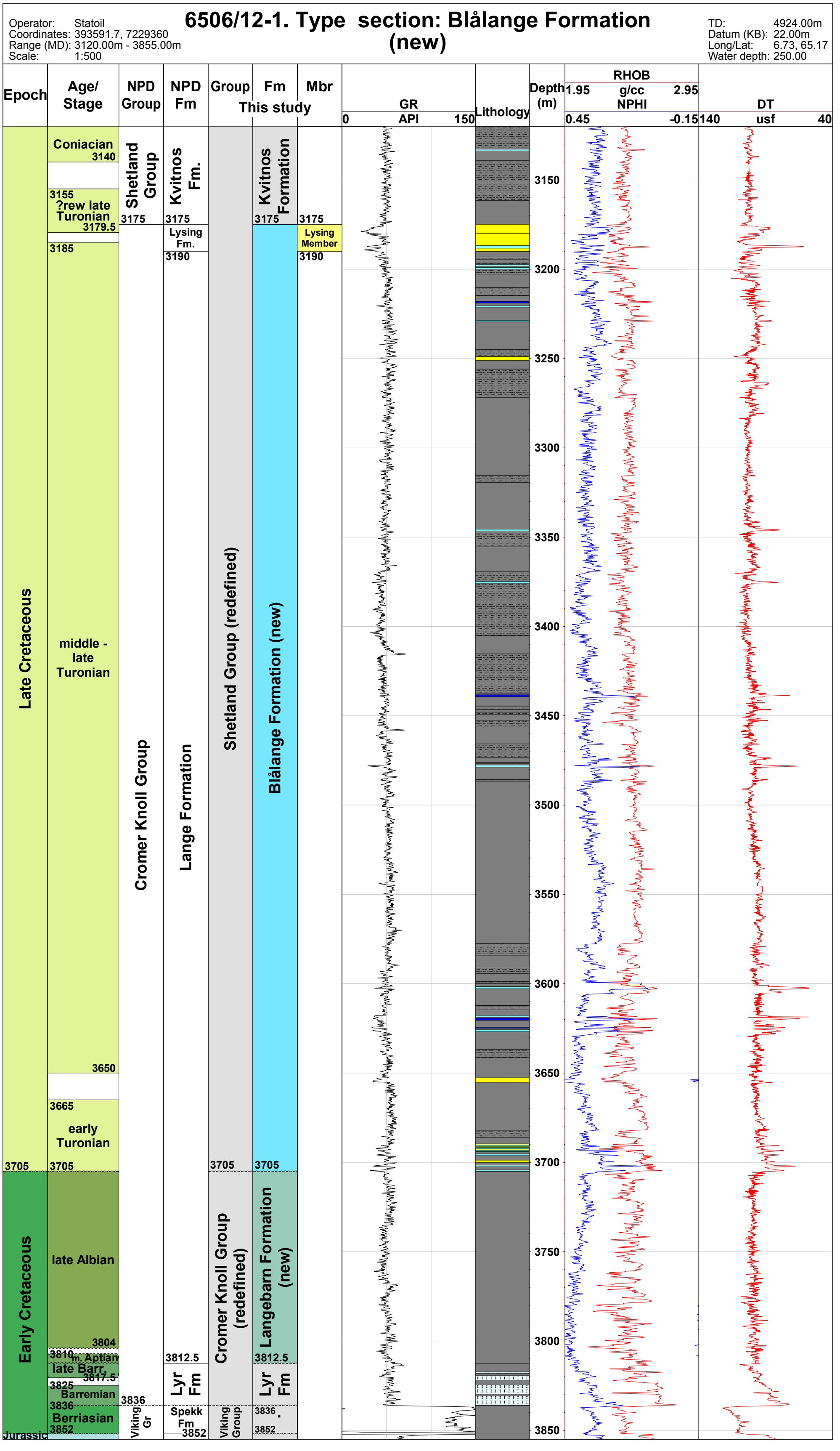


Figure 3.14. Well logs and lithology section for the Blålange Formation in type well 6506/12-1, Norwegian Sea.

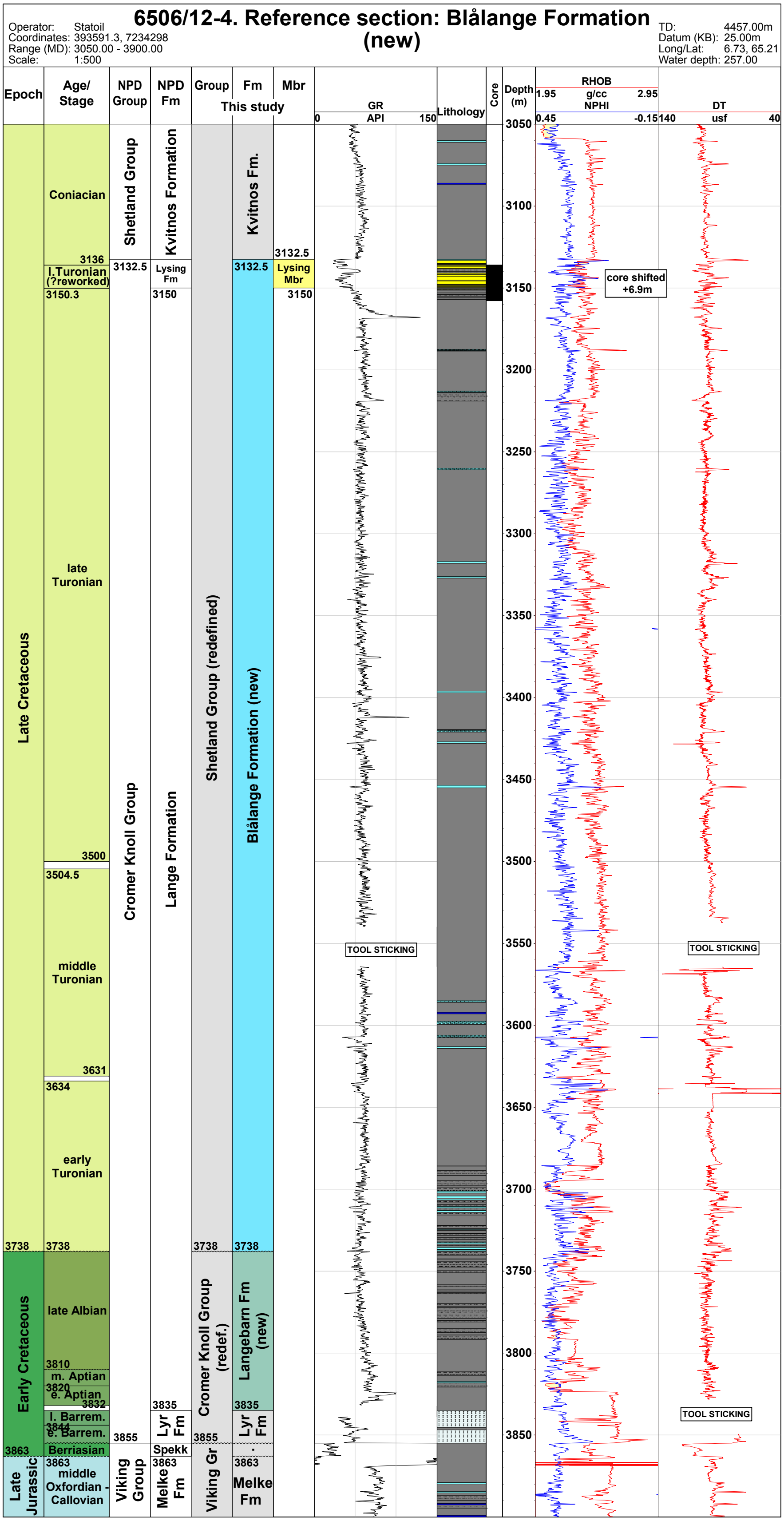


Figure 3.15. Well logs and lithology section for the Blålange Formation in reference well 6506/12-4, Norwegian Sea.

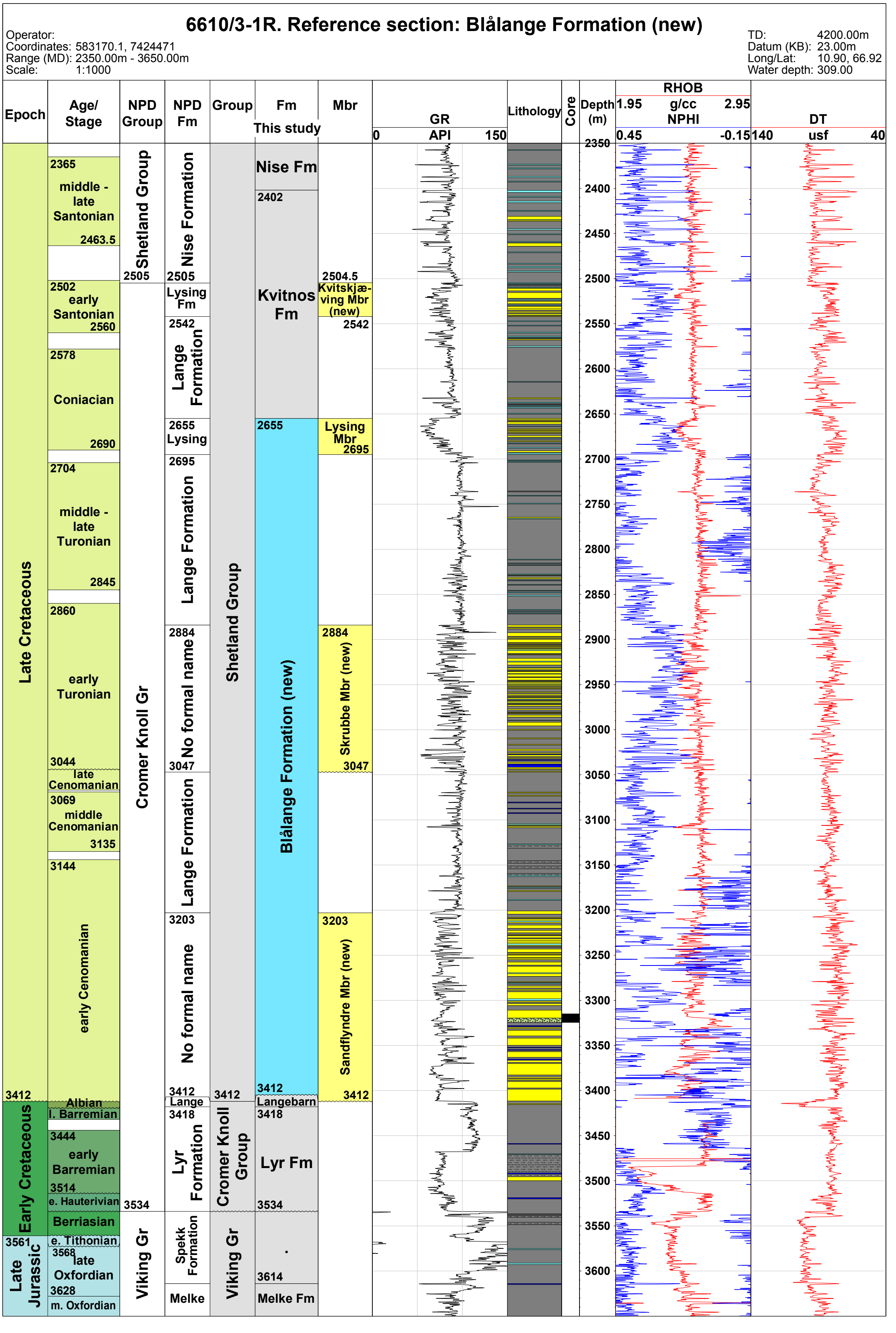


Figure 3.16. Well logs and lithology section for the Blålange Formation in type well 6610/3-1R, Norwegian Sea.

Drilling operator name: Den norske stats oljeselskap a.s (Statoil a.s.)
Completion date: 11.12.1993
Status: suspended, re-entered later.
Interval of reference section & thickness in reference well: 3412 m - 2655 m, 757 m thickness.

Upper and lower boundaries

Upper boundary

The top of the Blålange Formation normally coincides with the top of the Lysing Member in the Halten and Dønna Terraces, and in deep-water wells in the Vøring Basin. At these sites, the top of the Blålange Formation marks a downward change from mudstones of the Kvitnos Formation to sandstones and interbedded mudstones of the Lysing Member. This is typically defined by a marked downward decrease in gamma ray values and an increase in sonic velocity. In wells in quadrants 6406, 6407 and 6507, where the boundary represents a continuous sequence of mudstones, the boundary can be recognised by a slight downward decrease in average gamma ray values, an increase in average resistivity values and/or slight increase in average sonic velocity e.g. 6507/3-4. The latter probably relates to compactional differences of the mudstones.

Lower boundary

The base of the Blålange Formation in the type area of the Halten and Dønna Terraces, and the boundary with the underlying Langebarn Formation (new) is characterised by a down-section decrease in sonic velocities. This represents an unconformity that appears to correspond to the Lower/Upper Cretaceous boundary.

Well log characteristics

The gamma-ray and sonic log profiles of the Blålange Formation are less uniform than those of the underlying Lange Formation, due to the frequency of thin bedded limestone stringers e.g. 6506/12-1. In addition, there are several high gamma spikes that are considered to represent thinly bedded tuffs. These provide a means of correlation between wells and are identified (in ascending order) as k54a to k58a (the 'a' suffix denoting presumed ash bed). On gamma logs these tend to have sharp, well defined bases and gradually decreasing upper values e.g. k55a, 6506/12-1, 3417 m. These high gamma features appear to be restricted to the Blålange Formation and Turonian sediments, being absent in the overlying Kvitnos Formation. The k58a marker, e.g. 6506/12-4, 3168 m is a regional marker that is typically developed towards the top of the Blålange Formation but below the Lysing Member and provides an independent stratigraphic means of distinguishing this unit from underlying, Turonian--restricted sandstones.

Biostratigraphy

The main stratigraphic control of the Blålange Formation is provided by dinoflagellate cysts. Towards the top of the formation and generally below the base of the Lysing Member are the LO *Stephodinium coronatum* and LO *Cyclonephelium membraniphorum*. This assemblage indicates a Turonian age. In this interval characteristic down-hole increases of specimens are observed of *Palaeohystrichophora infusorioides* and *Heterosphaeridium difficile.*

In the type area on the Halten and Dønna Terraces, where the Blålange Formation rests unconformably upon the Lower Cretaceous Lange Formation (redefined), the oldest dinocyst markers are early Turonian in age, and include LAO *Surculosphaeridium longifuratum*, LCO *C. membraniphorum* and rare *Litosphaeridium siphoniphorum.* The FO *H. difficile* in sidewall or core samples provides a valuable datum to identify an age no older than Turonian and the degree of truncation e.g. 6506/12-1, 3696.5 m (swc). It also provides a datum to demonstrate Cenomanian - Albian reworking from the underlying sediments. In the more complete sections of the Vestfjorden Basin, the Blålange Formation extends in lower Cenomanian and contains the Sandflyndre Member. In this area, and represented by well 6610/3-1R, a more complete and typical Cenomanian succession of LO (few) *Litosphaeridium siphoniphorum*, LO *Rhombodella paucispina* (late Cenomanian), LO *Epelidosphaeridia spinosa* (middle Cenomanian), LAO *'Sidridinium borealis'* and LO *Ovoidinium verrucosum* (early Cenomanian) is present in the lower part of the Blålange Formation.

Micropaleontologically, the Blålange Formation is generally devoid of calcareous foraminifera including planktonic types. Small, smooth *Hedbergella* spp, such as the LO *Hedbergella delrioensis* may be present in the upper part of this formation, but generally planktonic foraminifera increase in numbers in the underlying Lange Formation (redefined), notably LCO *Hedbergella*. The exception being the stratigraphically more complete wells in the Vestforden area e.g. 6610/3-1R where planktonic foraminifera are frequent in the older i.e. Cenomanian part of the Blålange Formation. Influxes of 'cenosphaerid-type' radiolarians are typical of levels within the formation. Generally, the planktic bivalve *Inoceramus* is common in the overlying Kvitnos Formation and decreases in numbers above the Blålange Formation although this is probably related to post sedimentary, diagenetic processes rather than biostratigraphy.

Age

Late Cretaceous, early Cenomanian - 'arliest' Coniacian. The Blålange Formation is predominantly of Turonian age. In the type well 6506/12-1 the base of the Blålange Formation is typically unconformable with the underlying Lange Formation (redefined). This unconformity is regionally significant in the Halten--Dønna Terrace area, where the Blålange Formation progressively onlaps the Cromer Knoll Group. In the reference well 6610/3-1R, in the Vestfjorden area, the Blålange Formation extends to the base of the Cenomanian.

Correlation

The Blålange Formation is laterally equivalent to the lower Kyrre Formation, and the more calcareous Tryggvason Formation, in the Shetland Group of the northern North Sea. Time equivalents to the North Sea Cenomanian Blodøks and Svarte Formations are generally not developed, being within the unconformity at the Blålange/Lange boundary. Equivalent sediments are sporadically present in the Vestfjorden Basin (Quadrant 6610) as sandstones of the Sandflyndre Member, and locally on the Halten and Dønna Terraces as sandstones and mudstones of the Gapeflyndre Member.

Depositional environment

The Blålange Formation was deposited in a relatively deep but restricted marine paleoenvironment with mainly dysoxic bottom conditions developed in a semi-restricted basin. Connections with the North Atlantic oceanic realm were limited (Gradstein *et al.*, 1999). An increase in paleo-waterdepth is inferred from east (Halten Terrace) to west (Vøring Basin).

Remarks

The Blålange Formation represents deposition with the K3 sequence of Swieciciki *et al.* (1998), K50 to lower K80 sequences of Vergara *et al.* (2001) and the K40 - lower K60 sequence of Færseth and Lien (2002).

Sandflyndre Member [new]

Blålange Formation, Norwegian Sea (Table 3.2)

Name

Derivatio nominis: Norwegian for the Common Dab *Limanda limanda*. This fish is appropriately found on sandy substrates down to about 100 m water depths along the whole of the Norwegian coast.

Lithology

The member consists of interbedded sandstones, conglomerates and mudstones. In the type well 6610/3-1R, 9 m of core (core #2) was taken in the middle part of the member and shows both uniform, structureless, fine to medium grained grey sandstones and conglomerates with large (up to dm scale) rounded to sub-rounded clasts that are both grain supported and within a fine-medium sandstone matrix.

Upper and lower boundaries

Lower boundary

The lower boundary of the Sandflyndre Member is well defined on wireline logs by an abrupt decrease in GR values, increase in sonic log values and negative separation between neutron and density logs.

Upper boundary

The upper boundary is relatively sharp and well defined on GR logs representing the development of mudstones.

Thickness

The gross thickness of the member is 211 m in the type well.

Geographical distribution

This member is the lowermost sandstone of the Blålange Formation (Shetland Group) and developed in the Vestfjorden Basin SW of the Røst Island, Lofoten Islands. It is also approximately time equivalent, i.e. Cenomanian age, to the geographically distinct Gapeflyndre Member (eastern Møre margin) and Smørflyndre Member (Dønna Terrace). This indicates input of coarse clastic sediments into basinal/terrace areas at this time. On the interactive website of Norlex (at *www.nhm2.uio.no|norlex*) is a link under this unit to get the occurrence of member tops in wells.

Type well (revised)

Well name: 6610/3-1 R (Figure 3.17)
WGS84 coordinates: N 66°55'29.70", E 10°54'06.28"
UTM coordinates: 7424470.29 N 583170.04 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s
Completion date: 11.12.1993
Status: Suspended and re-entered later
Interval of type section and thickness in type well: 3412 m - 3201 m MD, 211 m thickness.

Reference wells

None designated.

Well log characteristics

The member shows a blocky to serrate GR log profile with thicker, more massive beds being developed towards the base.

Age

Late Cretaceous, Cenomanian.

Depositional environment

Deep marine. Core was taken over a small percentage (4%) of the member in the type well 6610/3-1R, and this core may not be representative of the whole member. The member is interpreted as being deposited as basin floor/slope turbidites and mass gravity flows, and amalgamated channel and lobe, interlobe and lobe fringe and basin mudstones.

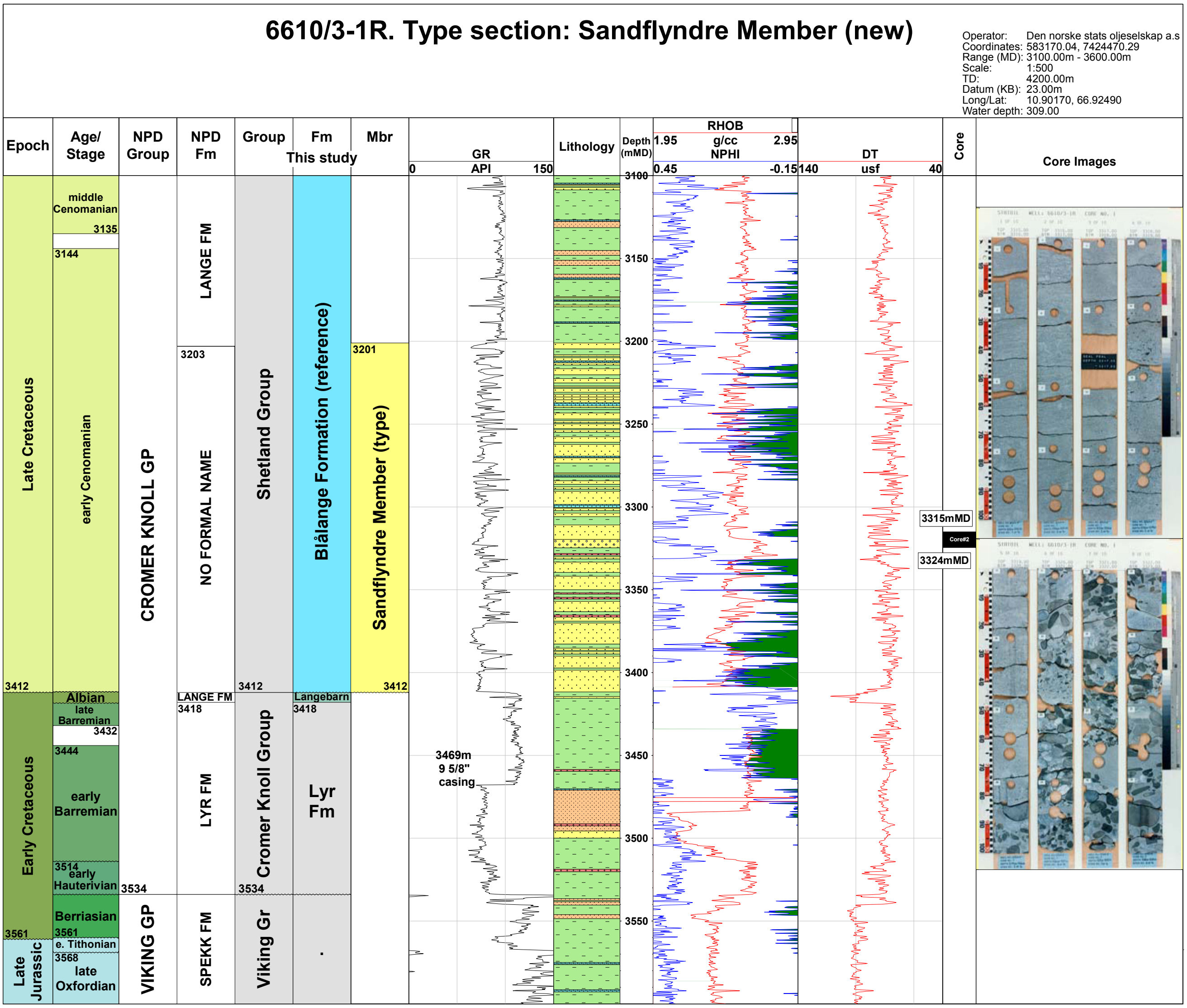


Figure 3.17. Well logs and lithology section for the Sandflyndre Member of the Blålange Formation in type well 6610/3-1R, Norwegian Sea.

Gapeflyndre Member [new]

Blålange Formation, Norwegian Sea

Name

Derivatio nominis: Norwegian for the American plaice or sole, *Hippoglossoides platessoides.* Appropriately, this fish is found on soft bottoms, most often in water depths of 90 - 250 m in the North Atlantic region, including the Norwegian Sea.

Informal name: Lange sandstones.

Lithology

Interbedded sandstones, siltstones and mudstones. The sandstones frequently contain glauconite or kaolinite. Not cored in the type well.

Upper and lower boundaries

Lower boundary

The lower boundary of the Gapeflyndre Member is characterised by negative separation between density and neutron porosity logs defining the development of sandstones above a predominantly mudstone interval and is well defined on both gamma ray and sonic logs.

Upper boundary

The upper boundary is more difficult to define due to the progressive decrease in the frequency of sandstone interbeds.

Thickness

The gross thickness of the member is 221.5 m in the type well.

Geographical distribution

This member is attributed to the Blålange Formation (Shetland Group) and found in the Slørebotn Sub-basin, on the eastern Møre margin. On the interactive website of Norlex at *www.nhm2.uio.no|norlex* is a link under this unit to get the occurrence of member tops in wells.

Type well

Well name: 6305/12-1 (Figure 3.18)
WGS84 coordinates: N 63°01'25.73", E 05°47'23.94"
UTM coordinates: 6991476.94 N 641178.97 E
UTM zone: 31
Drilling operator name: Norsk Hydro Produksjon AS
Completion date: 18.09.1991
Status: P & A
Interval of type section and thickness in type well: 3451.5 - 3230 m, 221.5 m thickness.

Reference wells

None designated.

Well log characteristics

The member shows an irregular and serrate GR log profile and a series of cleaning-upward profiles that probably represent repeated sandstone input.

Age

Late Cretaceous, Cenomanian.

Depositional environment

Deep marine. Core is lacking, but based on log character and location within the Slørebotn sub-basin, the member is considered to be a series of interbedded basin mudstones/mud-dominated turbidites, and lobe fringe or interlobe overbank turbidite sandstones.

Remarks

A possible 'Blodøks Formation Equivalent' was noted by the Operator in the type well 6305/12-1 above this member between 3140 - 3158 m MD. An equivalent of the Gapeflyndre Member is recognized in the 6205/3-1 R well (2925 - 2973 m). This well is located in a more basinal position and the lithology dominated by siltstones.

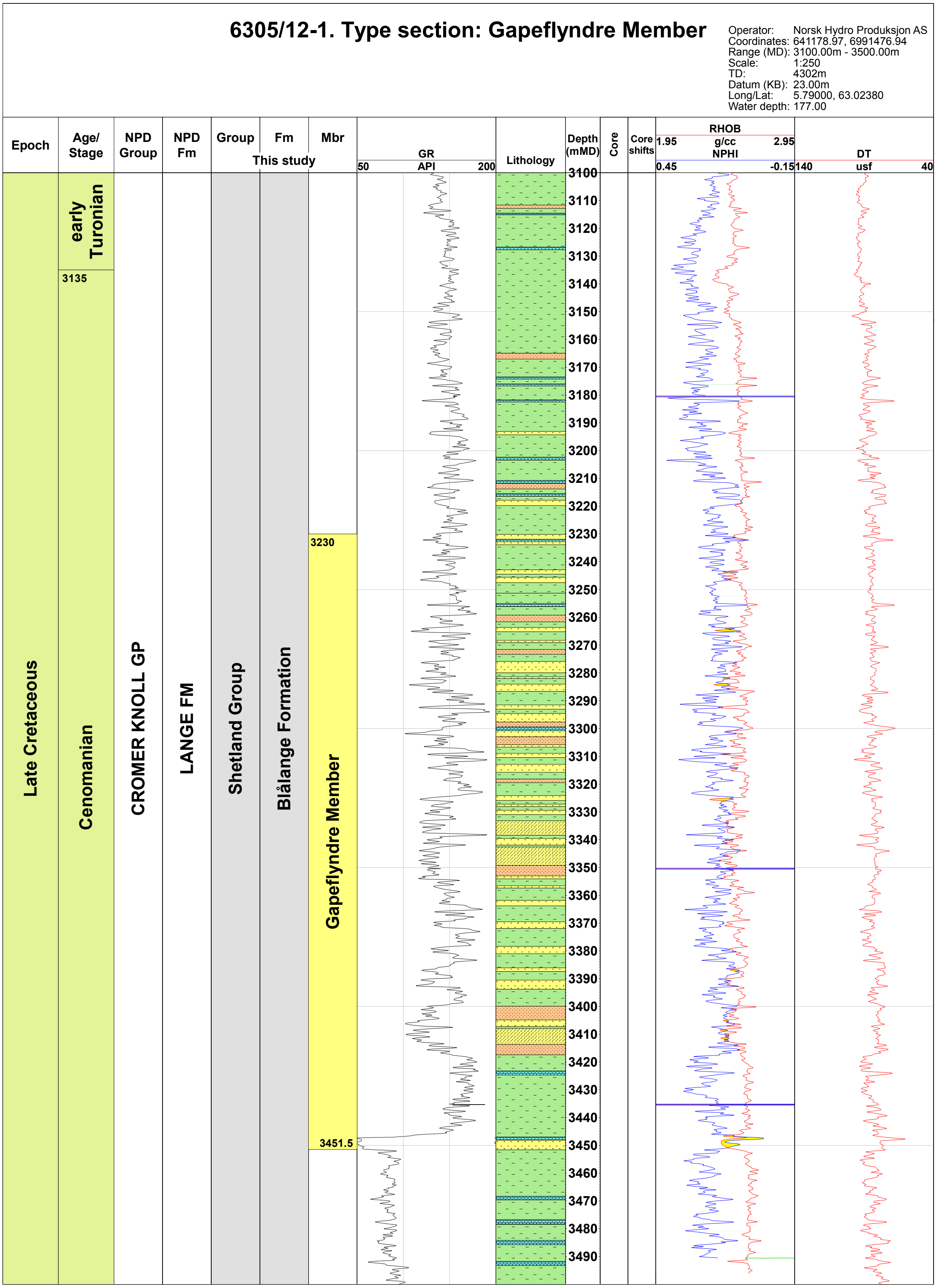


Figure 3.18. Well logs and lithology section for the Gapeflyndre Member of the Blålange Formation in type well 6305/12-1, Norwegian Sea.

Skrubbe Member [new]

Blålange Formation, Norwegian Sea

Introduction

The Skrubbe Member is a new member of Blålange Formation (new herein) and is an interval of lower Turonian sandstones found locally in the Vestfjorden Basin.

Name

English/ Norwegian and any previous names: Described informally as the 'Lange sandstone 1' by the operator Statoil and indicated as a unit with no formal name in the type well 6610/3-1 R on the NPD fact pages.

Derivatio nominis: The name Skrubbe is Norwegian for the flounder fish species *Platichthys flesus.* This flatfish is usually found living on muddy bottoms in shallow depths of 0 - 75 m along the whole of the Norwegian coastline and in the fjords.

Lithology

The Skrubbe Member consists of interbedded sandstones and claystones with occasional thin stringers of limestone and dolomitic limestone especially developed in the lower part.

The sandstones are light to medium dark grey, with clear to translucent grains, fine to coarse, occasionally very coarse, poor to moderately sorted, sub-angular to sub-rounded, friable to moderately hard, calcareous cement or occasionally abundant argillaceous matrix, micaceous, glauconitic, carbonaceous in part, with poor to no visible porosity, occasionally grading to sandy claystone.

The claystones are medium dark grey to olive black, blocky to sub-fissile, moderately hard, silty or sandy in parts, micro-micaceous to very micaceous in parts, occasional micro-pyrite, trace carbonaceous material, predominantly slightly to non calcareous.

Occasional thin stringers of limestone or dolomitic limestone throughout this unit are greyish white to light brown, soft to hard, blocky, micro-crystalline, argillaceous, occasionally glauconitic, sandy and silty in parts grading to calcareous sandstone.

Base definition

The base of the Skrubbe Member is defined by a decrease in gamma ray log response and an increase in resistivity values in response to the up-section development of sandstones. There is an associated weak decrease in interval transit times but overall, both the gamma ray and sonic log values are more irregular than the underlying mudstones.

Sample depository

Palynological preparations (organic matter depository)

Type well 6610/3-1 R: 12 slides including 9 sidewall core samples deposited at the Norwegian Petroleum Directorate, covering the interval 2890 m swc - 3040 m swc.

Core photographs

Type well 6610/3-1 R: no cores were taken in this member.

Thickness

The Skrubbe Member is less than 170 m thickness.

Geographical distribution

The Skrubbe Member is locally developed in the Vestfjorden Basin.

Type well

Well name: 6610/3-1 R
WGS84 coordinates: N 66°55'29.70", E 10°54'06.28"
UTM coordinates: 7424470.29 N 583170.04 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s
Completion date: 11.12.1993
Status: suspended, re-entered later.
Interval of type section and thickness in type well: 3047 - 2884 m and 163 m thickness.

Reference wells

Not designated

Well log characteristics (Figure 3.19)

The Skrubbe Member is characterised by a serrate profile on gamma ray logs in response to the sandstone - claystone interbedded nature of the unit. Sandstone beds are more frequent in the upper part of the member although these never exhibit large scale, blocky log profiles. Some sandstones show gradational (fining upward) profiles with the overlying, thinner mudstone interbeds.

Type seismic section

Location: ST 9104-437 and SP. 335 (well 6610/3-1R)

Biostratigraphy

The Skrubbe Member is developed between the dinocyst events LCO *Cyclonephelium membraniphorum,* LO *Cribroperidinium edwardsii* (early Turonian) and the LO (few) *Litosphaeridium siphoniphorum* (Cenomanian). The Turonian restricted FO *Heterosphaeridium difficile* occurs in swc in the upper part of this member. Reworking of Albian - Cenomanian dinocysts probably derives from the underlying sediments from up-slope locations. Small planktonic Foraminifera are frequent in the underlying Cenomanian claystones, mainly *Hedbergella delrioensis* and *H. planispira.*

Age

Late Cretaceous, early Turonian.

Correlation

The Skrubbe Member is developed in the lowermost part of sequence K50 of Færseth and Lien (2002). In the type well 6610/3-1 R the early Turonian Skrubbe Member lies between the Sandflyndre Member (Cenomanian) and Lysing Member (Coniacian).

Depositional environment

There are limited available data on the depositional setting of this member and cores are lacking. The sandstones are considered to be derived by gravity flow processes into a relatively deep marine, slope or local sub-basinal paleoenvironment. An upper bathyal, slope setting is indicated by the prevalence of low diversity, deep water agglutinated foraminifera (DWAF) in the microfaunas of the adjacent mudstones. The general lack of calcareous taxa suggests a reducing sub-oxic bottom environment. The base of the Skrubbe Member in the 6610/3-1R well is considered to be a minor stratigraphic break, and probably the result of erosion of the underlying sediments during deposition.

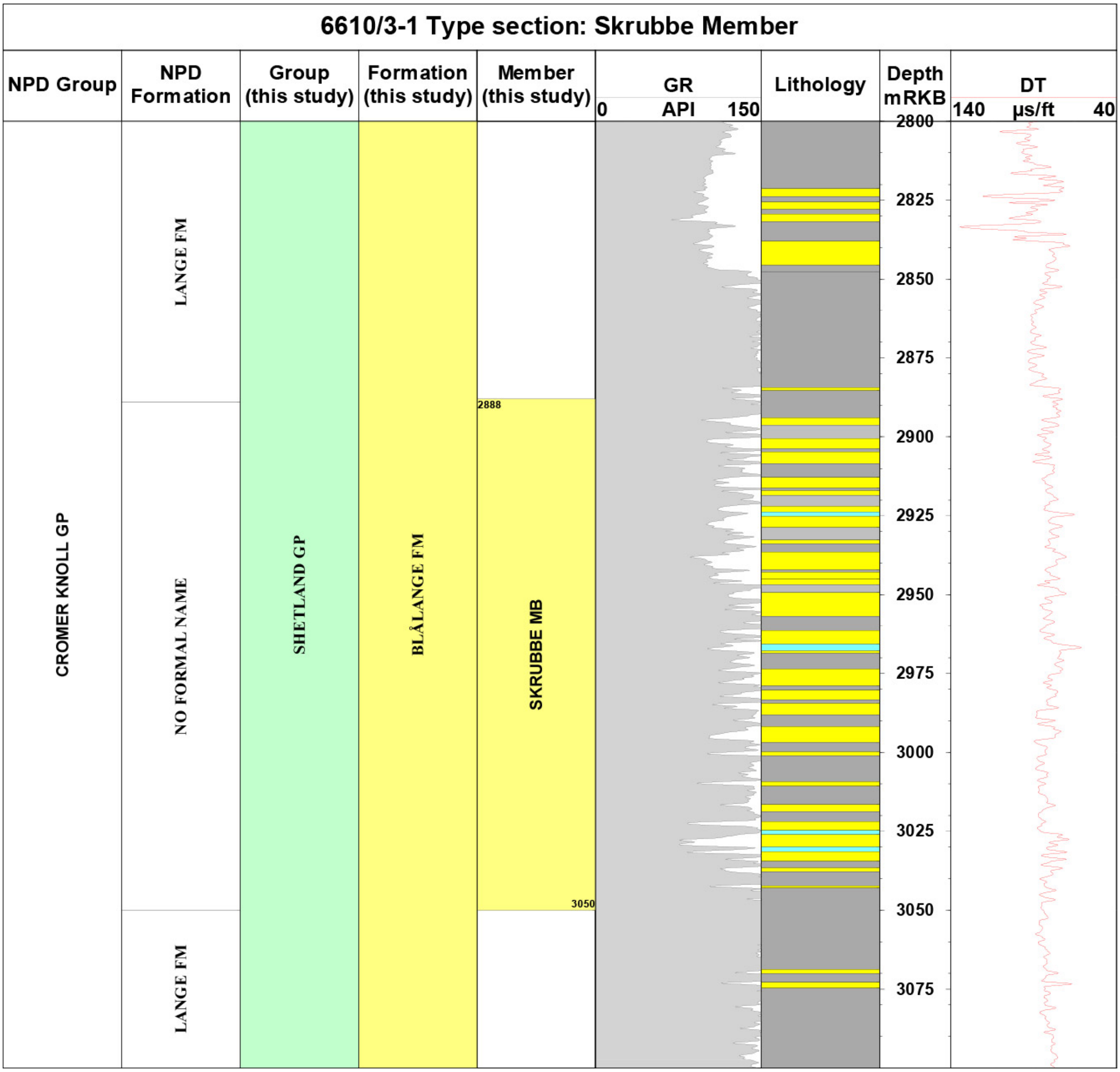


Figure 3.19. Well logs and lithology section for the Skrubbe Member of the Blålange Formation in type well 6610/3-1R, Norwegian Sea.

Breiflabb Member [new]

Blålange Formation, Norwegian Sea

Introduction

The Breiflabb Member (new) is part of the Blålange Formation (new). The new member comprises an interval of interbedded sandstones and mudstones of Late Cretaceous, early Turonian age found along the Halten and Dønna Terraces.

The stratigraphic relationship with the overlying Lysing Member may be seen in the well 6507/7-1 (reference well), where over 450m of Turonian mudstone separates the two sand-prone units.

Name

English/ Norwegian and any previous names: The Breiflabb Member is informally recorded on the completion logs of the type well 6507/2-2 by the operator as the 'lower Lange Sandstone II'. The underlying Smørflyndre Member (new) was informally assigned 'lower Lange Sandstone I' by the same operator. Confusingly, in other wells the unit is described as 'intra Lange Sandstone' I to V depending on various operators naming conventions in ascending or descending order. In the reference well 6507/7-1 the unit is described by the operator as the 'Upper Cretaceous Sandstone II'; the Lysing Member being originally described as 'Upper Cretaceous Sandstone I' and separated by over 450 m of 'Upper Cretaceous shales'.

Derivatio nominis: The name Breiflabb is the Norwegian name for the angler fish *Lophius piscatorius,* a bottom dwelling fish living from the littoral zone down to 600 m depth or more along the Norwegian coast and fjords.

Lithology

The Breiflabb Member consists of interbedded sandstones and mudstones.

The *sandstones* are white, light grey, yellow grey to grey brown, clear to frosted quartz grains, very fine to medium, occasionally coarse, occasionally fine, occasionally very coarse to conglomerate, moderate to poorly sorted, angular to sub-rounded, friable to moderately hard, locally calcareous, dolomitic and siliceous cemented, occasional argillaceous matrix, very micaceous with traces of pyrite and glauconite, poor visible porosity. In the type core 6507/2-2 clasts of mudstones, sandstones and conglomerate, e.g. 3280.5 m MD are present. Sandstone bed thickness varies from a few centimetres to 5.5 m.

The *mudstones* are medium dark grey to olive black, soft to firm, predominantly non-calcareous, dolomitic in part, micro-micaceous, silty and locally carbonaceous with trace glauconite.

Basal stratotype

In the type well 6507/2-2 the base of the Breiflabb Member is well defined in core at 3295.15 m MD at the base of a 30 cm thick sandstone bed. The base represents a sharp boundary between sandstones and dark mudstones of the underlying (and laterally adjacent) Blålange Formation. This is represented by a sharp and well defined decrease on the gamma ray logs at 3292.7 m (implying a -2.5 m MD discrepancy between core and logs). The change in bulk density logs is slightly higher at 3292.25 m level and above this the log shows a distinctive irregular response.

See below for a complete description of both the lower and upper boundaries and well log characteristics of the Breiflabb Member.

Sample depository

Palynological preparations (organic matter depository)

Type well 6507/2-2 not listed on NPD fact pages.
Reference well 6507/7-1: No slides deposited at the NPD.

Core photographs

Type well 6507/2-2: core #2 3295.8 m MD - 3273 m MD RKB. Core photographs (Core Photographs CP9-13) show the well defined lower boundary at 3295.15 m MD (3298 m corrected core depth) at the base of a 30 cm thick sandstone bed. No cores were taken in reference well 6507/7-1.

Thickness

The Breiflabb Member varies in thickness from 3 m to 89.5 m MD e.g. 6506/11-7 with an average 35 m MD. Its thickest development is in block 6506/11 (Smørbukk area). An interactive isochore map for the Breiflabb Member is on the Norlex website under the description of this member.

CP9. Core 2, 3273-3278m, Breiflabb Mb, type well 6507/2-2.

CP10. Core 2, 3278-3283m, Breiflabb Mb, type well 6507/2-2.

CP11. Core 2, 3283– 3288m, Breiflabb Mb, type well 6507/2-2.

CP12. Core 2, 3288– 3293m, Breiflabb Mb, type well 6507/2-2.

CP13. Core 2, 3293– 3295m, Breiflabb Mb, type well 6507/2-2.

Geographical distribution

The Breiflabb Member is developed in Quadrants 6406 (blocks 1, 2 and 6), 6407 (block 7), 6506 (blocks 11 and 12) and 6507 (blocks 2, 5 and 7) along the western margin of the Halten and Dønna Terraces where it is locally sourced from up-dip locations on the Trøndelags Platform and from local highs.
Occurrences of member tops in wells.

Type well

Well name: 6507/2-2
WGS84 coordinates: N 65°55’01.69”, E 07°30’54.56”
UTM coordinates: 7311658.70 N 432390.90 E
UTM zone: 32
Drilling operator name: Norsk Hydro Produksjon AS
Completion date: 16.03.1992
Status: P & A
Interval of type section and thickness in type well:
3293 - 3263 m, 30 m thickness.

Reference well

Well name: 6507/7-1
WGS84 coordinates: N 65°27’16.7”, E 07°12’52.6”
UTM coordinates: 726081.16 N 417247.40 E
UTM zone: 32
Drilling operator name: Conoco Norway
Completion date: 01.12.1984
Status: P & A
Interval of type section and thickness in type well:
3523 - 3495.5 m, 27.5 m thickness.

Upper and lower boundaries

Lower boundary

In the type well 6507/2-2 the base of the Breiflabb Member is well defined in core at 3295.15 m MD at the base of a 30 cm thick sandstone bed and represents a sharp boundary between sandstones and dark mudstones of the underlying (and laterally adjacent) Blålange Formation. This is represented by a sharp and well defined decrease on the gamma ray logs at 3292.7 m (implying a -2.5 m MD discrepancy between core and logs) (Figure 3.20). The change in bulk density logs is slightly higher at 3292.25 m level and above this the log shows a distinctive irregular response. The Breiflabb Member has a similar log response in the reference well 6507/7-1.

Upper boundary

The upper boundary is well defined on wireline logs (Figure 3.20). It can be seen in the type well 6507/2-2 to be defined on an abrupt increase in gamma ray values and decrease in resistivity logs interpreted as representing the sudden cessation of sandstone deposition. The sonic log response is less significant but still quite marked and shows an up-section change from irregular to more constant values. There is also an associated pronounced up-section positive separation on neutron porosity and density logs in response to the rapid termination of sandstones and the deposition of uniform and monotonous sequence of mudstones of the overlying, and encapsulating Blålange Formation.

Well log characteristics

The log response of the Breiflabb Member is characterised by an irregular to serrate log profile on gamma-ray, bulk density and sonic velocity logs, reflecting the interbedded nature of the sandstones and mudstones.

Type seismic section

NH90-10-102

Biostratigraphy

The main stratigraphic control of the Blålange Formation and the Breiflabb Member, in particular, are dinoflagellate cysts. Planktonic foraminifera are scarce or are locally common at single horizons. They are represented by small hedbergellid species, most notably *H. delrioensis* that are typical of a Turonian or older age. Below the Breiflabb Member is the FO *Heterosphaeridium difficile* (in sidewall cores in the type well 6507/2-2), providing an age no older than early Turonian. Further support for an early Turonian age is the FO *Chatangiella dittissima* in the lower part of the member.

In the reference well 6507/7-1, the Breiflabb Member is developed above the Cenomanian dinocyst markers LO *Gonyaulacysta cassidata*, LO *Rhombodella paucispina* and LO *Epelidosphaeridia spinosa* and within the range of rare *Litosphaeridium siphoniphorum* (early Turonian).

Dating of the upper boundary of the Breiflabb Member is more difficult to establish but appears to be close to the early/middle Turonian boundary based on the influx of *Surculosphaeridium longifuratum* in the upper part of the member in cores. The LCO *Cyclonephelium membraniphorum* within the middle part of the Breiflabb Member is a typical early Turonian dinocyst event.

The microfaunal associations are dominated by agglutinated foraminifera, and these provide important information on the environment of the deposition rather than the age (see below). An influx of siliceous radiolarian above the member is a useful correlative event

In summary, the Breiflabb Member is mainly early Turonian age, or may extend into the 'earliest' middle Turonian.

Reworking of Cenomanian dinocysts complicates the dating, but when properly distinguished (within the range of the Turonian restricted *H. difficile*) provides an indication of the sediment source. The sediments in this member likely derived from up-dip slope locations, or from the Trøndelag Platform.

Age

Late Cretaceous, early Turonian - 'earliest' middle Turonian.

Correlation

The interbedded sandstones and mudstones of the Breiflabb Member pass laterally into mudstones of the Blålange Formation. The stratigraphic relationship with the overlying Lysing Member can be seen in the well 6507/7-1 (type well) where over 450 m of Turonian mudstones separate the two sand-prone units.

The Breiflabb Member is part of the K60 sequence of Vergara *et al.* (2001), K50 sequence of Færseth and Lien (2002) and Lien (2005) and K66- K67 sequences of Fugelli and Olsen (2005).

Depositional environment

Based on the operator's descriptions of core from the type well 6507/2-2, the sandstones of the Breiflabb Member are considered to have been deposited as mostly submarine fan lobe deposits on a slope or basin floor setting.

Three sedimentary facies were distinguished by the

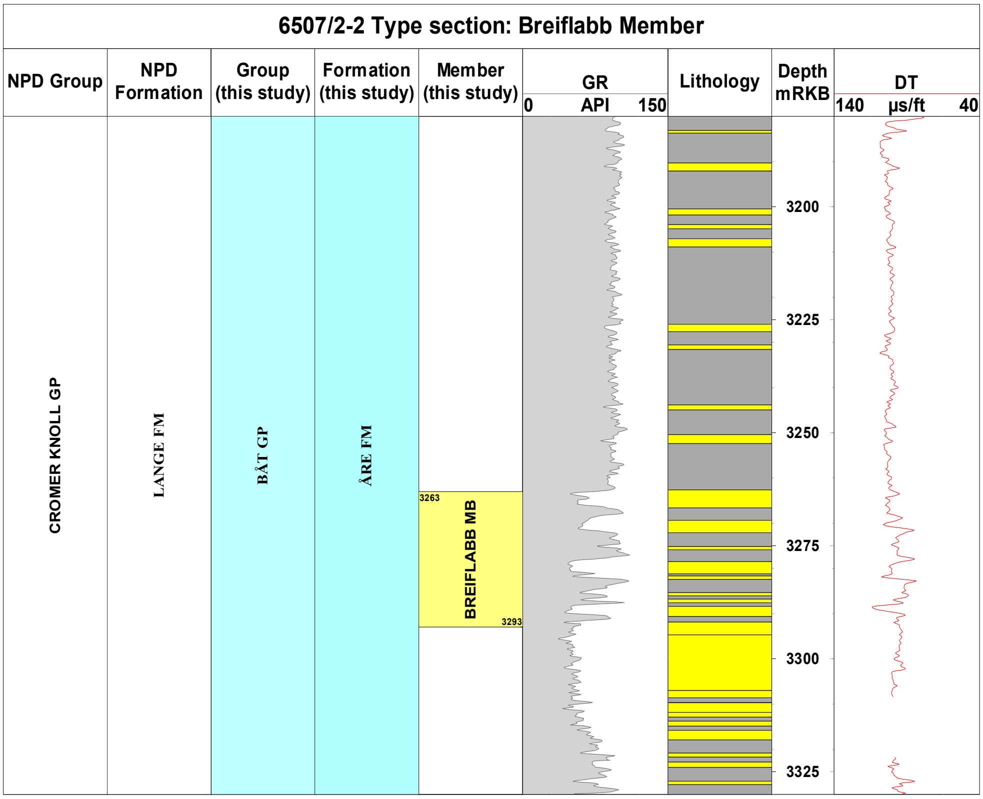


Figure 3.20. Well logs and lithology section for the Breiflabb Member of the Blålange Formation in type well 6507/2-2, Norwegian Sea.

1) a lower interbedded unit (3295.98 m base - 3286 m) of high density turbidites and debris flows and bioturbated hemipelagic mudstones deposited on a slope or basin floor setting,

2) a middle unit (3286 - 3279 m) representing a single amalgamated turbidite interpreted as a fan lobe and

3) an upper unit (3279 - 3273 m) of more interbedded low density turbidites and hemipelagic mudstones deposited on a distal submarine fan.

Study of the biofacies shows that rare lituolid-agglutinated foraminifera are present in the cores e.g. 3479.2 m MD, and these suggest a relatively deep marine setting with dysoxic bottom conditions. Some of the thicker dark mudstones are devoid of benthic microfauna and may suggest a temporarily anoxic sea floor, or highly depleted oxygen levels within the uppermost few centimetres of sediment.

Remarks

Sandstones of the Breiflabb Member have had less attention compared to those of the overlying Lysing sand complex where the facies architecture has been studied at a variety of different scales and compared with outcrop analogues (see Olsen 2005 a, b). Vergara *et al.* (2001) however, described a possible middle Cenomanian tectonic event and relative sea level fall that may coincide with the deposition of the Breiflabb Member, and that this event caused extensive emergence and erosion along the Halten Terrace and western Trøndelags Platform. It is suggested (this study) that this event is not a single event but a more complex development with a series of step-wise unconfomities at base Cenomanian, middle Cenomanian and early Turonian levels as determined by the progressive onlap of the Turonian mudstones of the Blålange Formation onto progressively older Cenomanian e.g. type well 6507/2-2 or Lower Cretaceous, Albian sediments of the Lange Formation. It is therefore likely that the deposition of the Breiflabb Member is related to this event, and the result of erosion of up-dip areas either during the lowered base level or subsequent early transgressive phase.

Skolest Member [new]

Blålange Formation, Norwegian Sea

Introduction

Sandstones and minor subordinate mudstones of the Skolest Member are developed within the Blålange Formation in quadrants 6305 (northerly part of the Ormen Lange Field), and 6306 in the Slørebotn sub-basin on the eastern margin of the Møre Basin. These frequently glauconitic sandstones are of middle/ late Turonian age and are characterised by relatively uniform and blocky log profiles. The Skolest Member is stratigraphically older than the Lysing Member of the Halten-Dønna Terraces, and equivalent sandstones of the overlying Tunge Member developed along the eastern Møre margin. There is no core data or published information on the depositional setting of the Skolest Member. Based on the biofacies, the Skolest Member was deposited in a fully marine, offshore paleoenvironment below storm wave base.

Name

English/ Norwegian and any previous names: None. The operator Norske Shell included the reference well 6306/10-1 as part of the 'Lysing Formation'.

Derivatio nominis: The Skolest Member is derived from the Norwegian for the fish species *Corypheonides rupestris* or round-nosed grenadier. This relative of the cod is a benthopelagic to bathypelagic fish usually found from 400 m to 1200 m water depth in the North Atlantic and Norwegian Sea, and locally in either the Norwegian fjords or on the banks off the coast of Møre and Trøndelag.

Lithology

The Skolest Member consists of sandstones and minor, subordinate mudstones.

The sandstones are white - light grey, clear to translucent quartz, predominantly fine grained but maybe very fine to coarse grained, angular to sub-rounded, predominantly moderately sorted, loose grains with traces of calcareous cement, firm to moderately hard, with trace to abundant glauconite, rarely micaceous and rare pyrite.

The mudstones are medium dark grey - dark grey, sub-blocky, firm to moderately hard, non-calcareous, traces of micro-micaceous and rare traces of micro-pyrite.

Basal stratotype

In the type well 6305/1-1 the base of the Skolest Member is taken at 4529 m MD RKB and is characterised by a transitional change from mudstones of the underlying Blålange Formation to a sequence of predominantly sandstones of the Skolest Member. On wireline logs it is marked by an upward transitional profile but distinct decrease in gamma ray values and an increase in sonic velocities. The lower boundary is more marked on resistivity logs where the boundaries is represented by an abrupt upward increase in values and the unit is characterised by a uniform resistivity log profile.

See below for a complete description of both the lower and upper boundaries and well log characteristics of the Skolest Member.

Sample depository

Palynological preparations (organic matter depository)

Type well 6305/1-1: No slides are available from this member at the NPD.

Reference well 6306/10-1: No slides are available from this member at the NPD.

Core photographs

Type well 6305/1-1: no cores taken in this member.

Reference well 6306/10-1: no cores taken in this member.

Thickness

The Skolest Member is between 10 - 25 m thick, based on the available limited well data. An interactive isochore map for the Skolest Member may be found on the Norlex website under the description of this member.

Geographical distribution

Based on the available, but limited well data, sandstones of the Skolest Member are developed in the northern area of the Ormen Lange Field in quadrant 6305 and in the Slørebotn sub-basin, quadrant 6306, towards the eastern margin of the Møre Basin. Occurrences of member tops in wells may be found under

under the description of this member on the Norlex website.

Type well

Well name: 6305/1-1
WGS84 coordinates: N 63°46'59.72", E 05°16'19.57"
UTM coordinates: 7075028.48 N 611981.31 E
UTM zone: 31
Drilling operator name: Norsk Hydro Produksjon AS
Completion date: 19.11.1998
Status: P & A
Interval of type section and thickness in type well: 4529 - 4504 m, 25 m thickness.

Reference well

Well name: 6306/10-1
WGS84 coordinates: N 63°09'26.32", E 06°19'41.45"
UTM coordinates: 7006099.05 N 365416.35 E
UTM zone: 32
Drilling operator name: A/S Norske Shell
Completion date: 17.12.1990
Status: P & A
Interval of type section and thickness in type well: 1999 - 1992 m, 7 m thickness.

Upper and lower boundaries

Lower boundary

In the type well 6305/1-1 the base of the Skolest Member is taken at 4529mMD RKB, and is characterised by a change from mudstones of the underlying Blålange Formation to predominantly sandstones of the Skolest Member. On wireline logs (Figure 3.21) the change is marked by a distinct decrease in gamma ray and density log values, and an increase in sonic velocities.

The lower boundary is more marked on resistivity logs where the boundaries is represented by an abrupt upward increase in values and the unit is characterised by a uniform resistivity log profile. In the reference well 6306/10-1, the lower boundary at 1999 m MD RKB has a similar transitional decrease in gamma ray values, but a more distinct increase in sonic velocities and increase in resistivity values.

Upper boundary

In both the type well 6305/1-1 and reference well 6306/10-1, the top of the Skolest Member is marked by a sharp change in gamma ray, resistivity and sonic logs (Figures 3.21 and 3.22) reflecting the change from sandstones to mudstones of the overlying and surrounding Blålange Formation. The upper boundary is defined by a marked decrease in gamma-ray values, and increase in sonic velocity. In the 6306/10-1 reference well the upper boundary is associated with a pronounced downward negative separation between neutron porosity and density logs in response to the rapid termination of sandstones.

Well log characteristics

In both the type and reference wells the Skolest Member is characterised by relatively blocky gamma-ray and sonic log profile with a slightly funnel-shaped lower boundary.

Type seismic section

NH 9602- INLINE 2016 & X-LINE 6916

Biostratigraphy

In the type well 6305/1-1 the presence of the dinocyst *Stephodinium coronatum* (4526 m swc) suggests an age no younger than Turonian. In the reference well 6306/10-1, the Skolest Member is developed below the Tunge Member of Coniacian age, and within a 'latest' middle - late Turonian age interval. The dinocyst marker LO *Microdinium setosum* below the member defines a an intra-middle Turonian level. Above the Skolest Member is an influx of planktonic foraminifera with LAO *Hedbergella delrioensis* and the dinocyst LO *Stephodinium coronatum* characteristic of the late Turonian. The Skolest Member is therefore developed close to the middle/late Turonian boundary.

Age

Late Cretaceous, middle - late Turonian.

Correlation

The sandstones of the Skolest Member pass laterally into mudstones of the Blålange Formation.The Skolest Member is stratigraphically older than the Lysing Member of the Halten-Dønna Terrace area and the Møre Basin equivalent Tunge Member. This relationship may be demonstrated in the reference well 6306/10-1. It is therefore part of the K70 sequence of Vergara *et al.* (2001), K50 sequence of Færseth and Lien (2002) and Lien (2005) and K67 - K68 sequence

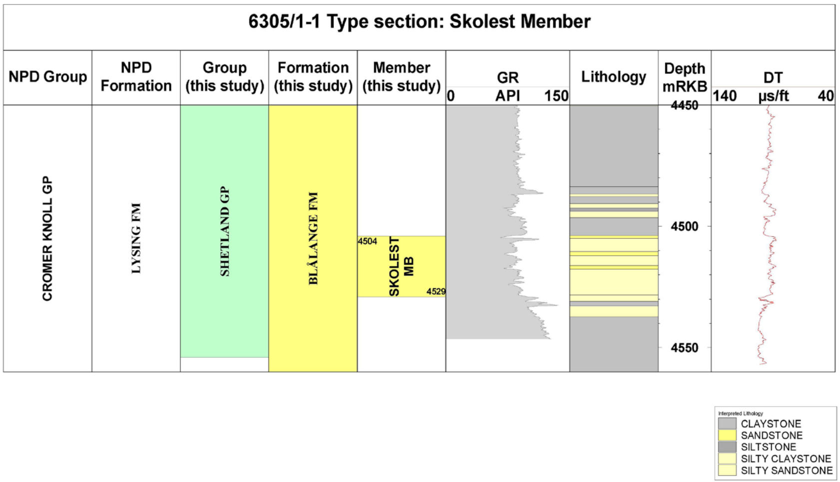


Figure 3.21. Well logs and lithology section for the Skolest Member of the Blålange Formation in type well 6305/1-1, Norwegian Sea.

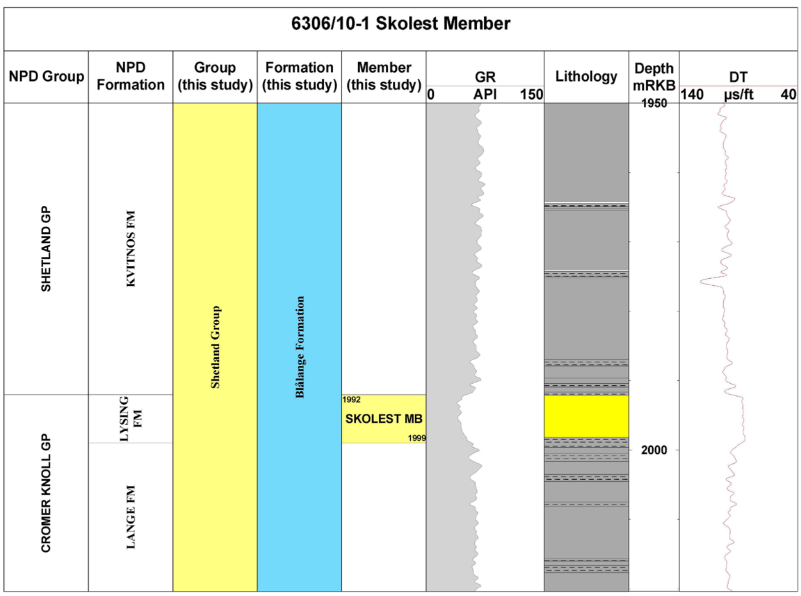


Figure 3.22. Well logs and lithology section for the Skolest Member of the Blålange Formation in reference well 6306/10-1, Norwegian Sea.

of Fugelli and Olsen (2005a).

Depositional environment

There is limited data available on the depositional setting of the Skolest Member. No cores were taken. In the absence of any apparent stratigraphic breaks in the adjacent sections it is likely to be at least below storm base level. Marine microplankton diversity is high (30-40 species), and suggests an open marine, offshore environment. In terms of benthic foraminiferal biofacies the assemblage is impoverished. Tubular deep water agglutinated foraminifera DWAF are common in the overlying Blålange Formation down to 4130 m MD, reflecting a deep marine environment and coinciding with a level associated with an up-section decrease in average sonic velocities. Below this level 4134 m MD - 4560 m MD TD within the development of the Skolest Member, recovery is poor and largely dominated by pyritised microfossils..

Remarks

The sandstones of the Skolest Member may contain abundant glauconite, as in the type well 6305/1-1, and this may be a distinctive feature of this member. It is unsure whether the glauconite grains are *in situ*, or represent reworking from up-dip continental margin settings.

Lysing Member [new status]

Blålange Formation, Norwegian

Introduction

The Lysing Member is mainly a unit of sandstones attributed to the uppermost Blålange Formation, developed on the Halten and Dønna Terraces along the margins of the Nordland Ridge, and within parts of the Vøring Basin. It is predominantly Coniacian to latest Turonian in age.

Name

English/ Norwegian and any previous names: The name "Lysing Formation" was introduced by Dalland *et al.* (1988) as the only sandstone unit recognised in the Norwegian Sea area at that time, the other formations being dominated by mudstones. This study reduces the unit to member status within the Blålange Formation, on the basis of being detached sandstone bodies, and for consistency with other new sandstone members recognised in the area. It is also reassigned to the Shetland Group (formerly Cromer Knoll Group of Dalland *et al.*, 1988) following the revised group definitions in the Norwegian Sea area.

Derivatio nominis: The name Lysing is derived from the Norwegian word for the fish species Merluccius merluccius or hake.

Publication: Dalland *et al.* (1988)

Lithology

The Lysing Member consists predominantly of clear to white-grey or grey-greenish quartzitic sandstones with subordinate interbedded mudstones. The sandstone grain size is fine to medium or occasionally coarse, with moderately sorted sub-angular to sub-rounded grains, occasionally sub-spherical. The *sandstones* are frequently glauconitic (imparting the grey-green colouration), or have traces of mica and are calcite cemented. The *mudstones* are medium dark grey, firm to hard, weakly laminated, sub-fissile, micro-micaceous and non- to slightly calcareous, with traces of fine crystalline pyrite and mica. In cores of the reference well 6506/12-4 (Figure 3.23), the sandstones form thick 0.3 to 1.5 m beds, or thin sandstone laminae within the subordinate interbedded mudstones.

Basal stratotype

Sandstones of the Lysing Member rest on mudstones of the underlying Blålange Formation. In the type well 6507/7-1 (Figure 3.24), the basal stratotype is defined by a gradual decrease in the gamma-ray log, and an upward increase in sonic velocities response at the onset of a more serrate pattern on the resistivity and sonic logs.

Sample depository

Palynological preparations (organic matter depository)

Type well 6507/7-1: 1 slide from the ditch cuttings sample at 2930 m at NPD. Reference well 6506/12-4: 15 slides, of which 14 are core samples and 1 ditch cuttings sample, covering the interval 3129.1 - 3144.3 m are available at the NPD. Note that these fall in the (+5.9 m) corrected core range of the member.

Core photographs

Type well 6507/7-1: no cores were taken in this formation.

Reference well 6506/12-4: core #1, interval 3129 - 3150 m (3142.9 m uncorrected core depth; Core Photographs CP14-17). Note there is at least a +5.9 m core correction to this core.

Reference well 6506/3-1 (new additional reference well): core #1 3101.5 - 3171.5 m (Core Photographs CP18-21; uncorrected core depth). The lowermost part of the member is cored including the base of the member at 3109.41 m (uncorrected core depth). Note that core #1 has a +1.07 m core to log correction.

Thickness

The Lysing Member varies in thickness from 1 m, e.g. in well 6608/10-1 to 120 m, e.g. in well 6506/11-4s. Average thickness is about 35 m, based on released well data. These figures exclude the informal 'lower Lysing sandstones' of late Turonian age developed below this member in some wells that require better description before classification.

Geographical distribution

The member is widely distributed on the Halten and Dønna Terraces, particularly along the margin of the

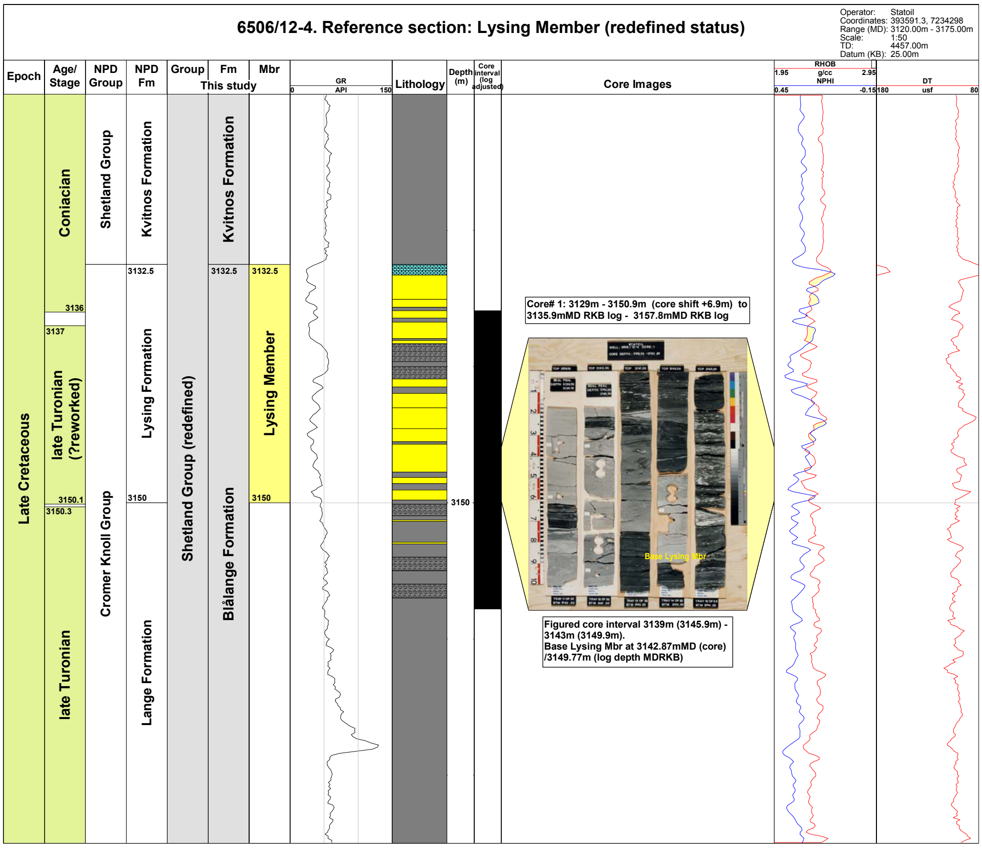


Figure 3.23. Well logs and lithology section for the Lysing Member of the Blålange Formation in type well 6507/7-1, Norwegian Sea.

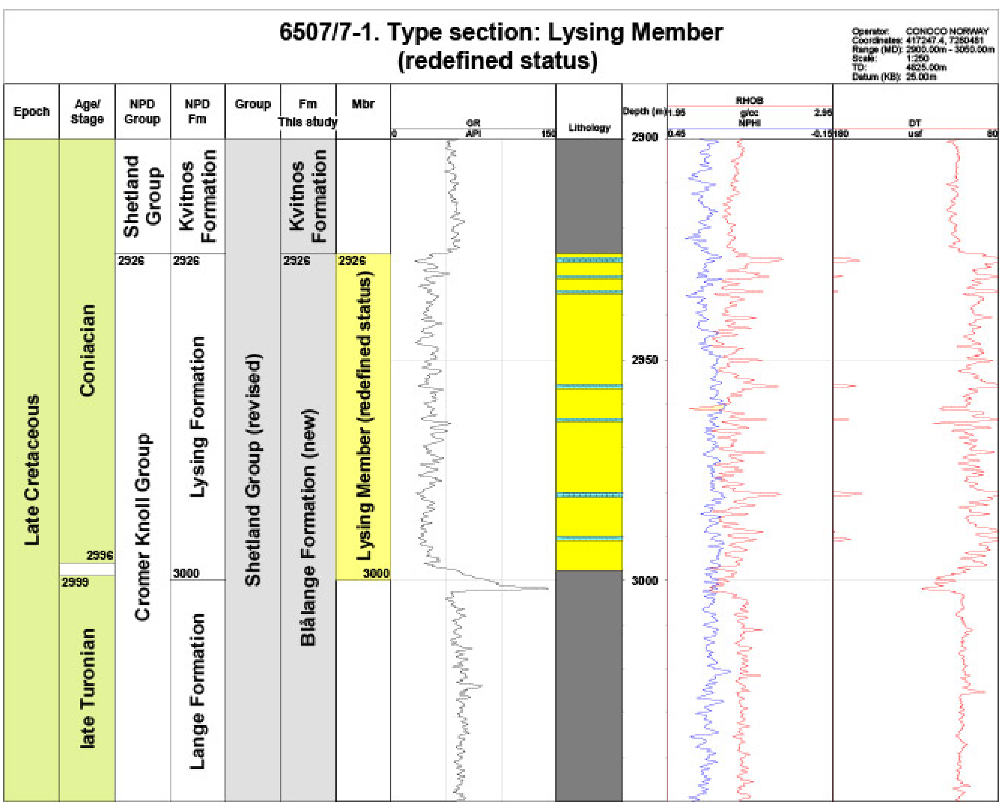
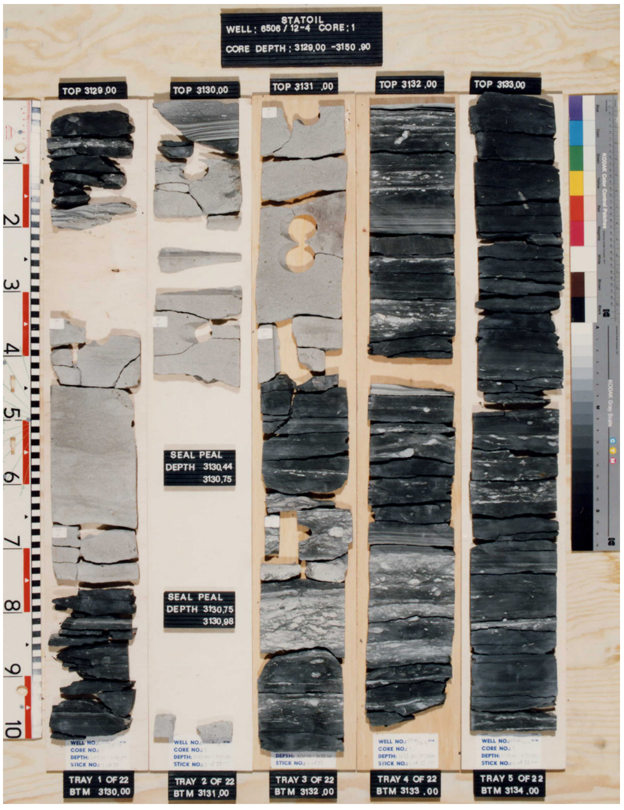
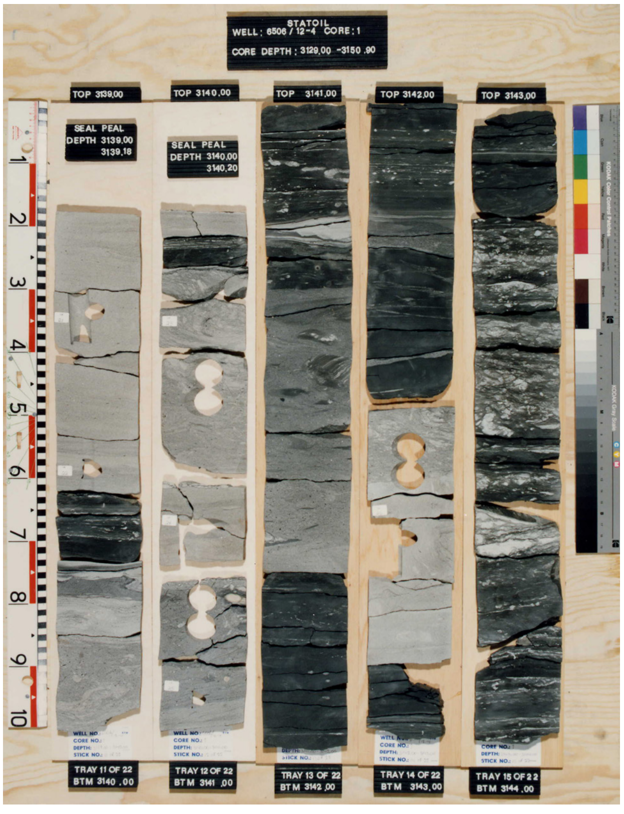


Figure 3.24. Well logs and lithology section for the Lysing Member of the Blålange Formation in reference well 6506/12-4, Norwegian Sea.



CP14. Core 1, 3129– 3133m, Lysing Mb, reference well 6506/12-4.

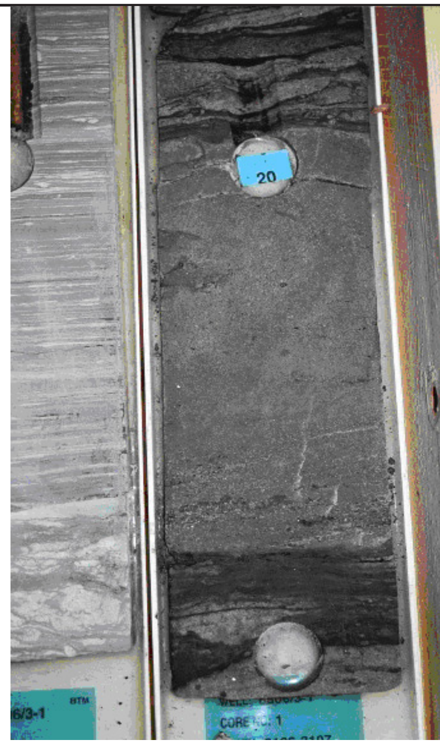
CP15. Core 1, 3134– 3138m, Lysing Mb, reference well 6506/12-4.



CP16. Core 1, 3139– 3143m, Lysing Mb, reference well 6506/12-4.

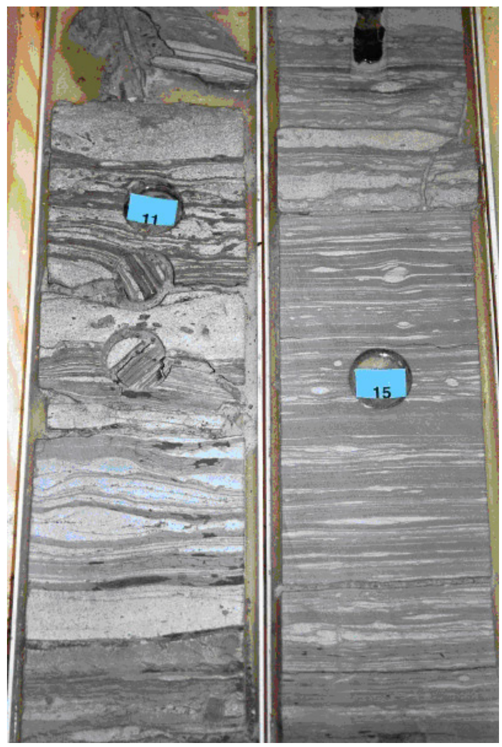
CP17. Core 1, 3144– 3148m, Lysing Mb, reference well 6506/12-4.

CP18.



CP19.

CP20.



CP21.

CP18-21. Core 1, 3101.5– 3171.5m, lowermost Lysing Mb, well 6506/3-1. **CP18:** Core 1 at 3109.41m MD RKB. This well is a reference well for the Lysing Member; the core shows the base of the Lysing Member, marked by the first (up hole) sandstone bed; the bed contains scattered glauconite. **CP19:** Core at 3106.96m MD RKB. Normally graded, 27cm thick wells sorted sandstone, with glauconite grains at base. Low-angle cross stratification may be present. **CP20:** Core at 3106.69m MD RKB; cross-laminated sandstone with glauconite along the lamina. **CP21:** Core 1 at 3104.8 m MD RKB; thin, massive and ripple laminated glauconitic sandstone beds, alternating with striped mudstones

Nordland Ridge. It is generally thin (< 5 m) e.g. in wells 6507/2-1 and 6507/5-5, and absent on the Trøndelag Platform.

It is also variably developed in wells that have penetrated the deeper parts of the Vøring Basin e.g. 6605/8-1 (Stetind), but was not present in the 6504/5-1 well (Gemini prospect) that was also drilled in the Vigrid syncline (Heskestad *et al.* 2009). In this well, the time-equivalent section was represented by mainly mudstones with thin sandstones, siltstone and limestone stringers. Maximum thicknesses of over 100 m (gross) are on the westerly flank of the Halten Terrace in block 6506/11 (Morvin Field) e.g. 6506/11-4 S (120 m) and 6506/11-7 (111 m).

Occurrences of member tops in wells maybe found in a button-marked routine on the Norlex internet site under Lysing Member.

Type well

Well name: 6507/7-1
WGS84 coordinates: N 65°27'16.7", E 07°12'52.6"
UTM coordinates: 7260481.16 N 417247.40 E
UTM zone: 32
Drilling operator name: Conoco Norway
Completion date: 01.12.1984
Status: P & A
Interval of type section and thickness in type well: 3000 - 2926 m, 74 m thickness.

Reference well

Well name: 6506/12-4
WGS84 coordinates: N 65°12'46.97"N, E 06°43'30.37"
UTM coordinates: 7234298.14 N 393591.29 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil AS)
Completion date: 13.08.1985
Status: P & A
Interval of type section and thickness in type well: 3150 m to 3132.5 m, 17.5m thickness. The lower 15 m of the formation are cored, including the base at 3142.87 m MD RKB (uncorrected core depth). Note core #1 has a +6.9 m core to log correction.

In order to better display the well logs variation within the Lysing Member, an additional reference section was selected in well 6506/3-1.

Well name: 6506/3-1
WGS84 coordinates: N 65°48'20.75"N, E 06°44'32.64"
UTM coordinates: 7200300.07 N 396769.02 E
UTM zone: 32
Drilling operator name: Norsk Chevron AS
Completion date: 09.08.2001
Status: P & A
Interval of type section and thickness in type well: 3110.5 m MD RKB (3109.41 m uncorrected core depth - 3090 m MD RKB, 20.5 m thickness.

Upper and lower boundaries

Upper boundary

The Kvitnos Formation locally overlies the Lysing Member. The boundary between the two units is usually characterised by an upward increase in gamma ray values, and a decrease in sonic velocities representing the change from sandstones to mudstones.

Lower boundary

Sandstones of the Lysing Member rest on mudstones of the underlying (and often surrounding) Blålange Formation. In the type well 6507/7-1, the basal stratotype is defined by a gradual decrease in the gamma--ray log, and an upward increase in sonic velocities response at the onset of a more serrate pattern on the resistivity and sonic logs. In other wells, e.g. 6506/6-1, 3080 m MD RKB, the base of the member may be sharp and reflects the abrupt input of sandstones.

In some instances, the base of the Lysing Member has been defined at a prominent high gamma marker (informal sequence k58a) within the upper part of the Blålange Formation e.g. 6506/12-10 (6580 m MDRKB). However, the position of this regional correlative event may be as much as 30 m below the first development of sandstones and is not recommended, e.g. 6506/3-1 (3110.5 m MD RKB). In the type well 6507/7-1 the informal k58a marker is almost coincident with the base of the Lysing Member, presumably due to local erosion at the base of the unit. However, this useful marker, which may represent a synchronous ash bed, provides a means of distinguishing Lysing Member sandstones from older sandstones of the underlying Blålange Formation based only on wireline log information.

Well log characteristics

The wireline log response of the Lysing Member is variable. In the type well 6507/7-1, the member is characterised by a serrate but generally blocky gamma-ray profile with a funnel shaped basal section. Dalland *et al.* (1988) in their original description also noted that the resistivity and sonic log patterns were generally serrate with respect to the underlying and overlying intervals, but these probably relate to zones of calcite cementation within the sandstones or thin limestone stringers. In the reference well 6506/12-4, however, the Lysing Member has a generally irregular gamma-ray log profile and in the 6506/3-1 well, a lower irregular unit is divided from an upper, funnel shaped, cleaning upward unit by a unit of mudstones . This variation in log profile reflects local differences in the depositional style of the member.

A prominent high gamma ray feature (informal k58a event) e.g. 6507/7-1 (3002 m MD RKB) provides a useful and regionally correlatable event below the member.

Biostratigraphy

In the type well 6507/7-1, the Lysing Member is late(st) Turonian through Coniacian in age, with the late Turonian dinocyst marker LO *Stephodinium coronatum* occurring 2 m above the base of the member in sidewall samples at 2998 m. In the type well, there is an increase in *Heterosphaeridium difficile* at the same level, although the lack of separation of these two events may suggest some minor (local) erosion at the base of the member.

The FO *Chatangiella 'spinosa'* appears to be within the middle part of this member and suggests an age no older than Coniacian, e.g. 6507/7-1, 2964.5 m swc. The Lysing Member is generally within the abundance ranges of the *Palaeoperidinium pyrophorum* and *Palaeohystrichophora infusorioides* palynoevents that are regionally typical of the early Coniacian.

Planktonic foraminifera are generally absent in the Lysing Member, but pyritised diatoms such as *Stellarima* spp. and radiolarians (cenosphaerid and spumellarian types) are frequent, particularly towards the base.

In the reference well 6506/12-4, dating is problematic, since many Triassic palynomorphs are present. This indicates a Triassic origin of the sands during Coniacian time. It is uncertain whether the sporadic occurrences of *S. coronatum* throughout the member are in situ or reworked.

More meaningful biostratigraphic data are derived from the additional reference well 6506/3-1 where LO *S. coronatum* occurs in mudstones immediately below the member (3111.04 m corrected core). The increase in *H. difficile* (from 3100 m dc and extending within the lower cored interval of the member to 3108.98 m corrected core) suggests that in this well, the Lysing Member straddles the Turonian-Coniacian boundary.

Additional dinocyst events that assist correlating the Lysing sandstones are the LO of *Psaligonyaulax deflandrei*, LO *Spiniferites* porosus and acme *C. 'spinosa'* in the overlying Kvitnos mudstones and the LO of *Cyclonephelium membraniphorum* either within or below the member.

In summary, the Lysing Member in a majority of wells is assigned an early Coniacian age. Some sandstones developed within the lower part of the member may be late Turonian in age.

Age (redefined)

Late Cretaceous, latest Turonian – Coniacian.

The main sandstones of the Lysing Member are usually early Coniacian age but the member may straddle the Turonian/Coniacian stage boundary in some wells. In some instances, the biostratigraphic dating is complicated by syn-sedimentary reworking. This review suggests a considerable reduction in the age uncertainty than presented earlier by Dalland *et al.* (1988).

Correlation

In the deeper locations of the Vøring Basin, e.g. wells 6607/5-1 and 6605/8-1, an informal three fold reservoir zonation of the Lysing Member is proposed for practical purposes. The 'upper' Lysing Member is typical of wells on the Dønna terrace and is Coniacian age. The Turonian/Coniacian boundary lies within a middle unit dominated by mudstones. The informal 'lower' Lysing member is typically late Turonian age and represents an earlier phase of deposition, that without biostratigraphic control is difficult to recognise on lithological criteria alone.

Depositional environment

When Dalland *et al.* (1988) first formally described the unit there was considerable uncertainty on the depositional processes and setting of these sandstones. Interpretations varied from shallow to deep marine and possibly sandstone dominated fan lobe deposits as suggested for the type well 6507/7-1 by Hastings (1987) and Vergara *et al.* (2001). Since that time, there have been several more publications on the depositional setting of the Lysing sandstones from most areas of the Norwegian Sea.

This review of the current literature suggests deposition in a variety of settings on the upper slope, lower slope and basin floor. Significantly, there are no interpretations that support an in situ shallow marine, tidal interpretation in spite of the development of a sedimentary facies in core e.g. 6506/12-5 that is characterised by cross stratified, glauconitic sandstones. These have interpreted as being a slumped unit of tidal sediments (Shanmugam *et al.*, 1994) that may be related to the slumping identified by seismic facies mapping in the southern Halten Terrace south of Quadrant 6406 (Vergara *et al.,* 2001), or atypical in situ deep marine sediments emplaced by episodic bottom traction currents (oceanic contourites) in a deep, basin floor setting (Hastings 1986; Walker 1998 unpubl.).

Significantly, in their argument to support slumping and mass transport complexes, Vergara *et al.* (2001) undertook backstripping of sections across the Halten Terrace to indicate paleo-water depths of several hundred metres during their K80 (Lysing time) sequence. Although not a period of tectonic activity, Lien (2005) in his development of the Cretaceous to Eocene deep-water hydrocarbon reservoirs of the Norwegian Sea recognised that the Lysing (Sequence K60) was part of the late post-rift phase representing a time of passive infill, high subsidence rates and subsequent sediment loading in the basin causing basin margin uplift and tilting.

Gradstein *et al.* (1999) studied the micropaleontology of the Lysing Member interval for the purpose of paleobathymetry. Sparse planktonic foraminifers indicate normal salinity, open marine conditions. A poor benthic foraminiferal assemblage with few calcareous taxa including *Dentalina, Gyroidinoides, Pleurostomella.*, and few coarse agglutinated ones like *Bathysiphon, Psammosphaera, Trochammina* and *Ammodiscus* may reflect restricted bottom conditions in a deep neritic or bathyal setting. Small pillbox diatoms are common, and pyritized, pyritized radiolarians occur rarely, but also testify to normal marine salinity, and bathyal conditions. A high sedimentation rate under restricted bottom conditions, together with some sorting, and diagenetic loss of taxa due to dissolution, probably combined to yield the 'impoverished' microfossil assemblage.

Of interest is that several levels in wells, poor in microfossils, give the impression being sorted hydrodynamically, with a prevalence of spherical, tubular or disk-shaped forms, including *Psammosphaera, Bathysiphon, Ammodiscus*, and sideritic and pyritic concretions that maybe tiny burrows. The environment of deposition probably was largely dysaerobic, semi-restricted, and of high energy due to turbidite scouring, and on average unfavourable to a diversified benthic life. A bathyal setting is most likely, in agreement with the fairly common presence of tubular agglutinated taxa, like *Bathysiphon*. In discussion with W. Kuhnt and T. Sæther (pers. comm., 1996), the possibility was raised that such a benthic foraminiferal assemblage might represent overbank deposits at bathyal depth, to the side of a mass-flow sand conduit. Where sands were sampled, presumably in these conduits, no foraminiferal assemblage was recovered, also no shallow marine taxa that could be considered transported down slope.

Another scenario is that common *Psammosphaera*, found as dominant taxon in many Lysing Member samples, was an early seafloor colonizer after a mass--mortality event, reflecting a disturbed environment, due to repeated sand scour in a 'fan sand delta'. A low oxygen watermass impinging on the slope would keep benthic diversity low, further threatened by repeated erosional events from sand scour. Such an environment would favour *Psammosphaera* as an opportunistic, early seafloor settler, in a bathyal environment.

For a more general overview of the various depositional settings of the Lysing sandstones, the reader is referred to Fugelli and Olsen (2005a,b). Some details are given in the following summary. In their basin screening study of deep marine reservoirs and associated risk assessment and play fairway analysis of the Vøring and Møre Basins, the Lysing sandstones and time equivalent sediments (K72 sequence) were cited as examples and the main focus for comparison with

with outcrop analogues from the early Cenozoic Ainsa Basin, Spain and Permian Delaware Basin in Texas, USA. These outcrops studies were used to construct a (composite) shelf-slope to basin floor transect. The authors documented the seismic character, gross facies elements, reservoir architecture and inferred scale and geometry of the various depositional systems of the Lysing sandstones and time equivalent sediments. The authors interpreted their K72 sequence as being deposited in medial basin-floor fans within the Vøring Basin (example 2) e.g. 6706/11-1 area; lower slope basin floor fans on the margin of the Trøndelags platform (example 3) e.g. down-dip of 6507/5-3 (Snadd Field) and 6507/2-3 wells; upper slope basin floor fan conduit (example 4) e.g. 6507/5-3 (Snadd Field) representing the main sediment fairway into the down-dip fan complex; slope deposits (example 5) e.g. 6204/11-1; and slope-channel deposits (example 6) e.g. 6204/10-1 located in the Slørebotn sub-basin. Examples 5 and 6 are time equivalent to the Lysing sandstones that are present on the eastern margin of the Møre Basin. In a more area specific study, Fugelli and Olsen (2007) described how the tectonically confined sub-basins on the Dønna Terrace controlled the deposition of the "Lysing Formation". Based on an integrated, multidisciplinary approach, they constructed a detailed depositional model for the deposition of the Lysing sandstones as turbidite complexes within a series of slope (sub) basins.

In terms of details of the sedimentary facies, in the cored 6506/12-4 reference well, located in the Smørbukk Field area, the Lysing Member consists mainly of fine grained sandstones with thin mudstones. The sandstone beds (average thickness 50 cm within a range 17-105 cm) typically have sharp bases and are characterised by fluid escape structures (vertical or inclined pipes and contorted internal structures) suggesting rapid deposition from turbidity currents. However, these sandstones do not show the range of features typically associated with 'classical' turbidites such as the alternation of thin sandstones and mudstones. The sandstones are in some instances interbedded with hemipelagic, generally non- or rarely bioturbated black mudstones with a similar character to those of the underlying interval with rare *Planolites, Teichichnus* and *Zoophycos* traces suggesting a relatively deep-water, quiet environmental setting. The boundary with the underlying Blålange Formation mudstones is transitional and does not represent a sharp contact or abrupt facies change. The 'background' mudstones become progressively more bioturbated upwards and sandstone beds appear below the boundary at 3142.87 m MD RKB (uncorrected core depth). This supports the interpretation that the Lysing Member is genetically linked to the Blålange Formation. Elsewhere in the Smørbukk Field area, seven sedimentary facies have been identified from cores within the Lysing Member (Walker unpublished report, 1998) namely:

facies 1 - thick structureless sandstones,
facies 2 - sandstones with fluid escape structures (6506/12-4 core),
facies 3 - thin bedded sandstones,
facies 4 - glauconitic sandstones,
facies 5 - bioturbated sandstones and mudstones,
facies 6 - dark argillaceous sandstones, and
facies 7 - pinstriped mudstones.

In terms of sedimentary processes, facies 1, 2 and 6 are interpreted as being deposited rapidly from turbidity currents. Somewhat controversial is the presence of glauconitic sandstones (facies 4) showing cross stratification e.g. 6506/12-5 (3160.76 - 3165.31 m). Shanmugam *et al.* (1994) interpreted these units as a progradational delta front succession with tidal influence and therefore of shallow water affinity that may have "slid into deep water". However, the critical association of these glauconitic sandstones with hemipelagic pinstriped black mudstones and the lack of any basal slide plane led Walker (1998) to suggest that these cross stratified sandstones were emplaced by episodic bottom traction currents (oceanic contourites) in a deep, basin floor setting. These units yielded a microfauna dominated by deeper water (bathyal) agglutinated foraminifera (Gradstein *et al.*, 1999).

The Lysing Member is cored in the additional reference well 6506/3-1, located in the north-western part of the Dønna Terrace. In this core, the Lysing Member is represented by a heterolithic succession characterised by two facies: fine grained glauconite rich sandstones (equivalent to facies 4 of Walker) and pin-striped mudstones (facies 7 of Walker). The sandstones are typically thin (1-10 cm) beds with sharp bases, with massive to normal grading or ripple internal structures and *Planolites* dominating the moderate bioturbation (BI 3), whereas the pinstriped mudstones contain *Zoophycos* traces. The sandstones are interpreted as representing glauconite-rich, amalgamated low density turbidites. The lack of mudclasts and the sandstones association with pin-striped mudstones representing the background sedimentation suggest that these are the distal or lateral parts of a submarine fan lobe. The pin-striped mudstones may represent low density turbidity currents or reworking by weak ocean bottom currents in an outer shelf setting. The common glauconite is probably derived by re-deposition from a shallower marine setting. According to seismic interpretation, the Lysing sandstones in this well represent part of a lateral pinch-out of a large deep-marine system.

The sediment source direction of the Lysing sandstone is still controversial. It is likely that the sandstones were multi-sourced, being derived from easterly i.e. from the Trøndelags Platform, north-easterly and westerly directions i.e. east Greenland margin. This might be focus for future studies utilizing heavy minerals and microfossil reworking ages. Swieckicki *et al.* (1998) included the Lysing sands as part of their (mega) Sequence K4, and attributed the source of the sands to a response to the rejuvenated uplift of the Nordland Ridge. They noted that the main depocentre was on the Dønna Terrace and that the seismic facies evidence suggested a westerly shale out of an interval away from the Nordland Ridge.

The Lysing Member is also tentatively assigned to Coniacian sandstones north of the Trøndelags Platform e.g. 6610/3-1, although these are probably locally sourced from either the Grønøy High or directly from Norwegian mainland via the Vestfjorden Basin. Vergara *et al.* (2001) suggested that in the area of the Helland Hansen Arch the sediment source was probably from the east in contrast to earlier studies by Sanchez- Ferrer *et al.* (1999). They also suggested the Lysing sandstones in the Vøring Basin well 6607/5-1 to be sourced from the north-east as a lobe of the Någrind Syncline Fan. Well 6707/11-1 probably has a similar source direction from the north-east). Lysing sandstones on the Vema Dome e.g. 6706/11-1 are probably sourced from the north-west from the area of the Vøring Marginal High.

Tunge Member [new]

Blålange Formation, Norwegian Sea

Introduction

The Tunge Member is introduced for a unit of interbedded sandstones, mudstones and siltstones within the upper part of the (new) Blålange Formation. Sandstones of this member are found in the Rås Basin and Slørebotn sub-basin in blocks 6306/10 and 6305/12 on the eastern margin of the Møre Basin, and are assigned a Coniacian age. The Tunge Member is therefore geographically distinct but a time equivalent to the Lysing Member developed on the Halten-Dønna Terraces along the western margin of the Trøndelags Platform. In the absence of cores there is limited detailed published data on the depositional setting of the Tunge Member. Regional seismic mapping suggests this member is part of a sand-prone slope apron system developed on the eastern margin of the Møre Basin. The unit may represent slope fans derived from an easterly, up-dip source area on the Frøya High, or possibly locally derived slumped debris flow units from the Gossa High.

Name

English/ Norwegian and any previous names: In the type well 6306/10-1 the Tunge Member is noted on the NPD fact pages as a unit without formal name within the Kvitnos Formation. The operator Norske Shell referred to the unit informally as a 'Senonian sandstone unit'.

Derivatio nominis: The name Tunge is derived from the Norwegian for the common sole fish species *Solea solea*. The fish is usually found in numbers in the North Sea and northwards to Trondheimsfjorden, living on muddy bottoms from the littoral zone down to 150 m depth and having a habit of migrating upwards through the water mass at night.

Lithology

The Tunge Member consists of interbedded sandstones, mudstones and siltstones.

The *sandstones* are white - light grey to green, very fine to fine grained, with clear to translucent quartz grains, sub-angular, moderate to well sorted, firm to very hard, generally weakly cemented or occasionally with calcareous cement, abundant glauconite and with poor visual porosity.

The *mudstones* are light grey to dark greenish grey, moderately soft to firm, blocky to sub-blocky, non-calcareous and slightly micaceous.

The *siltstones* are medium dark grey, firm to moderately hard, blocky, micromicaceous and non-calcareous.

Basal stratotype

The base of the Tunge Member is characterised by a transitional change from sandstones and interbedded mudstones to more uniform mudstones of the underlying Blålange Formation. In the type well 6306/10-1, this boundary is defined at 1858 m D RKB by a gradational but still marked downward increase in gamma-ray values and decrease in density logs representing the deepest few thin sandstone beds. The decrease in sonic velocity and positive separation between neutron porosity and density logs is slightly higher in the section at 1851.5 m MD and represents the base of the sand-rich interval. Below is a more complete description of both the lower and upper boundaries and well log characteristics of the Tunge Member.

Sample depository

Palynological preparations (organic matter depository)

Type well 6306/10-1. There are no palynological slides available with the Norwegian Petroleum Directorate for the type well covering the interval of this member. Reference well 6305/12-1: Three sidewall cores (Hydro preparations) are available at 2608 m, 2632 m and 2646 m at the NPD covering the unit, upper and lower boundaries of the member.

Core photographs

Type well 6306/10-1: no cores were taken in this member.
Reference well 6305/12-1: no cores were taken in this member.

Thickness

The Tunge Member varies in thickness from 10 m to 33 m.

Geographical distribution

The Tunge Member is developed on the eastern margin of the Møre Basin in quadrants 6205, 6305 and 6306 in the Rås Basin and Slørebotn sub-basin around the Gossen High. It is presumably sourced from the Norwegian mainland to the east or locally from structural highs in the area. Its thickest development is in the type well 6306/10-1. On the Norlex website at *www.nhm2.uio.no|norlex* is a link under Tunge Member to find occurrences of member tops in wells.

Type well

Well name: 6306/10-1
WGS84 coordinates: N 63°09'26.32", E 06°19'41.45"
UTM coordinates: 7006088.05 N 365416.35 E
UTM zone: 32
Drilling operator name: A/S Norske Shell
Completion date: 17.12.1990
Status: P & A
Interval of type section and thickness in type well: 1858 - 1825 m, 33 m thickness.

Reference well

Well name: 6305/12-1
WGS84 coordinates: N 63°01'25.73", E 05°47'23.94"
UTM coordinates: 6991476.94 N 641178.97 E
UTM zone: 31
Drilling operator name: Norsk Hydro Produksjon AS
Completion date: 18.09.1991
Status: P & A
Interval of type section and thickness in type well: 2642 - 2616 m, 26 m thickness.

Upper and lower boundaries

Lower boundary

The base of the Tunge Member is characterised by a transitional change from sandstones and interbedded mudstones to more uniform mudstones of the underlying Blålange Formation. In the type well 6306/10-1 (Figure 3.25), this boundary is defined at 1858 m D RKB by a downward increase in gamma-ray values, and decrease in density logs representing the deepest thin sandstone beds. The decrease in sonic velocity and positive separation between neutron porosity and density logs is slightly higher in the section at 1851.5 m MD, and represents the base of the sand-rich interval.

Upper boundary

In the type well 6306/10-1 (Figure 3.25), the top of the Tunge Member is taken at a downward change from Kvitnos mudstones with minor limestone stringers to interbedded sandstones and mudstones. The change is sharp and the upper boundary is defined by a marked decrease in gamma-ray values and increase in sonic velocity. There is also an associated pronounced negative separation on neutron porosity and density logs in response to rapid termination of sandstones.

Well log characteristics

In both the type well 6306/10-1 and the reference well 6305/12-1, the Tunge Member is characterised by an irregular to serrate gamma-ray log profile that is either funnel-shaped or sharp in the lowermost part of the member. This reflects the heterolithic nature of the interbedded sandstone and mudstone sequence.

Type seismic section

NMI-822 & SP. 380

Biostratigraphy

The Tunge Member is developed between the Coniacian dinocyst markers LO *Florentinia deanei*, LAO *Chatangiella 'spinosa'* and LCO *Heterosphaeridium difficile* and late Turonian marker LO *Stephodinium coronatum*. The member is therefore Coniacian age. In the type well 6306/10-1 planktonic foraminifera are particularly common below the Tunge Member and are represented mainly by hedbergellids. The member itself contains few planktonic species but LO *Archaeoglobigerina cretacea* is recorded in the overlying mudstones of the Kvitnos Formation.

Age

Late Cretaceous, Coniacian.

Correlation

The interbedded sandstones and mudstones of the Tunge Member pass laterally into mudstones of the Blålange Formation.
The Tunge Member is a time equivalent of the Lysing Member of the Halten-Dønna Terrace area and therefore part of the K80 sequence of Vergara *et al.* (2001), K60 sequence of Færseth and Lien (2002) and Lien (2005), and K72 sequence of Fugelli

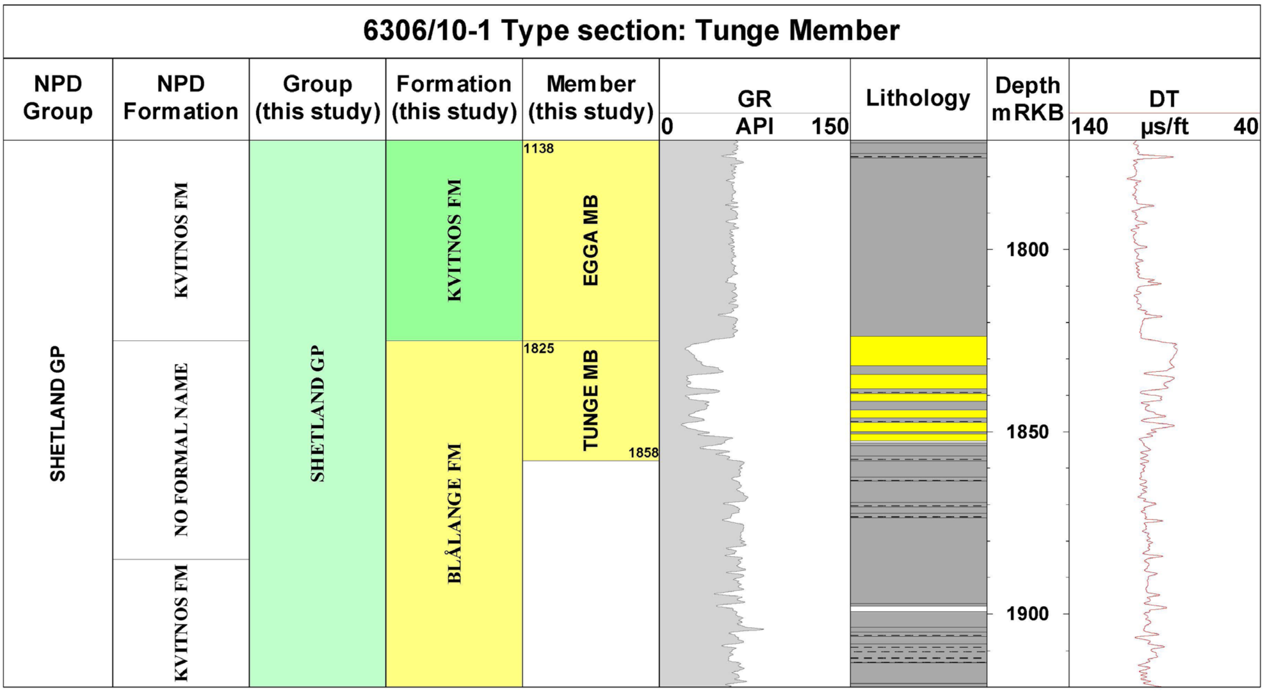


Figure 3.25. Well logs and lithology section for the Tunge Member of the Blålange Formation in type well 6306/10-1, Norwegian Sea.

and Olsen (2005a)

Depositional environment

There is limited detailed published data on the depositional setting of the Tunge Member. Vergara *et al.* (2001) in their regional seismic mapping study of the Norwegian Sea included these sandstones within their K80 sequence, in an area of the eastern Møre margin forming part of a slope apron system. This was characterised by sand-prone slope fans derived from an easterly, up-dip source area on the Frøya High or possibly as locally derived slumped debris flow units from the Gossa High and other local emergent structures (see their figure 10).

In terms of the benthic foraminiferal biofacies, both the type and reference wells are characterised by low diversity deep water agglutinated foraminifera (DWAF), primarily *Rhabdammina-Haplophragmoides* spp. and pyritised microfossils that is consistent with a depositonal setting on a paleo-slope and suggest dysoxic bottom conditions. The marine microplankton is characterised by high diversities (22 - 26 species/sample) suggesting an open marine, normal salinity setting also.

Remarks

The Tunge sandstones, located in the Rås Basin and Slørebotn sub-basin on the eastern margin of the Møre Basin are inferred to have a different source provenance than those of the Lysing Member, being derived locally and eastwards from the Norwegian mainland.

Kvitnos Formation

Shetland Group, Norwegian Sea

Introduction

The Kvitnos Formation was originally introduced by Dalland *et al.* (1988) for a widespread unit of calcareous mudstones developed below the Nise Formation.

Two new sandstone members are defined within this formation: the Tumler Member, an interval of intra-Kvitnos sandstones in the Vøring Basin, and the Kvitskjæving Member, a unit with a similar stratigraphic position developed in the Vestfjorden Basin.

Name

English/ Norwegian and any previous names: No previous formal or published informal names.

Derivatio nominis: Kvitnos is the Norwegian name for the white-beaked dolphin or *Lagenorynchus albirostris*. This small (up to 3m long) 'springar-type' species is found in flocks up to 30 individuals over large parts of the North Atlantic, around the British Isles and the Norwegian and Barents Seas. It prefers shallow coastal areas, in contrast to the closely related Kvitskjæving, which is found in deeper waters.

Lithology

The Kvitnos Formation consists predominantly of calcareous mudstones with subordinate carbonate and sandstone stringers (Dalland *et al.*, 1988). The *mudstones* are light-medium grey, green-grey, occasional medium-dark grey, soft, plastic, amorphous, occasional firm to blocky, subfissile, slightly to moderately calcareous and slightly silty. The *limestone* stringers are grey-white, occasionally light brown, soft to moderately hard, occasionally argillaceous and micritic. The *dolomite* stringers are light brown to light orange brown, moderately hard to hard. The thin *sand beds* are predominantly loose, light grey-white, very fine to fine, occasionally coarse, clear translucent quartz, sub-rounded to subangular, sub-spherical, well sorted, and occasionally weakly calcite cemented.

Sample depository

Palynological preparations (organic matter depository)

Type well 6506/12-4: 44 slides (dc and 6 swc) covering the interval 2614 - 3124 m dc (Stratlab, RRI and Saga preparations) deposited at the Norwegian Petroleum Directorate. Note that the four core samples analysed between 3129.1 - 3132.5 m fall within the depth range of the formation but due to a core shift of +5.9 m are part of the Blålange Formation and Lysing Member, and have been excluded from this formation (see below).

Reference well 6506/12-1: 75 slides (dc and 2 swc samples) covering the interval 2660 - 3170 m dc (Stratlab, RRI and NPD preparations) deposited at the Norwegian Petroleum Directorate(NPD).

Core photographs

No cores were taken in the designated type 6506/12-4 and reference 6506/12-1 wells. Note that in the type well 6506/12-4, core #1 (3129 - 3150.9 m MD RKB) falls within the depth range of the formation, but due to a +5.9 m depth shift lies entirely within the Blålange Formation and Lysing Member, rather than the Kvitnos Formation.

Thickness

The Kvitnos Formation has a thickness range of 3.5 m to 1108 m. On the Norlex website under Kvitnos Formation a regional isochore of the Kvitnos Formation thickness in the Norwegian Sea maybe downloaded. This map is based on released well data. The isochore map is generated from Norlex data using thin plate splines (thickness constrained to original range). Note that this map on the website itself is only a regional interpretation and the user can generate more specific, local area isochore maps interactively within Norlex using the link.

Geographical distribution

The formation is laterally continuous in the Vøring Basin and on the Halten-Dønna Terrace areas. The main depositional centres of the Kvitnos Formation are recorded in wells on the structural highs in the Vøring Basin e.g. 6707/10-1 (1108 m at well TD), 6706/11-1 (1037 m), Helland Hansen Dome well 6505/10-1 (933 m) and the Ormen Lange Dome well 6305/1-1 (862 m) in the Møre Basin. An anomalously thick interval is developed in the 6507/1-1 well located on the Dønna Terrace, where the Kvitnos Formation reaches almost 1000 m. Generally thicknesses decrease on the Halten-Dønna Terrace areas to between 600 -150 m. The Kvitnos Formation is, together with other Cretaceous formations, either thin or absent on the Nordland Ridge e.g. 6507/6-1 or on the crest of fault structures on the Halten Terrace such as the Heidrun Field e.g. 6507/7-6 (3.5 m). Occurrences of formation tops may be interactively obtained under Kvitnos Formation on the Norlex website.

Type well

Well name: 6506/12-4 (Figure 3.26)
WGS84 coordinates: N 65°12'46.97", E 06°43'30.37"
UTM coordinates: 7234298.14 N 393591.29 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 13.08.1985
Status: P & A
Interval of type section and thickness in type well: 3132.5 - 2600 m, 532.5 m thickness.

Reference well

Well name: 6506/12-1 (Figure 3.27)
WGS84 coordinates: N 65°10'07.58", E 06°43'44.07"
UTM coordinates: 7229359.52 N 393591.68 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 06.02.1985
Status: P & A
Interval of type section and thickness in type well: 3175 - 2658 m, 517 m thickness.

Upper and lower boundaries

Upper boundary

The top of the Kvitnos Formation and the boundary with the overlying Nise Formation reflects a downward change to more calcareous mudstones. This change is marked on logs by a downward decrease in gamma-ray values and an increase in average sonic velocity and density values (Figure 3.25). Dalland *et al.* (1988) also noted a corresponding downward increase in resistivity values.

Lower boundary

The base of the Kvitnos Formation is normally taken at a downward change from calcareous mudstones to non-calcareous mudstones of the Blålange Formation or local sandstones of the Lysing Member. It is marked on logs by a downward decrease in average gamma-ray values and increase in average sonic velocity (Figure 3.26). Dalland *et al.* (1988) also noted a corresponding downward increase in resistivity values (typically when associated with the underlying Lysing member).

Well log characteristics

The Kvitnos Formation has a relatively uniform profile on gamma-ray logs reflecting the deposition of marine mudstones. However, the formation can be sub-divided into a series of regionally correlatable units based on the sonic log. A downward increase in average sonic velocity within the lower part of the formation appears to coincide with the Santonian/Coniacian boundary as defined on biostratigraphy, and provides an important regional log feature informally denoted k66 e.g. in well 6506/12-1 at 3033 m. This provides well log control prior to the penetration of Lysing sandstones. Similarly, higher in the formation at approximately the mid-point, there is another downward increase in average sonic velocity that appears to be close to the early/middle Santonian boundary and is informally named k68, e.g. in 6506/12-1 at 2950 m. Above this event sonic velocities appear to be more irregular than those in the lower part of the formation, and may reflect the increased frequency of sandstones.

Biostratigraphy

The lower boundary of the Kvitnos Formation is above the Turonian dinocyst markers LO *Stephodinium coronatum* and *Cyclonephelium membraniphorum.* The lower part of the Kvitnos Formation is characterised by a marked increase in *Heterosphaeridium difficile* and *Palaeoperidinium pyrophorum*.
As indicate above in the well log character, within the Kvitnos Formation are some discrete, regionally identifiable units defined on the sonic log. The Coniacian/Santonian boundary, as defined by the LO *Florentina deanei* and more reliably, a marked down-section increase in *Chatangiella 'spinosa,'* that is close to the informal surface k66 defined on sonic logs.
The upper boundary of the Kvitnos Formation is

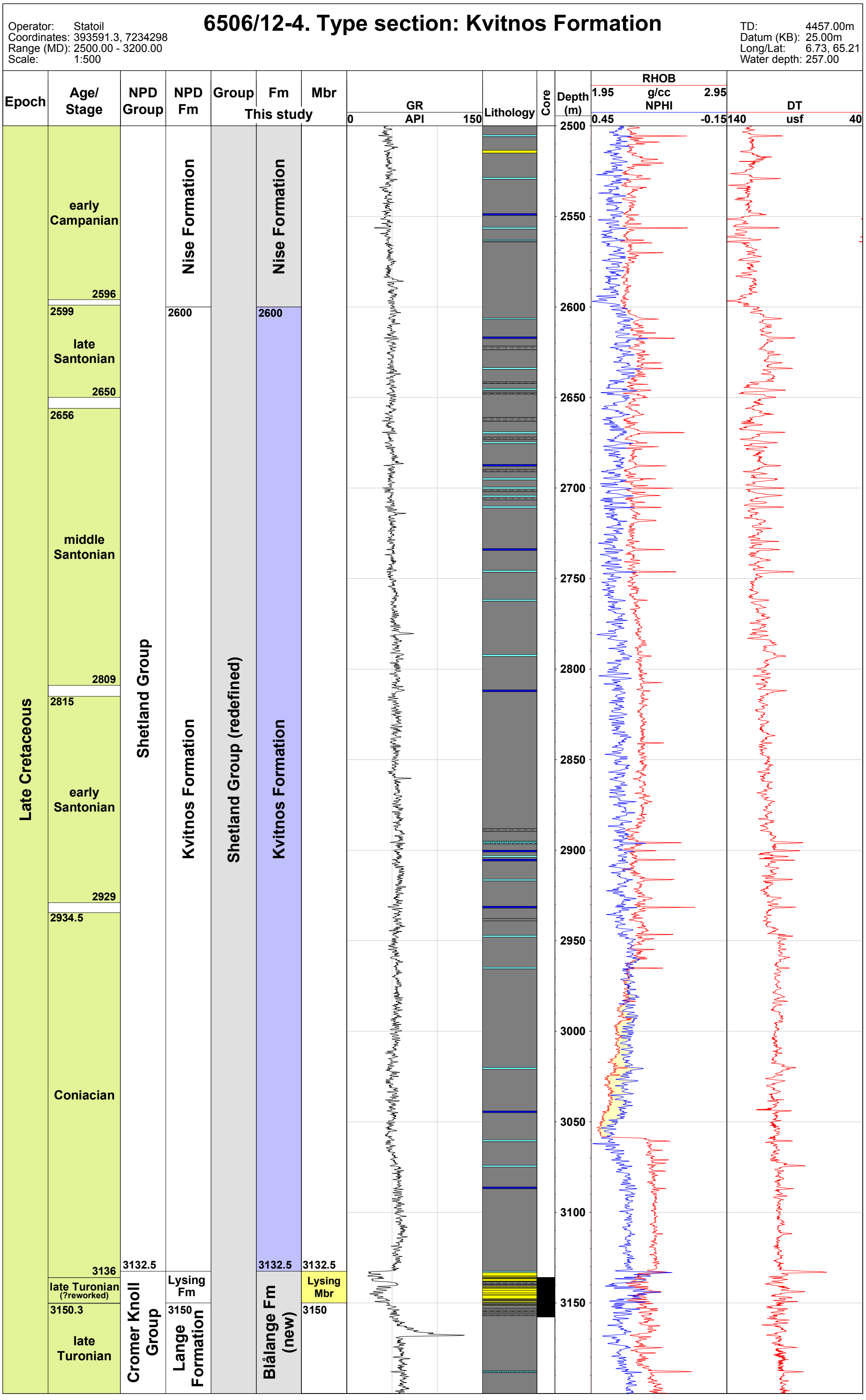


Figure 3.26. Well logs and lithology section for the Kvitnos Formation in type well 6506/12-4, Norwegian Sea.

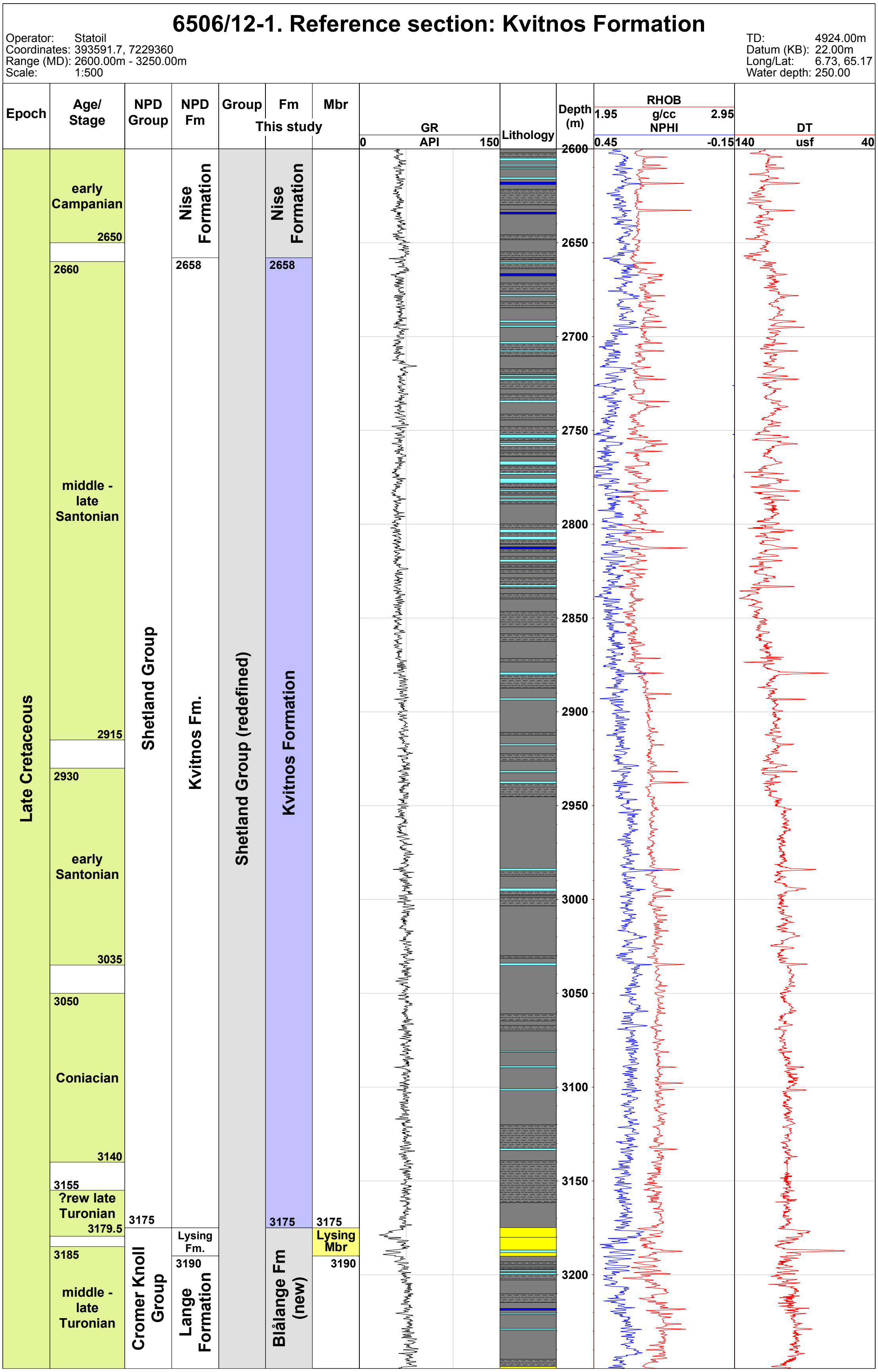


Figure 3.27. Well logs and lithology section for the Kvitnos Formation in reference well 6506/12-1, Norwegian Sea.

close to the (down-section) influx of the planktonic bivalve *Inoceramus*, and probably reflects a general increase in calcium carbonate within the formation. This is the key event for the definition of the top Kvitnos Formation. The LO *Spongodinium cristatum* and LO *Whiteinella baltica* are developed within the basal part of the overlying Nise Formation. .

Age

Late Cretaceous, Coniacian to late Santonian.

Dalland *et al.* (1988) had a Turonian - Santonian age range in their definition of the formation. The lower boundary is generally close to but above the Turonian/Coniacian stage boundary, i.e. earliest Coniacian, and the upper boundary is broadly coincident with that of the Santonian/Campanian stage boundary, within the limits of the available dinoflagellate cyst biostratigraphy.

Correlation

The Kvitnos Formation is laterally equivalent to the middle part of the Kyrre Formation developed in the Shetland Group of the northern North Sea. It also is a lateral equivalent of the Thud and upper Narve Formations (formerly part of the Hod Formation) in the Chalk province of the North Sea.

Depositional environment

Open marine, outer shelf - upper bathyal with more open marine circulation than developed during the underlying Blålange and overlying Nise Formations. This is indicated by the increase in calcareous lithologies and floods of *Inoceramus* needles (Gradstein *et al.*, 1999).

Remarks

A thin sandstone unit of early Santonian age is developed in the lower part of the Kvitnos Formation in the Vema Dome well 6706/11-1 (3737 - 3750 m) and below the Tumler Member. This unit is retained as informal due to insufficient data, but it may represent a correlative interval in the deeper parts of the Vøring Basin. The Kvitnos Formation represents deposition within the lower part of the K4 sequence of Swiecicki *et al.* (1998), K80 of Vergara *et al.* (2001) and most of the K60 sequence of Færseth and Lien (2001).

Kvitskjæving Member [new]

Shetland Group, Kvitnos Formation, Norwegian Sea (Table 3.2)

Introduction

The Kvitskjæving Member is introduced for a unit of interbedded sandstones and mudstones of Santonian age within the Kvitnos Formation developed in the south-west Vestfjorden Basin in block 6610/3 (Nordland III area) of the Norwegian Sea. Limited published data are available on the depositional setting of these sandstones. These sediments are considered to have been deposited mainly as turbidites within a submarine fan system in a deeper marine, outer shelf to upper bathyal paleoenvironment.

Name

English/ Norwegian and any previous names: In the type well 6610/3-1, the interval was informally designated 'Lysing Sandstone I' by the operator Statoil on the final completion log.

Derivatio nominis: Kvitskjæving is the Norwegian name for the Atlantic white-sided dolphin *Lagenorhynchus albirostris* and appropriately, a close relative of the Kvitnos (white-beaked dolphin). It is endemic to the North Atlantic area. In Norwegian waters, the species is seldom found north of Trondheimsfjorden, and generally in water depths between 40 - 250 m related to the continental shelf.

Lithology

The Kvitskjæving Member consists of interbedded sandstones and mudstones.

The *sandstones* are medium grey, clear to transparent quartz, fine to medium, occasionally coarse, poor to moderately sorted, sub-angular to sub-rounded and calcite cemented, moderately hard, sometimes argillaceous, micaceous and slightly glauconitic.

The *mudstones* are light olive grey to black, firm to moderately hard, blocky, partially silty to sandy, micro-micaceous to micaceous, micro-pyritic, carbonaceous, glauconitic and moderately calcareous, poor visible porosity.

Sample depository

Palynological preparations (organic matter depository)

Type well 6610/3-1: Four slides from core samples deposited at the NPD covering the interval 2512.2 - 2530.4 m (Statoil preparations). Additional micropaleontological and palynological slides have been prepared by Robertson Research Int. Ltd. and PetroStrat in the course of non-propriety multi-well studies.

Core photographs

In the type well 6610/3-1 core #6 interval 2514 - 2531.47 m represents the middle part of the member (Core Photographs CP 32-36).

Thickness

The Kvitskjæving Member varies in thickness from 9m to 39m based on released well data.

Geographical distribution

The Kvitskjæving Member is locally developed in the south-westerly parts of the Træna and Vestfjorden Basins (Quadrants 6609 and 6610). Based on released well data it has a maximum thickness of 39 m in the type well 6610/3-1. On the Nordland Ridge, and in wells 6610/7-1 and 6610/7-2 located to the south in the Helgeland Basin on the Trøndelags Platform, the equivalent section is represented by an unconformity. The northerly extent of the member, away from wells 6609/5-1 and 6610/3-1 (original holes and sidetracks), is not determined due to a lack of well control in the Nordland VI area. The time-equivalent section in well 6710/10-1 appears to be below the well TD depth.

Unit tops in wells may be found under the member button on the Norlex website

Type well

Well name: 6610/3-1
WGS84 coordinates: N 66°55'29.70", E 10°54'06.28"
UTM coordinates: 7424470.29N 583170.04 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s.
Completion date: 17.02.1993
Status: Suspended Re-entered later
Interval of type section and thickness in type well: 2543 - 2504 m and 39 m thickness.

Reference well
None designated. The member was also penetrated in the re-drilled well 6610/3-1 R, but this sidetrack hole provides no additional information on the characteristics of the member compared to the original hole. In well 6609/5-1 the member is only 9 m thick.

Upper and lower boundaries
Upper boundary
The top of the Kvitskjæving Member is represented by a transition from predominantly argillaceous sediments of the overlying (and encompassing) Kvitnos Formation to a sequence of interbedded sandstones and mudstones. In the type well 6610/3-1 this boundary is represented by a gradual decease in gamma--ray (Figure 3.28), and increase in sonic velocity values. The upper boundary is better defined on resistivity logs in the type well where there is a downward increase in resistivity values.

Lower boundary
In the type well 6610/3-1, the base of the Kvitskjæving Member is marked by a downward gradual change from interbedded sandstones and mudstones to more argillaceous sediments of the underlying Kvitnos Formation. It is characterised on logs by a downward increase in gamma-ray values (Figure 3.28), and a marked decrease in resistivity values but only a weak increase decrease in average sonic velocities.

Well log characteristics
The member is characterised by a serrate gamma-ray log profile (Figure 3.28), reflecting the interbedded sandstone and mudstone content. The member shows funnel- and bell-shaped log profiles in response to the transitional nature of both the lower and upper boundaries.

Type seismic section
ST 9104-437 and SP. 335 (well 6610/3-1)

Biostratigraphy
The Kvitskjæving Member is developed below LO *Whiteinella baltica* and LO *Stensioeina granulata polonica*, and between the LO and LCO *Chatangiella 'spinosa'* suggesting an early Santonian age. The sporadic records of the Coniacian dino-cyst *Florentina deanei* above this member in the type well are considered reworked. In the cored interval of the type well 6610/3-1 *Hystrichosphaeridium difficile* shows a marked increase in numbers within the middle part of the member that maybe useful for correlative purposes.

Age
The member is assigned to an early Santonian age, Late Cretaceous.

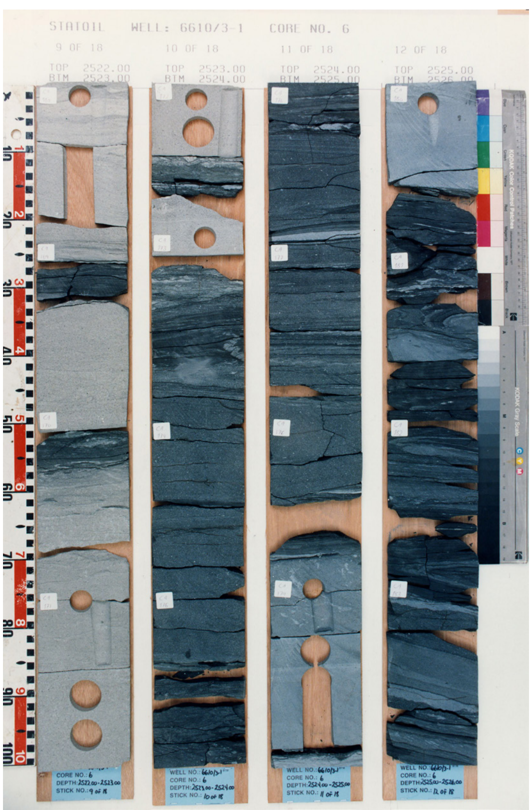
Correlation
The interbedded sandstones and mudstones of the Kvitskjæving Member pass laterally into the mudstones of the Kvitnos Formation. The member is time equivalent to some minor and un-named lower Santonian sands penetrated in the deeper wells in the Vøring Basin e.g. Vema Dome well 6706/11-1 (3737 - 3750 m MD RKB).

Depositional environment
Limited published data are available on the depositional setting of this member. The sandstones are considered to have been largely deposited as turbidites within a submarine fan system in a deep marine, outer shelf to upper bathyal paleoenvironmental setting.
A simple agglutinated foraminiferal assemblage was observed in cores of the type well 6610/3-1 e.g. at 2528.65 m MD, particularly with *Rhabdammina*, in agreement with above paleoenvironmental interpretation. Needle fragments of the planktonic *mollusc Inoceramus* also occur. Pyritised diatoms and nodosariid - calcareous benthic foraminiferal species are rare, e.g. smooth *Lenticulina* and *Nodosaria* spp.

Remarks
This member is stratigraphically younger than the Lysing Member, assigned a Coniacian age. It was referred to informally as the 'Lysing Sandstone I' by the operator on the final completion log of the type well 6610/3-1. On the NPD fact pages, the Kvitskjæving Member is the upper one of two units assigned informally to the Lysing Formation, separated by the Lange Formation. The latter is incorrect use of lithostratigraphy.

CP32. Core 6, 2514-2518m, Kvitskjæving Mb, type well 6610/3-1.

CP33. Core 6, 2518-2522m, Kvitskjæving Mb, type well 6610/3-1.



CP34. Core 6, 2522-2526m, Kvitskjæving Mb, type well 6610/3-1.

CP35. Core 6, 2526-2530m, Kvitskjæving Mb, type well 6610/3-1.

CP36. Core 6, 2530-2531m, Kvitskjæving Mb, type well 6610/3-1.

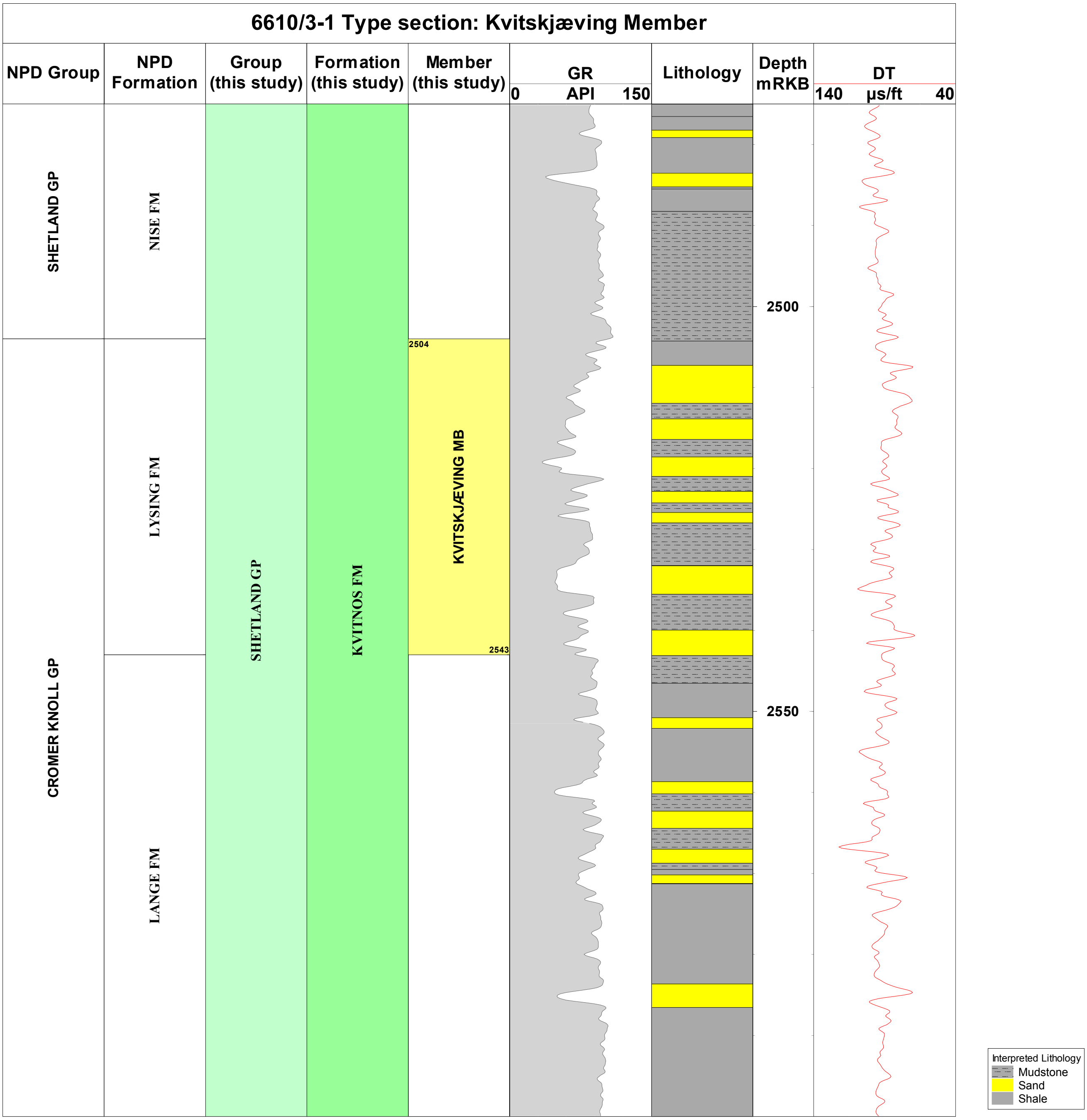


Figure 3.28. Well logs and lithology section for the Kvitskjæving Member of the Kvitnos Formation in type well 6610/3-1, Norwegian Sea.

Tumler Member [new]

Shetland Group, Kvitnos Formation, Norwegian Sea

Introduction

The Tumler Member is a new member developed in the upper part of the Kvitnos Formation in the Vøring Basin. It is characterised by sandstones and thin interbeds of mudstones of Late Cretaceous, Santonian age. It may be distinguished from the younger, sandstone-rich, Spekkhogger Member, developed in the overlying section of the Tumler Member type well 6707/10-1, by a thick (>100 m) interval of mudstones.

The Tumler Member has a geographically more restricted distribution than the overlying Spekkhogger Member within the Vøring Basin. It is interpreted as being deposited under similar depositional processes i.e. mainly by episodic high density turbidity currents within a large scale submarine fan complex, that developed in response to rapid subsidence in the Vøring Basin.

Name

English/ Norwegian and any previous names: The Tumler Member was originally assigned to the 'Lysing Formation' by the operator BP Norway in the type well 6707/10-1, in spite of it being recognised as being a younger age. The sand unit is recorded on the NPD fact pages as the lower part of the informal Delfin Formation.

Derivatio nominis: The name Tumler is derived from the Norwegian name for the bottle-nosed dolphin species *Tursiops truncates*. The species is a member of the sea going dolphin family (Delphinidae), and together with the killer whale Orca is the most numerous dolphin species on a world basis. The species has a cosmopolitan distribution from tropical to cold temperate waters, and extends as far north as the Norwegian Sea.

Lithology

The Tumler Member mainly consists of sandstones with thin interbeds of mudstones and occasional limestone and dolomite stringers.

The *sandstones* are white - very light grey or medium light grey - dark grey in clour. Grains vary from very fine to coarse, predominantly fine to medium, locally very coarse. The grains are made of clear to translucent quartz, locally hard, predominantly loose, angular to sub-rounded, predominantly sub-angular to sub-rounded, moderately to well sorted. Sandstone cement is mostly siliceous, locally weak to moderately calcareous or kaolinitic, rarely dolomite. The sandstone may be silty, locally with argillaceous matrix, common glauconite in parts, micaceous, locally with common plant fragments, pyritic, with poor to moderate visible porosity.

The *mudstones* are medium grey to brownish grey, rarely dark grey to olive black in colour. Texture is soft to firm, moderately hard, amorphous to sub-blocky, silty, commonly grading to siltstone or as thin laminae with sandstones, carbonaceous, slightly micro-micaceous, traces of very fine disseminated pyrite, trace glauconite, non to slightly calcareous, commonly grading to siltstones.

The occasional dolomite stringers are light brown to dark yellow brown, olive grey in part, moderately hard to brittle, argillaceous, occasionally sandy, crypto-crystalline grading to limestone.

The minor limestones are light grey, white, soft to firm, blocky, argillaceous or sandy.

Sample depository

Palynological preparations (organic matter depository)

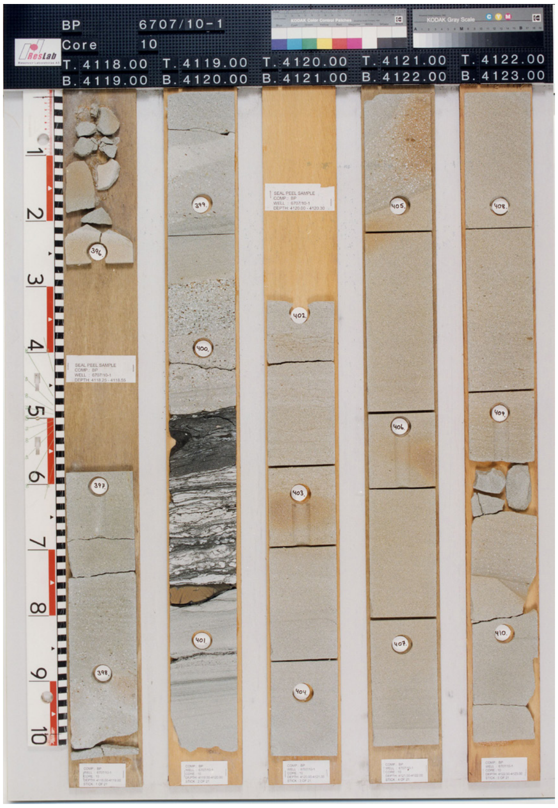
Type well 6707/10-1: Four slides from core samples covering the interval 4119.5 - 4138.2 m and one ditch cuttings sample at 4147 m deposited at the NPD (NPD preparations).

Reference well 6706/11-1: Nine slides from core samples (cores #3 and #4) covering the upper part of the Tumler Member over the interval 3108 - 3136 m and eleven slides from ditch cuttings samples between 3146 - 3461 m deposited at the NPD (RRI preparations).

Core photographs

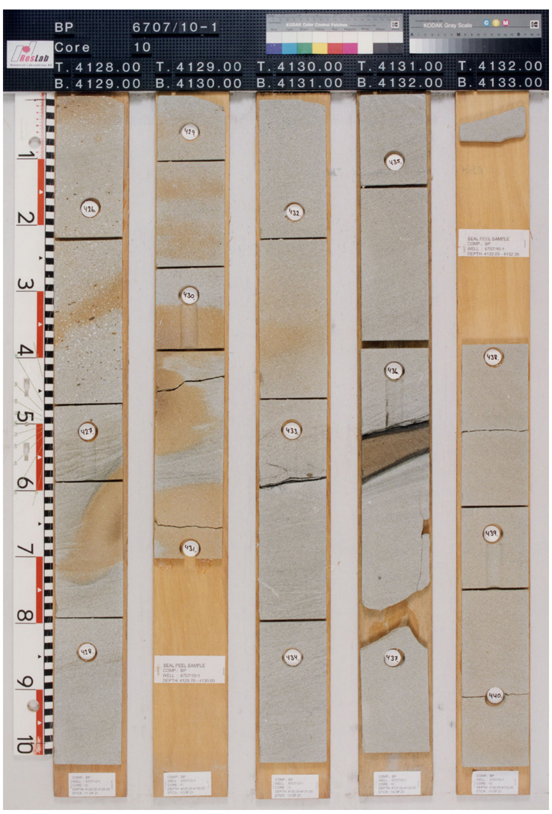
Type well 6707/10-1: Core #10 covering the interval 4118 m MD - 4138.20 m MD (Core Photographs CP 22 - 26).

The deepest core (core #10) of the Nyk well 6707/10-1 recovered sandstones and minor mudstones of the (new) Tumler Member. These together with those of the overlying Spekkhogger Member (new herein)



CP22. Core 10, 4118– 4123m, Tumler Mb, type well 6707/10-1.

CP23. Core 10, 4123– 4128m, Tumler Mb, type well 6707/10-1.



CP24. Core 10, 4128– 4133m, Tumler Mb, type well 6707/10-1.

CP25. Core 10, 4133-4138m, Tumler Mb, type well 6707/10-1.

CP26. Core 10, 4138-4138m, Tumler Mb, type well 6707/10-1.

were collectively described by Kittilsen *et al.* (1999) as part of their 'Lysing Formation'.

Reference well 6706/11-1: Cores #3 and #4 between 3107.5 m MD - 3136.65 m MD RKB (Core Photographs CP 27 - 31).

Thickness

The Tumler Member has only been penetrated in a few wells located in the Vøring Basin. The member varies in thickness from 302m in well 6707/10-1 (type section) to 368 m in well 6706/11-1.

Geographical distribution

Sandstones of the Santonian Tumler Member lie below those of the Campanian Spekkhogger Member and have a geographically more restricted distribution in the Vøring Basin, using available well data.

In wells 6607/5-1 and 6607/5-2 on the Utgard High and 6605/8-1 on the Fles North structure, time equivalent mudstones of the Kvitnos Formation are developed and provide an easterly and southern limit on the members distribution based on the available released well data. This distribution of the Tumler Member is more restricted than the overlying Spekkhogger Member where sandstones are present in well 6607/5-2, on the westerly flank of the Utgard High. The westerly limit of the member is undefined since the time equivalent section is below the well TD in well 6704/12-1, drilled on the Gjallar Ridge.

On the Norlex website under Tumler Member is a routine to find tops of the units in wells.

Type well

Well name: 6707/10-1
WGS84 coordinates: N 67°04'07.85", E 07°00'36.51"
UTM coordinates: 7440629.70 N 413490.42 E
UTM zone: 32
Drilling operator name: BP Norway Ltd.
Completion date: 23.07.1997
Status: P & A
Interval of type section and thickness in type well: 424 - 3939 m and 302 m thickness (Figure 3.29).

Reference well

Well name: 6706/11-1
WGS84 coordinates: N 67°04'24.77", E 06°27'47.70"

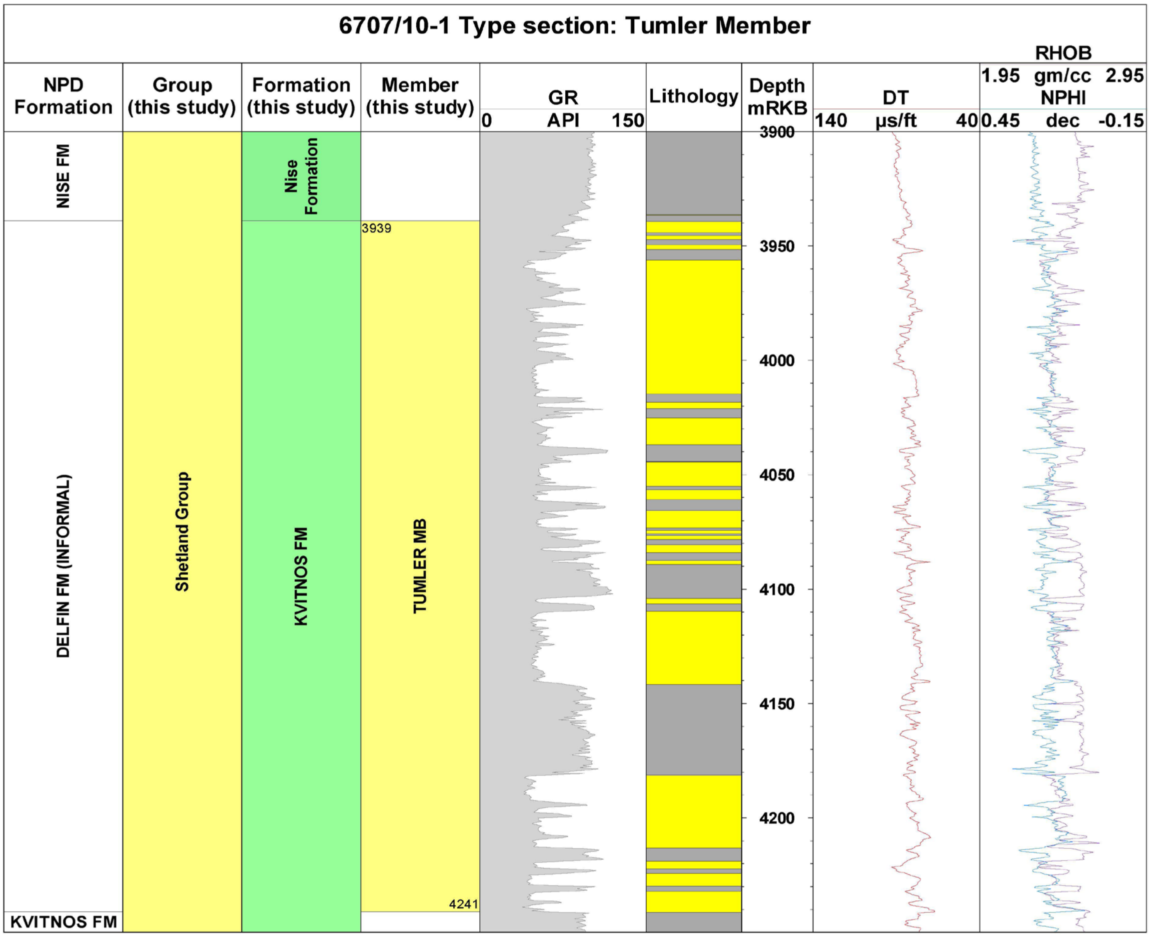


Figure 3.29. Well logs and lithology section for the Tumler Member of the Kvitnos Formation in type well 6707/10-1.

UTM coordinates: 7442018.41 N 389745.19 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s.
Completion date: 22.03.1998
Status: P & A
Interval of type section and thickness in type well: 3469 - 3101 m and 368 m thickness (Figure 3.30).

Upper and lower boundaries

Upper boundary

In the type well 6707/10-1, the top of the Tumler Member is taken at a downward change below a thick interval of mudstones within the lowermost part of the Nise Formation into an interbedded sequence of sandstones and mudstones. The change is transitional in the type well 6707/10-1 at 3939 m MD RKB, and the sandstone rich section is slightly deeper in the section at 3956 m MD. The upper boundary is therefore marked by a decrease in gamma-ray and density log values and an increase in sonic velocities.

In the reference well 6706/11-1, the upper boundary is marked by an abrupt shift and marked decrease in gamma-ray values, presumably in response to rapid abandonment of the sand system.

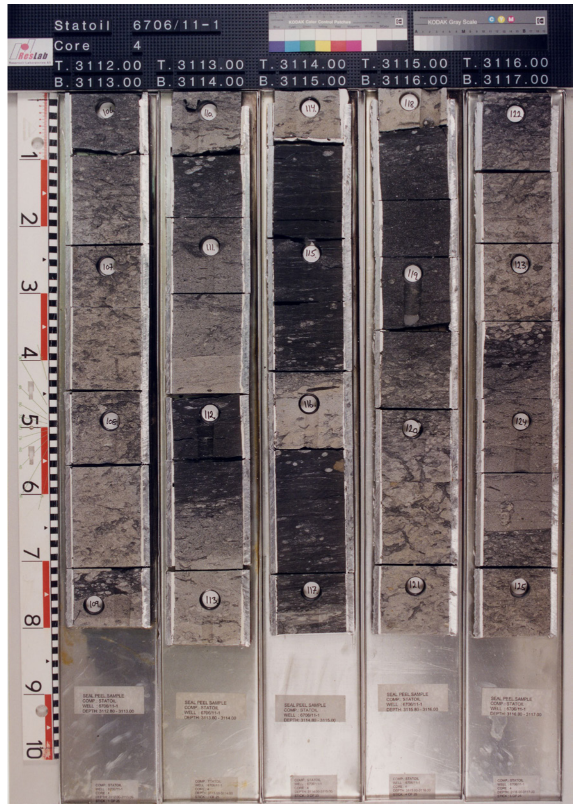
Lower boundary

The base of the Tumler Member is normally marked by a sharp downward change from sandstones to mudstones of the underlying Kvitnos Formation. In the type well 6707/10-1, it is defined on logs by a sharp downward increase in gamma-ray values, a decrease in sonic velocity and a sharp positive separation between neutron and density logs.

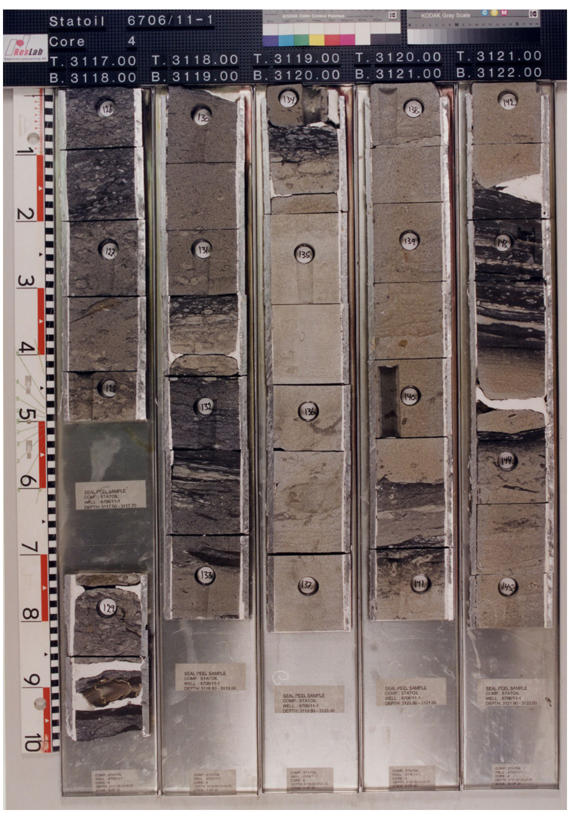
Well log characteristics

In the type well 6707/10-1, the Tumler Member is characterised by at least three discrete sandstone

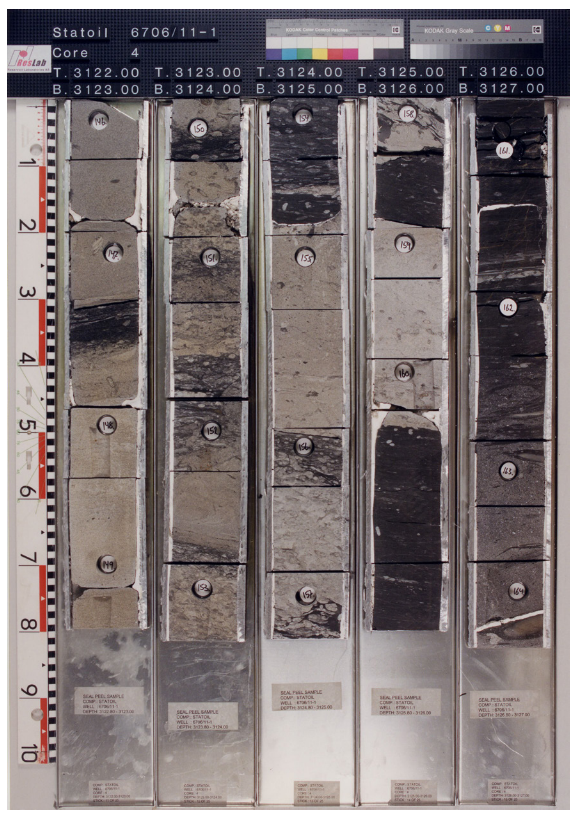
CP27. Core 3, 3107-3112m, Tumler Mb, reference well 6706/11-1.



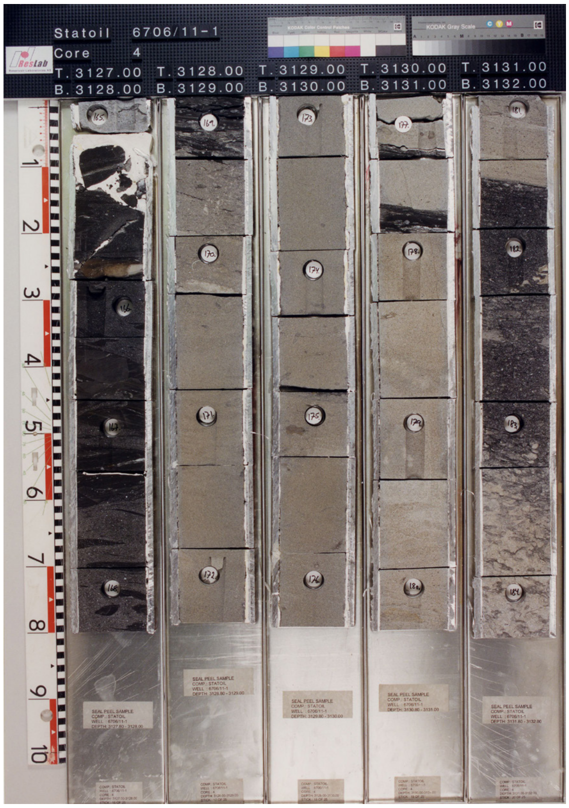
CP28. Core 4, 3112-3117m, Tumler Mb, reference well 6706/11-1.



CP29. Core 4, 3117-3122m, Tumler Mb, reference well 6706/11-1.



CP30. Core 4, 3122-3127m, Tumler Mb, reference well 6706/11-1.



CP31. Core 4, 3127-3232m, Tumler Mb, reference well 6706/11-1.

units with blocky log profiles. The sandstone beds vary from approximately 5 - 15 m thickness. The mudstones generally form thin interbeds with the sandstones or more infrequently as discrete units with minor sandstone interbeds up to 15 m thick. In the reference well 6706/11-1, the Tumler Member is mud-prone and characterised by a more finely serrate gamma-ray log profile although sandstone beds are more significant in the uppermost part.

Biostratigraphy

The Tumler Member lies within the Santonian stage, being above the dinocyst markers LCO *Heterosphaeridium difficile* and LCO *Chatangiella 'spinosa'.*

The upper boundary is developed below the LO *Spongodinium cristatum*. Planktonic foraminifera are generally absent in this member although the Santonian marker *Whiteinella baltica* is present in the overlying mudstones in association with the calcareous benthonic foraminifera *Gavelinella-Eponides* spp. and radiolarians. Probable reworking of early Santonian (or older) palynomorphs in association with recycled Cenomanian taxa was recorded in the reference well 6706/11-1.

Age

Late Cretaceous, middle – late Santonian. The Santonian Tumler Member can be distinguished from the overlying Campanian-aged Spekkhogger Member by a thick (approx. 100 m) mudstone unit with radiolarians, e.g. in well 6706/11-1.

Correlation

The sandstones of the Tumler Member pass laterally into mudstones of the Kvitnos Formation. The Tumler Member is part of the K85 sequence of Vergara *et al.* (2001, and within the upper part of the K60 sequence of Færseth and Lien (2002) and Lien (2005).

Depositional environment

In the type well 6707/10-1, core #10 was taken within the Tumler Member as part of the extensive coring programme undertaken of the overlying Spekkhogger Member; the results were documented by Kittilsen *et al.* (1999). These authors describe the whole sedimentary package collectively as being deposited mainly

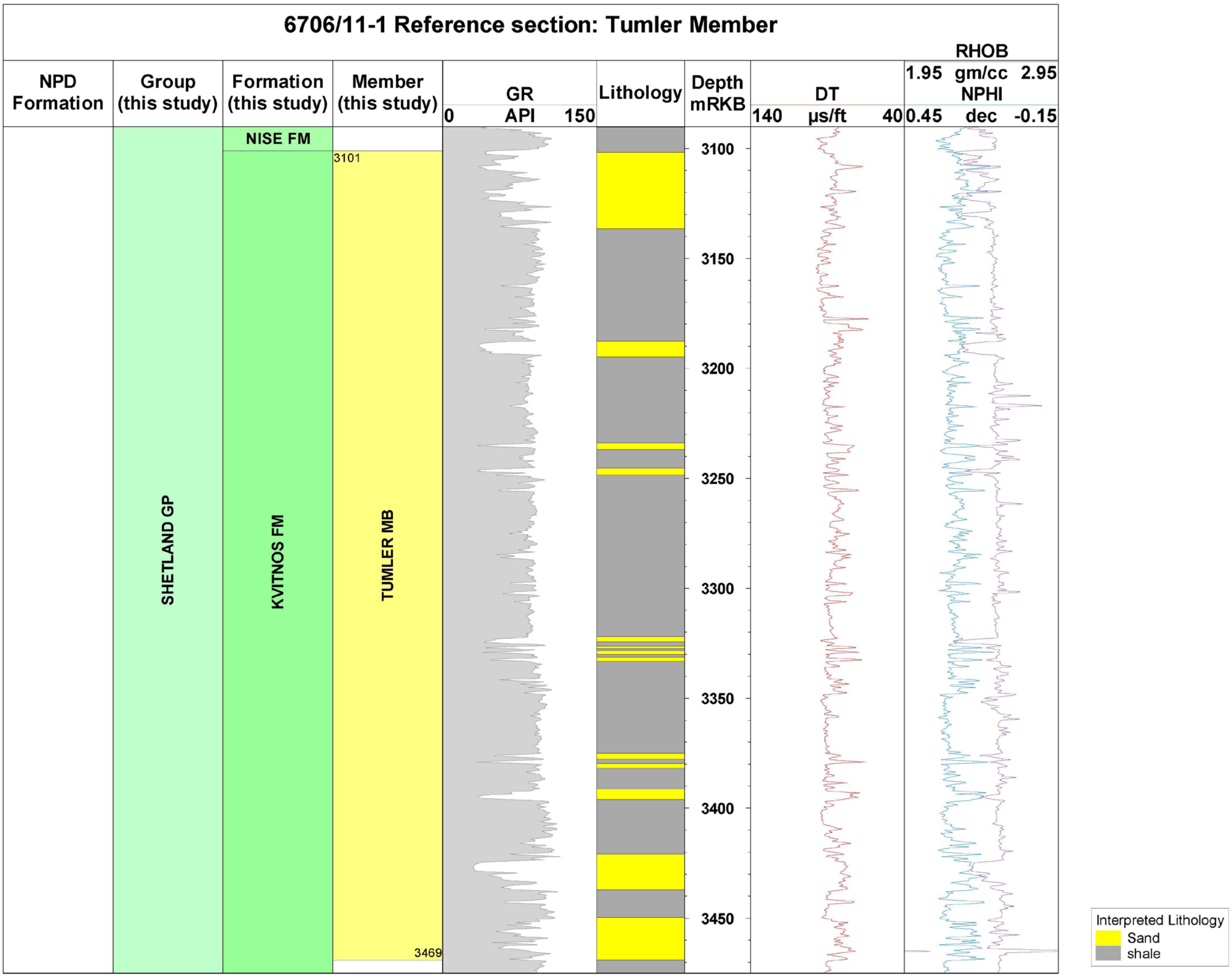


Figure 3.30. Well logs and lithology section for the Tumler Member of the Kvitnos Formation in reference well 6706/11-1.

by episodic high density turbidity currents or by linked debris flows, which evolved from the tails of the turbidite flows within a large scale submarine fan complex. Although not specific to any particular cored interval, Kittilsen *et al.* (1999) observed that there was little evidence of erosion of the turbidite sandstones into the background mudstones, suggesting the turbidite flows were largely unconstrained in this part of the submarine fan, and predicted them to occur as laterally extensive 'sheet sands'.

The subordinate, sand laminated mudstones and bioturbated background mudstones were considered to be of turbidity or hemipelagic origin. These mudstones in core yield a low diversity, deep water agglutinated foraminifera micro fauna (DWAF): The assemblage is dominated by simple tubular forms, and suggests a deep marine, bathyal paleoenvironment with poorly oxygenated bottom conditions.

Nise Formation

Shetland Group

Introduction

The term Nise Formation was introduced by Dalland *et al.* (1988) for a thick unit of predominantly non-calcareous marine mudstones between the Kvitnos and Springar Formations. It is typical for the Norwegian Sea region.

Two new sandstone members are defined within this formation: the Spekkhogger Member, an interval of thick sandstones found in the Vøring Basin, and the Nebbhval Member, a unit with a similar stratigraphic age developed in the Vestfjorden Basin. The age of the sands is Campanian. The new assignment and proper description of these siliciclastic reservoir units ends considerable stratigraphic and nomenclatorial confusion, and wrong application of the formation concept, in well completion reports and on the NPD 'Facta siden'.

Name

English/ Norwegian and any previous names: None.

Derivatio nominis: The name Nise comes from the Norwegian for the harbour porpoise species *Phocoena phocoena*. This is a small, widespread, toothed whale (up to 2 m long) found in both temperate coastal waters in the North Atlantic and colder latitudes of the North Sea, Norwegian Sea and westerly parts of the Barents Sea.

Lithology

The Nise Formation mainly consists of mudstones with subordinate siltstones, sandstones and occasional carbonate stringers.

The *mudstones* are light - medium grey, occasionally green-grey or brown-grey, predominantly soft, plastic, occasionally blocky-firm, non to weakly calcareous, silty or occasionally sandy, and occasional grade to siltstone.

The *siltstones* are argillaceous, soft-firm, friable to loose with pyrite and glauconite.

The *sandstone* interbeds are light brown, very fine to fine, occasionally medium or coarse, clear quartz, sub- angular to sub-rounded grains, moderate to well sorted, predominantly loose, occasionally calcite cemented with glauconite, mica and pyrite.

The *limestone stringers* are white-grey, soft, occasionally argillaceous, micritic and occasionally sandy and the subordinate dolomite stringers are orange brown to light brown and firm to hard.

Sample depository

Palynological preparations (organic matter depository)

Type well 6506/12-4: Seventeen slides (dc and 2 swc) from samples covering the interval 2381 m dc - 2599 m (Stratlab preparations), available at the Norwegian Petroleum Directorate.

Reference well 6506/12-1: Thirty-five slides (dc and 1 swc at 2582 m) from samples covering the interval 2450 - 2645 m (Stratlab, RRI and NPD preparations) available at the Norwegian Petroleum Directorate.

Core photographs

No cores were taken in the Nise Formation in either the designated type 6506/12-4, or reference 6506/12-1 wells.

Thickness

The Nise Formation has a thickness range of 5.5 - 1041 m. An interactive regional isochore map of the Nise Formation thickness in the Norwegian Sea may be found under Nise Formation on the Norlex website.

Geographical distribution

The Nise Formation is widely distributed in the Norwegian Sea area, notably in the Vøring Basin e.g. 6706/11-1, and on the Halten Dønna Terrace. Depo-centres are associated with the sandstones of the Spekkhogger Member in wells within the Vøring Basin, e.g. 6707/10-1, where the formation is typically more than 1000 m thick.

The formation is either thin or absent along parts of the the Nordland Ridge, or on local highs e.g. 6507/8-5 (5.5 m thick). A truncated Nise unit is located on the Omega Horst, Sør High. The Nise Formation is typically 100 - 200 m thick in wells on the Halten – Dønna Terrace areas, and more thinly developed on the Trøndelags Platform. On the Norlex website under Nise Formation a button is located to obtain occurrence of formation tops in wells.

Type well

Well name: 6506/12-4 (Figure 3.31)
WGS84 coordinates: N 65°12'46.97", E 06°43'30.37"
UTM coordinates: 7234298.14 N 393591.29 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 13.08.1985
Status: P & A
Interval of type section and thickness in type well: 2600 m to 2380 m and 220 m thickness.

Reference well

Well name: 6506/12-1 (Figure 3.32)
WGS84 coordinates: N 65°10'07.58", E 06°43'44.07"
UTM coordinates: 7229359.52 N 393591.68 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 06.02.1985
Status: P & A
Interval of type section and thickness in type well: 2658 - 244 m, 21 m thickness.

Upper and lower boundaries

Upper boundary

The top of the Nise Formation and boundary with the overlying Springar Formation is usually defined by a prominent downward increase in sonic velocity (Figure 3.31). There is a minor associated increase in density, but typically no gamma-ray response at this level.

Lower boundary

The base of the Nise Formation with that of the underlying Kvitnos Formation is considered to reflect a down section increase in the calcareous nature of the mudstones. This is normally marked on logs by a downward increase in sonic velocity and density values (Figure 3.32). There is no apparent associated response on gamma-ray logs.

Well log characteristics

In mudstone dominated intervals of the Halten and Dønna Terrace areas, the stepwise shift in average sonic velocity values allows the Kvitnos, Nise and Springar Formations to be distinguished relatively easily. These trends probably reflect compaction trends within broad, marine mudstones depositional units. The boundaries may reflect periods of still-stand or regionally transgressive events, since the formation boundaries appear to be broadly synchronous within the region.

Within these mudstone dominated intervals on the margins of the Vøring Basin, there also is a subtle upward decrease in average gamma ray values near the base of the Nise Formation. The latter may reflects deposition of sandstone into the basin. Towards the top of the formation, but not coincident with the velocity change defining the upper boundary, is an increase in gamma-ray values e.g. in well 6506/12-1 at 2475 m, that probably reflects the decrease in basinward sandstone deposition. This appears to occur close to the local lower /middle Campanian boundary. A prominent high gamma ray spike within the formation is identified as a regionally correlatable tuff horizon, e.g. in well 6506/12-1 at 2542 m.

Biostratigraphy

Biostratigraphic data is generally poor in the type well 6506/12-4. However, the base of the Nise Formation appears to be close to the Santonian/Campanian boundary, being closely associated with the (down-section) influx of the planktonic bivalve *Inoceramus* typical of a Santonian age (Zone NCF15 of this study). This influx is probably related to the downward development of more calcareous mudstones. Support is provided by the earliest Campanian dinocyst marker LO *Spongodinium 'cristatum'* in the basal part of the formation.

The upper boundary of this formation appears to be in Zones NCF 16 and 17, close to the early/middle Campanian boundary being between between the dinocyst markers LO *Callaiosphaeridium asymetricum* and LAO *Trithyrodinium suspectum.* The top abundant record (LAO) *Trithyrodinium suspectum* is a key marker near the top of the Nise Formation.

Age

Late Cretaceous, latest Santonian – middle Campanian (revised this study). Dalland *et al.* (1988) assigned a broader Santonian – Campanian age range.

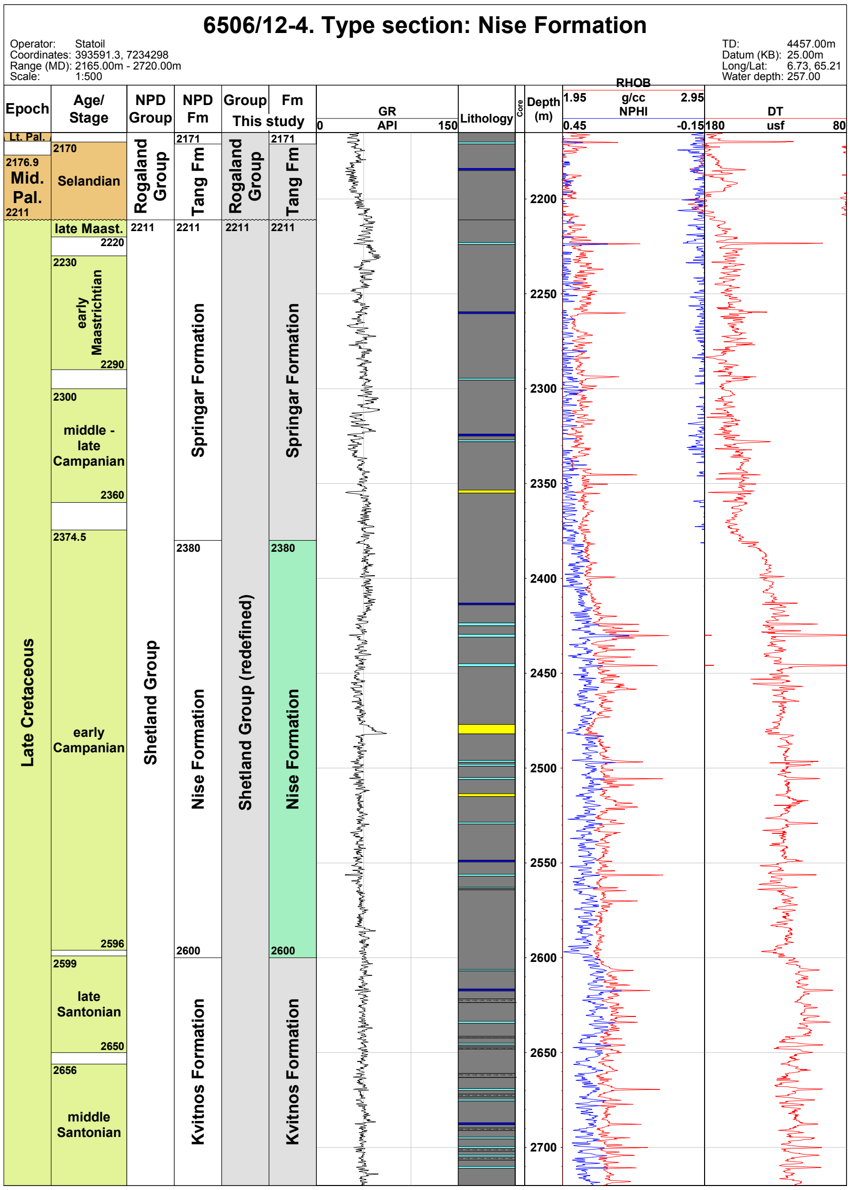


Figure 3.31. Well logs and lithology section for the Nise Formation in type well 6506/12-4, Norwegian Sea.

Correlation

The Nise Formation is laterally equivalent to the Kyrre Formation developed in the Shetland Group of the northern North Sea and Magne Formation (formerly upper Hod formation) of the North Sea Chalk Group.

Depositional environment

The Nise Formation was generally deposited in a deep, bathyal paleoenvironment under restricted water circulation, developed in response to a deep but narrow seaway between Norway and Greenland, connecting the area to the Atlantic oceanic realm (Gradstein *et al.,* 1999).

Deeper water, non-calcareous agglutinated Foraminifera (DWAF) dominate the microfossil assemblage, with a composition similar to correlative assemblages in the North Atlantic. Diatoms are abundant at certain levels; all shells are pyritized, as would be expected at this burial depth.

Remarks

The Nise Formation represents deposition within the upper part of K4 sequence of Swiecicki *et al.* (1998), K85 and K90 of Vergara *et al.* (2001), and the K70 sequence of Færseth and Lien (2002).

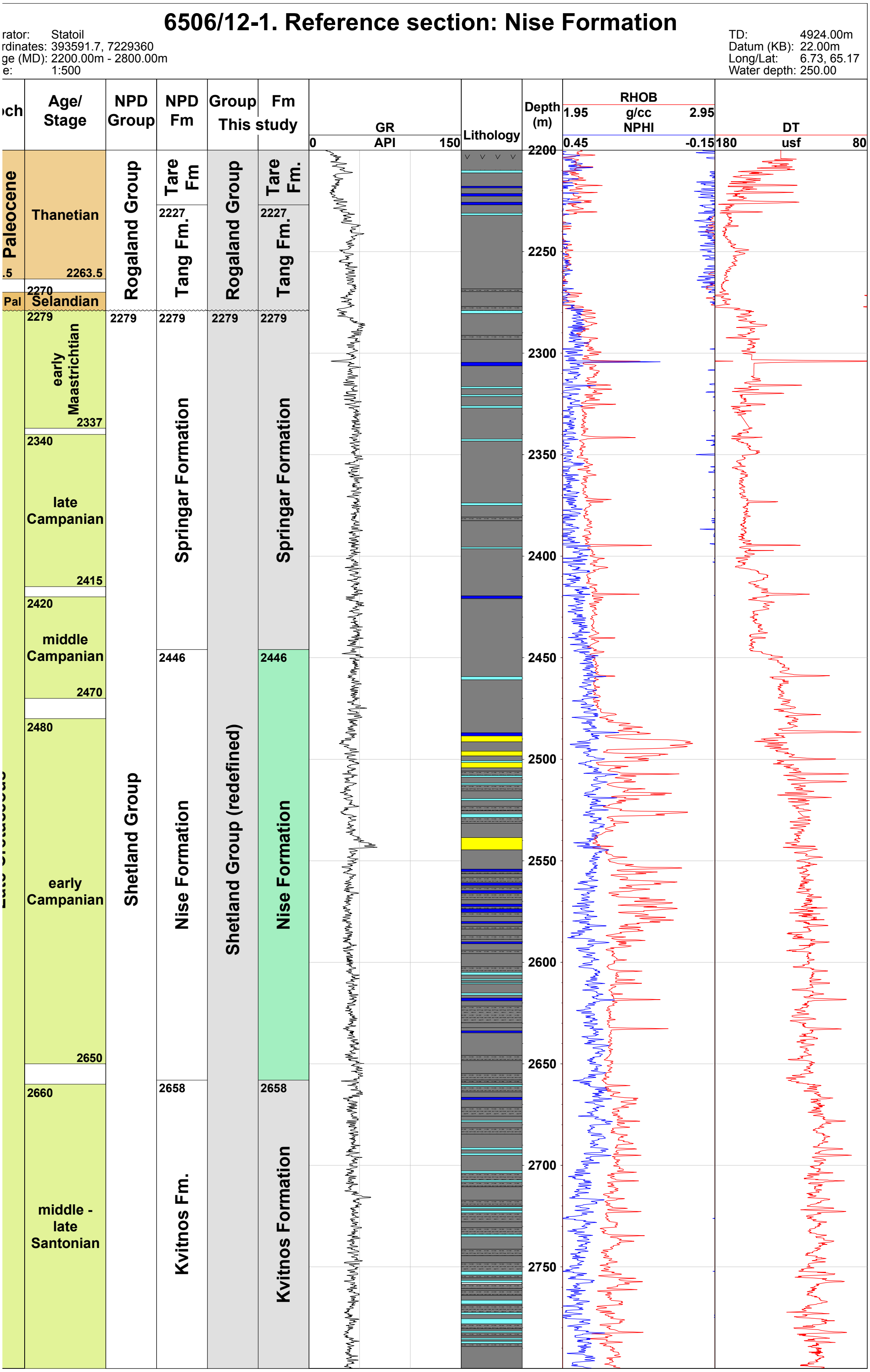


Figure 3.32. Well logs and lithology section for the Nise Formation in reference well 6506/12-1, Norwegian Sea.

Spekkhogger Member [new]

Shetland Group, Nise Formation

Introduction

The Spekkhogger Member is a new member of the Nise Formation. It is a thick (over 800 m) sandstone dominated succession of Late Cretaceous, early Campanian age developed in the Vøring Basin.

The Spekkhogger Member, together with the underlying Tumler Member were targeted by the first exploration well to be drilled in the deep water Vøring Basin, the Nyk High well 6707/10-1 (Kittilsen *et al.,* 1999). Excellent quality sandstone reservoirs were recovered over 1000 m thick, containing a 156 m thick column of dry, thermogenic gas.

The major input of siliciclastic sediments is considered to have been derived from sources to the north or north-west, towards Greenland, based on heavy mineral analysis. A minor provenance input is from the north-east, linked to the initial phase of Campanian-Paleocene rifting in the Norwegian Sea, prior to initiation of seafloor spreading.

Name

English/ Norwegian and any previous names: In the type well 6707/10-1, the Spekkhogger Member was originally and correctly identified by the operator BP Norway as a sandstone unit within the Nise Formation. It is equivalent in part (together with the Tumler Member) to the informal 'Utgard sandstone' of Swiecicki *et al.* (1998), and the upper part (only) of the informal Delfin Formation on the fact pages of the NPD. The fact pages of NPD list two Delphin units separated by Nise Formation; this is not a correct form of lithostratigraphy and violates the stratigraphic code.

Derivatio nominis: Spekkhogger is the Norwegian name for the killer whale species *Orcinus orca*. This is appropriately the largest species of the oceanic dolphin family (Delphinidae) reaching up to 9 m in length and 6-8 metric tons in weight. The species is widespread in the North Atlantic and can been seen along the Norwegian coast. The most famous individual being, of course, Keiko whose final home was in the bays off Halsa in Møre and Romsdal, mid Norway.

Lithology

The Spekkhogger Member consists of thick sandstones with subordinate mudstone interbeds and rare dolomitic limestone stringers.

The *sandstones* are light to medium grey, light olive grey, brownish grey and pale yellow brown, transparent to translucent quartz grains, locally colourless to pale grey, rarely pale orange, very fine to medium, predominantly fine to medium, locally coarse, sub--angular to sub-rounded, occasionally sub-elongate to sub-sphaerical, moderate to well sorted, generally loose, occasionally firm, friable, weak silica or dolomitic/calcareous cement, locally argillaceous matrix, occasional kaolinitic matrix, silty, micaceous, occasionally disseminated pyrite, common to abundant glauconite, fine carbonaceous material, fair to good visible porosity.

The *mudstones* are medium light grey to dark olive grey, with occasional black streaks and speckles, soft to firm, amorphous to sub-blocky, plastic to crumbly, slightly silty in places or fine sand, trace disseminated pyrite, micro-carbonaceous, micro-micaceous, occasionally glauconitic, non-calcareous or slightly dolomitic in part.

The rare *dolomitic limestone* stringers are buff to off white or light grey-light yellow, soft to firm, occasionally hard to very hard, sub-blocky to blocky, crumbly to angular, occasionally glauconitic, occasionally grading to sandy limestones, microcrystalline.

Sample depository

Palynological preparations (organic matter depository)

Type well 6710/10-1: 44 slides from core samples covering the interval 2978.7 - 3145.54m available at the NPD (NPD preparations).
Reference well 6704/12-1: 5 slides from sidewall core samples covering the interval 3698 - 3904 m available at the NPD (RRI preparations).

Cores

Type well 6707/10-1: core #1 to core #9: 2967 m MD RKB – 3145 m MD RKB
Reference well 6704/12-1: no core taken in this member.

Core photographs

During the drilling of the Nyk High 6707/10-1 gas discovery well, 10 cores totally 206 m in thickness were cut with excellent recovery (Kittilsen *et al.*,1999). With the exception of core #10 that was cut in the underlying Tumler member (new), all other cores were cut in the upper part of the Spekkhogger Member, or 10m in the overlying mudstones of the surrounding Nise Formation.

Core photographs CP 37-48 from the images of all cores under Spekkhogger Member on *www.nhm2.uio.no|norlex* have been selected to give a suitable visual overview of the massive sand interval, with overlying laminated mudstones of the Nise Formation.

Thickness

The Spekkhogger Member varies in thickness from 140 m, e.g. in well 6607/5-2 to 833 m, e.g. in well 6707/10-1, based on released well data.

Geographical distribution

Sandstones of the Campanian Spekkhogger Member are geographically restricted to the Vøring Basin based on released well data. The depositional centre axis is close to the Nyk High well 6707/10-1, where the unit attains an enormous 833 m thickness. The Spekkhogger Member decreases significantly in thickness both to the west e.g. in well 6704/12-1 (321.5 m) and south-east e.g. in well 6607/5-2 (140 m), away from the main depositional fairway (Transect Figure 3.33).

Vergara *et al.* (2001) inferred that sandstones in their equivalent K85 -K90 sequence covered a large area of the (northern) Vøring Basin based on seismic interpretation and favoured a source from the north and north-east. Morton and Grant (1988) proposed a source from the north or north-west based on provenance studies on sandstones from the Utgard High well.

Time equivalent mudstones of the Nise Formation are developed in well 6605/8-1 and define a southerly limit of the member based on the available well coverage.

The seemingly two-fold division of the Spekkhogger Member in the 6607/5-2 maybe due to sand injection, associated with a volcanic intrusion ?

On the Norlex website at *www.nhm2.uio.no|norlex* under the link to Spekhogger Member, is a button to obtain occurrences of member tops in wells.

Type well

Well name: 6707/10-1
WGS84 coordinates: N 67°04'07.85", E 07°00'36.51"
UTM coordinates: 7440629.70 N 413490.42 E
UTM zone: 32
Drilling operator name: BP Norway Ltd.
Completion date: 23.07.1997
Status: P & A
Interval of type section and thickness in type well: 3810 - 2977 m (2977.4 m core depth) and 833 m thickness.

Reference well

Well name: 6704/12-1
WGS84 coordinates: N 67°07'25.00", E 04°42'44.70"
UTM coordinates: 7446374.14 N 574282.36 E
UTM zone: 31
Drilling operator name: Saga Petroleum
Completion date: 24.07.1999
Status: P & A
Interval of type section and thickness in type well: 3968 - 3646.5 m and 321.5 m thickness.

Upper and lower boundaries

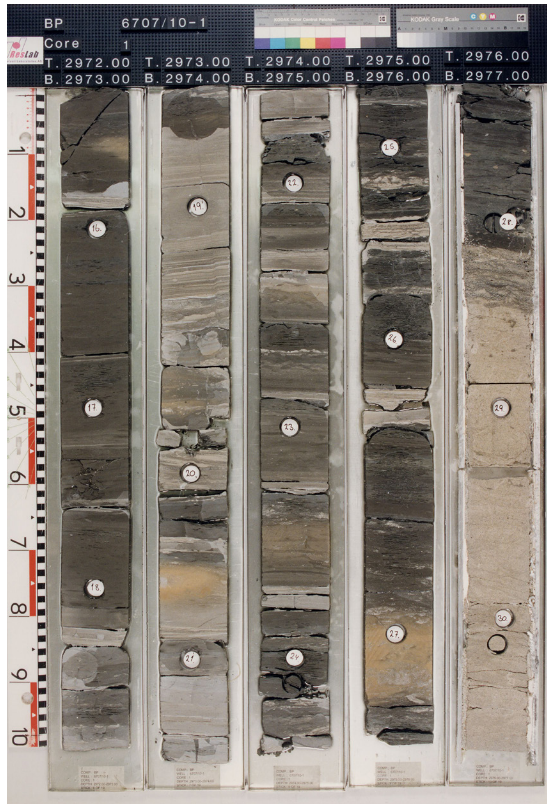
Upper boundary

In the type well 6707/10-1 (Figures 3.33 and 3.34), the top of the Spekkhogger Member is defined in core #1 at 2977.4 m (uncorrected depth) at the top of the sandstone-rich section. This is associated with a sharp downward decrease in both gamma-ray and sonic velocity values at 2977 m MD. This does not coincide with the top of the first thin sandstone bed which occurs higher in the section at 2957 m MD within a predominantly mudstone interval assigned to the Nise Formation.

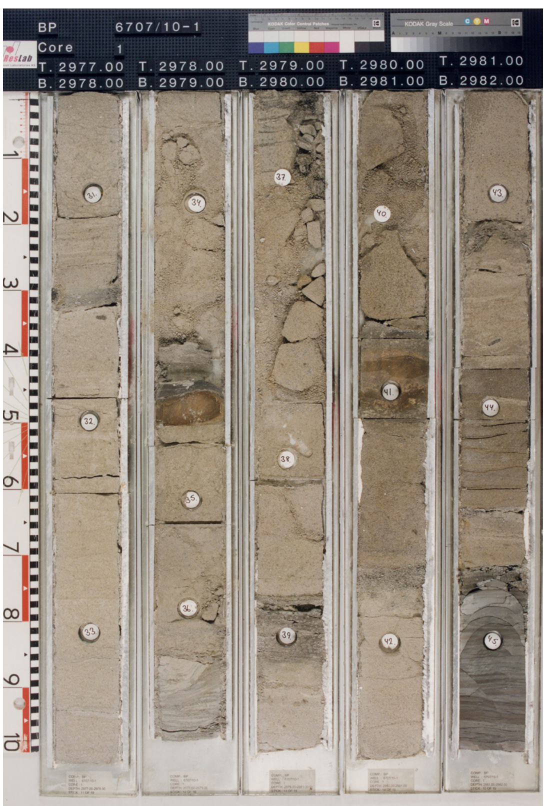
Lower boundary

The base of the Spekkhogger Member is well defined on logs and marked by downward change from sandstones to mudstones of the Nise Formation. On wireline logs it coincides to a down section increase in gamma-ray and decrease in sonic log values. In the type well 6707/10-1 (Figure 3.34), the base is marked by a downward positive separation in neutron and density logs.

CP37. Core 1, 2967-2972m, Spekkhogger Mb, type well 6707/10-1.



CP38. Core 1, 2972-2977m, Spekkhogger Mb, type well 6707/10-1.

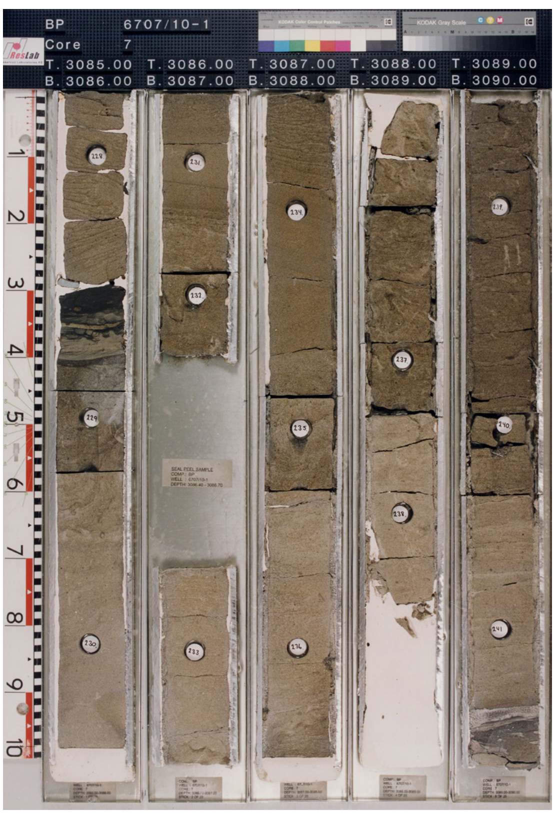


CP39. Core 1, 2977-2982m, Spekkhogger Mb, type well 6707/10-1.

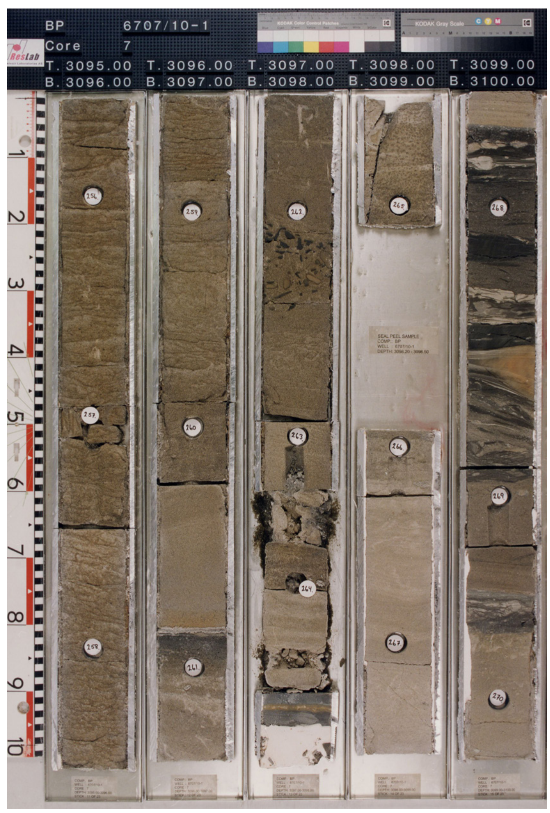
CP40. Core 3, 3017-3022m, Spekkhogger Mb, type well 6707/10-1.

CP41. Core 3, 3022-3027m, Spekkhogger Mb, type well 6707/10-1.

CP42. Core 4, 3030-3035m, Spekkhogger Mb, type well 6707/10-1.

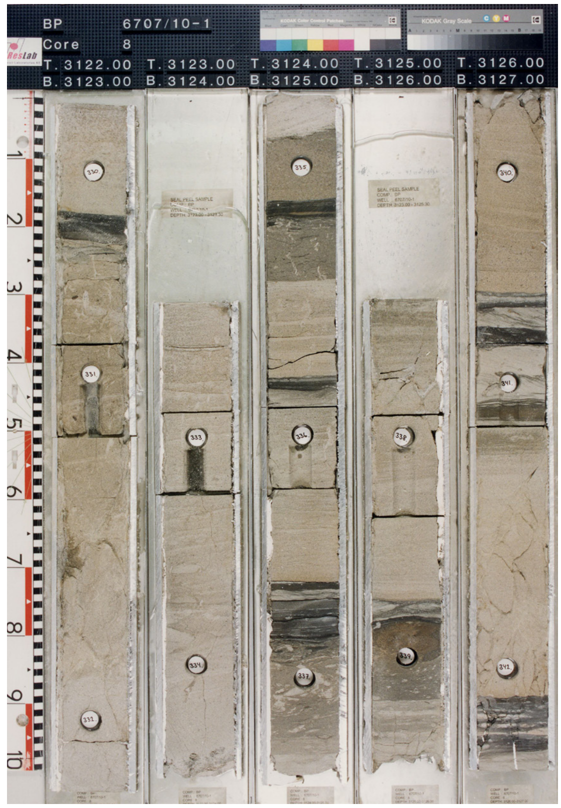


CP43. Core 7, 3085-3090m, Spekkhogger Mb, type well 6707/10-1.



CP44. Core 7, 3095-3100m, Spekkhogger Mb, type well 6707/10-1.

CP45. Core 8, 3117-3122m, Spekkhogger Mb, type well 6707/10-1.



CP46. Core 8, 3122-3127m, Spekkhogger Mb, type well 6707/10-1.

CP47. Core 9, 3132-3137m, Spekkhogger Mb, type well 6707/10-1.

CP48. Core 9, 3137-3142m, Spekkhogger Mb, type well 6707/10-1.

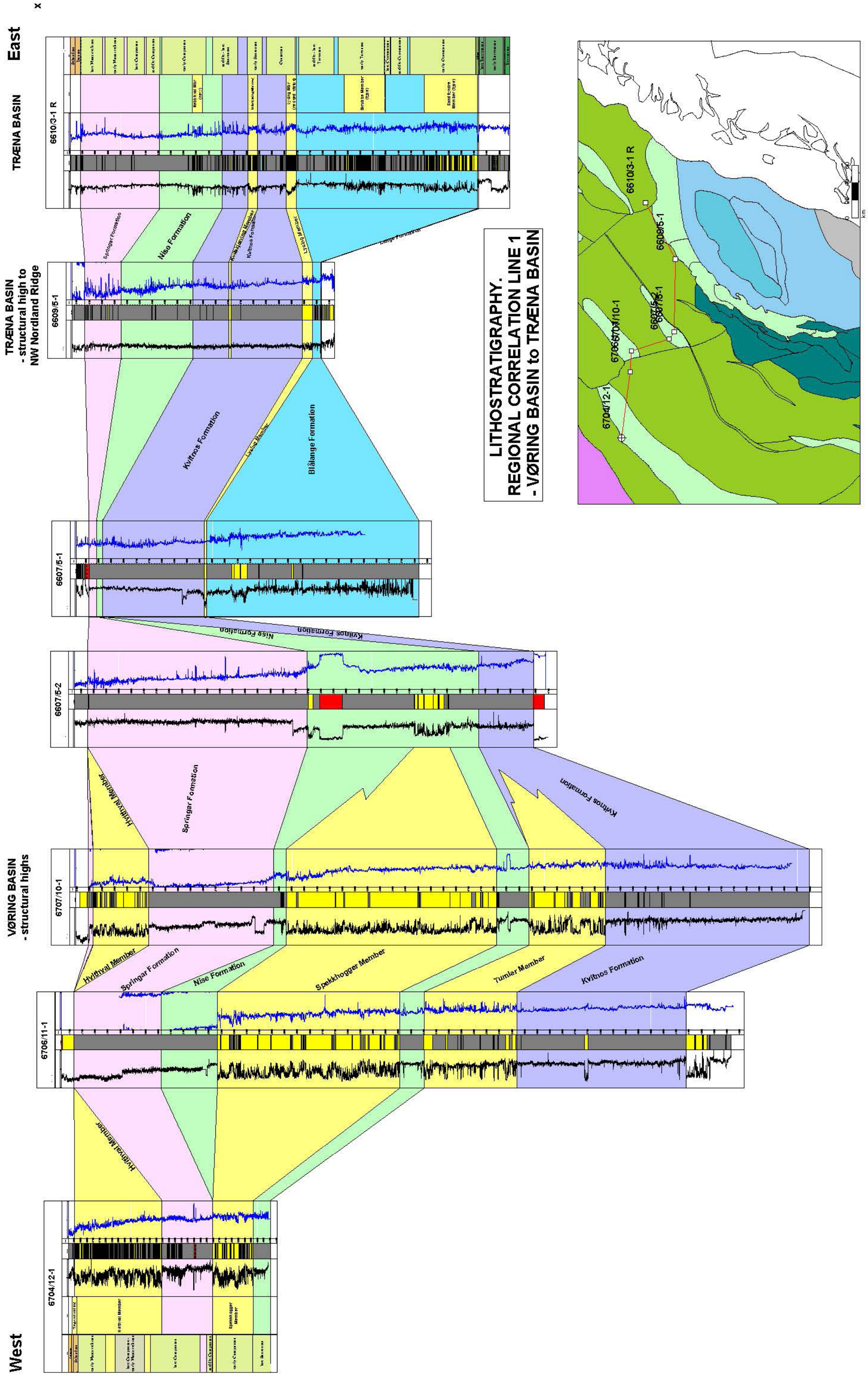


Figure 3.33. Regional transect of Upper Cretaceous lithologic units from the Vøring Basin to the Træna Basin, with typical Spekkhogger and Tumler Members outlined in the wells.

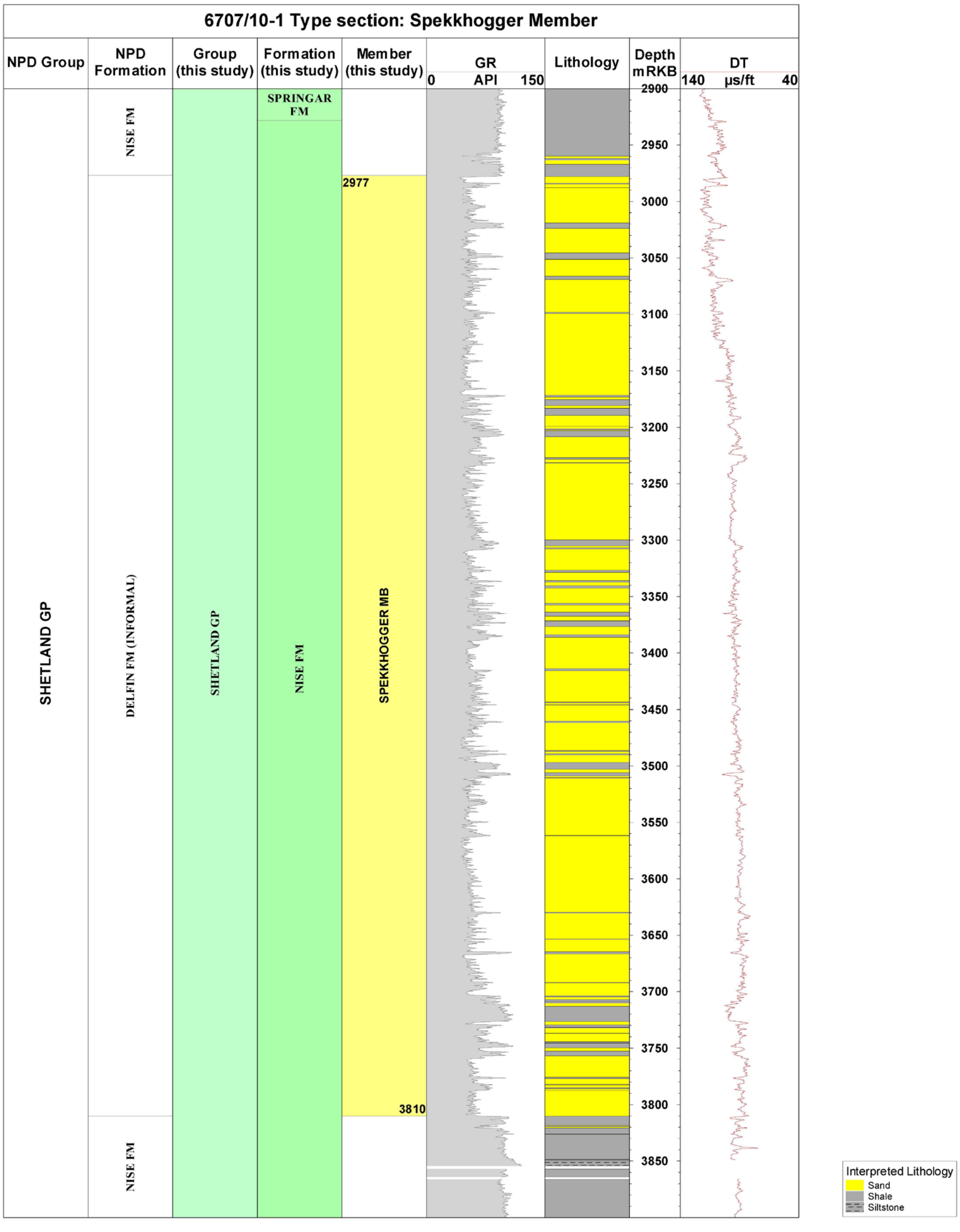


Figure 3.34. Well logs and lithology section for the Spekkhogger Member of the Nise Formation in type well 6707/10-1, Norwegian Sea.

Well log characteristics

In the type well 6707/10-1 (Figure 3.34), the thick and sandstone dominated Spekkhogger Member is characterised by a series of serrated, blocky or funnel-shaped gamma-ray log profiles that reflect a series of thickening and sandier upward cycles. In the lower part of the cored interval (cores #6 to 9), there are a series of cycles where the sandstone beds become progressively thinner upwards, but these trends are generally not distinguishable on gamma-ray logs due to the frequency of glauconite. Overall there is little variation throughout the interval of the member. Thick mudstone dominated intervals (Core Photograph CP 41) are infrequent. There is a relatively abrupt decrease in average sonic velocities and density values within the upper part of the member above 3130 m MD RKB. Density values are also generally more irregular above this depth.

Biostratigraphy

The upper boundary of the Spekkhogger Member lies below the LO *Callaiosphaeridium asymmetricum*.

The Campanian dinocyst marker LCO *Trithyrodinium suspectum* is developed within the upper part of the member. The upper boundary in the type well is associated with a down- section increase in pyritised diatoms, notably LO *Fenestrella bellii*. These taxa indicate that the Spekhogger Member maybe assigned to our micropaleo zones NCF16 and lower part of NCF17, lower to lower part of middle Campanian. The base of the Spekkhogger Member lies close, but generally below the dinoflagellate cyst LO *Spongodinium 'cristatum'* (earliest Campanian – latest Santonian age) and above the LO *Valensiella reticulata* (late Santonian). Planktonic foraminifera are absent throughout this member but in the underlying mudstone (developed between the Tumler and Spekkhogger Members) are the rare LO *Whiteinella baltica* (Santonian), an increase in calcareous benthonic foraminifera with *Gavelinella - Eponides* spp. and diatoms that forms a regional correlative marker.

Age

Late Cretaceous, early – early part of middle Campanian.

The lower boundary of the Spekkhogger Member (and Nise Formation) appears to be close to the Santonian/ Campanian boundary. The Spekkhogger Member is predominantly early Campanian in age. This age interpretation is consistent with the original interpretation of the type well 6707/10-1 published by Kittilsen *et al.* (1999).

Correlation

Sandstones of the Spekkhogger Member under- and overlie and pass laterally into mudstones of the Nise Formation. Figure 3.33 is a transect of the Spekkhogger Member through wells in the deep Vøring Basin. The figure clearly shows that the Nise Formation is more or less embracing this member sand unit.

The member is part of the K85- K90 sequences of Vergara *et al.* (2001), K70 sequence of Færseth and Lien (2002) and Lien (2005) and the K80 sequence of Fugelli and Olsen (2005a) and represents the main input of clastic sediments into the Vøring Basin during the initial phases of the Campanian- Paleocene rift episode associated with the continental separation of the North Atlantic region and the Norwegian Sea (Færseth and Lien, 2002) and the development of the 'Cretaceous seaway' between the Norway and Greenland (Gradstein *et al.* 1999).

Depositional environment

The upper part of the Spekkhogger Member is extensively cored in the type well 6707/10-1 well (see Core Photographs CP 37-48). Kittilsen *et al.* (1999) describe the strata as being predominantly composed of a trendless stack of poorly amalgamated, metre scale, clean, fine grained sandstone beds that commonly show fining upward cycles. The authors interpreted the sands episodic, high density turbidity currents, within a large scale submarine fan complex. In addition, there are classical, thinly bedded turbidites with Bouma-type sequences (Ta-c) with ripple laminated intervals in the upper part.

The authors noted that many of the turbidite beds pass upwards into "clay-prone, mud clast-rich caps" often associated with an increase in carbonaceous material and interpreted these as linked debris flows which evolved from the tails of the turbidite flows.

The debris flows are overlain by sand laminated mudstones and bioturbated 'background' mudstones of both turbiditic or hemipelagic origin. These 'background' mudstones contain deep water agglutinated foraminifera (DWAF) that suggests a bathyal environment, with sub-oxic bottom conditions well below wave base.

Kittilsen *et al.* (1999) also observed that there was little evidence of erosion of the turbidite sandstones into the 'background' mudstones, suggesting the turbidite flows were largely unconstrained in this part of the submarine fan, and predicted them to occur as laterally extensive.

On a more regional scale, Vergara *et al.* (2001) described the geometry and distribution of these sandstones within their sequences K85-K90. They inferred from seismic that large areas of the Vøring Basin were covered by turbidites sourced from multiple entry points. They indicated that the sandstones in well 6707/10-1 were close to the main depositional centre or fairway, and favoured a source from the north or towards the northeast, in contrast to Morton and Grant (1998), who, in an earlier provenance study, described the sandstones from the Utgard High well as 'K2 type sandstones' with a provenance from the north or northwest.

Nebbhval Member [new]

Shetland Group, Nise Formation

Introduction

The Nebbhval Member is a local member of the Nise Formation characterised by sandstones and interbedded mudstones developed in the south-western part of the Vestfjorden Basin.

Timing suggests that the Nebbhval Member is related to the same tectonic episode that introduced the thick Spekkhogger Member sandstones into the deeper Vøring Basin. This has been attributed to the initial phase of Campanian-Paleocene rifting that led to the continental separation between the North Atlantic and the Norwegian Sea.

Whereas the sandstones of the Spekkhogger Member are considered to have been derived from the north or northeast, the sandstones of the Nebbhval Member are probably derived from the Norwegian mainland. The Nebbhval sands have been assigned to Zone NCF16, dated as Late Cretaceous, earliest Campanian age.

Name

English/ Norwegian and any previous names: In the type well 6610/3-1, the Nebbhval Member was noted informally as an 'intra Nise sandstone' by the operator Statoil, and is currently indicated as a unit without a formal name on the NPD fact pages.

Derivatio nominis: Nebbhval is the Norwegian name for the northern bottlenose whale species *Hyperooden ampullatus*. This is a toothed whale up to 10m size that can be found in increasing numbers in the deeper water areas of the Norwegian Sea around Iceland and Jan Mayen in addition to west of Svalbard and in the North Atlantic.

Lithology

The Nebbhval Member consists of interbedded sandstones and mudstones.

The *sandstones* are light olive grey to olive grey, clear to transparent or translucent quartz grains, fine to medium, occasionally medium or coarse to very coarse in places, moderately sorted, angular to sub-rounded, white to light grey matrix, moderate calcareous cement, friable to moderately hard, occasionally micaceous with common glauconite.

The *mudstones* are medium dark grey to olive grey, predominantly firm, moderately hard, sub-fissile to blocky, micro-micaceous, micro-pyritic, slightly or moderately calcareous and sandy or silty in parts.

Sample depository

Palynological preparations (organic matter depository)

Type well 6610/3-1: 7 slides from 6 core samples and 1 swc sample covering the interval 2293.4 - 2318 m available at the NPD (Statoil preparations).

Core photographs

Type well 6610/3-1: cores #3 to #5 covering the interval 2292 - 2313.9 m (Core Photographs CP 49-56).

Thickness

The Nebbhval Member varies in thickness from 24 m, e.g. in well 6610/3-1 (type section), to 40 m.

Geographical distribution

The Nebbhval Member is restricted to the Nordland III area, located in the south-westerly part of the Vestfjord Basin in Quadrant 6610, where it varies from 24 m to 40 m based on released well data.

Type well

Well name: 6610/3-1 (Figure 3.35)
WGS84 coordinates: N 66°55'29.70", E 10°54'06.28"
UTM coordinates: 7424470.29 N 583170.4 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s.
Completion date: 17.02.1993
Status: Suspended, re-entered later.
Interval of type section and thickness in type well: 2306 m (2309.43 m uncorrected core depth) - 2282 m, and 24 m thickness.

Reference well

None designated.

Upper and lower boundaries

Upper boundary

In the type well 6610/3-1 (Figure 3.35) the top of the

Nebbhval Member is taken at a downward change from mudstones of the Nise Formation to sandstones with interbedded mudstones. It is marked on wireline logs by a sharp downward decrease in gamma-ray values and increase in sonic velocity and resistivity values.

Lower boundary

The base of the Nebbhval Member is defined by a downward increase in gamma-ray values and an associated decrease in average resistivity values reflecting the change from sandstones to mudstones. In the type well, 6610/3-1, there is only a slight increase in average sonic velocities at 2306 m MD, and the downward increase in average density values is a few metres lower at 2313 m MD.

Well log characteristics

In the type well 6610/3-1 the log character is irregular to serrate (Figure 3.35) reflecting the heterolithic, interbedded nature of the Nebbhval Member.

Biostratigraphy

The Nebbhval Member is located between the dinocyst markers LCO *Trithyrodinium suspectum* and LO *Spongodinium 'cristatum,'* and is earliest Campanian in age.

Deeper in the section is the LO *Valensiella reticulata*. Within this member occurs an influx of *Chatangiella bondarenkoi* that maybe useful for local correlation.

Age

Late Cretaceous, earliest Campanian. The base of the Nebbhval Member lies close to the Santonian/ Campanian boundary.

Correlation

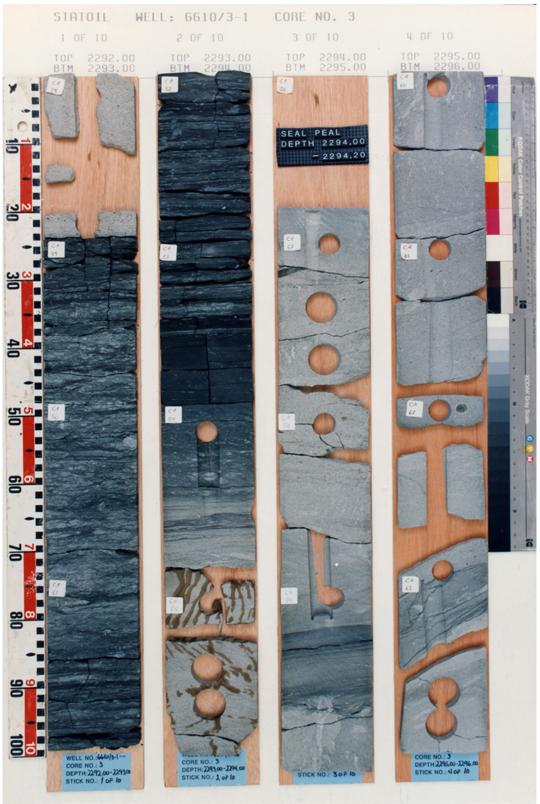
The sandstones and interbedded mudstones of the Nebbhval Member pass laterally into mudstones of the Nise Formation.

The Nebbhval Member is a time equivalent of the oldest part of the *Spekkhogger Member* developed in the Vøring Basin, and part of the K85-K90 sequence of Vergara *et al.* (2001), and K70 sequence of Færseth and Lien (2002) and Lien (2005). These sandstones were probably generated during the same Campanian rifting event associated with the Spekkhogger Member although they have a different source direction towards the Norwegian mainland.

Depositional environment

There is limited published data available on the depositional setting of the Nebbhval Member. The sandstones are interpreted as part of a sand prone slope fan, presumably with a source from the Norwegian mainland (see Figure 11 of Vergara *et al.*, 2001).

The microfaunas, recovered from cores in the type section 6610/3-1 within this member, are dominated by abundant, simple, tubular, agglutinated foraminifera e.g. *Rhabdammina* spp. This suggests a deeper water, bathyal paleoenvironment and possibly somewhat restricted bottom conditions with lower oxygen.



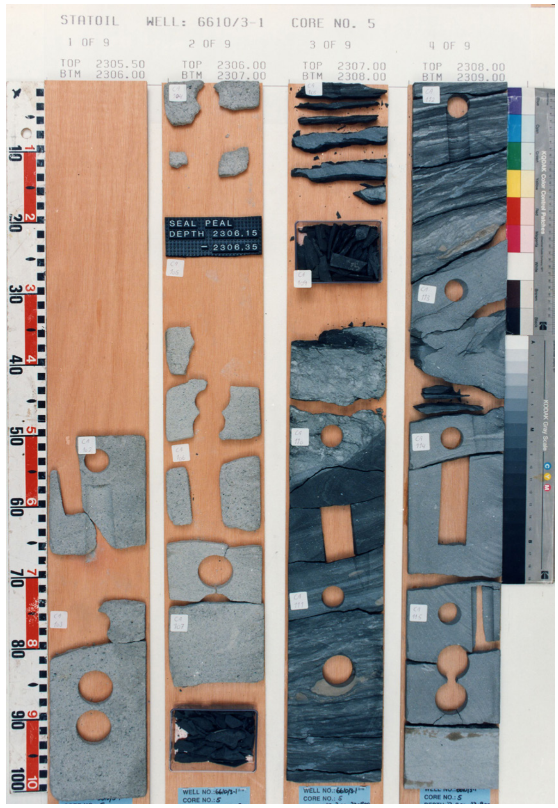
CP49. Core 3, 2292-2296m, Nebbhval Mb, type well 6610/3-1.

CP50. Core 3, 2296-2300m, Nebbhval Mb, type well 6610/3-1.

CP51. Core 3, 2300-2301m, Nebbhval Mb, type well 6610/3-1.

CP52. Core 4, 2302-2305m, Nebbhval Mb, type well 6610/3-1

CP53. Core 4, 2305-2306m, Nebbhval Mb, type well 6610/3-1.



CP54. Core 5, 2306-2309m, Nebbhval Mb, type well 6610/3-1.

CP55. Core 5, 2309-2313m, Nebbhval Mb, type well 6610/3-1.

CP56. Core 5, 2313.0-2313.9m, Nebbhval Mb, type well 6610/3-1.

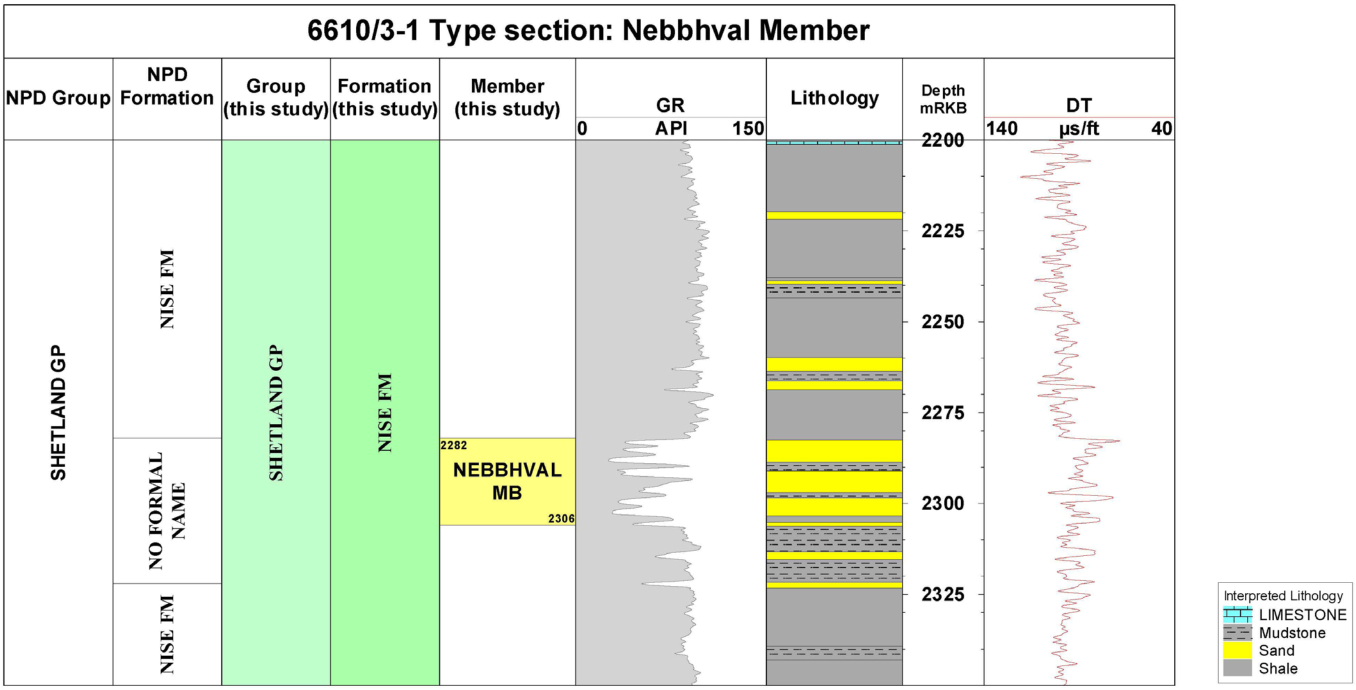


Figure 3.35. Well logs and lithology section for the Nebbhval Member of the Nise Formation in type well 6610/3-1, Norwegian Sea.

Springar Formation

Shetland Group

Introduction

The definition of the Springar Formation follows Dalland *et al.* (1988). The formation is generally a thick, widespread sequence of marine mudstones developed throughout the Norwegian Sea region.

Two new sandstone members are defined within this formation:

1. The Hvithval Member, an interval of sandstones locally found in the Vøring Basin, and assigned a Campanian-Maastrichtian age.
2. The Grindhval Member, a unit of sandstones present in the Ormen Lange Field in the Møre Basin, assigned a late Maastrichtian age.

Name

English/ Norwegian and any previous names: None

Derivatio nominis: A Norwegian collective name for small whales (Dalland *et al.*, 1988) or more accurately, a group of toothed, sea going dolphins (Delphinidae) of the genus *Lagenorhynchus* e.g. Kvitnos. It has not been possible to use names from springar-types to define the two members since the name Kvitnos is already occupied for a formation. The names of the two new members Hvithval and Grindhval are considered appropriate since these are also small to moderate sized toothed whale species.

Lithology

The formation contains predominantly mudstones, with rare limestone, dolomite and sandstone stringers. The mudstones are light grey, occasionally dark grey, grey green, and red-brown, generally soft, slightly plastic, amorphous, blocky, firm, subfissile, non- to slightly calcareous, slightly silty, occasionally micro-micaceous, with minor glauconite and pyrite. The limestones are moderately argillaceous, predominantly soft-firm, clear white, firm to hard. The dolomites are light brown, orange -brown, brown-yellow, firm to moderately hard and slightly argillaceous. The minor sandstones are light brown, grey, predominantly loose, very fine to fine quartz, moderately sorted with occasional calcareous or argillaceous cement.

Sample depository

Palynological preparations (organic matter depository)

Typ e well 6506/12-4: 11 slides (10 dc and 1 swc) from samples covering the interval 2220 m dc - 2375 m swc (Stratlab preparations) available from the Norwegian Petroleum Directorate.

Reference well 6506/12-1: 31 slides (dc and 2 swc at 2337 m and 2415 m) from samples covering the interval 2280 m - 2440 m (Stratlab, RRI and OD preparations) available from the Norwegian Petroleum Directorate.

Core photographs

No cores were taken in this formation in either the designated type well 6506/12-4, or in the reference well 6506/12-1.

Thickness

The Springar Formation ranges in thickness from 9 m - 1753 m.

The Norlex website hosts an interactive ischore map for the Springar Formation. Such map is generated from Norlex data using thin plate splines (thickness constrained to original range).

Geographical distribution

The Springar Formation is widely distributed in the Norwegian Sea region. The thickness ranges from 9 m in e.g. well 6407/7-4, where it is truncated by subsequent Paleocene erosion, to the exceptionally thick 1753 m, e.g. in well 6607/12-1. In the latter well the base of the formation was not reached at the well TD. The anomalous thickness is attributed to the well being drilled in a mini-graben-like feature, close to a fault plane on the western margin of the Dønna Terrace.

With the exception of well 6607/12-1, the greatest thicknesses are typically in the Vøring Basin where the formation contains sandstones of the Hvithval Member. In this area the formation still reaches thicknesses over 1000 m, e.g. in well 6704/12-1. On the Halten and Dønna Terrace areas, the Springar Formation is typically between 100 - 200 m in thickness, diminishing to less than 100m in the southern part of the Halten Terrace e.g. in well 6306/6-1 and around the Nordland Ridge, where it is thin or locally absent, e.g. in well 6608/11-1.

Sandstones of the Hvithval Member are geographically restricted to the Vøring Basin, and those of the Grindhval Member are locally developed in the Møre Basin.

The Norlex website has a link to find occurrences of formation (member) tops in wells.

Type well

Well name: 6506/12-4
WGS84 coordinates: N 65°12'46.97", E 06°43'30.37"
UTM coordinates: 7234298.1 N 393591.29 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 13.08.1985
Status: P & A
Interval of type section and thickness in type well: 2380 - 2211m, 169 m thickness (Figure 3.36).

Reference well

Well name: 6506/12-1
WGS84 coordinates: N 65°10'07.58", E 06°43'44.07"
UTM coordinates: 7229359.52 N 393591.68 E
UTM zone: 32
Drilling operator name: Den norske stats oljeselskap a.s. (Statoil a.s.)
Completion date: 06.02.1985
Status: P & A
Interval of type section and thickness in type well: 2446 - 2279 m, 167 m thickness (Figure 3.37).

Upper and lower boundaries

Upper boundary

The top of the Springar Formation coincides with the top of the Shetland Group, and with the Cretaceous/Paleogene boundary. The top normally coincides with stratigraphic break of varying extent, but Danian sediments are typically absent in wells in the Halten Terrace - Dønna Terrace areas. The boundary with the overlying Tang Formation is usually defined by a marked downward decrease in sonic velocity, and an increase in density values. This log feature reflects the unconformity. Limestones are generally more prominent in the Springar Formation than in the overlying Tang Formation; locally, a limestone stringer occurs at the top surface.

Lower boundary

The base of the Springar Formation, and boundary with the underlying Nise Formation is normally defined by a prominent downward increase in sonic velocity. There is typically no gamma ray response at this level but the sonic log change is generally associated with a minor increase in density.

Well log characteristics

The Springar Formation is a relatively distinct unit of mainly mudstones, characterised by a relatively uniform sonic velocity developed between the Nise and Tang Formations. The gamma-ray values are generally more variable.

Biostratigraphy

The lower boundary of the Springar Formation appears to be close to the top of the lower Campanian as defined by the dinoflagellate cyst event LAO *Trithyrodinium suspectum*. This is the key marker for the base of the Springar Formation. In stratigraphically complete sections, unaffected by erosion in response to the base Cenozoic/top Cretaceous unconformity, e.g. in Ormen Lange well 635/5-1, the upper boundary of the Springer Formation is of late Maastrichtian age and characterised by the last occurrence of planktonic foraminifera, notably LO *Rosita contusa*, LO *Abathomphalus mayaronsis*, LO *Racemiguembelina fructicosa*, LO *Globigerinelloides asper*, LO *Heterohelix* spp., and the dinocyst LO *Palynodinium grallator*.

In the area of the type and reference wells located on the western margin of the Trøndelags Platform, the top of the Springer Formation is truncated and of early Maastrichtian or intra-late Maastrichtian age, as defined by the LO *Triblastula utinensis*, LO *Odontochitina operculata* and/or *Hystrichodinium pulchrum*. The stratigraphic break with the overlying onlapping sediments of the Middle Paleocene Tang Formation is on the order of 10 m.y. in duration.

Age

Late Cretaceous, early Campanian to late Maastrichtian.

Correlation

The Springar Formation is laterally equivalent to the

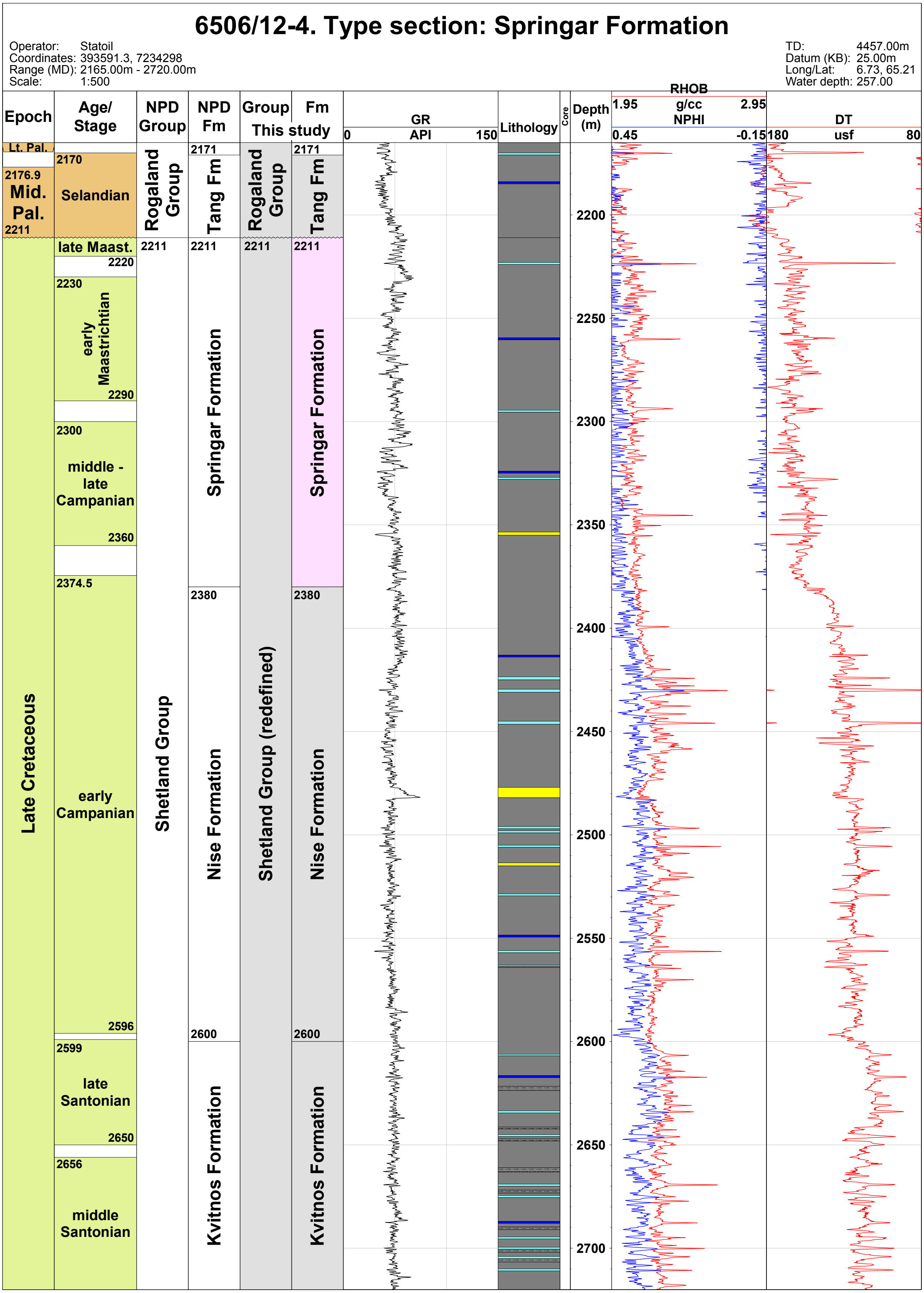


Figure 3.36. Well logs and lithology section for the Springar Formation in type well 6506/12-4, Norwegian Sea.

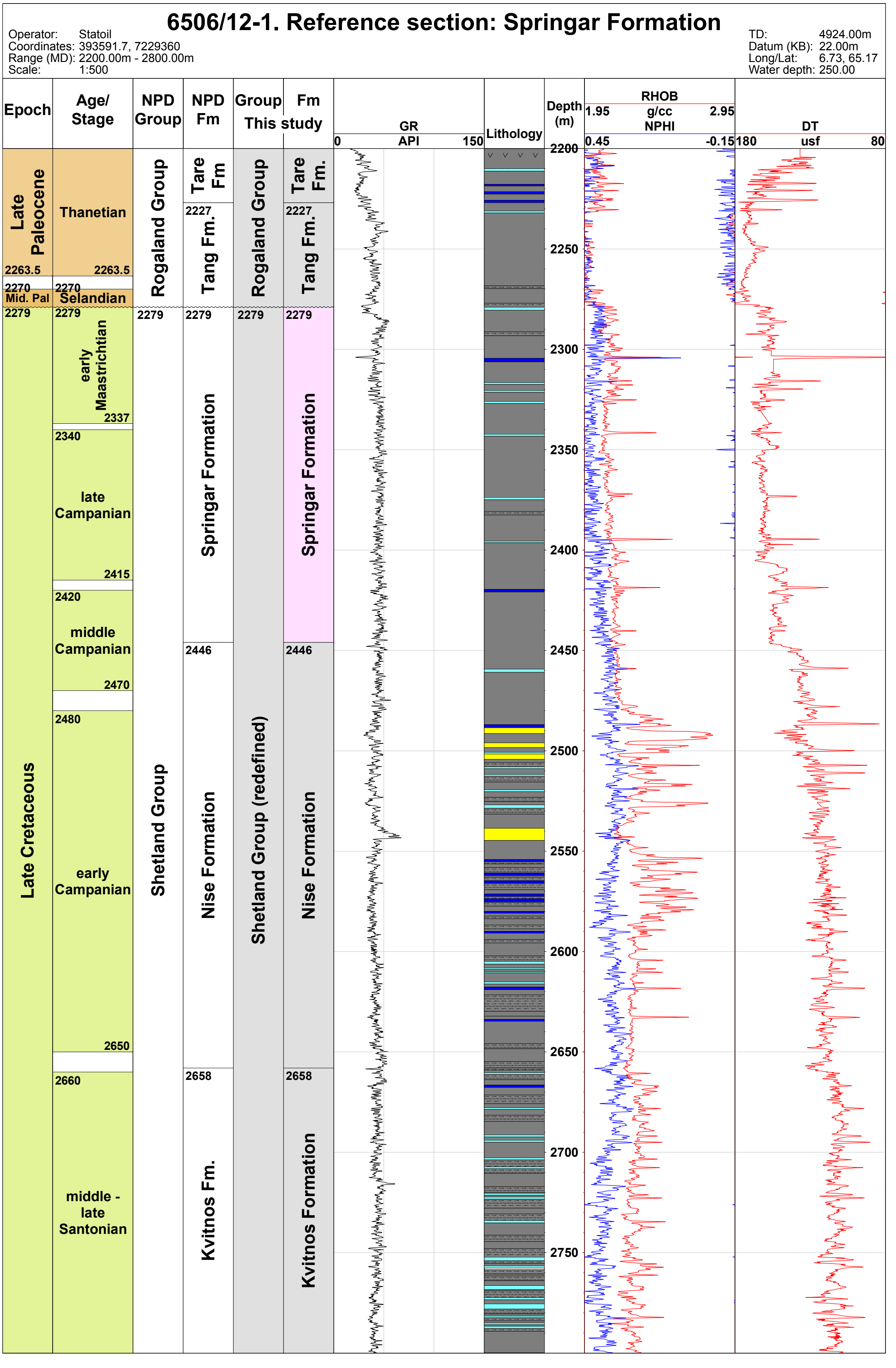


Figure 3.37. Well logs and lithology section for the Springar Formation in type well 6506/12-1, Norwegian Sea.

the siliclastic Jorsalfare Formation, upper Kyrre Formation and more carbonate-rich Hardråde Formation, developed in the northern North Sea region. It is also a time equivalent of the Tor and Magne Formations (formerly uppermost Hod Formation) in the Chalk Group in the North Sea.

Depositional environment

The Springar Formation was generally deposited in a deep outer shelf to bathyal paleoenvironment, with somewhat restricted water circulation. There are indications of temporary periods of more open marine circulation in response to the episodic opening of the Cretaceous seaway between Norway and Greenland (Gradstein *et al.*, 1999).

Deep water, non-calcareous agglutinated foraminifera (DWAF) dominate the microfossil assemblage, with calcareous benthonic foraminifera, planktonic foraminifera and radiolarians present at certain levels.

Remarks

The Springar Formation is widely distributed in the Norwegian Sea area, and represents deposition during the entire K5 sequence of Swiecicki *et al.* (1998), K95 and K100 of Vergara *et al.* (2001) and K80 and K90 sequences of Færseth and Lien (2001).

Hvithval Member [new]

Shetland Group, Springar Formation

Introduction

The Hvithval Member is a member of the Springar Formation, as found in the Vøring Basin. It has been drilled in wells on the structurally high areas of the Gjallar Ridge, e.g. 6704/12-1 and Nyk High e.g. 6707/10-1. The member consists of sandstones with subordinate, interbedded mudstones and siltstones.

The member is assigned a Late Cretaceous, late Campanian - Maastrichtian age.

Hvithval sandstones are considered to have been deposited by mass flow processes into a deep marine basin. Provenance is from the north or north-west during a period of basin margin uplift and rifting, and within the period of the rift climax stage of Færseth and Lien (2002).

Name

English/ Norwegian and any previous names: In the reference well 6707/10-1, the operator BP Norway originally included this sandstone unit in the Tang Formation (Upper Paleocene).

Derivatio nominis: The name Hvithval is the Norwegian name for the white whale or Beluga species *Delphinapterus leucas*. The species is a toothed whale of moderately large size (reaching up to 4.5 m long); it is found in small schools or flocks in Arctic seas, such as the Polar Sea around Svalbard and in the Barents Sea.

Lithology

The Hvithval Member consists of sandstones with subordinate, interbedded mudstones and siltstones, and with rare limestone and dolomite stringers.

The *sandstones* are white - yellow light grey, medium grey - medium dark grey to light brown grey, clear quartz grains, transparent to translucent, colourless, white to pink, very hard, loose, very fine to coarse, predominantly fine to medium, occasionally very coarse, angular to rounded, generally sub-angular to sub-rounded, poorly to moderately sorted, well cemented, siliceous cement with occasional calcite cement, argillaceous, silty, occasionally pyritic, glauconitic, chloritic, micaceous, trace of carbonaceous material, with no or poor visible porosity, occasionally grading to siltstone.

The subordinate *mudstones* are light - medium grey to brown grey, predominantly firm, occasionally soft to moderately hard, amorphous to blocky or sub-fissile, with disseminated and nodular pyrite, glauconitic, micaceous, silty, sandy, occasionally very sandy, and moderately calcareous with occasional dark laminae.

The *siltstones* (developed particularly in the lower part of the member), are light to medium grey, soft to firm, friable, argillaceous matrix, disseminated pyrite, arenaceous with very fine to fine sand, micaceous, glauconitic, non to moderately calcareous.

The infrequent *limestone* stringers are white- very light grey to medium dark grey- brown grey, firm, microcrystalline, silty, occasionally sandy with traces of glauconite and micro- mica.

The *dolomite* stringers are white to very light grey, firm to moderately hard and blocky.

Sample depository

Palynological preparations (organic matter depository)

Type well 6305/5-1: 19 slides from core samples covering the interval 2782.45 - 2812 m deposited at the NPD (RRI and OD preparations).
Reference well 6707/10-1: 4 slides from ditch cuttings covering the interval 2230 - 2410 m deposited at the NPD (DONG preparations).

Core photographs

Type well 6704/12-1: core #1 and core #2 covering the interval 2554 m MD RKB - 3005.4 m MD RKB (Core Photographs CP 57 - 63).

This interval represents the uppermost part of the member and includes the unconformable upper boundary with the overlying Rogaland Group. The boundary is a sand/sand contact and in addition to the marked difference in age, the overlying basal Tang Formation is characterised by glauconitic sandstones seen at the top of core #1 between 2554 m and 2555.1 m (uncorrected measured depth). The core shift is -2.3 m.
Reference well 6707/10-1: no core was taken in this member.

Thickness

The thickness of the Hvithval Member in released wells ranges from 221 - 691.3 m. An interactive isochore map is in the Norlex website under this member.

Geographical distribution

Sandstones of the Hvithval Member are geographically restricted to the Vøring Basin. With the available, albeit limited well coverage in this area, the sandstones are located on the (now) structurally high areas of the Gjallar Ridge, e.g. 6704/12-1 and Nyk High, e.g. 6707/10-1. It is absent, presumably due to early Cenozoic erosion, on the Vema Dome, e.g. 6706/11-1 and Utgard High, e.g. 6607/5-1. However, time equivalent, mudstone dominated successions assigned to the Springar Formation are developed in the wells 6607/5-2 (flank of the Utgard High), 6605/8-1 (Stetind prospect; western flank of the Fles North rotated fault block) and 6505/5-1 (Helland Hansen Dome), providing a southerly limit to the members extent.

Member tops may be searched on the Norlex website under this member.

Type well

Well name: 6704/12-1
WGS84 coordinates: N 67°07'25.00", E 04°42'44.70"
UTM coordinates: 7446374.14 N 574282.36 E
UTM zone: 31
Drilling operator name: Saga Petroleum ASA
Completion date: 24.07.1999
Status: P & A
Interval of type section and thickness in type well: 3244 - 2552.7 m (2555.1 m MD core depth) and 691.3 m thickness. See Figure 3. 38.

Reference well

Well name: 6707/10-1
WGS84 coordinates: N 67°04'07.85", E 07°00'36.51"
UTM coordinates: 7440629.70 N 413490.42 E
UTM zone: 32
Drilling operator name: BP Norway Ltd
Completion date: 23.07.1997
Status: P & A
Interval of type section and thickness in type well: 2434 - 2213 m and 221 m thickness. See Figure 3.39.

Upper and lower boundaries

Upper boundary

In the type well 6704/12-1, the top of the Hvithval Member is poorly defined in core although it represents the unconformable K/C boundary with the overlying Upper Paleocene Tang sandstones (informal) at 2555.1 m MD (2552.8 m corrected core depth). The boundary, therefore, represents a contact between two sandstones units of significantly different age separated by a stratigraphic break in the order of 10 m.y.

The thin sandstones of the Tang Formation are characterised by glauconitic and bioturbated sandstones. These sediments are interpreted as representing a relatively shallow marine transgressive lag deposit that unconformably overlies the deep marine sandstones of the Hvithval Member. This unconformity is represented on wireline logs by a minor downward decrease in gamma-ray values. The log signature may be related to the down-section decrease in glauconite content of the sandstones and an increase in sonic velocity.

Lower boundary

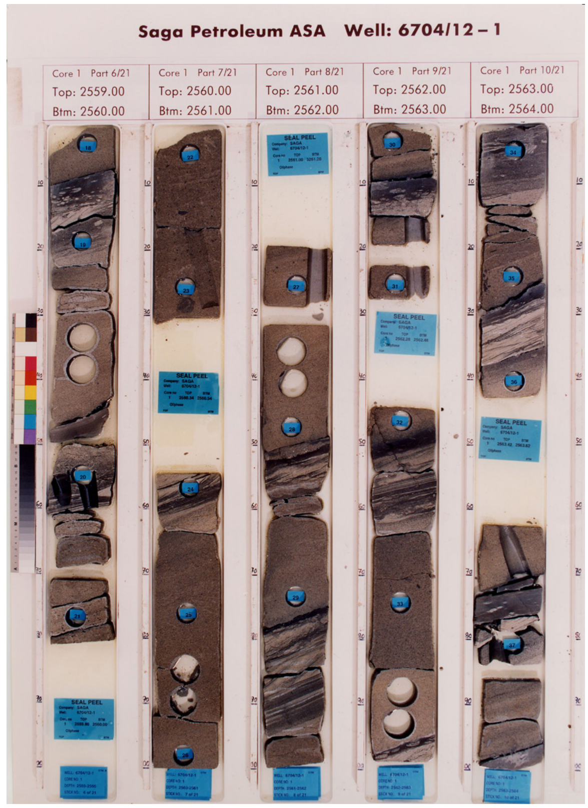
The base of the Hvithval Member is marked by the down section change from sandstones with interbedded mudstones to argillaceous sediments of the Springar Formation. It is marked on logs by a downward increase in gamma-ray values and a minor decrease in average sonic velocity. In the type well 6704/12-1, there is downward positive separation between neutron and density logs reflecting the down section development of mudstones but this is slightly above the gamma and sonic changes.

Well log characteristics

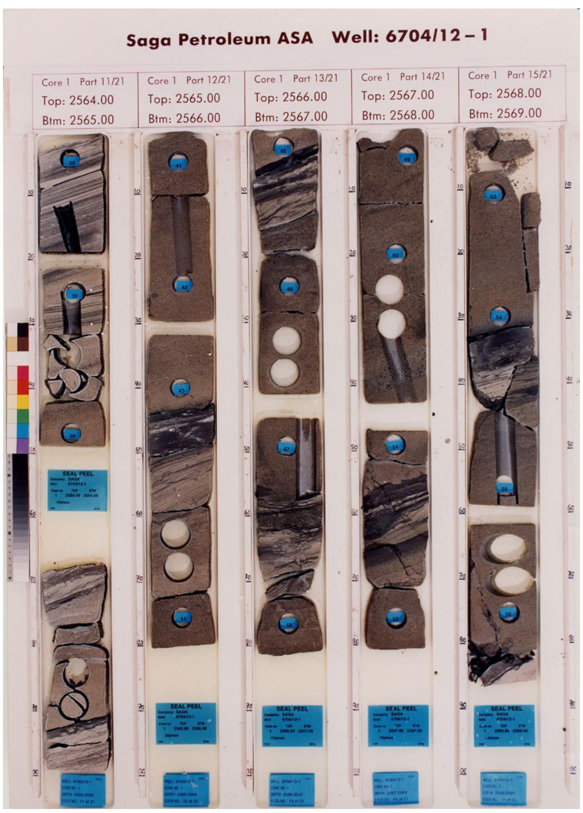
In the type well 6704/12-1, the log profile of the Hvithval Member is generally irregular or serrate and this reflects the heterolithic character of the member. The gamma-ray log shows a predominantly serrate profile but cone-shaped, funnel-shaped and, more rarely, blocky-type profiles are developed. The latter reflect variations in the original depositional setting and suggest that the sand was deposited in mass-flows. The overall character of the log shows that the member is made of successive, and possibly cyclic intervals of sandstones and mudstones.

The marked increase in gamma- ray log values in the upper part of the Hvithval Member, at 2685 m MD

CP57. Core 1, 2554-2559m, Hvithval Mb, type well 6704/12-1.



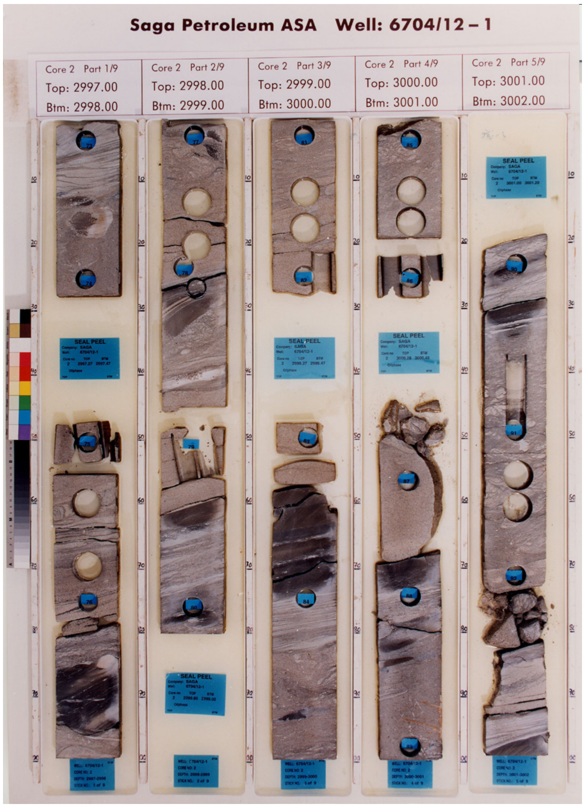
CP58. Core 1, 2559-2564m, Hvithval Mb, type well 6704/12-1



CP59. Core 1, 2564-2569m, Hvithval Mb, type well 6704/12-1.

CP60. Core 1, 2569-2574m, Hvithval Mb, type well 6704/12-1.

CP61. Core 1, 2574-2575m, Hvithval Mb, type well 6704/12-1.



CP62. Core 2, 2997-3002m, Hvithval Mb, type well 6704/12-1.

CP63. Core 2, 3002-3005m, Hvithval Mb, type well 6704/12-1.

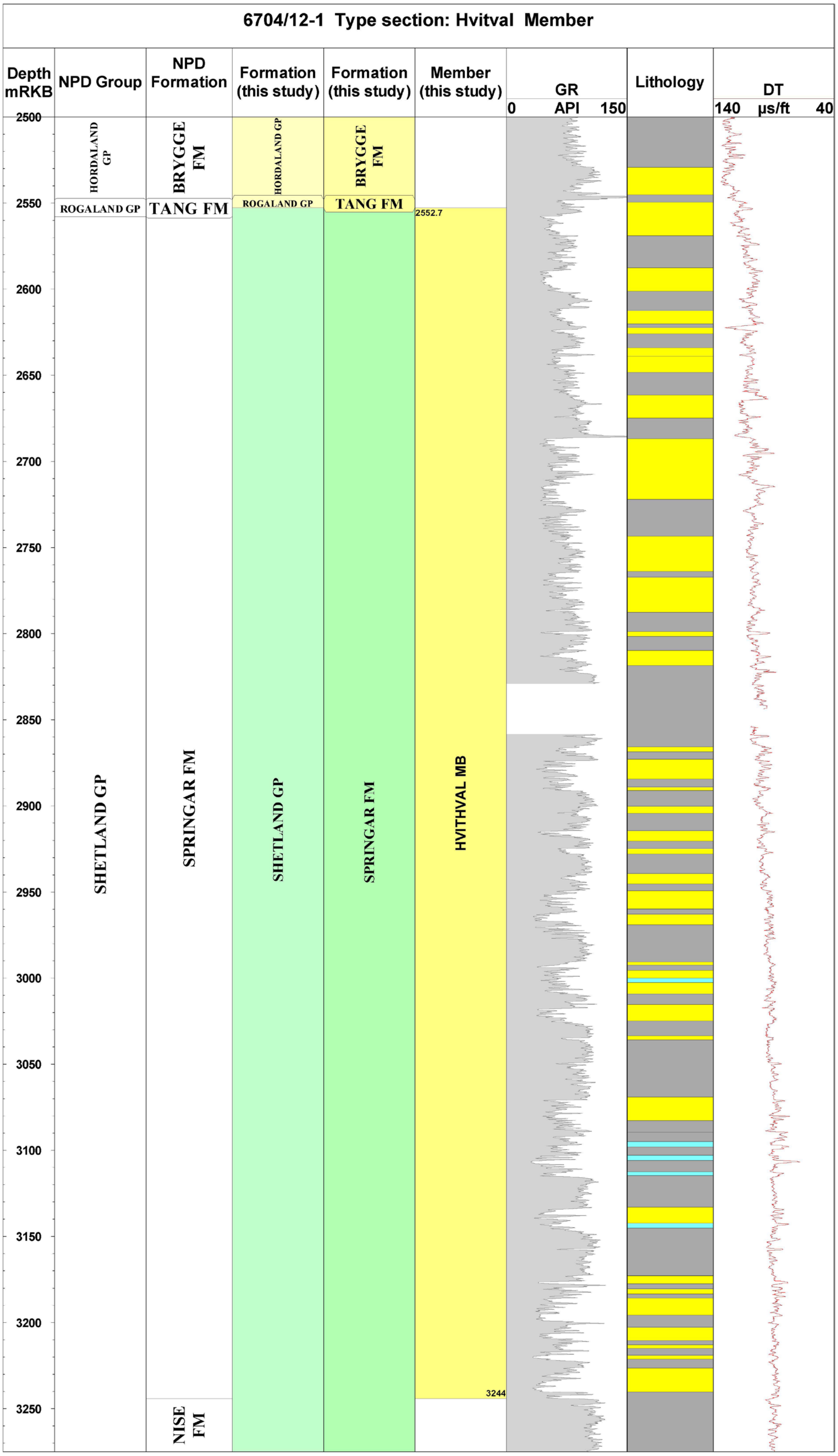


Figure 3.38. Well logs and lithology section for the Hvithval Member of the Springar Formation in type well 6704/12-1, Norwegian Sea.

RKB in the type well 6704/12-1 (possible maximum transgressive surface) separates two progradational trends gamma- ray profiles that may be tied to a prominent seismic reflector.

Biostratigraphy

The dating of the Hvithval Member is complicated by reworking from older stratigraphic levels (a mixture ranging from Permo-Triassic to Maastrichtian ages) and probably intra- member recycling. The age is primarily based on dinoflagellate cysts.

In the basal part of the member in the Gjallar Ridge type well 6704/12-1, the LCO *Odontochitina operculata*, LO *O. costata* and LO *O. 'wetzelii'* Wilson 1974 suggest an age at least as old as early Maastrichtian. The occurrence of *Palaeohystrichophora infusorioides* is more typical of late Campanian. The LAO *Heterosphaeridium heteracanthum* in the underlying mudstones of the Nise Formation confirms a late Campanian age. In the Nyk High reference well 6707/10-1 the base of the Hvithval Member is slightly younger, being above the *Odontochitina plexus*.

The youngest extent of the member in the type well 6704/12-1 is early Maastrichtian, and developed below the LO *Alterbidinium acutulum*. In the reference well 6707/10-1, the upper part of the member is within the acme of *Impagidium 'septentrionalis'*, indicating a slightly younger intra-late Maastrictian age.

In general, the Foraminifera assemblage is dominated by LO *Caudammina ovula*, LO *Rzehakina epigona*, LO *Kalamopsis gryzybowskii* and the planktonic taxon LO *Heterohelix globulosa*.

In the type well 6704/12-1 the upper boundary of the Hvithval Member is unconformable and coincides with the base of glauconite rich sandstones of the Tang Formation. This may be observed in core at 2555.1 m MD (2552.7 m corrected core depth). A stratigraphic break in the order of 10 m.y. is indicated. The overlying interval yields the Middle Paleocene dinocyst markers LO *Isabelidinium viborgense*, LO *Palaeocystodinium bulliforme* and LCO *Palaeoperidinium pyrophorum*.

Age

Late Cretaceous, late Campanian - late Maastrichtian, but mainly early Maastrichtian.

Correlation

The Hvithval Member passes laterally into mudstones of the Springar Formation. This member is part of the K100 sequence of Vergara *et al.* (1999), and the K90 sequence of Færseth & Lien (2002), Lien (2005) and Fugelli & Olsen (2005a and 2005b).

Depositional environment

Little is published on the depositional setting of the Hvithval Member.

The sandstones were deposited within a large scale, deep-water, distal basin floor fan (Fugelli and Olsen, 2005b) as part of their play 1 concept. Deposition was probably by mass flow, with the sediments originating from the north or north-westerly locations towards the Greenland mainland.

In their study of outcrop analogues, Fugelli and Olsen (2005a), considered the sand-rich fan complex of the Brushy Canyon Formation in the Delaware Basin, USA to be an analogous system.

In the mudstones mass of the member, the presence of agglutinated Foraminifera indicates upper to middle bathyal water depths, with oxygen restricted bottom conditions.

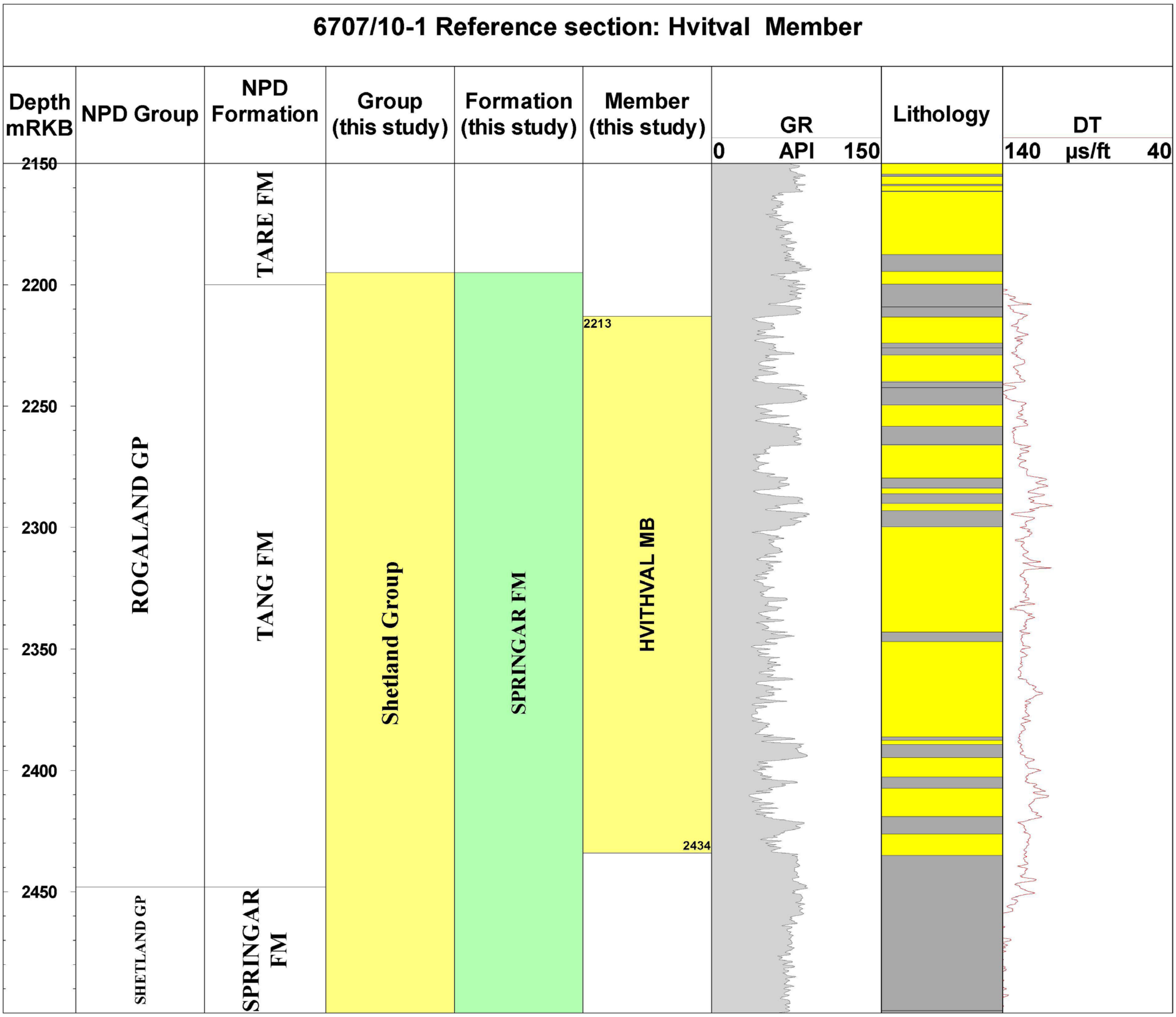


Figure 3.39. Well logs and lithology section for the Hvithval Member of the Springar Formation in reference well 6707/10-1, Norwegian Sea.

Grindhval Member [new]

Shetland Group, Springar Formation

Introduction

The Grindhval Member consists of sandstones and interbedded mudstones present around the Ormen Lange Field, located in the eastern Møre Basin. The unit is assigned a Maastrichtian age and occurs below the Egga (reservoir sandstone) Member assigned to the Paleocene. The bulk of the Grindhval sandstones were deposited as high or low density gravity flows and turbidites, sourced from the Norwegian mainland to the east.

Name

English/ Norwegian and any previous names: Upper Cretaceous, Maastrichtian turbidite sandstones were first described by Gjelberg *et al.* (2001) in core from the Ormen Lange Field, Møre Basin. The sandstones were collectively and informally assigned to the Jorsalfare Formation, using the North Sea lithostratigraphic terminology *sensu* Isaksen and Tonstad (1989).

Derivatio nominis: The name Grindhval comes from Norwegian for the small pilot whale Globicephala melas. It is usually between 4 - 6 m in size, and found commonly along the northern Norwegian coastline, and in the open sea around Greenland and Iceland in the Norwegian Sea.

Lithology

The Grindhval Member consists of sandstones with interbedded mudstones.

The *sandstones* are medium grey to light olive grey, with clear to translucent quartz grains and occasionally pink quartz, very fine to medium grained, occasionally coarse grained, moderate to well sorted, sub-angular to sub-rounded, friable to firm, moderately hard, occasionally very hard, slight to moderate calcareous cement, occasionally very calcareous, micro-pyritic, rarely micaceous and glauconitic, occasionally slightly argillaceous, with fair to good visible porosity in parts.

The *mudstones* are medium dark grey to dark grey, olive grey to dark green-grey, moderately hard to hard, sub-fissile to sub-blocky, occasionally very fine sandy in parts, micaceous to micro-micaceous, rarely glauconitic, with generally abundant micro-pyrite, slightly to moderately calcareous or occasionally very calcareous, occasionally grade to siltstones.

One or two thin (< 15 cm) bioturbated *chalk* beds maybe developed in the upper part of the member (observed in core).

Sample depository

Palynological preparations (organic matter depository)

Type well 6305/5-1: 19 slides from core samples covering the interval 2782.45 - 2812 m deposited at the NPD (RRI and OD preparations).

Reference well 6305/8-1: 10 slides from 4 core pieces and 6 ditch cuttings samples covering the interval 2978.28 m core - 3003 m dc deposited at the NPD (RRI preparations).

Core photographs

The Grindhval Member was cored in its entireity in the type well 6305/5-1 and described by Gjelberg *et al.* (2001) (Core Photographs CP 64-72 and Figure 3.40). The core includes the lower boundary of the member within the Springar Formation (~ 2814.4 m), and the upper boundary with the overlying Rogaland Group, Tang Formation (~2774.5 m). The upper boundary was also cored in the reference well 6305/8-1 (~2960.2 m).

Type well 6305/5-1: core #4 - core #6 (2771.75 m MD RKB – 2816.3 m MD RKB). The core covers the entire section, with a minor gap between 2783 - 2790m (Core Photographs CP 64-72).

Reference well 6305/8-1: core #4 and core #5 (2959.1 m MD RKB – 2987.65 m MD RKB) covering the majority of the member and the upper boundary with the overlying Tang Formation, Rogaland Group, Tang Formation (Core Photographs CP 73-79).

Thickness

The Grindhval Member varies in thickness from 8m to 36 m based on released well data. The Norlex website contains a link to create interactive isochore maps.

Geographical distribution

Sandstones of the Grindhval Member are geographically restricted to the Ormen Lange sub-basin (Quadrant 6305), located on the eastern margin of the Møre Basin. In the Ormen Lange Field, the member

Thickness

The thickness of the Hvithval Member in released wells ranges from 221 - 691.3 m. An interactive isochore map is in the Norlex website under this member.

Geographical distribution

Sandstones of the Hvithval Member are geographically restricted to the Vøring Basin. With the available, albeit limited well coverage in this area, the sandstones are located on the (now) structurally high areas of the Gjallar Ridge, e.g. 6704/12-1 and Nyk High, e.g. 6707/10-1. It is absent, presumably due to early Cenozoic erosion, on the Vema Dome, e.g. 6706/11-1 and Utgard High, e.g. 6607/5-1. However, time equivalent, mudstone dominated successions assigned to the Springar Formation are developed in the wells 6607/5-2 (flank of the Utgard High), 6605/8-1 (Stetind prospect; western flank of the Fles North rotated fault block) and 6505/5-1 (Helland Hansen Dome), providing a southerly limit to the members extent.

Member tops may be searched on the Norlex website under this member.

Type well

Well name: 6704/12-1
WGS84 coordinates: N 67°07'25.00", E 04°42'44.70"
UTM coordinates: 7446374.14 N 574282.36 E
UTM zone: 31
Drilling operator name: Saga Petroleum ASA
Completion date: 24.07.1999
Status: P & A
Interval of type section and thickness in type well: 3244 - 2552.7 m (2555.1 m MD core depth) and 691.3 m thickness. See Figure 3. 38.

Reference well

Well name: 6707/10-1
WGS84 coordinates: N 67°04'07.85", E 07°00'36.51"
UTM coordinates: 7440629.70 N 413490.42 E
UTM zone: 32
Drilling operator name: BP Norway Ltd
Completion date: 23.07.1997
Status: P & A
Interval of type section and thickness in type well: 2434 - 2213 m and 221 m thickness. See Figure 3.39.

Upper and lower boundaries

Upper boundary

In the type well 6704/12-1, the top of the Hvithval Member is poorly defined in core although it represents the unconformable K/C boundary with the overlying Upper Paleocene Tang sandstones (informal) at 2555.1 m MD (2552.8 m corrected core depth). The boundary, therefore, represents a contact between two sandstones units of significantly different age separated by a stratigraphic break in the order of 10 m.y.

The thin sandstones of the Tang Formation are characterised by glauconitic and bioturbated sandstones. These sediments are interpreted as representing a relatively shallow marine transgressive lag deposit that unconformably overlies the deep marine sandstones of the Hvithval Member. This unconformity is represented on wireline logs by a minor downward decrease in gamma-ray values. The log signature may be related to the down-section decrease in glauconite content of the sandstones and an increase in sonic velocity.

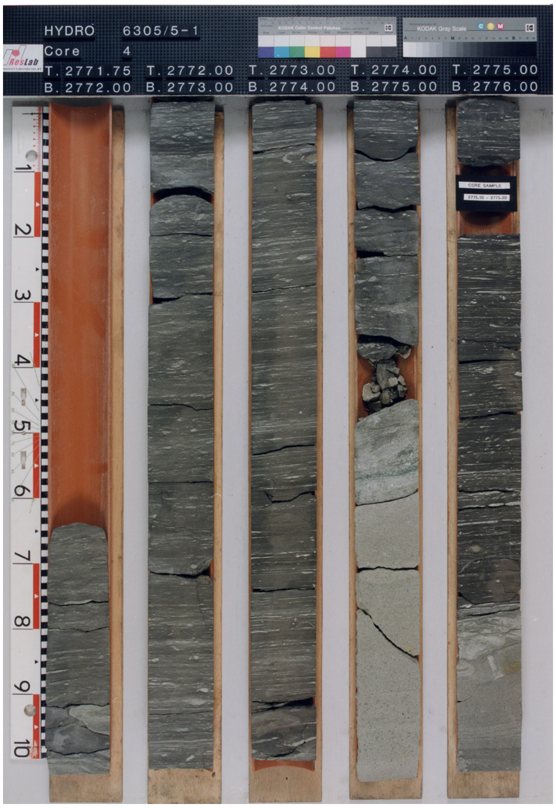
Lower boundary

The base of the Hvithval Member is marked by the down section change from sandstones with interbedded mudstones to argillaceous sediments of the Springar Formation. It is marked on logs by a downward increase in gamma-ray values and a minor decrease in average sonic velocity. In the type well 6704/12-1, there is downward positive separation between neutron and density logs reflecting the down section development of mudstones but this is slightly above the gamma and sonic changes.

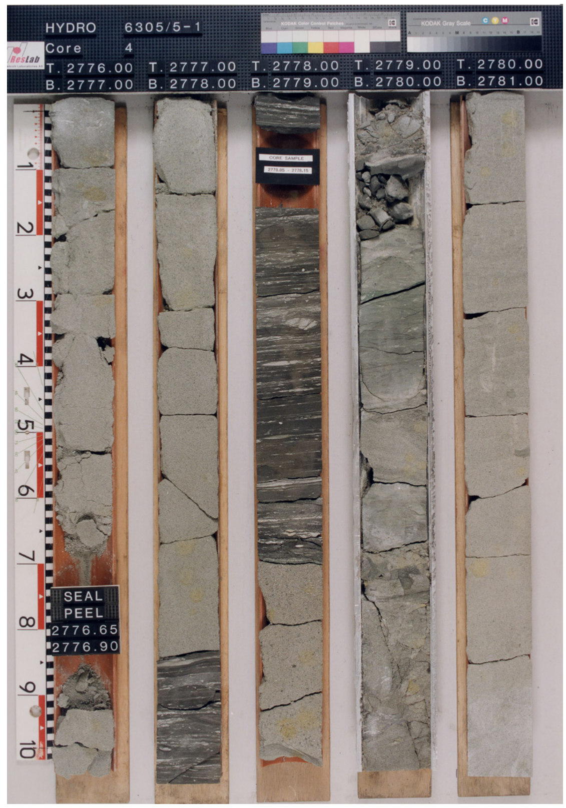
Well log characteristics

In the type well 6704/12-1, the log profile of the Hvithval Member is generally irregular or serrate and this reflects the heterolithic character of the member. The gamma-ray log shows a predominantly serrate profile but cone-shaped, funnel-shaped and, more rarely, blocky-type profiles are developed. The latter reflect variations in the original depositional setting and suggest that the sand was deposited in mass-flows. The overall character of the log shows that the member is made of successive, and possibly cyclic intervals of sandstones and mudstones.

The marked increase in gamma- ray log values in the upper part of the Hvithval Member, at 2685 m MD

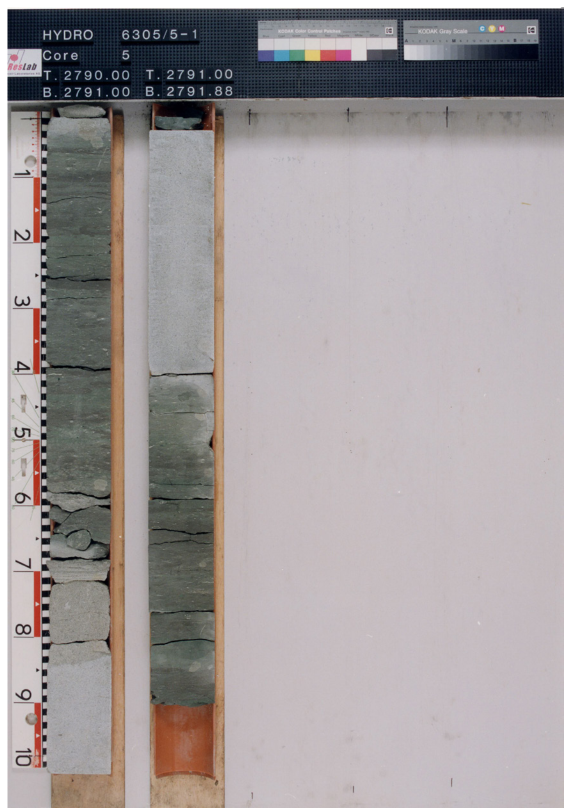


CP64. Core 4, 2771-2776m, Grindhval Mb, type well 6305/5-1.

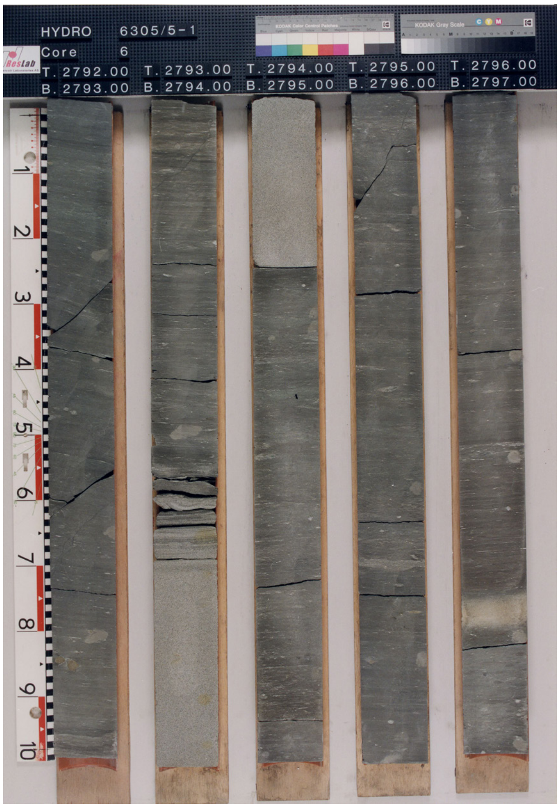


CP65. Core 4, 2776-2781m, Grindhval Mb, type well 6305/5-1.

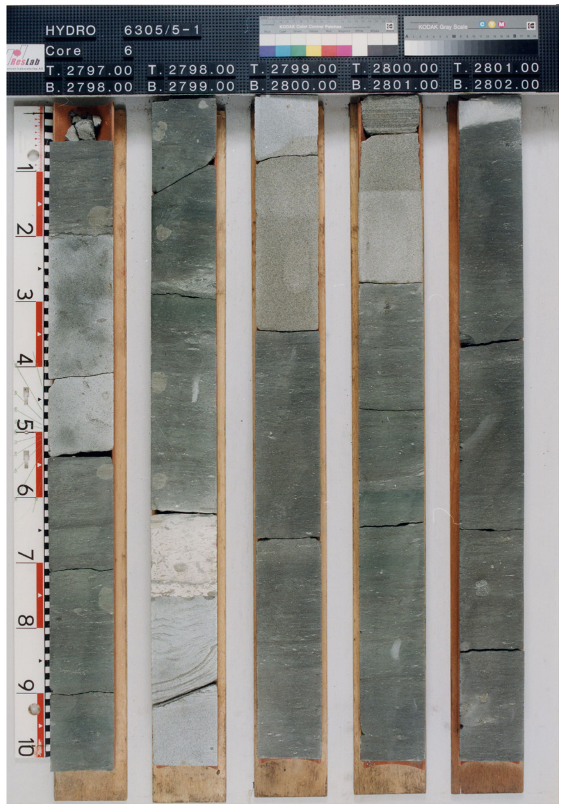
CP66. Core 4, 2781-2783m, Grindhval Mb, type well 6305/5-1.



CP67. Core 5, 2790-2792m, Grindhval Mb, type well 6305/5-1.

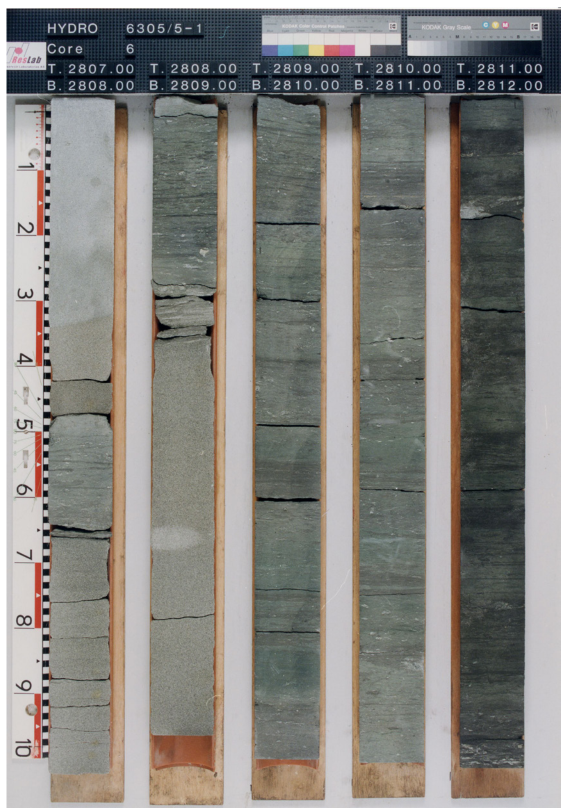


CP68. Core 6, 2792-2797m, Grindhval Mb, type well 6305/5-1.



CP69. Core 6, 2797-2802m, Grindhval Mb, type well 6305/5-1.

CP70. Core 6, 2802-2807m, Grindhval Mb, type well 6305/5-1.



CP71. Core 6, 2807-2812m, Grindhval Mb, type well 6305/5-1.

CP72. Core 6, 2812-2816m, Grindhval Mb, type well 6305/5-1.

reaches its maximum drilled extent, varying from 18m e.g. 6305/4-1 to 36 m e.g. 6305/7-1, but is usually about 30 m thickness.

To the east of the field, in the Slørebotn sub-basin and in up-dip locations, it is either thin and partially eroded, e.g. in well 6305/9-1 (8 m), 6305/12-1 (13 m) or absent, e.g. in well 6306/10-1. The absence is the result of erosion by the overlying Egga Member.

To the west and north, including the northern part of the Ormen Lange Dome, e.g. in well 6305/1-1, the member passes laterally into time equivalent Springar mudstones.

The Norlex website has a link to search for member tops in wells.

Type well

Well name: 6305/5-1
WGS84 coordinates: N 63°32'27.50, E 5°20'14.90
UTM coordinates: 7048160.15 N 616189.14 E
UTM zone: 31
Drilling operator name: Norsk Hydro Produksjon AS
Completion date: 07.10.1997
Status: Suspended
Interval of type section and thickness in type well: 2813.5 m (2814.4 m core depth) – 2779 m (log) (2779.3 m core depth) and 34.5 m thickness (see Figure 3.41).

Reference well

Well name: 6305/8-1
WGS84 coordinates: N 63°28'34.70", E 5°24'14.40"
UTM coordinates: 7041080.68 N 619765.50 E
UTM zone: 31
Drilling operator name: Norsk Hydro Produksjon AS
Completion date: 08.09.2000
Status: P & A
Interval of type section and thickness in type well: 3005 - 2972 m (2971.8 m core depth) and 33 m thickness (see Figure 3.42).

Upper and lower boundaries

Upper boundary

In the type well 6305/5-1, the top of the Grindhval Member coincides with the top of the Springar Formation. This reflects a change in sedimentation at the C/P boundary from greenish and frequently

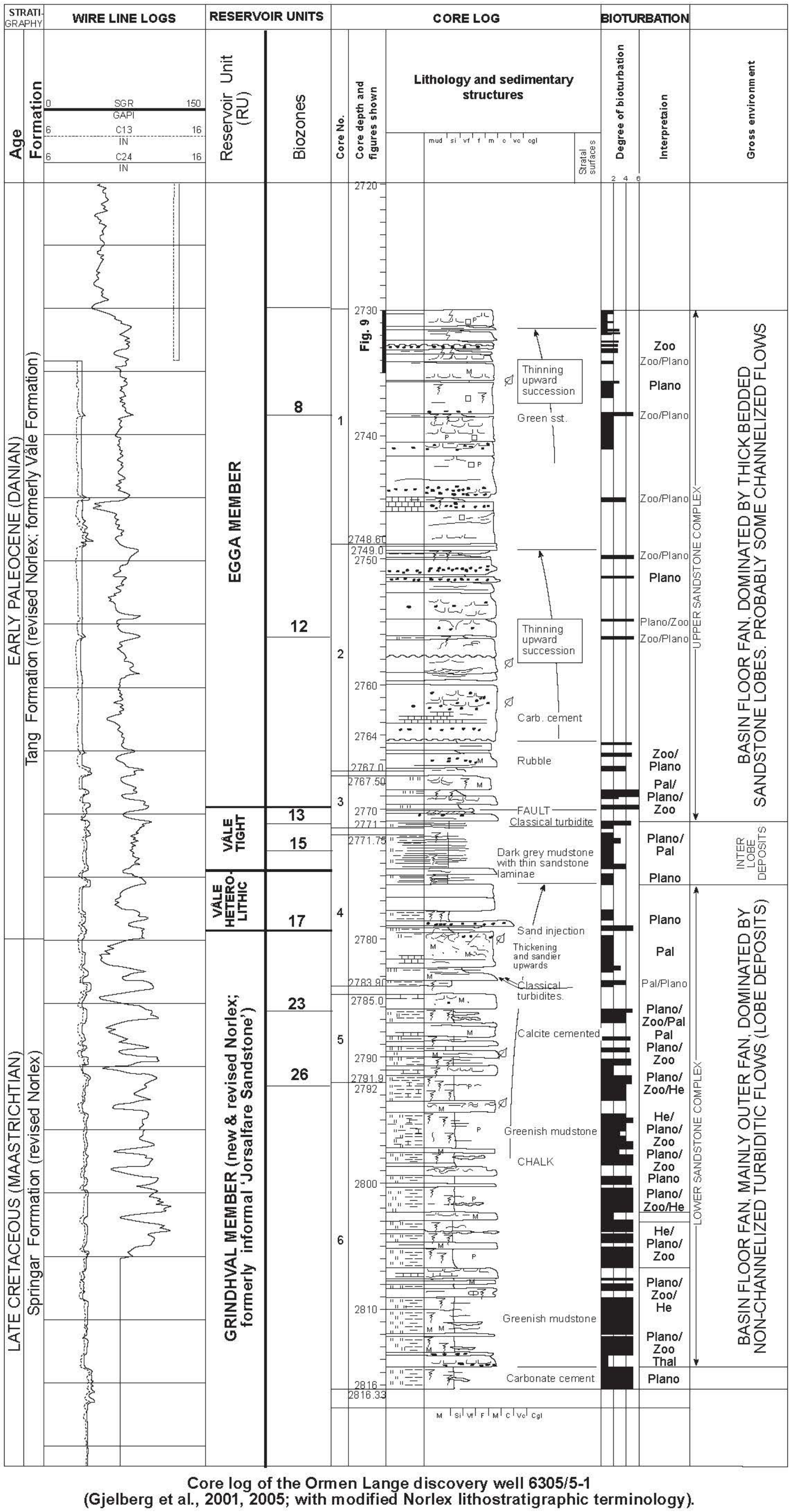


Figure 3.40. Core log of the Ormen Lange discovery well 6305/5-1 (Gjelberg *et al.*, 2001, 2005; with modified lithostratigraphic terminology, showing Grindhval Member lithology and sedimentary structures)..

frequently calcareous mudstones, typical of the upper of the Springar Formation, and associated Grindhval Member to hemipelagic, black and non-calcareous mudstones of the Tang Formation.

In addition to differences in the 'background' mudstones, the sandstones in the upper part of the Grindhval Member are frequently carbonate cemented, and may be distinguished from those of the overlying Egga Member by high sonic velocity.

Lower boundary

The base of the Grindhval Member is marked by the down section change from sandstones with interbedded mudstones to a unit of siltstones in the lower part of the Springar Formation. It is well defined on wireline logs by an abrupt downward increase in gamma-ray values and a marked decrease in sonic velocity. In the type section 6305/5-1, where the boundary is cored, the base of the member can be seen below the thin sandstone bed at 2814.4 m MD (2813.5 m corrected depth).

Well log characteristics

In the type well 6305/5-1, the gamma log of the Grindhval Member shows a typical serrate profile with an overall upward trend from a spiky log character, reflecting the thin sandstone bedded nature of the lower part, to thicker, sub-blocky log characters developed towards the top of the member. The latter reflects an increase in the proportion of thicker sandstone beds. In well 6305/7-1, located in the southern part of the Ormen Lange Field, the upper part of the Grindhval Member has generally thicker and more frequent sandstone beds and a blockier log character.

Biostratigraphy

The Grindhval Member is well constrained both micropaleontologically and palynologically. Planktonic Foraminifera are common in the upper part, and are particularly associated with two chalk beds (see correlation below).

The member is developed below the LO of late Maastrichtian planktonic Foraminifera, including LO *Rosita contusa*, LO *Abathomphalus mayaronsis*, LO *Racemiguembelina fructicosa*, LO *Globigerinelloides asperus*, LO *Heterohelix* spp. and the dinocyst LO *Palynodinium grallator*. The base is close to the LO *Alterbidium acutulum* (early Maastrichtian) and above LO *Odontochitina operculata*.

The sporadic record of the dinocyst marker *Hystrichodinium pulchrum*, within the lower part of the member in the type well 6305/5-1, is considered to be due to intra-formational reworking from up-slope locations.

Age

Late Cretaceous, late Maastrichtian. With the available data, this member appears to be restricted to the late Maastrichtian with some reworking of early Maastrichtian palynomorphs. The base of the member appears to be close to the early/late Maastrichtian boundary.

Correlation

In the north of the Ormen Lange Field, e.g. in well 6305/1-1 T2, the Grindhval Member passes laterally into mudstones of the Springar Formation. South of 630 N. the member grades laterally into mudstones of the Jorsalfare Formation.

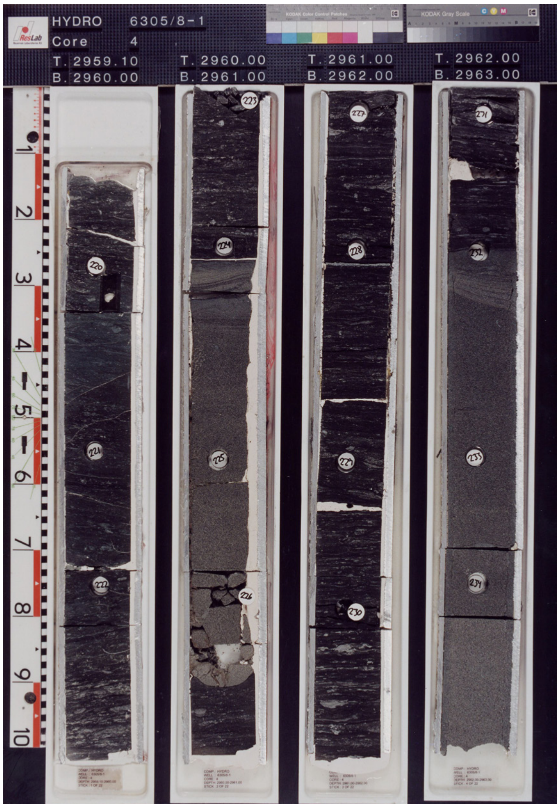
Minor un-named sands within the Træna Basin, north of the Trøndelags Platform e.g. in well 6710/10-1, are time equivalent of the Grindhval Member. These sands are also presumably sourced from the Norwegian mainland. They are slightly younger than the Hvithval Member in the Vøring Basin that is interpreted as being sourced from east Greenland.

On a local, field-scale, one or two, thin (<15 cm) chalk beds appear to be correlatable across the Ormen Lange Field, where core is available. These are characterised by common planktonic foraminifera *Rugoglobigerina rugosa* and *Globigerinelloides asperus*, and provide correlative horizons within the upper part of the member.

The change in background sedimentation from green, bioturbated mudstones of the Grindhval Member to black or grey, pin-stripped mudstones of the overlying, lowermost Tang Formation provides a correlative event at the top of the member.

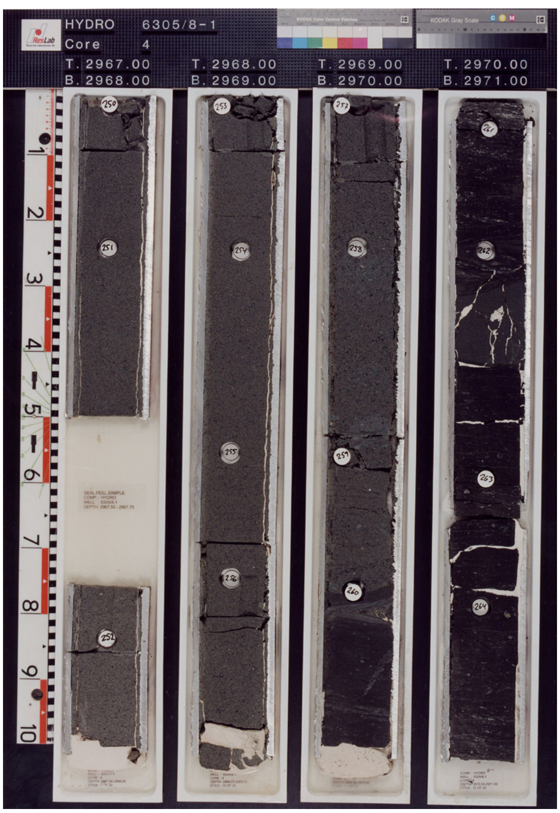
Depositional environment

The depositional environment of this member in well 6305/5-1 has been described in detail by Gjelberg *et al.* (2001) under their discussion of the Maastrichtian Jorsalfare Formation of the Ormen Lange Field.

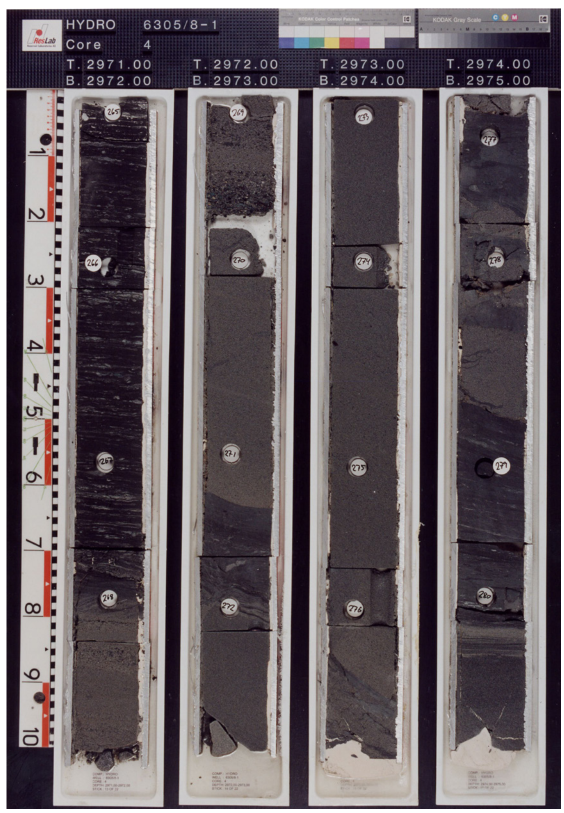


CP73. Core 4, 2559-2963m, Grindhval Mb, type well 6305/8-1.

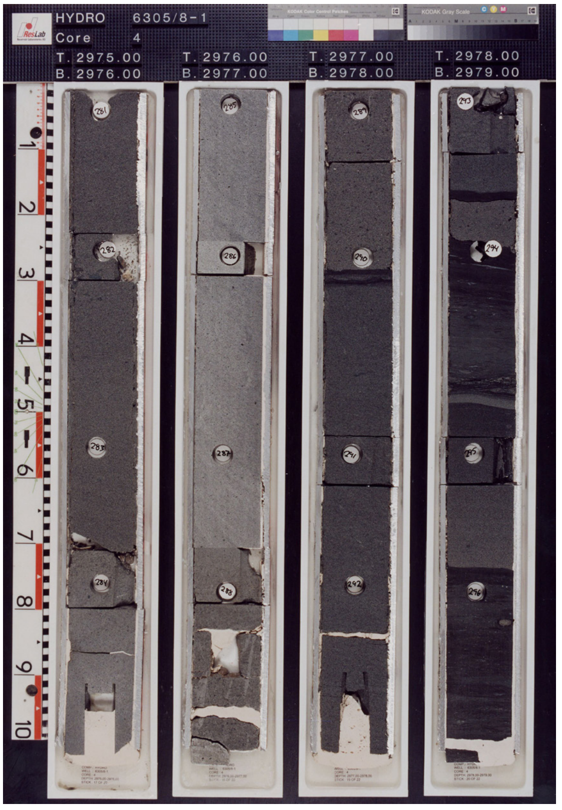
CP74. Core 4, 2963-2967m, Grindhval Mb, type well 6305/8-1.



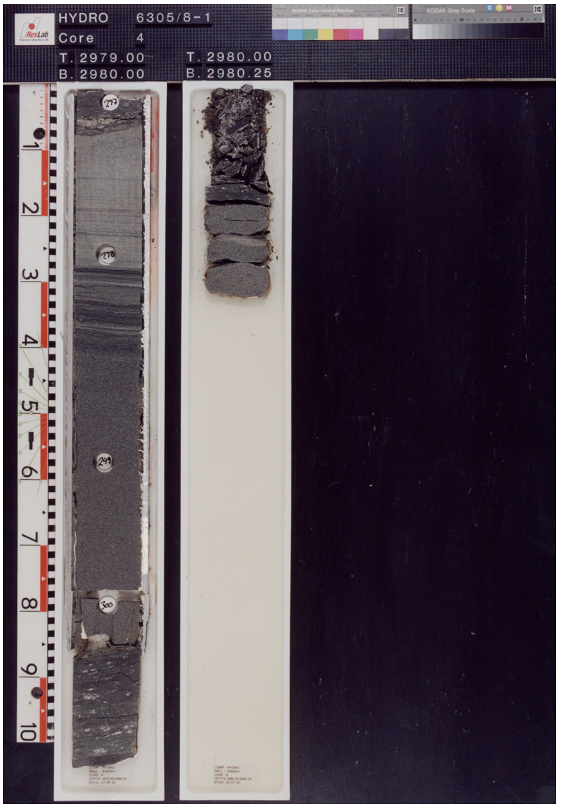
CP75. Core 4, 2967-2971m, Grindhval Mb, type well 6305/8-1.



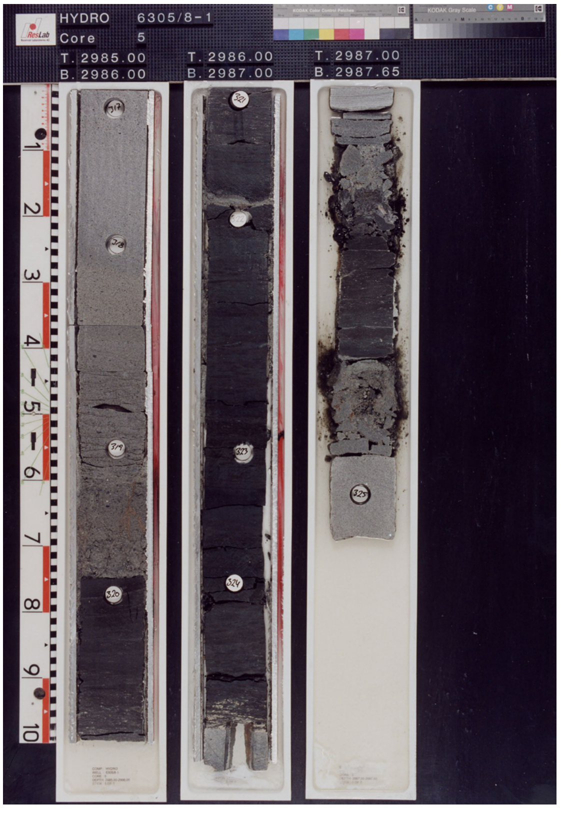
CP76. Core 4, 2971-2975m, Grindhval Mb, type well 6305/8-1



CP77. Core 4, 2975-2979m, Grindhval Mb, type well 6305/8-1.



CP78. Core 4, 2979-2980m, Grindhval Mb, type well 6305/8-1.



CP79. Core 6, 2985-2988m, Grindhval Mb, type well 6305/8-1.

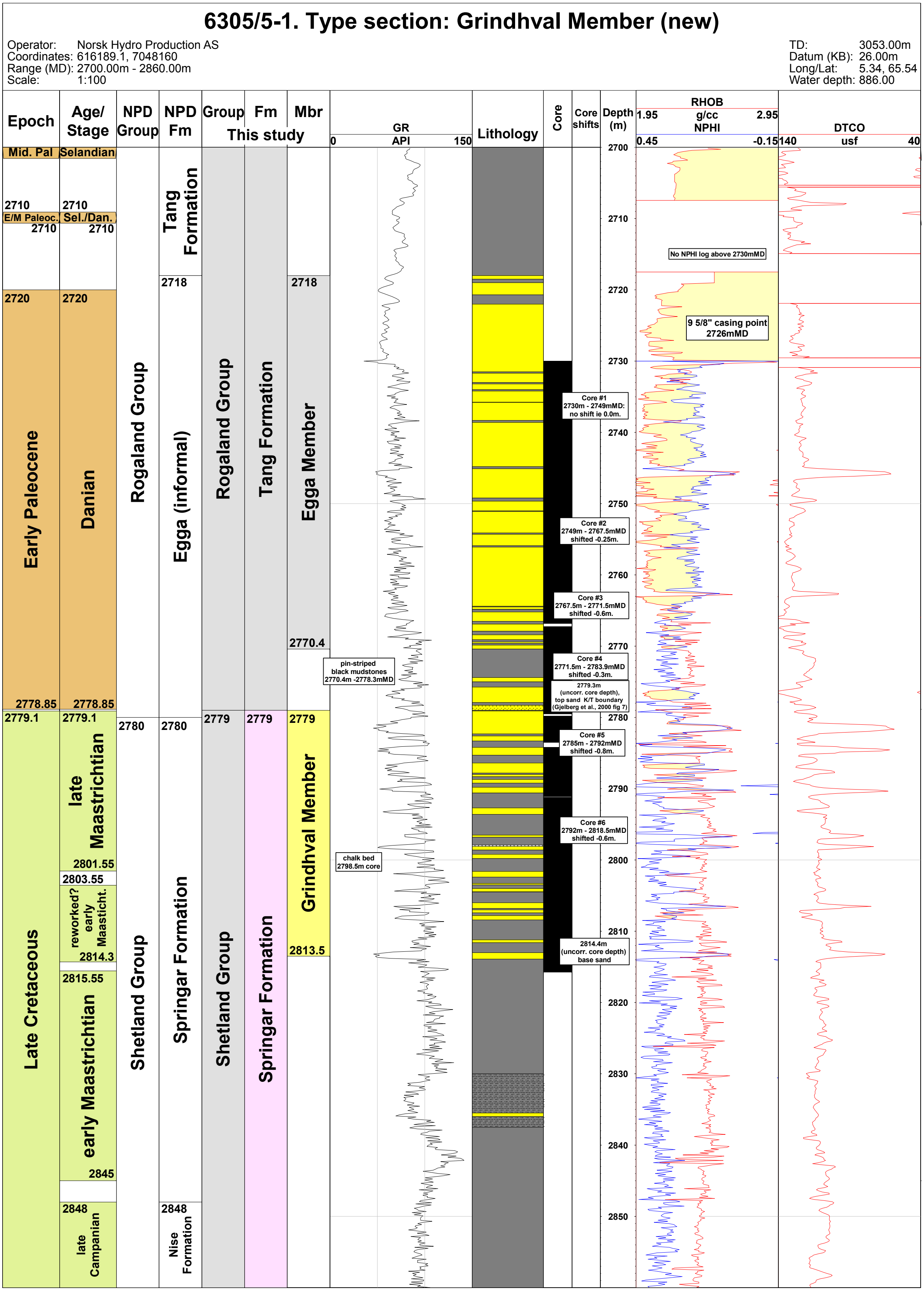


Figure 3.41. Well logs and lithology section for the Grindhval Member of the Springar Formation in type well 6305/5-1, Norwegian Sea.

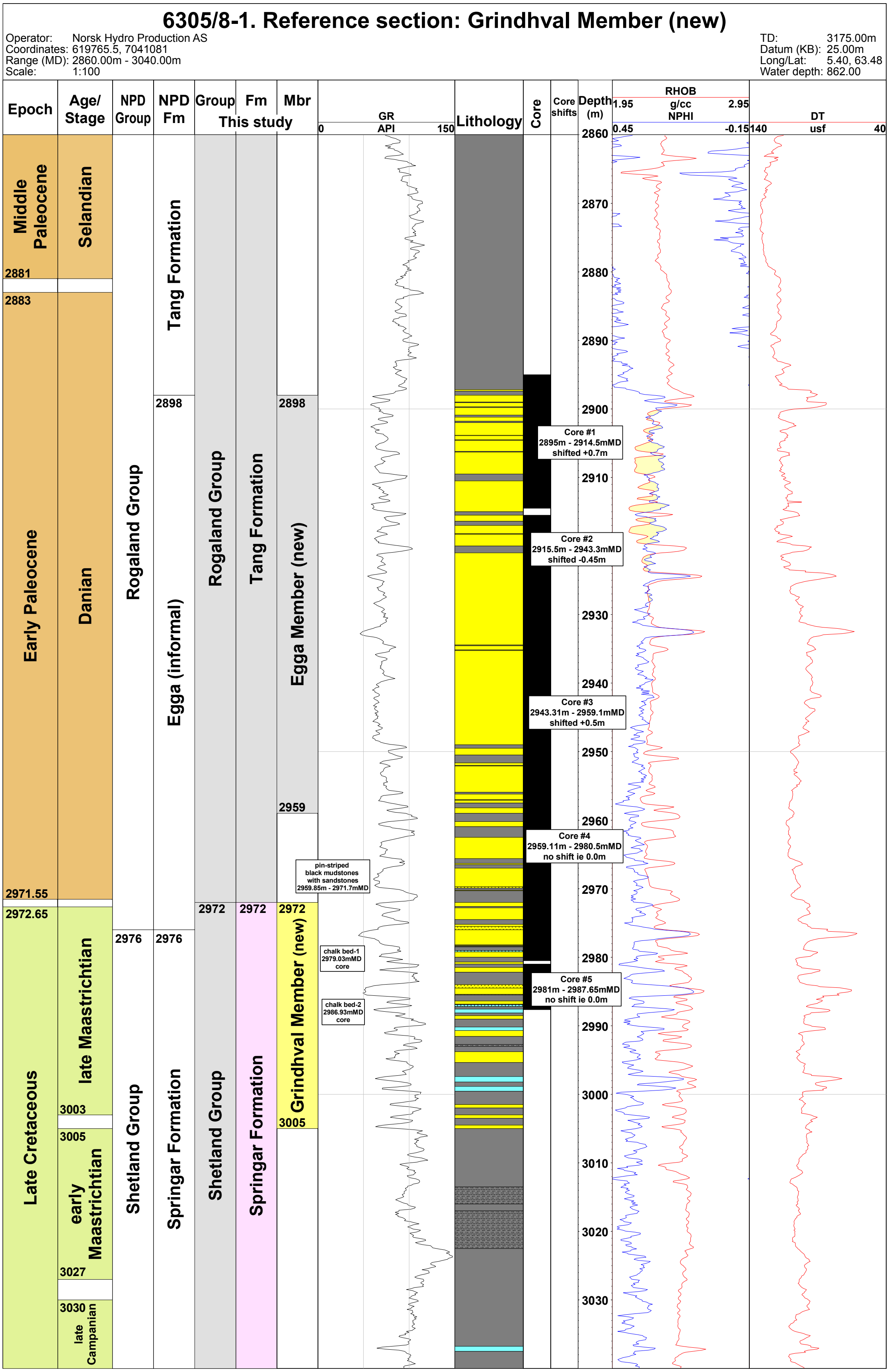


Figure 3.42. Well logs and lithology section for the Grindhval Member of the Springar Formation in reference well 6305/8-1, Norwegian Sea.

The geometry of the submarine fan system and the basin physiography is described by Møller *et al.* (2004).

The core log for well 6305/5-1 illustrated by Gjelberg *et al.* (1999) and their annotated core photographs are reproduced here. Their facies terminology is also adopted in the following discussion of the depositional setting for the Grindhval Member.

Overall, the Grindhval succession shows a poorly defined, sandier upwards development that is combined with a thickening upwards of individual sandstone beds. In general terms, Gjelberg *et al.* (2001) interpreted the section in well 6305/5-1 as representing deposition in a mainly outer fan setting on the basin floor of primarily non-channelised lobe deposits under turbiditic processes.

The sandstones were sourced into the Ormen Lange sub-basin from the Norwegian mainland via a narrow shelf developed along the eastern margin of the Møre Basin. In the Ormen Lange Field, the thickest sand development is in well 6305/7-1 in the southern region where more than 20m of sand-dominated facies are recorded. Northwards, sandstones decrease and in the 6305/1-1 T2 well sand is absent although the time equivalent isochore increases in thickness. This thickening towards the northwest maybe explained by interfingering of the Ormen Lange system with other fine grained systems derived from the north or west.

In detail, the lower part of the Grindhval Member consists mainly of thin bedded and massive or vaguely laminated sandstones (Facies A – sandy high density turbidites), and graded bedded, fine to medium grained sandstones (Facies B or low density "classical turbidites"). These are interbedded with thick beds of green and grey highly bioturbated and calcareous mudstones (Facies D) interpreted to represent mainly fine-grained, sediments deposited from suspension in a relatively deep water column, probably far below storm wave base. The microfaunas of agglutinated foraminfera are indicative of upper bathyal depths. The thick bedded nature of the background mudstones indicates that at the onset of Grindhval deposition, the background sedimentation was more or less uninterrupted for long periods of time between each turbidity current event.

A 13 cm bed of bioturbated chalk (Facies F) with *Planolites, Zoophycos* and possibly *Taenidium satanassi* trace fossils is present in the middle part of the Grindhval Member in well 6305/5-1 and rests, with a sharp base, on top of a high density turbidite current. In spite of its relative thinness, this chalk and others recognised in well 6305/8-1 are correlatable in other wells on the field where core is available. Gjelberg *et al.* (2001) interpreted this rare bed as being deposited under suspension in a brief period favourable for the production of coccoliths (and planktonic foraminifera).

According to Gjelberg *et al.* (2001), the upper part of the Grindhval Member contains more or less the same facies as in the lower part of the succession, with alternating high-density currents (Facies A) and green and dark-grey mudstones (Facies D). The main difference is that the individual turbidites are thicker, are commonly amalgamated and are separated by thinner mudstone intervals between the turbidites. This suggests that the frequency between each individual turbidite event increased.

Towards the top of the Grindhval Member and located at the K/C boundary in well 6305/5-1 (between 2779.65m- 2780m uncorrected core depths) is an atypical, relatively thick, deformed sandstone with contorted bedding and broken sandstone fragments that is commonly associated with sand injection (Facies G).

Overlying the sandstones of the Grindhval Member, at a level just above the K/C boundary is an interval of hemipelagic black and dark grey, non-calcareous mudstones with millimetre- scale thin laminae of silt or fine grained sandstones (Facies E). These 'pin-stripped mudstones', as they have been known, are distinct from the green mudstones developed both above and below this facies and the degree and diversity of bioturbation is generally low (BI 1 to 2) with only rare *Planolites* traces. This distinct facies and interval separates the Grindhval Member from the overlying Egga Member in the basal part of the Paleocene succession and appears to be a deep water and high latitude expression of the C/T boundary event or some significant change in basin physiography. Irrespective of its depositional origin, this interval provides a distinctive lithological feature to distinguish sandstones of the Cretaceous Grindhval Member from those of the overlying Paleocene Egga Member.

4. Cromer Knoll, Chalk and Shetland Groups in the North Sea (UK and Norwegian Sectors)

Geographic and Stratigraphic overview

The North Sea in this chapter encompasses both the UK and Norwegian sectors. Local geographic and structural nomenclature as utilized by petroleum industry is assembled in Figures 4.1 - 4.3 for the UK, and in the southern half of Figure 3.1 for Norway. Figures 4.4 and 4.5 provide schematic litho-chronograms contributed to the Norlex website; these sketches provide insight in facies distribution of units dealt with. The figures are not discussed in any detail.

This second lithostratigraphic part of the guide, contributed by C.N. Waters, F.M.Gradstein, M.Charnock and L.Vergara, provides a revision and update of the lithostratigraphy of the Cromer Knoll, Shetland and Chalk Groups for the UK and Norwegian North Sea. An abundance of recent well and seismic data sheds new light on terminology, lithology, provenance, geographic distribution, depositional environment, biostratigraphy and age of the many rock units in the Cromer Knoll and Shetland Groups, used widely in the search for oil and gas.

While finer siliciclastic units largely remain as previously defined, newly discovered sandstone/siltstone units are described; chalk units in the Chalk Group of the southern North Sea get updated definitions. With these lithostratigraphic refinements the Cromer Knoll-, Shetland- and Chalk Groups of the Norwegian sector now consist of 30 formations and 1 member, spanning Cretaceous through Danian.

The revisions are of three different types:

- Re-definition of groups and formations
- Re-definition of lithological criteria
- Introduction and definition of member

The present study thus updates the Norwegian lithostratigraphic bulletins of the nineteen eighties for the Norwegian and North Seas.

The internet site *www.nhm2.uio.no/norlex* provides an interactive digital version of this study, with links to well data, biozonations and core archives.

The contribution for the UK Sector offshore lithostratigraphy for the Cromer Knoll, Chalk and Shetland groups is sourced from two key reference reports, produced under the editorship of R.W.O'B Knox and W.G. Cordey for the member companies of the UK Offshore Operators Association (UKOOA).

The standard lithostratigraphical scheme for the Cretaceous succession of the Central and Northern North Sea was produced by Johnson & Lott (1993), representing an update on the pre-existing scheme of Deegan & Scull (1977). The equivalent report for the Southern North Sea, but covering Post-Triassic successions, was produced by Lott & Knox (1994), representing an update of Rhys (1974). Both of these UKOOA volumes, plus additional ones covering other parts of the stratigraphical column and offshore areas other than the North Sea, still present the formal definitions of the units covered (summarised in Table 4.1). They are available for download at *www.bgs.ac.uk/downloads/browse.cfm?sec=1&cat=195* and summary Lexicon entries are to be included in the online British Geological Survey (BGS) Lexicon of named rock units *www.bgs.ac.uk/Lexicon/*. This report reproduces these definitions with only minor modification. However, where units extended between the two areas covered by the two volumes, different definitions were provided for each area, resulting in no definitive description for such units. This aspect is addressed in this report by unifying the definitions. Numerous minor sandstone member units of UK formations are listed in the text but not enlarged upon with descriptions. Their usage often is informal and details are complex and not well known.

This work was in part undertaken for the Cromer Knoll Group by I.P. Wilkinson to form the basis of revised definitions in the BGS online Lexicon. This exercise has also been carried out for the Chalk Group; the Shetland Group is only present in the Northern North Sea and definitions of component formations are

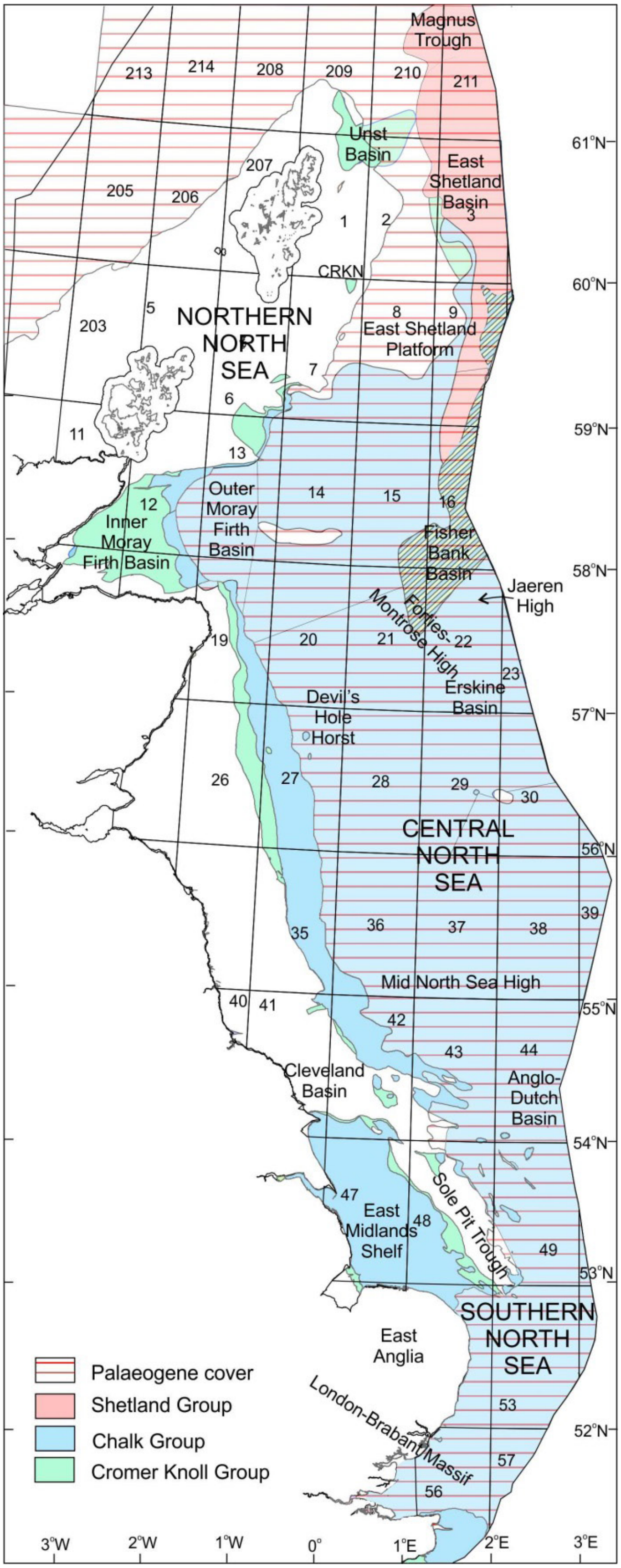


Figure 4.1. Geological map showing the distribution of the Cromer Knoll, Chalk and Shetland Groups in the UK sector of the North Sea at crop and beneath Paleogene and Quaternary strata. The map is 1:250,000-resolution; data sourced from BGS DiGRock 250k_v3.

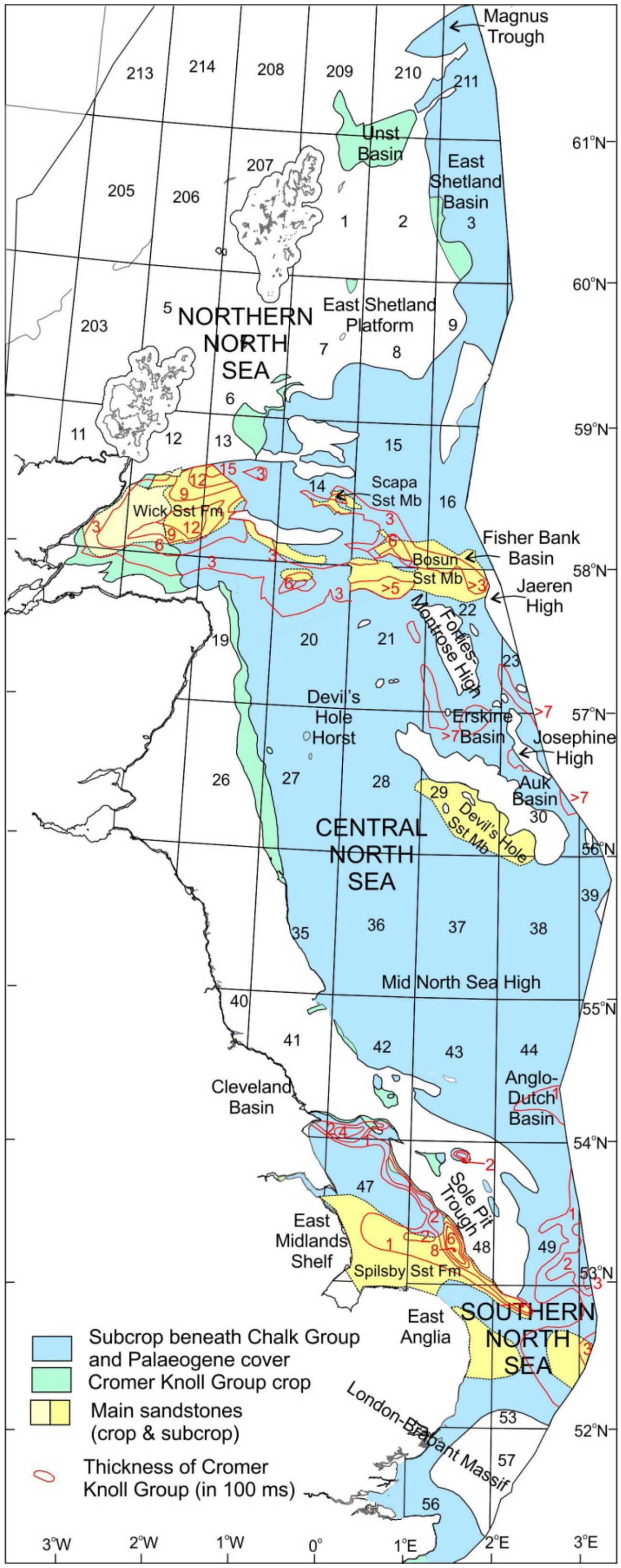


Figure 4.2. Distribution and thickness of the Cromer Knoll Group and main component sandstones (derived from Cameron *et al.*, 1992, fig. 79; Gatliff *et al.*, fig. 39; Andrews *et al.*, 1990, fig. 34; Johnson *et al.*, 1993, fig.47).

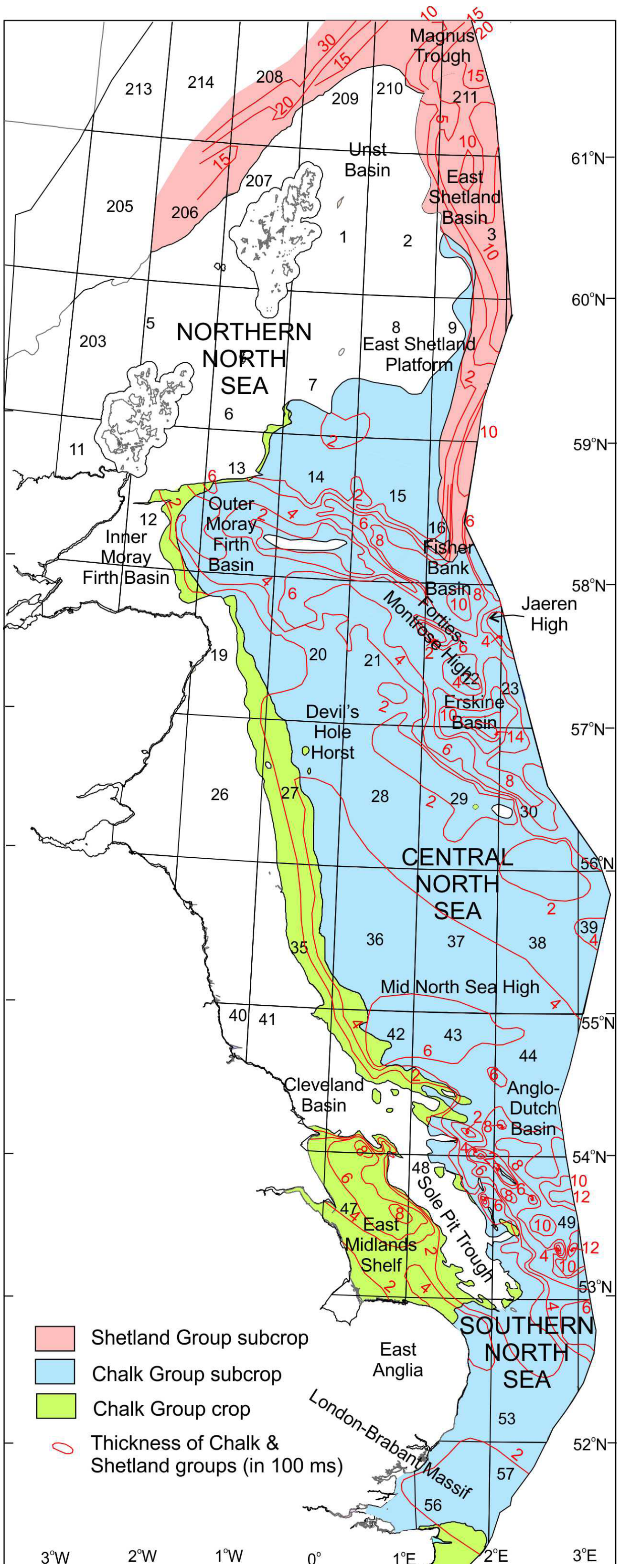


Figure 4.3. Distribution and thickness of the Chalk and Shetlands Groups (derived from Cameron *et al.*, 1992, fig. 82; Gatliff *et al.*, fig. 43; Andrews *et al.*, 1990, fig. 38; Johnson *et al.*, 1993, fig. 50).

restricted to the area covered by Johnson & Lott (1993). Additional information provided in a series of BGS offshore regional reports was also consulted. These reports cover the Northern North Sea (Johnson *et al.*, 1993), Moray Firth (Andrews *et al.*, 1990), Central North Sea (Gatliff *et al.*, 1994) and Southern North Sea (Cameron *et al.*, 1992).

The areas of study of the UKOOA volumes were limited to the UK Sector of the North Sea and no comprehensive comparison with lithostratigraphical schemes used in the adjacent sectors of Norway, Denmark, Germany and the Netherlands was carried out. In the summary provided here, correlation with the onshore UK lithostratigraphy is indicated.

The biostratigraphic marker scheme used is that of Wilkinson, Hine & Riding (in Johnson & Lott, 1993) and does not aim to be definitive, but selects microfossil events commonly and consistently used by industry, as they are well known and easily identifiable (Table 4.1). They are defined in this account in terms of first downhole occurrences (FDOs), or in some cases as downhole acme occurrences. The main biomarkers include the following: 1) calcareous nannofossils, mainly recognized by Sissingh (1977), Perch-Nielsen (1979, 1983, 1985), with the schemes outlined by Jakubowski (1987) for the Lower Cretaceous and Mortimer (1987) for the Upper Cretaceous were considered most relevant to the UKOOA studies; 2) dinoflagellate cysts summarised and illustrated by Costa & Davey (1992); and 3) foraminifera summarised and illustrated by Hart *et al.* (1989) notably for the North Sea Basin by King *et al.* (1989).

Cromer Knoll Group (UK Sector)

Introduction

The Cromer Knoll Group in the North Sea is essentially a Lower Cretaceous argillaceous unit (Table 4.1). The group was erected by Rhys (1974) to embrace three marine, arenaceous, argillaceous to marly formations of mainly Early Cretaceous age recognisable onshore and offshore. Deegan & Scull (1977) formally defined the group to include the sediments between the underlying Humber Group and Bream Formation and the overlying Shetland and Chalk groups. The Cromer Knoll Group is partly equivalent to the Speeton Clay Formation together with the Red Chalk Formation of the UK Sector (Rhys 1974).

Name

From the Cromer Knoll buoy in the southern North Sea. Named by Deegan & Scull (1977).

Type area

The type area is in the Southern North Sea (Figure 4.1). Rhys (1974) used UK well 48/22-2 to illustrate a typical section of the group, and Deegan & Scull (1977) used UK wells 29/25-1, 22/1-2A and 3/29-1, and Norwegian well 2/11-1.

Thickness

The thickness of the group varies considerably since the sediments were deposited in response to an active Late Jurassic tectonic phase. The group is thickest, exceeding 1500 m, in the Inner Moray Firth Basin (Figure 4.2), adjacent to the Little Halibut Fault (Andrews *et al.*, 1990). In the Magnus Trough, Northern North Sea, well 210/15-4 proved over 1590 m of Lower Cretaceous strata (Johnson *et al.*, 1993). In the Witch Ground Graben and Ettrick Basin the group is more than 900 m thick (Andrews *et al.*, 1990). In the Viking Graben, the Asta Graben and locally in the Central Trough the thickness is often more than 600 m, (e.g., 653 m recorded in well 2/11-1) gradually thinning towards the basin margins (Johnson & Lott, 1993). The average thickness in the Central North Sea is generally between 91 and 244 m (Deegan & Scull, 1977).

Lithology

The Cromer Knoll Group consists mainly of fine-grained, argillaceous, marine sediments with a varying content of calcareous material. Calcareous claystones, siltstones and marlstones dominate, but subordinate layers of limestone and sandstone occur. The claystones are generally light to dark grey, olive-grey, greenish and brownish, often becoming light grey, light greenish-grey and light olive-grey marlstones. Mica, pyrite and glauconite are common. Generally, marlstones become the more dominant lithology in both the upper and lower parts of the group.

Characteristics of the lower boundary

The lower boundary is usually well defined and is recognised by a distinct decrease in gamma-ray response and an increase in velocity when passing upward from the generally more organic-rich shales of the underlying Upper Jurassic Kimmeridge Clay Formation to the overlying Spilsby Sandstone Formation (e.g., 48/22-2) or Valhall Formation (e.g., 47/9-1).

Characteristics of the upper boundary

South of approximately 59° N, the upper boundary is the base of the chalk facies of the Chalk Group, defined by the onset of a decrease in gamma-ray response and an increase in velocity into the overlying carbonates. The uppermost Rødby Formation of the Cromer Knoll Group often appears on logs as a transition between the overlying carbonates of the Chalk Group and the more argillaceous parts of the Cromer Knoll Group. Further north, the upper boundary is the base of the siliclastic facies of the Shetland Group. This boundary is normally also shown by a decrease in gamma-ray response and an increase in velocity when passing into the overlying, generally more calcareous, Svarte Formation of the Shetland Group.

Distribution

Extensively across the UK Sector of the Southern, Central and Northern North Sea at outcrop or beneath Cenozoic deposits (Figures 4.1 and 4.2).

Age

Berriasian to Albian (Table 4.1).

Depositional environment

Open marine, with generally low energy.

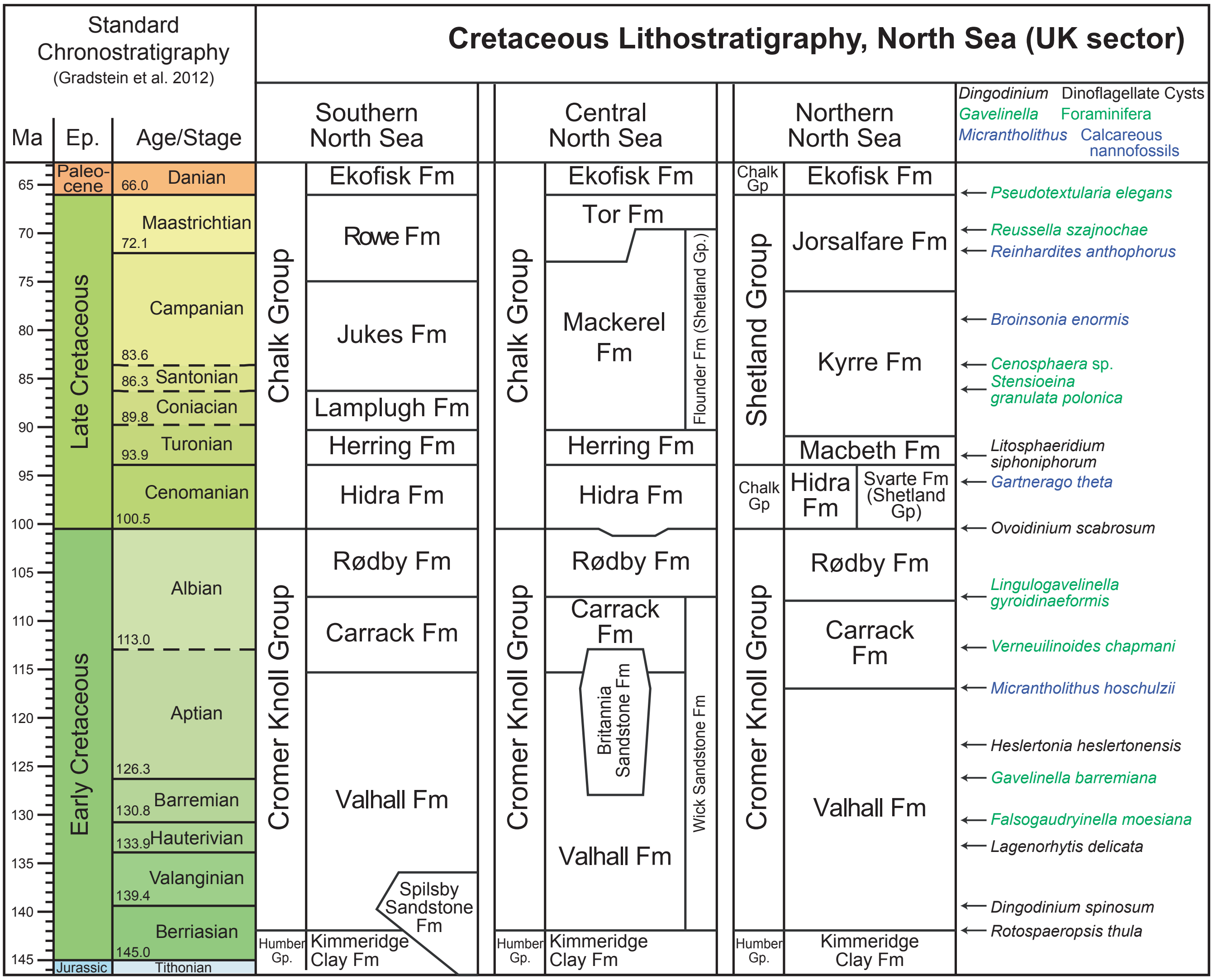


Table 4.1 Cretaceous lithostratigraphical schemes for the UK Sectors of the Southern North Sea (after Lott & Knox, 1994), Central and Northern North Sea (after Johnson *et al.*, 1993). The standard Cretaceous chronostratigraphy used is that of Gradstein *et al.* (2012). Key dinoflagellate cyst, calcareous nannofossil and foraminiferal markers are shown.

Subdivision

Several formations are recognized within the group in the North Sea (Table 4.1). In ascending order the Cromer Knoll Group includes the Valhall, Carrack and Rødby formations extending across the Northern, Central and Southern North Sea. More arenaceous units include the Spilsby Sandstone Formation of the Southern North Sea, Britannia Sandstone Formation of the Central North Sea and Wick Sandstone Formation of the Moray Firth (Table 4.1).

Valhall Formation (Cromer Knoll Group)

Introduction

The term Valhall Formation was introduced by Deegan & Scull (1977, p.24) in the Norwegian Central North Sea. The usage of the term Valhall Formation was redefined by Johnson & Lott (1993) for the Central and Northern North Sea areas, and extended into the southern North Sea area by Lott & Knox (1994), emphasising the continuity of the sequence over the North Sea as a whole (Figure 4.1).

The Valhall Formation (together with the Carrack Formation) replaces the term Speeton Clay Formation, introduced by Rhys (1974), for the unit of grey to black, calcareous mudstone and chalky mudstone of early Cretaceous age. The Valhall Formation therefore forms only the lower part of the Speeton Clay Formation as originally defined by Rhys (1974).

Name

From the Valhall Field in the Norwegian Central North Sea (Deegan & Scull, 1977, p.24).

Lithology

The Valhall Formation consists of olive-grey to dark grey to black calcareous mudstones, with occasional off-white chalky mudstones and thin limestones (Lott & Knox, 1994). Local sandstones and conglomerates also occur in the Central and Northern North Sea (Johnson & Lott, 1993). The mudstones and chalky mudstones are soft to firm or firm to hard, blocky, locally sandy and silty, micromicaceous, glauconitic, pyritic and carbonaceous. They are generally pale to dark grey but locally black, grey-green and red-brown. Thin, but widespread units of black, laminated, non-calcareous mudstone are developed at two levels ('Munk Marl Bed' and 'Fischschiefer'). Limestones are hard to soft, microcrystalline or argillaceous and locally microlaminated or sandy; white to pale grey, but locally tan and yellow-orange or red-brown. Locally, particularly on palaeohighs, where condensation occurs, lithologies are predominantly limestones, argillaceous limestones and chalky mudstone. Sandstones are fine- to coarse-grained, calcareous and locally pass into conglomerates (some sandstones have been given formal status: Devil's Hole Sandstone, Scapa Sandstone, Sloop Sandstone, Yawl Sandstone members). In some areas of the Southern North Sea, bentonite horizons occur (Lott & Knox, 1994).

Thickness

The maximum thickness of about 1000m is attained in the Central North Sea, although thicknesses of up to about 1800 m are indicated by seismic data (Gatliff *et al.*, 1994). In general the formation is <100m in thickness over most of its subcrop area of the Southern North Sea (Lott & Knox, 1994). However, in rim synclines marginal to major salt diapirs and along the Dowsing Fault Zone thicknesses in the order of c.500m have been proved e.g. 53/2-5; Cameron *et al.*, 1992). Up to 400m of strata, bounded at base and top by unconformities, is present in the Unst Basin of the Northern North Sea (Johns & Andrews, 1985) and up to 800 m in the Outer Moray Firth (Andrews *et al.*, 1990).

Geographical distribution

The Valhall Formation is widely distributed across the UK Sector of the Central and Southern North Sea Basin but thins, both to the north and south, onto the Mid-North Sea and Anglo-Brabant highs respectively (Lott & Knox, 1994). Eastwards the formation thickens into the Cleaver Bank Basin. Comparable strata of Valanginian to mid Barremian age are recognized in the Unst Basin of the Northern North Sea (Johns & Andrews, 1985).

Type well

Well name: N2/11-1 (Norwegian Sector)
WGS84 coordinates:
Lat. 56°14'17"N Long. 03°27'07"E
UTM coordinates: 6232804.37 N 528015.41 E
UTM zone: 31
Drilling operator name: Amoco Norway Oil Company
Completion date: 03.10.1969
Status: P & A
Interval of type section and thickness in type well: c. 2954 m to 3539 m (9691 - 11610 ft) below KB (revised depths; Johnson & Lott 1993). Deegan & Scull (1977, p.24, fig. 29) placed the formation boundaries at 2910 m (9548 ft) and 3540 m (11610 ft) below KB.

UK Reference wells

Central and Northern North Sea (Johnson & Lott, 1993)
14/4-1: 1329 -1754.5 m (4360-5756 ft)
Lat. 58°59'52"N Long. 00°23'44"W
14/20-8: 2771.5 - 3058 m (9092 -10032 ft)
Lat. 58°24'41.3"N Long. 00°06'20.9"W
16/12b-6: 4126.5 - 4367.5 m (13538 -14329 ft)
Lat. 58°37'23.076"N Long. 01°20'57.813"E
29/3-1: 3401 - 3859 m (11158 - 12660 ft)
Lat. 56°50'22.195"N Long.01°33'59.090"E

Central and Northern North Sea (Johnson & Lott, 1993)
42/13-1: 839 - 1020 m (2752 - 3346 ft)
Lat. 54°36'54.6"E Long. 00°35'13.8"E
48/17-1: 402 - 559 m (1318 - 1835 ft)
Lat. 53°22'09.7"N Long. 01°14'49.6"E
48/22-3: 430 - 553.5 m (1411-1816 ft)
Lat. 53°17'31.3"N Long. 01°15'58.9"E
49/25a-5: 1853 -1957 m (6080 - 6420 ft)
Lat. 53°13'34.6"N Long. 02°49'39.7"E

Upper and lower boundaries

Upper boundary

In the Central and Northern North Sea, the upper boundary is a downward change from dark grey, non-calcareous mudstones (Carrack Formation) to chestnut brown, brick-red, greyish red and pale grey calcareous mudstones, chalky mudstones and limestones. Red stained planktonic foraminifera are also a characteristic element of the upper Valhall Formation.

In the Southern North Sea the upper boundary is defined by a downward change from dark grey to brown, non-calcareous mudstones (Carrack Formation) to pale to dark grey chalky mudstones (Valhall Formation).

In the Outer Moray Firth and South Viking Graben there is a downward change from sandstone (Britannia Sandstone Formation) to calcareous and chalky mudstones (Valhall Formation) (e.g. Well 15/28a-3) and in the Inner Moray Firth there is also a downward change from sandstone (Wick Sandstone Formation) to the mudstones of the Valhall Formation (e.g. wells 13/14-1, 13/17-1 and 13/24-1, Johnson & Lott, 1993).

Lower boundary

In the Central and Northern North Sea, the base of the Valhall Formation is a sharp downward change from pale grey and grey interbedded calcareous mudstones, chalky mudstones and limestones (Valhall Formation) to dark brown-grey, olive-grey or black, variably calcareous to non-calcareous, organic-rich mudstones (Kimmeridge Clay Formation). Locally sandstones of the Valhall Formation rest directly on the Kimmeridge Clay Formation (e.g. Scapa Sandstone Member at 14/19-9 and 14/29a-2, Johnson & Lott, 1993). On some structural highs the Valhall rests on older strata. Locally, on the margins of the Central Graben (e.g. 29/24-1), calcareous sandstones (Devil's Hole Sandstone Member) rests on less calcareous sandstone of the Fulmar Formation.

In the Southern North Sea, the lower boundary of the Valhall Formation is marked by a downward change from dark calcareous mudstones to either sandstones of the Spilsby Sandstone Formation or to harder more variably calcareous olive-grey to black mudstones of the Kimmeridge Clay Formation (Lott & Knox, 1994).

Well log characteristics

On wireline logs the upper boundary of the Valhall Formation Central and Northern North Sea is marked by a sharp downward increase in velocity and density, together with a local small downward decrease in gamma-ray values (e.g. wells 15/23-6A and 15/23a-8 Johnson & Lott, 1993). In the Southern North Sea, there is a corresponding downward decrease in gamma response and increase in velocity (Lott & Knox, 1994).

The base of the Valhall Formation corresponds with a marked downward increase in gamma-ray values and a decrease in velocity on wireline logs. In the Southern North Sea, where the formation is underlain by sandstones there is a marked downward decrease in gamma values and increase in velocity. Where the formation is underlain by mudstones of the Kimmeridge Clay Formation (e.g. 42/13-1) there is a downward increase in gamma and decrease in velocity.

Biostratigraphy

Eleven calcareous nannoplankton biomarkers have been recognized in the Valhall Formation: *Nannoconus abundans, N. borealis, Stradnerlithus comptus,* *Tegulalithus septentrionalis, Tegulalithus septentrionalis* (acme), *Cruciellipsis cuvillier, Corolithion silvaradion, Eprolithus antiquus, Micrantholithus speetonensis, Sollasites arcuatus* and *Nannoconus* sp. (discs) (Johnson & Lott, 1993; Lott & Knox, 1994). Of the foraminifera, the following biomarkers occur: *Hedbergella infracretacea, Gavelinella barremiana*, small *Hedbergella* sp. (acme), *Epistomina caracolla, Gavelinella sigmoicostata, Falsogaudryinella moesiana, Ammovertella cellensis* and *Haplophragmoides* spp. (at the base of the formation; Lott & Knox, 1994). Of the ostracods, the FDOs of the following form useful biomarkers within the formation: *Protocythere intermedia, Protocythere triplicata, Paranotacythere inversa costata, Paranotacythere diglypta diglypta, Mandocythere frankei frankei, Protocythere hannoverana* and *Galliaecytheridea teres* (Lott & Knox, 1994). Valhall Formation dinoflagellate cyst floras are abundant, well preserved and diverse. The following biomarkers are present in the formation: *Ctenidodinium elegantulum, Batioladinium longicornutum, Kleithriasphaeridium corrugatum, Nematosphaeropsis scala, Lagenorhytis delicatula, Endoscrinium pharo* and *Dingodinium spinosum* (Lott & Knox, 1994).

Age

Late Berriasian to intra Late Aptian.

Correlation

The Valhall Formation as defined by Lott & Knox (1994), equates with part of the Speeton Clay Formation of the Cleveland Basin and the lithologically more varied marine Lower Cretaceous successions of the East Midlands and north Norfolk (Rawson, 1992).

Depositional environment

The calcareous mudstones of the Valhall Formation were deposited as hemipelagic muds in an offshore, low-energy, oxygenated marine setting (Lott & Knox, 1994). The mudstones are calcareous with abundant and varied macro- and microfaunal assemblages. Occasional off-white coccolith-rich, pelagic chalks are developed at some levels. A thin basal unit of anoxic mudstones is present in a cored sequence from the Southern North Sea (Lott *et al.* 1989) and particularly during deposition of the Munk Marl and Fischschiefer (unit V5) (e.g. Crittenden *et al.* 1991; Riley *et al.* 1992). In the Witch Ground Graben, sandstone members, e.g. Scapa Sandstone Member (Figure 4.2) mark active rifting, when submarine fan deposits accumulated in half-grabens (Harker & Chermak 1992). The Devil's Hole Sandstone Member (Figure 4.2) has been interpreted as a possible shallow marine deposit (Gatliff *et al.* 1994). Sporadic volcanic activity around the basin margins is apparent from the presence of thin bentonite horizons throughout the succession (Lott *et al.* 1985, 1986).

Subdivision

Harker *et al.* (1987) and Riley *et al.* (1992) defined formal members within the Valhall Formation. The Scapa Sandstone Member was defined Harker *et al.* (1987) in the Scapa Field of the Witch Ground Graben, with the definition revised and expanded to include more extensive and coeval mass-flow sandstones and laterally equivalent conglomerates in the Witch Ground Graben (Johnson & Lott, 1993). Riley *et al.* (1992) correlated thinly laminated, organic-rich mudstones of intra-early Aptian age in the North Sea Graben with similar, possibly coeval deposits of the 'Fisch-Schiefer' in the Lower Saxony Basin and gave it formal status as the Fischschiefer Member, used informally by Johnson & Lott (1993).

In the Central and Northern North Sea the formation has been divided into seven informal units (V1 to V7) based upon wireline-log responses that can be correlated across a wide area of the Central North Sea and South Viking Graben (e.g. Bisewski 1990, Crittenden *et al.* 1991) and fully described by Johnson & Lott (1993). Thicker, more widespread sandstone bodies have been defined as four formal members (Johnson & Lott, 1993): Devil's Hole Sandstone, Scapa Sandstone, Sloop Sandstone and Yawl Sandstone members. Gatliff *et al.* (1994) recognized the Devil's Hole Sandstone as a formation.

In the Southern North Sea, no formal subdivision of the Valhall Formation was presented by Lott & Knox (1994). However, the presence towards the top of the formation, of a prominent, thin, low gamma/high velocity chalky unit, beneath which a marked gamma spike may sometimes be developed (e.g. 49/25a-5; 44/24-1) suggests a possible correlation with the V6 and V5 ('Fischschiefer') units respectively, recognized more consistently in the Valhall Formation sequences of the Central North Sea area. Other chalky developments also occur, notably the thin unit at the base of the formation (?V1 equivalent), but are not formally named.

Spilsby Sandstone Formation (Cromer Knoll Group)

Introduction
The term Spilsby Sandstone Formation was introduced by Rhys (1974) for a unit of fine grained marine sandstones that lay between the Speeton Clay Formation (Cretaceous: now renamed Valhall Formation) calcareous mudstones above and Kimmeridge Clay Formation (Jurassic) variably calcareous mudstones below.

Name
From the village of Spilsby in Lincolnshire (Rhys 1974).

Lithology
The Spilsby Sandstone Formation consists of grey to white, poorly to well-cemented, very fine to medium grained sandstone, with thin interbeds of green to blue-green, firm to fissile mudstone. Glauconitic grains and phosphatic nodules commonly occur (Lott & Knox, 1994) and calcareous concretions occur at certain levels (Cameron *et al.*, 1992).

Thickness
The formation is generally thin (<50 m) over most of its subcrop area of the Southern North Sea (Figure 4.2) but thickens substantially along the western margin of the Sole Pit Inversion (Dowsing Fault zone) to >250 m (e.g. 53/2-5, Lott & Knox, 1994). Onshore, the formation has a maximum thickness of 200 m on the East Midlands Shelf and onto the Anglo-Brabant Massif (Cameron *et al.*, 1992).

Geographical distribution
The Spilsby Sandstone Formation is largely restricted to the southwestern margins of the Southern North Sea basin over the East Midlands Shelf and onto the northern flank of the London-Brabant Massif (Figure 4.2). Isolated occurrences of basal Cretaceous sandstones have been proved further eastwards in wells 50/16-1 and 54/1-2 (Lott & Knox, 1994).

Type well
Well name: 48/22-2
WGS84 coordinates:
Lat. 53°15'39.5"N Long. 01°22'35"E
(Rhys, 1974, pp. 79, fig. 7, table 5)
UTM coordinates:
UTM zone: 31
Drilling operator name: BP Exploration Operating Company Limited
Completion date: 28.01.1968
Status: P & A
Interval of type section and thickness in type well: 417 - 435 m (1368 - 1427 ft- amended depths by Lott & Knox, 1994).

UK Reference wells
Southern North Sea (Lott & Knox, 1994)
14/17a-2: 661 - 792 m (2170 - 2600 ft)
Lat. 53°24'35.90"N Long. 01°22'31.19"E
48/23-1: 769 - 905.5 m (2523 -2971 ft)
Lat. 53°12'57"N Long. 01°03'03"E
53/2-5: 836 -1104 m (2744 - 3622 ft)
Lat. 52°52'58.193"N Long. 02°14'27.706"E

Upper and lower boundaries
Upper boundary
The upper boundary of the Spilsby Sandstone Formation is defined by a marked downward change from calcareous mudstone of the Valhall Formation to sandstone lithologies (Lott & Knox, 1994).

Lower boundary
The lower boundary of the Spilsby Sandstone Formation is defined by a downward change from variably cemented sandstones to dark, variably calcareous mudstone lithologies of the Kimmeridge Clay Formation (Lott & Knox, 1994).

Well log characteristics
The upper boundary of the Spilsby Sandstone Formation corresponds with a reduction in the gamma-ray values and generally higher, irregular sonic log profile,

the latter related to the amount of carbonate cement present (Lott & Knox, 1994). Prominent gamma-ray spikes within and at the base of some sequences represent pebbly phosphatic horizons (e.g. 48/23-1 Lott & Knox, 1994). There is a corresponding marked increase in gamma values and the velocity becomes generally more regular at the lower boundary (Lott & Knox, 1994).

Biostratigraphy

Biostratigraphic data suggests that the lower part of the formation may span the Jurassic/Cretaceous boundary, as occurs in the equivalent onshore sandstone sequences of eastern England (Lott & Knox, 1994). The Spilsby Sandstone Formation yields variably abundant dinoflagellate cyst assemblages. The *Rotosphaeropsis thula* biomarker occurs within the formation (Lott & Knox, 1994).

Age

Tithonian (Volgian/Portlandian) to Valanginian (Table 4.1).

Correlation

The Spilsby Sandstone Formation equates, at least in part, with the sandy Spilsby and Sandringham formations of eastern England (Rawson *et al.* 1978) which range from Tithonian (Ryazanian) to Valanginian in age. In the UK Sector of the Central North Sea area partly equivalent basal Cretaceous sandstone developments are termed the Devil's Hole Sandstone Member (Figure 4.2) of the Valhall Formation (Johnson & Lott 1993).

Depositional environment

The Spilsby Sandstone Formation was deposited on the southern fringes of a well-oxygenated shallow marine shelf (Cameron *et al.*, 1992; Lott & Knox, 1994).

Subdivision

An informal subdivision into two units is possible with the lower unit (SP1) containing more mudstone interbeds than the upper, massive sandstone interval (SP2) (e.g. 48/17a-2, Lott & Knox, 1994).

Wick Sandstone Formation (Cromer Knoll Group)

Introduction

The Wick Sandstone Formation was proposed by Johnson & Lott (1993) for a thick unit of mass-flow sandstones, interbedded with siltstones and mudstones, in the Inner Moray Firth. These strata were not included in the formal nomenclature of Deegan & Scull (1977), although they were informally assigned to the 'Valhall Formation' or as the 'Wick Member of the Valhall Formation' informally in some oil company reports. 'Devil's Hole Formation' was used as an informal term in the Beatrice Field by Stevens (1991) for sandstones present between the Kimmeridge Clay and Valhall formations.

Name

From the Caithness town on the northeast coast of Scotland.

Lithology

The Wick Sandstone Formation comprises mainly sandstones with interbedded siltstones and mudstones. The sandstones are very fine- to coarse-grained, pebbly, generally poorly consolidated, locally argillaceous and poorly sorted. They are pale grey to grey brown, dominantly quartz sandstones. Glauconite grains, carbonaceous debris and lignite are widespread and calcareous concretions are common (Johnson & Lott, 1993).

The Mudstones and siltstones are similar to those of the Valhall formation. They are generally calcareous, medium to dark grey, occasionally pale grey, grey-brown, red-brown and grey-green. They are micromicaceous, pyritic, glauconitic and blocky. Sporadic, thin, white to tan, argillaceous, microcrystalline limestones occur.

Thickness

The Wick Sandstone Formation is thickest on the downthrown side of the Wick Fault (Figure 4.2), with 1400 m recorded in 13/11-1 (Johnson & Lott, 1993).

Geographical distribution

The Wick Sandstone Formation is present in the Inner Moray Firth and extreme northwestern margins of the Halibut Shelf and Halibut Horst (North Sea Quadrants 11-14 and 17). It is limited to the north by the Wick Fault (Figure 4.2).

Type well

Well name: 12/30-1

WGS84 coordinates:

Lat. 58°08'05.3"N   Long. 02°05'52.0"W

UTM coordinates:

UTM zone: 30

Drilling operator name: BHP Petroleum Limited

Completion date: 15.08.1974

Status: P & A

Interval of type section and thickness in type well: 962 - 991 m (3156-3251 ft), 1366-1405 m (4482-4610 ft) and 1457-1556 m (4780-5105 ft) below KB.

UK Reference wells

13/12-1: 1045.5 - 2144 m (3430-7034 ft)

Lat. 58°31'51"N   Long. 01°44'26"W

Upper and lower boundaries

Upper boundary

The top of the formation is usually taken at a downward change from argillaceous lithologies (Carrack Formation) to sandstones with interbedded siltstones and mudstones (Wick Sandstone Formation). It does not necessarily coincide with the top of the highest thin sandstone in the Cromer Knoll Group, but is placed at the top of the sandstone-rich section. Where the Wick Sandstone Formation is divisible into members a vertical succession of up to three formation tops are possible where strata of the Carrack or Valhall formations overlie the sandstone of the three members (Johnson & Lott, 1993).

Where the formation is undivided or where the Captain Sandstone Member (the highest member) is present, the top is normally taken at a downward change from dark grey, non-calcareous to slightly calcareous, low-velocity mudstone (Carrack Formation) to sandstones and interbedded mudstones (e.g. Well 12/30-1 and 13/11-1, Johnson & Lott, 1993). Locally, however, the Captain's Member is overlain by the Valhall Formation (e.g. Well 13/13-1 and 13/14-1, Johnson & Lott, 1993). Where the Captain Sandstone Member is absent, the Valhall Formation rests on the Wick Sandstone

Formation (e.g. Well 13/29-2, Johnson & Lott, 1993).

Lower boundary

The lower boundary is normally taken at a downward change from sandstones with interbedded siltsones and mudstones (Wick Sandstone Formation) to argillaceous strata (Valhall Formation). Where the formation can be divided into members, there are up to three formation bases where Wick Sandstone Formation rests on argillaceous deposits of the Valhall Formation. The base of the Wick Sandstone Formation does not necessarily coincide with the base of the lowest thin sandstone in the Cromer Knoll Group, but is placed at the base of the sandstone-rich sequence (Johnson & Lott, 1993). Locally the Wick Sandstone rests on interbedded sandstones and mudstones of the Kimmeridge Clay Formation (e.g.13/30-1). The lower boundary is then difficult to place on lithological criteria, although mudstones of the Wick Sandstone Formation are generally more calcareous and less carbonaceous than those of the Kimmeridge Clay Formation.

Well log characteristics

The Wick Sandstone Formation displays both blocky and serrated signatures on wireline logs, reflecting the massive sandstones units and thinly interbedded sandstones and mudstones units, respectively. Calcareous concretions give high velocity spikes on wireline logs. On wireline logs the lower boundary is marked by a downward increase in average gamma-ray values and a decrease in average velocity and the upper boundary is taken at a sharp downward decrease in gamma-ray values and an increase in velocity (Johnson & Lott, 1993).

Biostratigraphy

The microbiotas in the proximal area may be abundant compared to those in the distal parts of the unit (Johnson & Lott, 1993). Calcareous nannofossils are found throughout and the following biomarkers have been identified: *Micrantholithus hoschulzii* / *Micrantholithus obtusus* and *Rhagodiscus asper* (acme), *Nannoconus abundans, N. borealis, Stradnerlithus comptus, Tegulalithus septentrionalis, Tegulalithus septentrionalis* (acme), *Cruciellipsis cuvillier, Corolithion silvaradion, Eprolithus antiquus, Micrantholithus speetonensis, Sollasites arcuatus* and *Nannoconus* sp. (discs) (Johnson & Lott, 1993). Dinoflagellate cyst biomarkers include S*ubtilisphaera perlucida, Cerbia tabulate, Ctenidodinium elegantulum, Heslertonia heslertonensis, Hystrichodinium ramoides, Batioladinium longicornutum, Pseudoceratium anaphrissum, Kleithriasphaeridium corrugatum, Hystrichodinium furcatum, Canningia duxburyi, Nematosphaeropsis scala, Batioladinium varigranosum, Lagenorhytis delicatula, Tubotuberella apatela, Endoscrinium pharo* and *Dingodinium spinosum* (Johnson & Lott, 1993). Foraminifera are often patchily distributed and reworking is a problem in some cases. Biomarkers that have been recognized include *Globigerinelloides gyroidinaeformis, Verneuilinoides chapmani, Hedbergella infracretacea, Gavellinella barremiana, Falsogaudryinella moesiana* and *Trocholina infragranulata.*

Age

Berriasian to Albian (Table 4.1).

Correlation

The Wick Sandstone Formation passes laterally into argillaceous strata of the Carrack and Valhall formations (Table 4.1).

Depositional environment

Boote & Gustav (1987) interpreted Lower Cretaceous sandstones in the Inner Moray Firth as laterally extensive turbidites that were largely unconfined by fault topography within the rift. On the basis of the benthic fauna present in the mudstones, Linsley *et al.* (1980) suggested that the Valanginian sandstones in the Beatrice Field (Block 11/30) were deposited in moderately deep water marine channels. In contrast, Bird *et al.* (1987) used seismic profiles to delineate a mound-shaped, southwest-trending, fault-controlled, Lower Cretaceous channel deposit in the Beatrice Field and postulated that this broadened to the southwest into a fan-delta.

Subdivision

In the Inner Moray Firth the formation can be divided into three members (Captain, Coracle and Punt Sandstone members) defined by Johnson & Lott (1993).

Britannia Sandstone Formation (Cromer Knoll Group)

Introduction
The term Britannia Sandstone Formation was introduced by Johnson & Lott (1993). The formation was formerly known as the Kopervik Formation (informal in oil company reports; Bisewski, 1990; Guy, 1992), the Bosun Sands (informal oil company reports; Andrews *et al.*, 1990) and Bosun Sand Member, Sola Formation (Crittenden *et al.*, 1991).

Name
Named by Johnson & Lott (1993) after the Britannia Field in block 15/30, where the formation is a hydrocarbon reservoir.

Lithology
The formation comprises sandstones with interbedded mudstones. Sandstones are pale grey or tan and mainly fine- to medium-(locally coarse) grained. They vary from hard to friable, with patchy calcareous cement. Interbedded mudstones are typical of the Valhall and Carrack formations, into which they laterally pass.

Thickness
Up to 180m in the Fisher Bank Basin (Johnson & Lott, 1993).

Geographical distribution
The formation occurs in the southeast of the Outer Moray Firth, extending westwards into the Glenn Horst, and is most thickly developed in the Fisher Bank Basin (Quadrants 15-16, 21-22) of Central North Sea. The formation onlaps the Fladen Ground Spur, which is believed to have been a source area for the sands, along with the Glenn Horst and Jaeren High (Johnson & Lott, 1993).

Type well
Well name: 15/30-9
WGS84 coordinates:
Lat. 58°03’44.162”N Long. 00°56’42.070”E
UTM coordinates:
UTM zone: 31
Drilling operator name: Conoco (UK) Limited
Completion date: 02.09.1991
Status: P & A
Interval of type section and thickness in type well: 4027 - 4124.5 m below KB (13212-13764 ft) (Johnson & Lott, 1993).

UK Reference wells
Central North Sea (Johnson & Lott, 1993)
16/26-16: 3995 - 4195.5 m (13106-13764 ft)
Lat. 58°02’18.42”N Long. 01°07’06.45”E
21/2-6: 3342 - 3450 m (10964-11319 ft)
Lat. 57°58’07.184”N Long. 00°12’29.786”E
22/3a-1: 4140 - 4200 m (13583-13779 ft)
Lat. 57°58’50.05”N Long. 01°29’21.68”E

Upper and lower boundaries
Upper boundary
The upper boundary is normally defined by the downward change from mudstones (Carrack Formation) to sandstones (Britannia Sandstone Formation). Locally the Britannia Sandstone Formation is overlain by the Valhall Formation (e.g.22/1a-3, Johnson & Lott, 1993).

Lower boundary
The base is usually marked by a downward change from sandstones (Britannia Sandstone Formation) to mudstones and chalky mudstones (Valhall Formation). Locally (e.g. Well 16/27a-2, Johnson & Lott, 1993), the Britannia Sandstone Formation rests unconformably on the Valhall Formation.

Well log characteristics
The thick, massive sandstones display a blocky wireline log signature; the thinly interbedded sandstones and mudstones are characterised by serrated motifs and the upward fining units have gradually upward increasing gamma values. On wireline logs, the upper boundary is shown by low velocity of the mudstones to higher velocities of the sandstone and a downward decrease in gamma-ray values. The base of the formation corresponds with a downward increase in gamma-ray values and a decrease in velocity.

Biostratigraphy
The formation generally yields abundant palynofloras. The *Cerbia tabulata* biomarker occurs in the upper part of the formation, whereas *Ctenidodinium*

elegantulum, Heslertonia heslertonensis, Hystrichodinium ramoides, Batioladinium longicornutum and *Pseudoceratium anaphrissum* biomarkers occur in the lower part. A diverse fauna of agglutinated foraminifera are present at the top of the formation, where the *Verneuilinoides chapmani* biomarker is recognized (Johnson & Lott, 1993).

Age

Mid Barremian to late Aptian (Table 4.1).

Correlation

The formation passes laterally into the argillaceous Valhall and Carrack formations (Table 4.1).

Depositional environment

The formation consists largely of marine mass-flow sandstones and interbedded marine mudstones. The presence of small amounts of skeletal debris and glauconite indicates the sands were derived from contemporaneous shallow shelf sands (Downie & Stedman, 1993). Guy (1992) interpreted much of the sandstone succession as representing high and low density turbidites, whereas Downie & Stedman (1993) postulated emplacement mainly as debris flows or liquefied deposits.

Subdivision

In the Kilda Field (Block 16/26), the formation has been divided into six informal sandstone facies (Guy, 1992), but Johnson & Lott (1993) informally subdivide the formation into two (Upper and Lower).

Carrack Formation (Cromer Knoll Group)

Introduction
The term Carrack Formation was first defined by Johnson & Lott (1993) in the Central North Sea area as a unit of dark grey, essentially non-calcareous, marine mudstones lying between the Valhall and Rødby formations. This unit replaces the Sola Formation of Andrews *et al.*, (1990) and Gatliff *et al.* (1994). This unit has now been identified in the southern North Sea area (Lott & Knox, 1994), where it forms the poorly calcareous uppermost part of the Valhall Formation (Speeton Clay Formation as originally defined by Rhys, 1974).

Name
From the large sailing merchant-ship, equipped for warfare.

Lithology
In the Central and Northern North Sea the Carrack Formation comprises essentially non-calcareous, carbonaceous, pyritic, micaceous mudstones and siltstones with local sandstones (Johnson & Lott 1993). Mudstones are medium to dark grey and black (locally red-brown: e.g. Well 14/4-1), firm to hard and blocky to fissile, with some thin, greenish white tuffaceous layers (e.g. Well 15/21a-7 at 3142m; Well 14/20-8 at c. 2698 m). Thin beds of white to buff, microcrystalline, argillaceous limestones, dolomitic limestones and chalky mudstones are interbedded with the mudstones (e.g. Well 14/19-13). Local sandstones are fine- to coarse-grained and each sandstone unit usually displays upward fining. One of these sandstone units has been given member status (Skiff Sandstone Member).

In the Southern North Sea, the Carrack Formation consists of poorly calcareous, occasionally sandy mudstones. The mudstones may be dark grey to red--brown or variegated (Lott & Knox, 1994). Thin sandy beds and phosphatic pebbles may also occur in the unit.

Thickness
The Carrack Formation is generally between 40 and 100 m thick in the Central and Northern North Sea, although it is up to 200 m thick in the Moray Firth (Andrews *et al.*, 1990). The formation thins or is absent over the Forties/Montrose high and Auk Platform areas (Johnson & Lott (1993); it is generally thin (<25 m) over much of the Southern North Sea area (Lott & Knox, 1994).

Geographical distribution
The Carrack Formation, though generally thin is present over much of the Southern North Sea, area (Lott & Knox, 1994), Quadrants 35-39, 41-44, 47-49, 51-54. It is also widely distributed across the Central and Northern North Sea, Quadrants 6-9, 12-16, 19-23, 26-30. The formation may be absent over some intrabasinal highs, (e.g., Forties/Montrose High and Auk Platform) and its western limit is difficult to define on currently available well data (Johnson *et al.*, 1993).

Type well
Well name: 14/20-8
WGS84 coordinates:
Lat. 58°24'41.3"N Long. 00°06'20.9"W
UTM coordinates:
UTM zone: 30
Drilling operator name: Talisman Energy (UK) Limited
Completion date: 07.08.1976
Status: P & A
Interval of type section and thickness in type well: 2670.5 - 2771.5 m (8762-9092 ft) below KB (Johnson & Lott 1993, p.15).

UK Reference wells
Central North Sea (Johnson & Lott, 1993)
Well 15/16-14: 3094 - 3158 m (10151-10361 ft)
Lat. 58°22'11.4"N Long. 00°04'25.3"E
Well 20/8-1: 2251 - 2350 m (7385-7710 ft)
Lat. 57°47'59.7"N Long. 00°29'28.0"W
Well 29/9a-1: 4003 - 4091 m (13133-13421 ft)
Lat. 56°49'51.95"N Long.01°43'20.37"E

Southern North Sea (Lott & Knox, 1994)
44/24-1: 1393 - 1402 m (4570-4600 ft)
Lat. 54°15'09.8"N Long. 02°40'46.22"E
47/9b-6: 666 - 680 m (2185-2231 ft)
Lat. 53°45'24.687"N Long. 00°42'16.713"E
48/22-3: 420.5 - 430 m (1380-1411 ft)

Lat. 53°17'31.3"N Long. 01°15'58.9"E
49/25a-5: 1812-1853 m (5945-6080 ft)
Lat. 53°13'34.6"N Long. 02°49'39.7"E

Upper and lower boundaries

Upper boundary

The top of the formation is normally marked by a downward change from pale to dark grey and red brown calcareous mudstones, chalky mudstones and thin, interbedded limestones (Rødby Formation) to dark grey and black, non-calcareous (or poorly calcareous in the Southern North Sea) mudstones. It is marked by a downward increase in gamma-ray values and a downward decrease in velocity and density (Lott & Knox, 1994). Where the Rødby Formation is absent, the Chalk Group rests unconformably on the Carrack Formation.

Lower boundary

Central and Northern North Sea (Johnson & Lott, 1993): The base is normally taken at the downward change from dark grey-black, non-calcareous and carbonaceous mudstone (Carrack Formation) to chestnut brown, brick red, reddish grey or pale calcareous mudstones and chalky mudstones (Valhall Formation). It is marked on wireline logs by a sharp downward increase in velocity and density. Locally in the Central and Northern North Sea the formation rests on the Wick Sandstone and Britannia Sandstone formations.

Southern North Sea (Lott & Knox, 1994): The base of the Carrack Formation is normally characterized by a sharp downward change from dark, poorly calcareous mudstones to a paler, harder chalky mudstone development at the top of the underlying Valhall Formation. There is a corresponding decrease in gamma values and marked increase in velocity.

Well log characteristics

The mudstones have a low average sonic velocity. The tuffaceous layers correspond to high gamma-ray spikes (e.g. Well 15/21a-7 at 3142 m) and broader peaks (e.g. Well 14/20-8 at c. 2698 m) on wire line logs. Thin beds of limestones, dolomitic limestones and chalky mudstones, interbedded with the mudstones, produce relatively high velocity spikes (e.g. Well 14/19-13). In the Southern North Sea, the local presence of phosphatic pebbles results in occasional high gamma peaks.

Biostratigraphy

The top of the Carrack Formation is dominated by calcareous benthonic foraminifera characteristic of the *Globigerinelloides gyroidinaeformis* biomarker, although the biomarker itself is in the very basal part of the overlying formation, immediately above the Rødby/Carrack formational boundary. Agglutinated foraminifera are characteristic of the middle part of the formation and the *Verneuilinoides chapmani* biomarker is recognized by the influx of a diverse agglutinated assemblage. Near the base of the formation, the *Gaudryina dividens* biomarker, with calcareous benthonic foraminifera and the ostracod *Saxocythere tricostata* have been recorded (e.g. Lott *et al.*, 1985). The *Micrantholithus hoschulzii* / *Micrantholithus obtusus* and *Rhagodiscus asper* acme nannofossil biomarkers have been noted in the Carrack Formation. Dinoflagellate cyst floras from the Carrack Formation are abundant and diverse; the *Subtilisphaera perlucida* and *Cerbia tabulata* biomarkers occur within this formation.

Age

Late Aptian to early Albian (Table 4.1).

Correlation

The Carrack Formation passes laterally westwards into the upper part of the Speeton Clay Formation of the Cleveland Basin. The formation equates in part with the A-beds of the Speeton Clay and further south with the Carstone Formation and Sutterby Marl.

Depositional environment

The poorly calcareous marine mudstones of the Carrack Formation contain a moderately rich microfauna including benthonic foraminifera but dominated by agglutinating species such as *Glomospira* and *Recurvoides* (Crittenden, 1987b) suggesting a phase of basin restriction and bottom-water oxygen depletion. Mudstones with abundant planktonic foraminifera may represent transgressive pulses (Andrews *et al.*, 1990).

Subdivision

The Carrack Formation has the formal subdivision into the late Aptian Skiff Sandstone Member. It comprises fine- to coarse-grained mass-flow sandstone units, commonly displaying upward-fining, located in the South Viking Graben (Johnson & Lott, 1993).

Rødby Formation (Cromer Knoll Group)

The definition of this topmost formation of the group is provided in the description below of the Cromer Knoll Group (Norwegian Sector).

Cromer Knoll Group (Norwegian Sector)

Åsgard Formation (Updated) (Åsgardformasjonen)

Cromer Knoll Group, North Sea (Figures 4.4 and 4.5 and Table 4.2)

Name

Named from Norse mythology after the castle of the Norse gods, where Odin ruled.

Lithology

The formation is dominated by light to dark grey, olive-grey, greenish and brownish, often calcareous claystones, and passes into light grey, light greenish-grey and light olive-grey marlstones and stringers of limestone. Mica, pyrite and glauconite are common. The claystones may be silty, and siltstones or very fine-grained sandstone layers or laminae are present. Where major sandstone layers occur they are regarded as belonging to the Ran sandstone unit, defined below.

In a few Norwegian wells in the Central North Sea (eg. 1/9-3, 2/3-1, 2/7-2, 2/10-1, 2/11-1, 7/3-1, 7/8-2, 7/12-4, 7/12-5 and 8/1-1) a sequence of calcareous claystone, marlstone and limestone interbeds is recognised as the basal part of the Åsgard Formation (Figures 12 and 14 in Isaksen & Tonstad (1989)). This sequence is very difficult to correlate in the Norwegian Sector, even over small distances, and is therefore regarded as representing local variations in the lowermost part of the Åsgard Formation. It might be more useful stratigraphically as a set of local members. In the Danish Sector this sequence is defined as the Leek Member (Jensen *et al.*, 1986).

Thickness

The formation is 492 m thick in the type well 2/11-1, and 608 m thick in reference well 17/11-2. In the Central Trough area the thickness varies from a few metres to more than 500 m over short distances, showing the complex pattern of small, restricted Early Cretaceous basins.

An even thicker Åsgard unit was penetrated in the

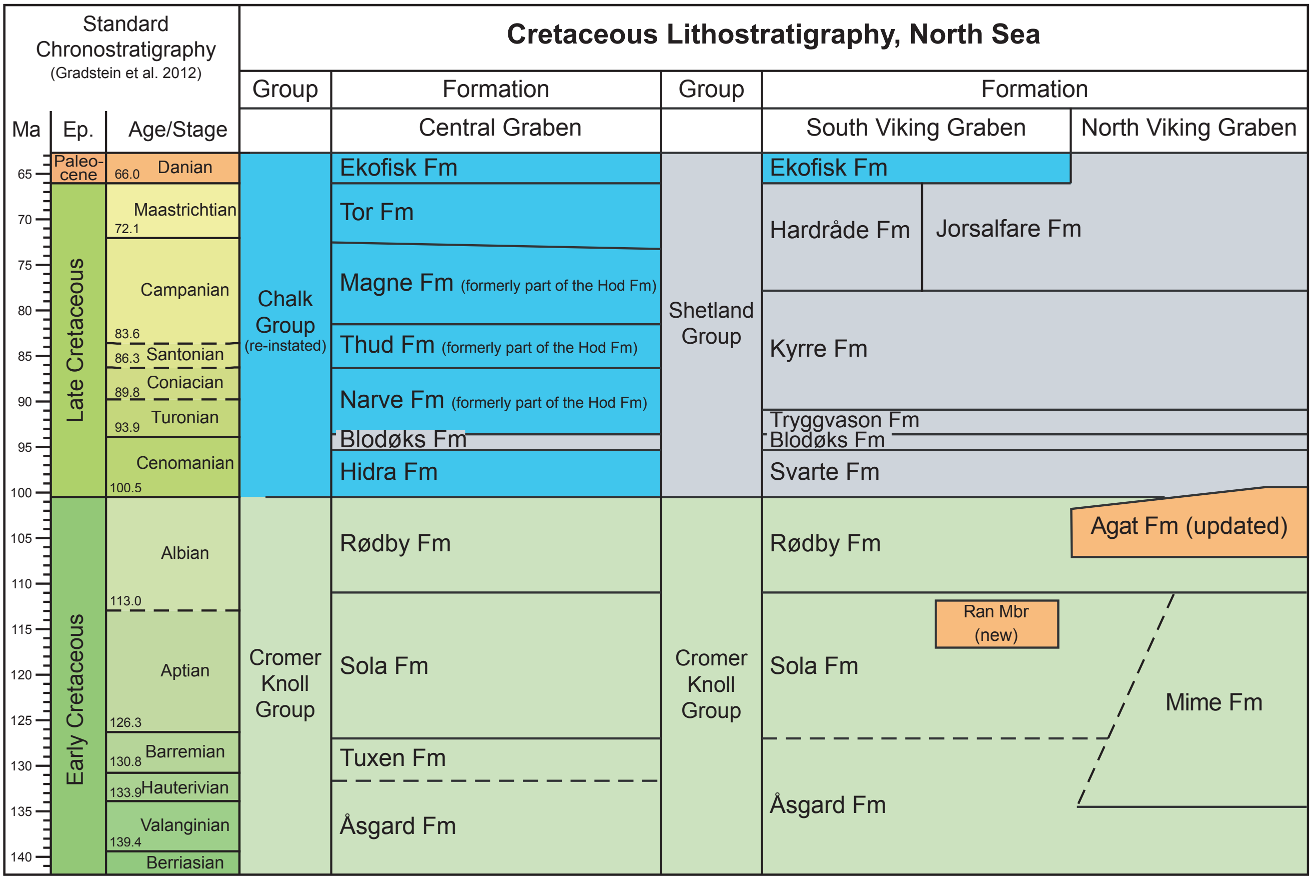


Table 4.2 Cretaceous lithostratigraphical schemes for the Norwegian Sector North Sea.

Norwegian-Danish Basin, and especially in the Asta Graben, where more than 700 m were encountered in well 17/12-3. The formation is thickest in the Sogn Graben where it is probably more than 1200 m thick, as indicated by seismic data.

Geographical Distribution

The Åsgard Formation is widespread in the North Sea (Figures 7-11 in Isaksen & Tonstad (1989)), as are the partial equivalents in the Danish Sector (Valhall Formation, Jensen *et al.*, 1986; Vedsted Formation, Larsen, 1966), UK Sector (Speeton Clay, Rhys, 1974) and Dutch Sector (Vlieland Shale Member, NAM & RGD 1980).

In the Norwegian Sector, the formation is absent from the highest parts of the Mandal, Jaeren and Utsira Highs, the Lomre Terrace, the Troll area, Tampen Spur and locally over salt pillows and diapirs in the Central Trough and the Norwegian-Danish Basin.

Formation tops in wells may be obtained from a routine on the Norlex website under this formation.

Type well

Well name: 2/11-1

Norwegian well 17/11-2: 2410 to 1802 m
Lat. 58°06'54.91"N, Long. 03°22'09.81"E
(Figure 13 in Isaksen & Tonstad (1989)). No cores.

Danish well 1-1: 3358 to 2986 m
Lat. 56°03'10"N, Long. 04°14'60"E
(Figure 14 in Isaksen & Tonstad (1989)). No cores.

Upper and lower boundaries

Upper boundary

The characteristics of the upper boundary vary with the overlying formations. Where the Tuxen Formation occurs, the boundary is defined by an upward decrease in the gamma-ray readings and an increase in velocity, reflecting slightly more calcareous claystones, marlstones and limestones compared with the underlying Åsgard Formation (Figures 14 and 15 in Isaksen & Tonstad (1989)). Where the Tuxen Formation

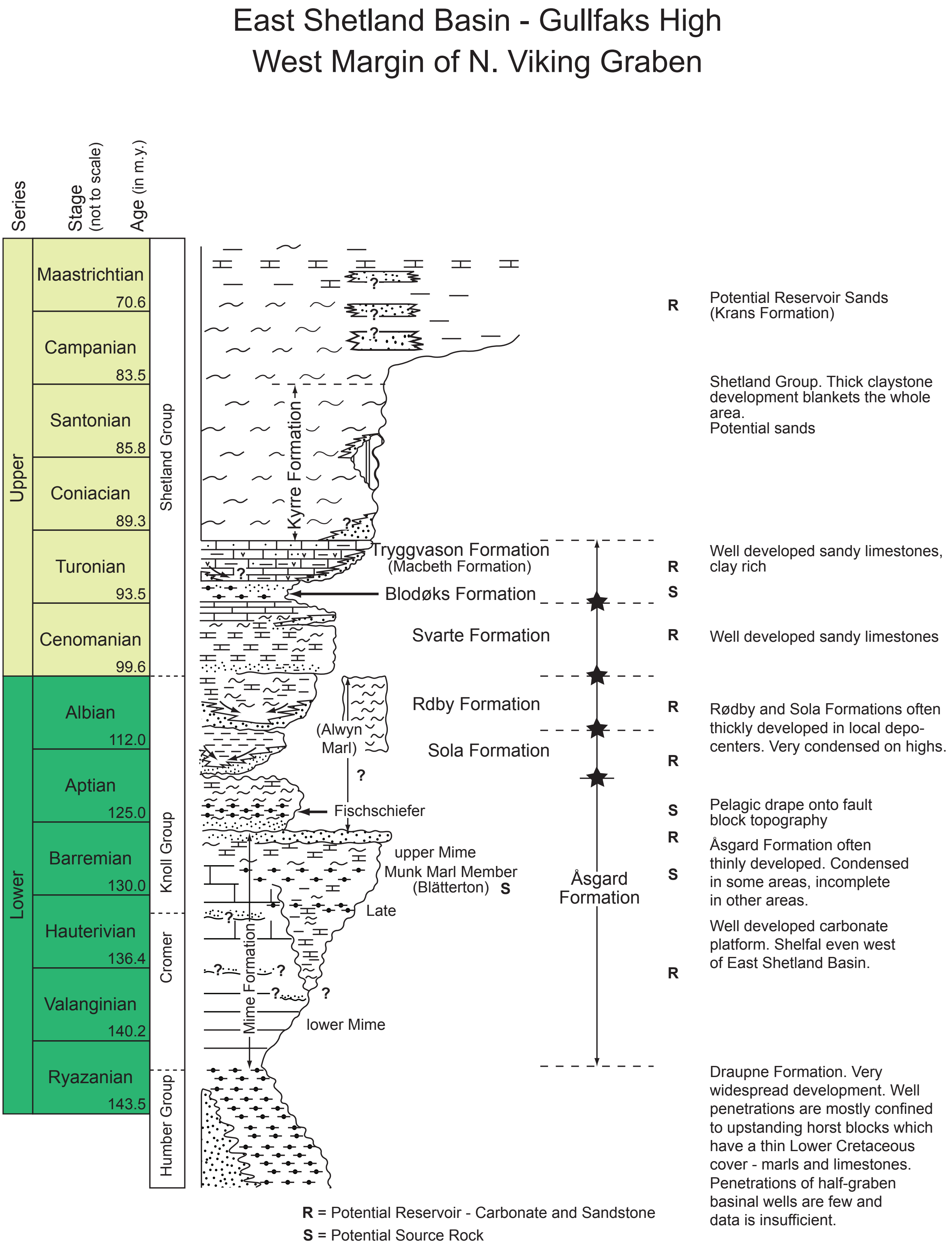


Figure 4.4. Schematic stratigraphic and facies transect of the Cretaceous strata, west margin of north Viking Graben and East Shetland Basin (S. Crittenden, pers.comm).

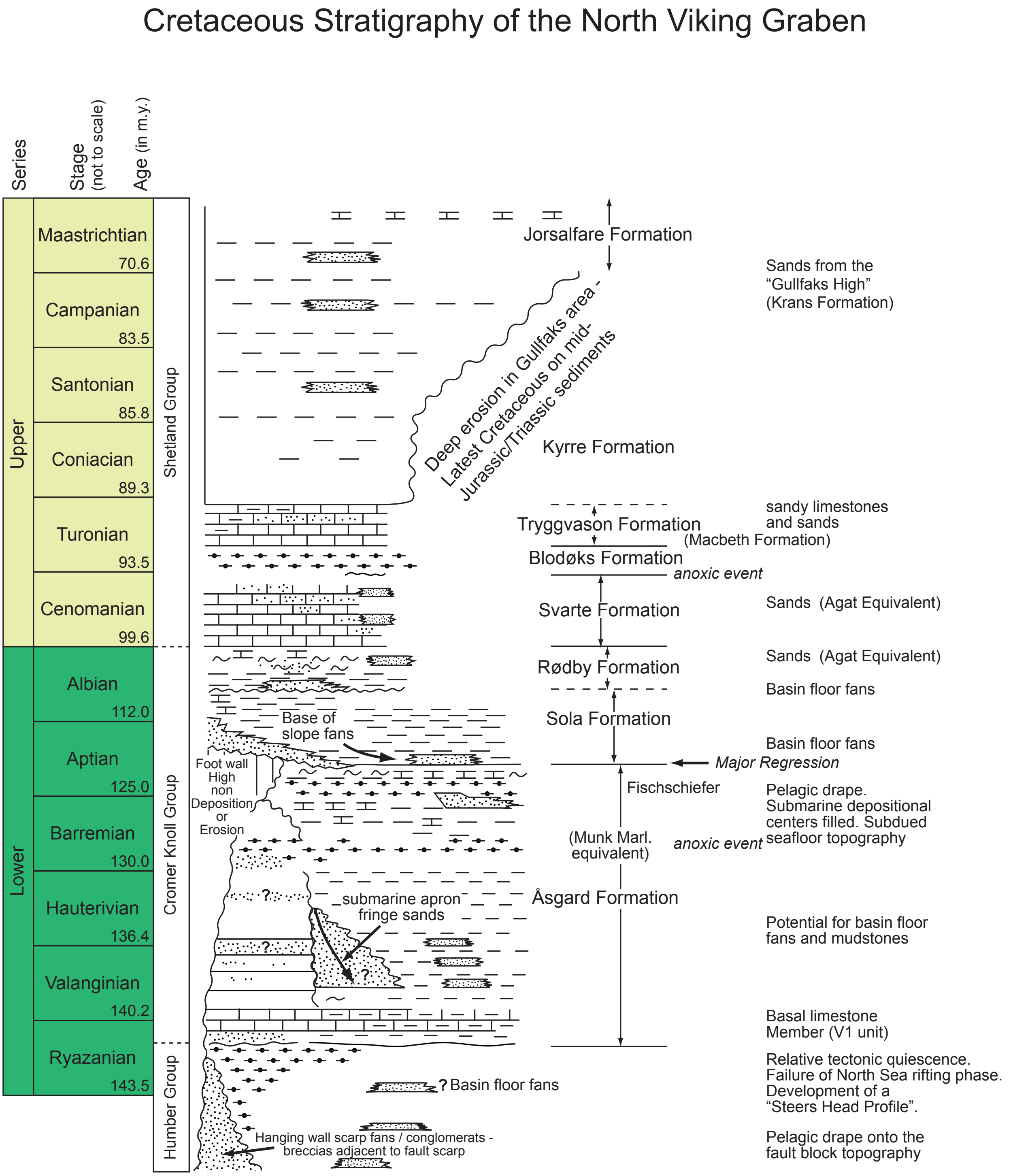


Figure 4.5. Schematic stratigraphic and facies transect of the Cretaceous strata, north Viking Graben (S. Crittenden, pers.comm).

is missing, and the Sola Formation is deposited on the Åsgard Formation, the boundary is defined by an upward increase in gamma-ray readings and a decrease in velocity (Figures 17, 18 and 23 in Isaksen & Tonstad (1989)).

If both the Tuxen and Sola Formations are missing, the boundary to the overlying Rødby Formation is defined by an upward decrease in gamma-ray readings and an increase in velocity.

Locally, the Åsgard Formation is overlain by the Ran sandstone units (Figure 22 in Isaksen & Tonstad (1989)) and the Agat unit (Figures 19 and 20 in Isaksen & Tonstad (1989)). This boundary is defined by an upward decrease in gamma-ray readings.

Lower boundary

The lower boundary is defined by a marked upward decrease in gamma-ray response and an increase in velocity in areas. This is true where the underlying sediments are slightly calcareous or non-calcareous, organic-rich claystones and shales, usually belonging to the Mandal, Flekkefjord, Tau or Draupne Formations (Figures 15 and 22 in Isaksen & Tonstad (1989)). Where the claystones and shales are less organic rich and more calcareous, the boundary on logs may be more difficult to identify.

Age

Where the Tuxen Formation occurs, the Åsgard Formation ranges in age from Berriasian to late Hauterivian. In areas where neither the Tuxen nor Sola Formations are recognised, the Åsgard Formation represents a lateral equivalent and may reach late Aptian to early Albian age.

Depositional environment

The formation was deposited in an open marine, low--energy shelf environment with well-oxygenated bottom water.

Remarks

Deegan & Scull (1977) divided the Cromer Knoll Group into the Rødby and Valhall Formations. Several lithostratigraphic units have later been described in the Valhall Formation (Hesjedal & Hamar, 1983, Jensen et al., 1986). The remaining claystones and marlstones of the originally defined Valhall Formation constitute the Asgard Formation.

Mime Formation (Updated) (Mimeformasjonen)

Cromer Knoll Group, Viking Graben (Figures 4.4 and 4.5 and Table 4.2)

Name

Named after a god from Norse mythology who was considered to be very wise.

Lithology

The formation is dominated by limestones and marls. It often contains impure carbonates that are reworked and mixed with smaller quantities of sand and silt. The formation is sometimes chalky. The matrix is usually calcareous, and oolites are observed in some wells in the East Shetland Basin. The formation colour is usually white or light pink, but may vary slightly on account of the sand/silt mixture.

Thickness

In the type well the Mime Formation is 11 m, and in the reference well it is 42 m thick. Usually, the thickness varies between 5 and 20 m.

Geographical distribution

The formation is found only as narrow zones along structural highs. On the flanks of the Viking Graben it may be seen almost continuously from approximately 58° to 62° N. It is also found as a thin carpet over most of the East Shetland Basin and along the Fladen Ground Spur, the Utsira High-Lomre Terrace, the northwest side of the Sele High, and the Jaeren High.

The formation is not encountered in the more central parts of the basins, and it is doubtful if it is present along the boundaries of the Fennoscandian Shield.

Formation tops in wells may be obtained from a routine on the Norlex website under this formation.

Type well

Well name: 34/10-18

WGS84 coordinates:

Norwegian well 34/10-18: 2351 to 2340 m
Lat. 61°14'22.48"N, Long. 02°03'18.83"E
(Figure 16 of Isaksen & Tonstad (1989)).
Cores (lower half of the formation).

Reference wells

Norwegian well 17/4-1: 2122 to 2080 m
Lat. 58°35'54.00"N, Long. 03°16'05.00"E
(Figure 17 of Isaksen & Tonstad (1989)). No cores.

Upper and lower boundaries

Upper boundary

The upper boundary is usually defined at the bottom of more or less calcareous shales in the Åsgard Formation. This boundary is reflected on the logs as an upward increase in gamma-ray readings and a reduction in velocity (Figure 17 of Isaksen & Tonstad (1989)). The upper boundary can also be defined by the overlying shales of the Sola or Rødby Formations. The boundary will normally be reflected on logs as described above (Figure 16 of Isaksen & Tonstad (1989)).

Lower boundary

In those wells where the Mime Formation is present it defines the lower boundary of the Lower Cretaceous, lying on Upper Jurassic sediments or older rocks. This boundary is always an unconformity, and can most often be seen on the logs as a decrease in gamma-ray readings and an increase in velocity upwards from underlying Jurassic sediments.

Age

The formation is time-transgressive, and is dated late Valanginian to Albian. It is oldest in the deeper parts along the basin margins and becomes younger up along the flanks. In most of the East Shetland Basin, along the Utsira, Bergen, Sele and Jaeren Highs, and along the flanks of the Viking Graben, it is usually of Barremian/Hauterivian age (Figure 4 of Isaksen & Tonstad (1989)).

Depositional environment

Paleontological investigations, together with the observation of oolites, indicate a transgressive, shallow marine, depositional environment.

Remarks

Hesjedal & Hamar (1983) described the impure, reworked limestones resting directly on the Base Cretaceous unconformity over the structural highs, as the Utvik Formation. This formation is formally defined as the Mime Formation in this paper, since the name suggested was not in accordance with existing recommendations.

Tuxen Formation (Tuxenformasjonen)

Cromer Knoll Group, Central Graben (Figures 4.4 and 4.5 and Table 4.2)

Name

Named by Jensen *et al.* (1986) from a bathymetric feature west of Blåvandshuk, the westernmost point of Jylland.

Lithology

The formation is dominated by white to greyish-pink, calcareous claystones and marlstones. Along some of the structural highs the marlstones grade into purer limestones. Generally, the formation terminates vertically upwards with a chalk sequence containing subordinate marlstone layers. This chalk is white to pale orange or yellowish-grey, occasionally greenish and reddish. The marlstones are generally light grey to greenish-grey or olive-grey, but may be reddish-brown in some wells.

A 0.3-1 m thick, radioactive, marlstone bed is fre¬quently encountered within the Tuxen Formation in the Danish Sector where it is defined as the Munk Marl Bed (Jensen *et al.*, 1986). This characteristic unit has also been recognised in some wells in the central Norwegian Sector (e.g. 2/1-2, 2/1-3, 2/1-8, 2/6-2, 2/11-7, 6/3-1, 16/8-1 and 16/10-1), (see also Figure 15 in Isaksen & Tonstad (1989)). In the Norwegian Sector, the Tuxen Formation above the Munk Marl Bed is often more calcareous than the rest of the sequence.

Thickness

The thickness of the formation varies from 1 m along structural highs to about 100 m in basinal areas. In the reference wells the thicknesses are 75 m (2/11-1) and 71 m (2/6-2). In the type well (1-1) the thickness is 88 m.

Geographical Distribution

The Tuxen Formation is widely distributed in the Norwegian and Danish Sectors (Jensen *et al.*, 1986). In the Norwegian Sector it is developed in the Central Trough, along the Jæren High and in parts of the Norwegian-Danish Basin.

In basinal areas in the Norwegian Sector it inter-fingers laterally with claystones and marlstones of the Åsgard Formation (Figures 4 and 7 in Isaksen & Tonstad (1989)).

Formation tops in wells may be obtained from a routine on the Norlex website under this formation.

Type well

Well name: 1-1

Danish well 1-1: 2986 to 2898 m
Lat. 56°03’10”N, Long. 04°14’60”E
(Figure 14 in Isaksen & Tonstad (1989)). No cores.

Reference wells

Norwegian well 2/11-1: 3063 to 2988 m
Lat. 56°14’16.98”N Long. 03°27’07.05”E (Fig. 12). No cores.

Norwegian well 2/6-2: 3935 to 3864 m
Lat. 56°30’48.90”N, 03°42’39.66”E
(Figure 15 in Isaksen & Tonstad (1989)). No cores.

Upper and lower boundaries

Upwards, the Tuxen Formation is generally in contact with the micaceous claystones and organic-rich shales of the Sola Formation (Figures 12 and 14 in Isaksen & Tonstad (1989)). This boundary is marked by an upward increase in gamma-ray readings and a decrease in velocity. Where the Sola Formation is missing, the Tuxen Formation is in contact with the marlstones of the overlying Rødby Formation (Figure 15 in Isaksen & Tonstad (1989)). The boundary is usually defined by an upward increase in gamma-ray readings.

The lower boundary is defined as the base of an upward decrease in gamma-ray readings and an increase in velocity, reflecting the passage from the slightly calcareous claystones of the underlying Åsgard Formation up into the more calcareous claystones and marlstones of the Tuxen Formation (Figures 12, 14 and 15 in Isaksen & Tonstad (1989)). The transition is generally gradual in basinal areas. Purer limestones were deposited along some structural highs, causing more distinct log breaks.

Age
Late Hauterivian to late Barremian (Heilmann-Clausen, 1987).

Depositional environment
Deposition was dominated by pelagic marl and chalk oozes, which covered large areas of the North Sea. The bottom waters were mainly well oxygenated (Jensen *et al.*, 1986).

Sola Formation (Updated) (Solaformasjonen)

Cromer Knoll Group, North Sea (Figures 4.4 and 4.5 and Table 4.2)

Name
Informally named by Hesjedal & Hamar (1983) after a village in southwestern Norway. Formally named by Jensen *et al.* (1986).

Lithology
The Sola Formation consists of shales interbedded with stringers of marlstone and limestone. The carbonate content is lower than that in the underlying Tuxen and Åsgard Formations, and the overlying Rødby Formation. The colour is black or dark grey, but olive-grey, brown and red colours occur. The shales are finely laminated and often very pyritic.

Thickness
The thickness in the type well is 39 m, and in reference well 2/11-1 it is 78 m. It generally varies between 20 m and 200 m. The formation is thick in the Viking Graben and Asta Graben, and thin in the East Shetland Basin and parts of the Fiskebank Sub-Basin.

Geographical Distribution
The formation is widespread in the North Sea. It is absent or thin on structural highs, salt-induced structures, and in parts of the Central Trough and Norwegian-Danish Basin.

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

Type well
Well name: 1-1

Danish well 1-1: 2898 to 2859 m
Lat.56°03’10”N Long. 04°14’60”E
(Figure 14 in Isaksen & Tonstad (1989)). No cores.

Reference wells
Norwegian well 2/11-1: 2988 to 2910 m
Lat. 56°14’16.98”N Long. 03°27’07.05”E
(Figure 12 in Isaksen & Tonstad (1989)). No cores.

Norwegian well 24/12-2: 4043 to 3985 m
Lat. 59°12’00.75”N Long. 01°52’53.34”E
(Figure 18 in Isaksen & Tonstad (1989). No cores.

Upper and lower boundaries
Upper boundary

The upper boundary is most often placed where the carbonate content starts to increase rapidly into the overlying Rødby Formation (Figures 12, 14, 18, and 22 in Isaksen & Tonstad (1989)). In some areas where, the Sola Formation is overlain by the Ran Member (Figure 23 in Isaksen & Tonstad (1989)), the boundary is defined by an upward decrease in gamma-ray response and an increase in velocity.

Lower boundary

The lower boundary is usually placed on the Tuxen or Åsgard Formations (Figures 12, 14, 17 and 18 in Isaksen & Tonstad (1989)). Generally, the gamma-ray response increases and the velocity decreases from the calcareous and sandy sediments up into the shaly and organic rich Sola Formation. In some wells in the east, on the Horda Platform, the gamma-ray response does not increase when the boundary from the Asgard Formation up into the Sola Formation is crossed. In such wells, a lower, more stable velocity identifies the Sola Formation.

Age
The Sola Formation is of mid Aptian-early Albian age. A possible middle (late) Barremian-Albian age is recorded from Danish wells (Heilmann-Clausen, 1987.

Depositional environment

The Sola Formation was deposited in a marine environment with alternating anoxic and oxic bottom conditions. Hesjedal & Hamar (1983) suggested that the formation was deposited during a regressive period, while Rawson & Riley (1982) held the opposite view.

Ran Member [new] (Ransandsteinsenhetene)

Cromer Knoll Group, Sola Formation, Viking Graben (Figures 4.4 and 4.5 and Table 4.2)

Name

Ran was the wife of the sea god Gir in Norse mythology. She liked to drag sailors down to the depths with her net.

Lithology

The colour of the sandstones ranges from white to light grey, green and brown to reddish-brown. The sandstones are generally argillaceous, sometimes calc¬areous and glauconitic, and usually do not represent potential reservoir rocks in these wells.

Thickness

The gross sandstone thickness varies from a few metres up to approximately 100 m. The gross thickness in the reference wells are 48 m (2/7-15), 16 m (7/3-1) and 35 m (17/11-2). Up to 130 m (gross) of Aptian-Albian sandstone sequences are penetrated in block 16/27 in the UK Sector (see Geographical Distribution).

Geographical Distribution

The Ran Member is encountered in only a few wells in the Norwegian Sector (Figure 21 in Isaksen & Tonstad (1989).

On the Norlex website under this unit is a button to find the occurrence of tops in wells, and a relative thickness map.

Type well

Well name: 1-1

Norwegian well 2/7-15: 3498 to 3450 m
Lat. 56°23’46.82”N   Long. 03°18’54.63”E
(Figure 22 in Isaksen & Tonstad (1989)). 16 m of cores in the lowermost part of the formation.

Norwegian well 7/3-1: 2412 to 2396 m
Lat. 57°50’35.25”N   Long. 02°44’55.61”E
(Figure 23 in Isaksen & Tonstad (1989)). No cores.

Norwegian well 17/11-2: 1802 to 1767 m
Lat. 58°06’54.9”N   Long. 03°22’09.8”E
(Figure 13 in Isaksen & Tonstad (1989)). No cores.

Upper and lower boundaries

Upper boundary

The upper boundary can usually be identified as an upward increase in the gamma-ray readings (Figure 22 in Isaksen & Tonstad (1989)) and generally by a slight decrease in the sonic velocity as it passes up into ???? Formation.

Lower boundary

The various sandstone bodies may be in stratigrapic contact with the Åsgard, Tuxen, Sola and Rødby Formations (Figures 4, 7, 8 and 9 in Isaksen & Tonstad (1989)). Their lower boundaries are generally defined as the base of an upward decrease in the gamma-ray response when passing into the sandstone units (Figures 22 and 23 of Isaksen & Tonstad (1989)).

The gamma-ray readings in the calcareous marlstones and chalks of the Tuxen Formation, especially its upper part, and the Mime Formation may be similar to those in the sandstones. The velocity curve is often less suitable, for defining the lower boundary.

Age

Berriasian-Albian; but shown only schematically in Table 4.4.

Depositional environment

The sandstones that have been penetrated are described as shallow (Norwegian Sector) and deep water (UK Sector) submarine fans.

Remarks

Hesjedal & Hamar (1983) recognised scattered sandstone sequences, which they described as the Kopervik and Klepp Formations in the Central Trough and Norwegian-Danish Basin, and the Florø

Formation in the Agat Field in blocks 35/3 and 36/1. The Kopervik and Klepp Formations are here described as the Ran Member. Since the units consist of several isolated sandstone bodies they should not have been given formation status; also, the names did not conform with existing recommendations. The Florø Formation is formally defined as the Agat Formation in this study.

In the UK Sector (the Andrew Field), just south of the Andrew Ridge and Fladen Ground Spur (Figure 4.2), Aptian-Albian sandstone bodies (Bosun Sandstone Member) are encountered in many wells, among others UK wells 16/27-1 and 16/27a-2 (100-130 m gross), 16/28-1 (50 m gross) and 16/28-6 (90 m gross). The Devil's Hole Sandstone Member (UK well 29/25-1) and the Scapa Sandstone Member (UK well 14/20-5) in the UK Sector are comparable to the Ran Member.

The paleogeographical position of these sandstones, i.e. basinal areas close to the subaerially exposed major structural highs mentioned above, may be quite similar to the paleogeographical situation along the western margin of the Måløy Fault Blocks. Here, up to 400 m (gross) thick sandstone bodies of Aptian-Early Cenomanian age were deposited in Norwegian blocks 35/3 and 36/1, and are defined as the Agat Formation in this paper.

Agat Formation (Updated) (Agatformasjonen)

Introduction

The Agat Formation is a complex lithostratigraphic unit that straddles the Cromer Knoll and Shetlands Groups in the eastern part of the northernmost Viking Graben (Table 4.2). Economic importance as a reservoir rock is demonstrated in the gas and condensate discovery in block 35/3.

It is a well-established unit, albeit not extensively documented in literature, and therefore is poorly understood. Discrepancies exist concerning age determinations, interpretations of the depositional environment, and well correlations in the literature. Following the website document by Vergara *et al.* on *www.nhm2.uio.no/norlex*, minor changes in the definition of the boundaries are introduced, and the main characteristics of the formation is better documented. Although good arguments might be made to retain the unit as a Memberwithin the Rødby Formation, we have refrained form such for now. The unit is retained as a lithostratigraphic Formation pending more detailed study on provenances of different Agat 'lobes'.

Derivatio nominis: Isaksen & Tonstad (1989) defined the unit after the sand bodies forming the reservoir for the Agat gas-condensate field in block 35/3.

Lithology

In the original definition Isaksen & Tonstad (1989) gave a detailed account of the lithology of the Agat Formation.

"In the type well the Formation consists of white to light grey, fine- to medium-grained moderately to well-sorted sandstones alternating with grey claystones. The sandstones are usually micaceous and glauconitic and sometimes contain small amounts of pyrite. The sandstones in the type well are carbonate- and silica-cemented in zones. In the reference well, the upper part of the Formation consists of medium- and coarse-grained to pebbly sandstones and conglomerates alternating with dark grey claystones. The conglomerates are both matrix- and grain-supported. The claystones are often found as 0.5-5 m thick layers between the sandstones. They are dark grey, usually calcareous and contain varying amounts of siltstone. They may occasionally pass into light grey, micaceous, calcareous and glauconitic siltstones."

Sample depository

Palynological preparations (organic matter depository)

Slides available from type well 35/3-4 for the interval 660 - 4043 m (NPD).

Core photographs

A suite of core photographs illustrates the main characteristics of the reservoir interval in wells 35/3-5, 35/3-4 and 35/3-2 (Photographs under description of the Agat Formation on the Norlex website at *www.nhm2.uio.no/norlex*).

Thin-sections
Not available.

Age
Tithonian (Volgian/Portlandian) to Valanginian (Table 4.1).

Thickness
In the type section of well 35/3-4 the formation measures near 200 m in thickness, and in the reference well 35/3-5 it spans over 380 m. In the 35/3 block gross thickness varies within this range. In the Gjøa area wells 35/9-3 and 36/7-3 encountered sand packages assigned to the Agat Formation, with 44 m and 100 m gross thickness, respectively.

Geographical distribution
The geographical distribution and regional setting of the Agat Formation is seen in Figures 4.6 and 4.7. The unit is hitherto only known in blocks 35/3, 35/9, 36/7, 6204 and 6205. The figures demonstrate a rugged and largely exposed basin at the beginning of the Cretaceous. This relief was the result of regional Late Jurassic-Early Cretaceous rifting. The former relief was filled during the Early Cretaceous thermal subsidence phase, and a more gentle morphology between basin and slope was created, whereas the ancestral shelf back-stepped to the East and is mostly absent today.

The Agat Formation description on the Norlex website has a function to determine the occurrences of Agat Formation tops in wells..

Type well
Well name: 35/3-4
WGS84 coordinates: 61°51'54.54" N 3°52'26.99" E
UTM coordinates: 6859631.80 N 545989.90 E
UTM zone: 31
Drilling operator name: Saga Petroleum
Completion date: 06.06.1981
Status: P & A G/C W
Interval of type section: The type section is from 3542 m (originally 3589 m, see below) to 3345 m; see Figure 4.8.

Reference well
Well name: 35/3-5
WGS84 coordinates: 61°47'46.71" N 03°54' 44.01" E
UTM coordinates: 6851990.69 N 548099.85 E
UTM zone: 31
Drilling operator name: Saga Petroleum
Completion date: 31.03.1982
Status: P & A dry
Interval of type section : The reference section is from 3605 m (originally 3620 m, see below) to 3219 m; see Figure 4.9.

Upper and lower boundaries
The boundaries are defined by Isaksen & Tonstad (1989) at the base and top of the sandstone interval as suggested by the gamma-ray and velocity logs, but the argument is made here to place the base at the base of massive sandstones, which occurs at 3542 m instead of 3589 m (Figure 4.8). As seen in this figure, both density and velocity logs exhibit changes that result in an acoustic impedance contrast. Likewise, in the reference section well 35/3-5 (Figure 4.9) the base is slightly shifted up from originally 3620 m to 3605 m. The upper limit in both well sections occurs at a gamma-ray spike, now viewed as representing a maximum flooding surface, and is maintained here. The boundaries picked for wells 35/3-1 and 35/3-2 (Figures 4.10 and 4.11) are in agreement with these criteria.

Both base and top of the Agat unit are diachronous, as reasonably expected from its 'multiple source mass-flow facies' (see below). Taking the base of the Shetland Group at the top of the Agat Formation in well 35/3-5 extends the Cromer Knoll Group very slightly in Upper Cretaceous, as reasonably locally expected from lithologic boundaries.

Well log characteristics
Figures 4.8 - 4.11 show the main logs for wells 35/3-4, 35/3-5, 35/3-2 and 35/3-1. The Agat Formation normally has a distinct expression that shows up well in the gamma ray log. In some cases the density log shows better contrasts, as in well 35/3-1 at the base of the unit. The array of logs illustrated here is suitable for recognizing the base of the sands that mark the boundaries of the unit.

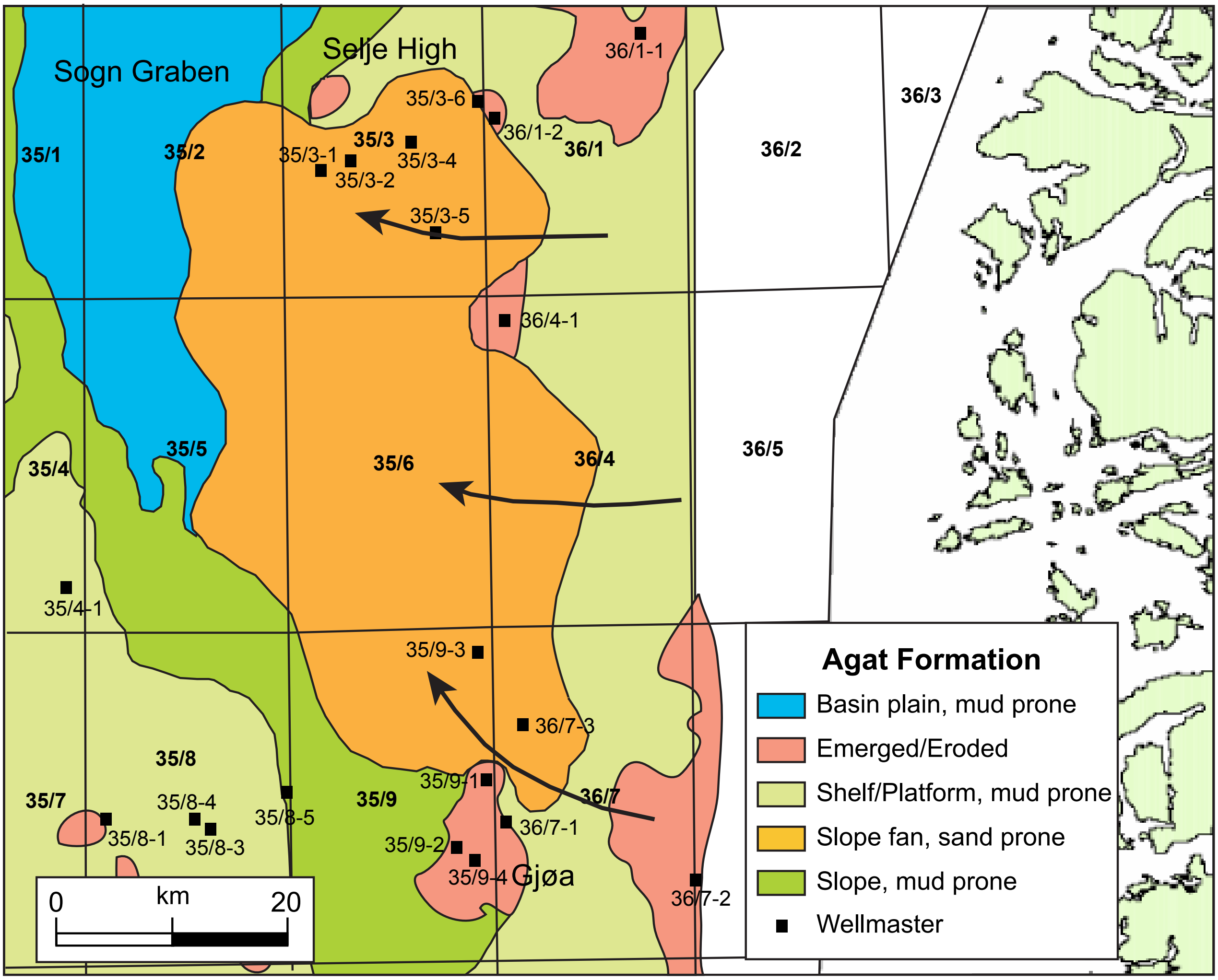


Figure 4.6. Geographical distribution and schematic transect setting of the Agat Formation. The unit is hitherto only known in blocks 35/3, 35/9, 36/7, 6204 and 6205. The figures demonstrate a rugged and largely exposed basin at the beginning of the Cretaceous. This relief was the result of regional Late Jurassic-Early Cretaceous rifting. The former relief was filled during the Early Cretaceous thermal subsidence phase, and a more gentle morphology between basin and slope was created, whereas the ancestral shelf back-stepped to the East and is mostly absent today.

Seismic characteristics

Figures 7, 8, 9, 10 and 11 in the Agat Formation description on the Norlex website in www.nhm2.uio.no/norlex, provide seismic characteristics. The type seismic section in Figure 7 (cross line 1505 of 3D survey GP3D93R02) shows the type seismic section that ties to type well 35/3-4. It illustrates well the top and base of the Agat Formation, the Base Cretaceous Unconformity (BCU), plus three additional intra Agat Formation markers. An in-line over the same well is presented in Norlex Figure 8.

For reference well 35/3-5 cross line 2129 (Norlex Figure 9) and in-line 555 (above Norlex Figure 10) are illustrated, and are called here reference seismic sections. In addition a random section tying both wells 35/3-4 and 35/3-5 (Norlex Figure 11) helps to illustrate the complexity of the seismic facies and deformation. Seismic sections over reference well 35/3-5 were published by Gulbrandsen (1987) and Shanmugan *et al.* (1994), while the Millennium Atlas (Copestake *et al.*, 2003) shows a line tying three key wells in Norlex Figure 12/20b.

Biostratigraphy

The first biostratigraphic reports are from Robertson Research (well 35/3-1), where they stated an Albian-Aptian age for the Agat sands. Based on the understanding of the zonal use of more than 20 20 foraminiferal and dinocyst events in the Agat region, fine-tune correlations in the reservoir sand interval

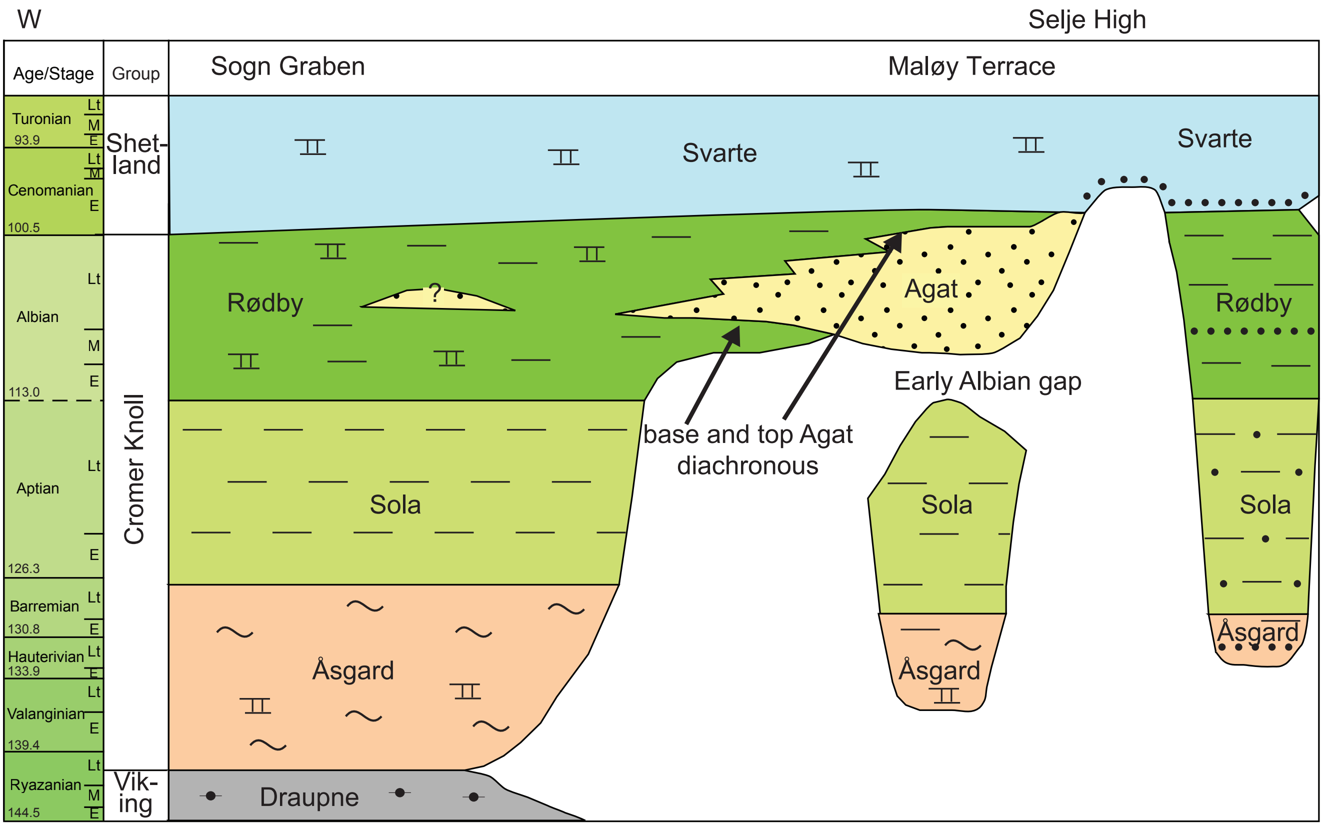


Figure 4.7. Geographical distribution and schematic transect setting of the Agat Formation. The unit is hitherto only known in blocks 35/3, 35/9, 36/7, 6204 and 6205. The figures demonstrate a rugged and largely exposed basin at the beginning of the Cretaceous. This relief was the result of regional Late Jurassic-Early Cretaceous rifting. The former relief was filled during the Early Cretaceous thermal subsidence phase, and a more gentle morphology between basin and slope was created, whereas the ancestral shelf back-stepped to the East and is mostly absent today.

were performed. The Cretaceous foraminiferal zonation compiled by Gradstein *et al.* (1999) is reproduced in Figures 2.7a and 2.7b of this study. The Agat reservoir sands mainly extend from Zone NCF6, mid Albian through Zone NCF10, late early Cenomanian.

Gradstein & Agterberg (1998) first proposed that *H. delrioensis* FCO & LCO are useful to correlate the Agat sands and further north; these levels separate more scattered Rødby sands, assigned to lower Cenomanian, from more massive Rødby sands, assigned to middle Cenomanian, Turonian or Coniacian. The planktonic LCO event, observed in 14 wells, evidently is a lull in sand sedimentation. In the 35 block (Agat) area, the *H. delrioensis* FCO event occurs in the uppermost NCF8 Zone with the LO of *Ovoidinium scabrosum* (Upper Albian), whereas the *H. delrioensis* LCO event marks the top of the NCF10 zone, at the transition from lower to middle Cenomanian, which here also includes the LO's of *Rhombodella paucispina, Plectorecurvoides alternans* and *Lingulogavelinella jarzevae.* In terms of local sands, the *H. delrioensis* FCO event in the Agat area appears abruptly almost at the top of the massive Agat sands of Albian age in well 35/3-4, and the LCO event occurs above some more Agat sands of possible Early Cenomanian age in 35/3-5. Hence, the stratigraphic range of common to abundant *Hedbergella delrioensis* is in the upper half of the Agat sands.

The age determinations are summarized in the wells chronogram of Figure 4.12 and well correlation Figure 4.13. Hydrocarbon bearing sands in the 35/3-2 and 35/3-4 wells are of mid - late Albian age, and more than 100 m thick (net) in 35/3-4. The upper massive sands in the 35/3-5 well, devoid of hydrocarbons, are of early Cenomanian age. In the most landward wells 36/1-1, 1-2 and 1-4, the Albian sediments are absent. Understanding of reworking in these wells is crucial to age determinations. Reworked Aptian assemblages occur in well 35/3-1 (3935 to 4085 m), while reworked Jurassic palynomorphs occur in a lower section

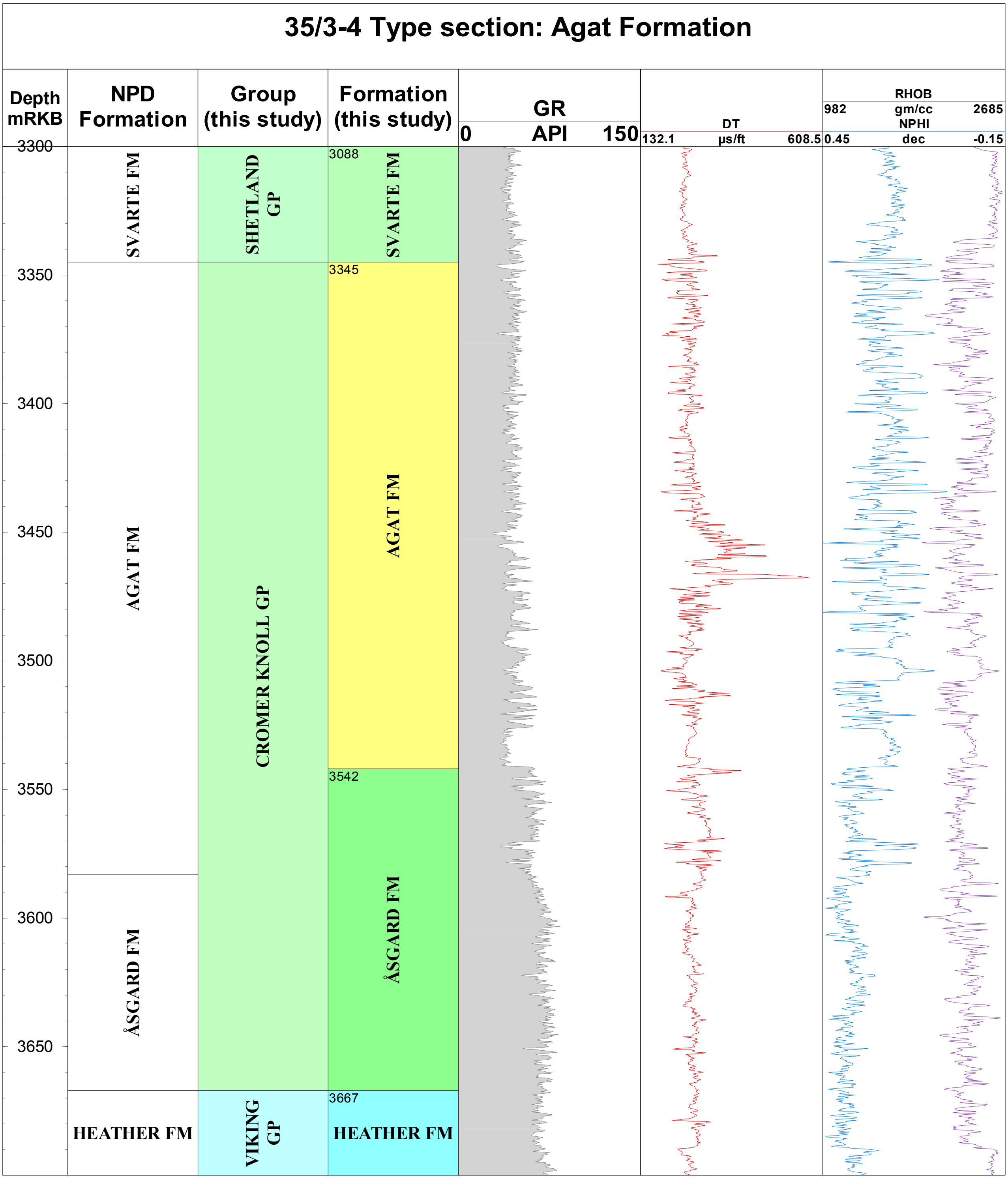


Figure 4.8. Principal well logs of the Agat Formation in type well 35/3-4, north Viking Graben.

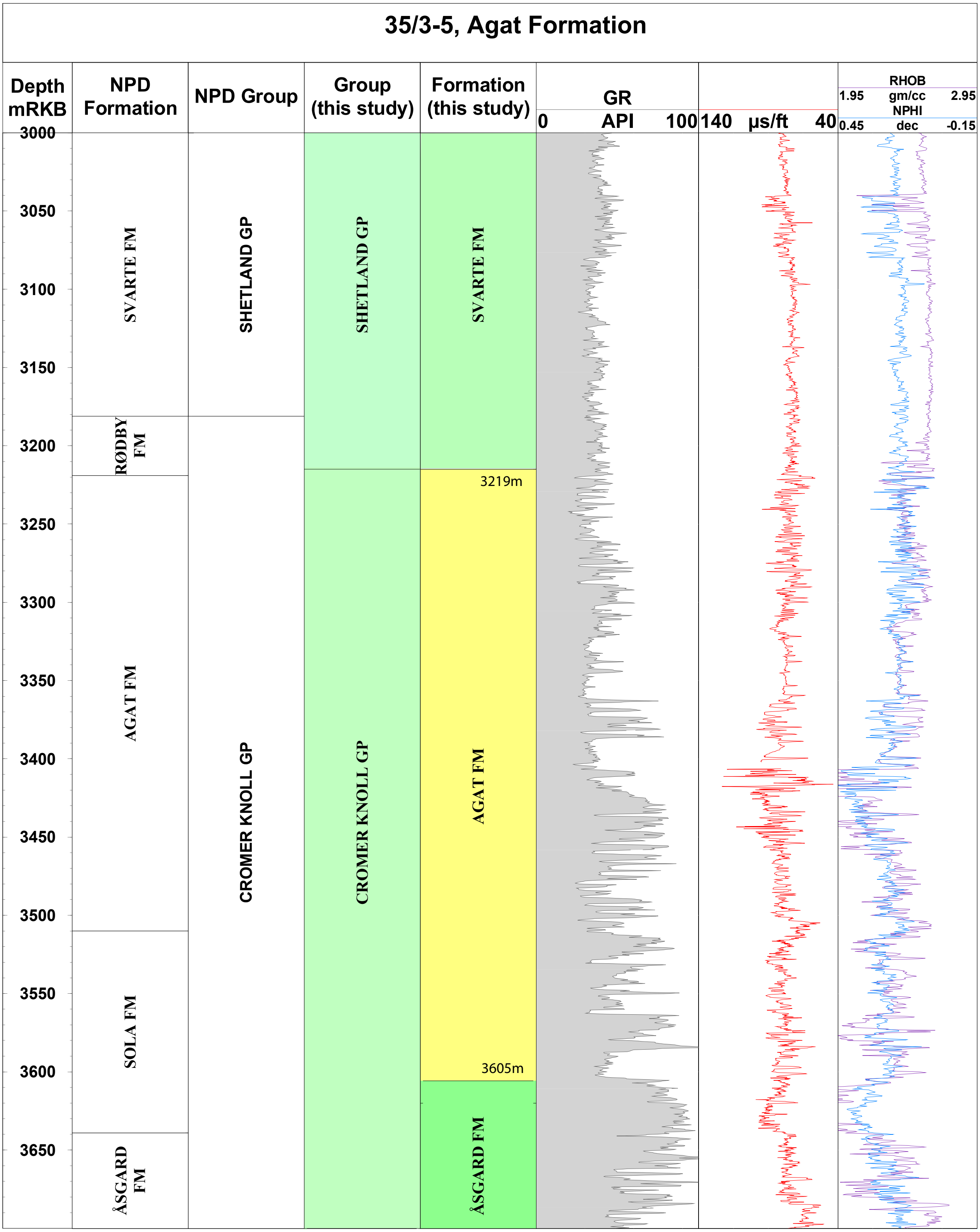


Figure 4.9. Principal well logs of the Agat Formation in reference well 35/3-5, north Viking Graben.

(4120-4141 m), and also in Albian sands of well 35/3-5, together with Lower Cretaceous dinoflagellate cysts. Apart from this, the base of the Agat Formation is diachronous, responding to deposition first in the East followed by slightly younger sand dispersal to the West.

In well 35/9-3 in the Gjøa area (map Figure 4.6), well 35/9-3 penetrated a reservoir section (2657.5 -2701.5 m) of Middle to Late Albian. A next well 36/7-3 encountered a massive sand reservoir section (2532-2632 m) dated Late Albian. Both intervals are assigned to the Agat Formation, and lateral to shales or marls of the Rødby Formation.

Note that Lower Albian strata are missing in block 35/3. The disconformity occurs in wells 35/3-1 at 4085 m, in well 35/3-2 at 3726 m, and in well 35/3-5 at 3620 m. The break approximately coincides with the base of the Agat Formation. Stratigraphic analysis of well 35/3-4 carried out by Mobil (Skibeli *et al.*, 1995), postulate a division of the Agat Formation into three sequences, bounded by maximum flooding surfaces. The oldest one at 3565 m coincides with the major break where the Lower Albian is absent.

Age

The Agat Formation is of mid Albian through early Cenomanian age.

Correlation

Different correlations for the classical wells 35/3-1, 3-2, 3-3, 3-4 and 3.5 of the Agat field were published by Gulbrandsen (1987), Skibeli *et al.* (1995) and Bugge *et al.* (2001). Yet another version appeared in the Millennium Atlas (Copestake *et al.*, 2003), with some more detail, particularly the non-extension of the Agat Formation from the type area east to well 36/4-1. It was early stated that the sands lack pressure communication between wells 35/3-2 and 35/3-4, supposing the existence of separate sandlobes (cf. Gulbrandsen, 1987). Figures 4.12 and 4.13 show the stratigraphic well correlations discussed earlier, whereas Figure 14 (in the Agat Formation description on the Norlex website) shows the wells with the major horizons correlated with use of 3D seismic. The latter was indispensable in unraveling biostratigraphic artifacts caused by reworking of microfossils, as in the interval 3935-4085 m of well 35/3-1 containing reworked Aptian material. Note that the seismic correlation supports the well correlations, and the previously discussed Early Albian break is in good accordance with the reflectors, consistently occurring just below the base of the Agat Formation. An additional cyclostratigraphic high-resolution correlation (RWE-Dea internal report, unpublished) is in agreement with the Early Albian gap previously determined by biostratigraphy.

Depositional environment

No aspect of the Agat Formation has been more debated than the depositional environment. The first sedimentological model by Gulbrandsen (1987) interpreted submarine fans with multiple point sources at the shelf break, and with an eastern provenance. Core photographs have only been published by Shanmugan *et al.* (1994, 1995) and Skibeli *et al.* (1995). Some of them are reproduced on the Norlex website under Agat Formation, where diverse facies are overprinted by secondary features, such as injected sands or possible glide planes.

According to this literature the main mechanism of sedimentation implies plastic flows, particularly slumps and sandy debris flows on an upper slope setting. Nystuen (abstract only, 1999) interpreted the dominant depositional process of the sandstones in the Agat wells as gravity flow (turbidity) currents, probably within a channel system. Both models are likely relevant, including not one, but multiple channel systems.

Depositional models have ascribed the lack of pressure communication between wells 35/3-2 and 35/3-4 to primary depositional features. Bugge *et al.* (2001) presented a model where slide scars from small-scale slumping and sliding created accommodation space for preservation of isolated sand bodies transported by turbiditic currents. The sands are interpreted as high-density turbidites, probably deposited proximally and close to the main sediment fairway.

In general, the Agat facies associations in the wells show predominantly turbidite deposition, interacting with debris flows. Figure 4.6 gives an idea of the local basin configuration in Early Cretaceous from basin margin to deeper marine basin. Diverse agglutinated benthic foraminiferal assemblages retrieved from intervening shales in the Albian of the Agat wells are indicative of bathyal conditions (Gradstein *et al.*, 1999), in accordance with a basin slope setting. Seismic facies extracted from 3D surveys in conjunction with isopach anomalies have constrained our depositional model by more accurately outlining the fan distribution. The upscaled regional depositional model (Figure 4.6) shows the generalized extension of the fans of the Agat Formation, on the slope of the Måløy terrace. This is roughly in agreement with the model of Copestake *et al.* (2003; Fig. 12/20). Its hypothetical extension into the Sogn Graben, as postulated by Shanmugan *et al.* (1984) and Skibeli *et al.* (1995), remains to be proven by drilling.

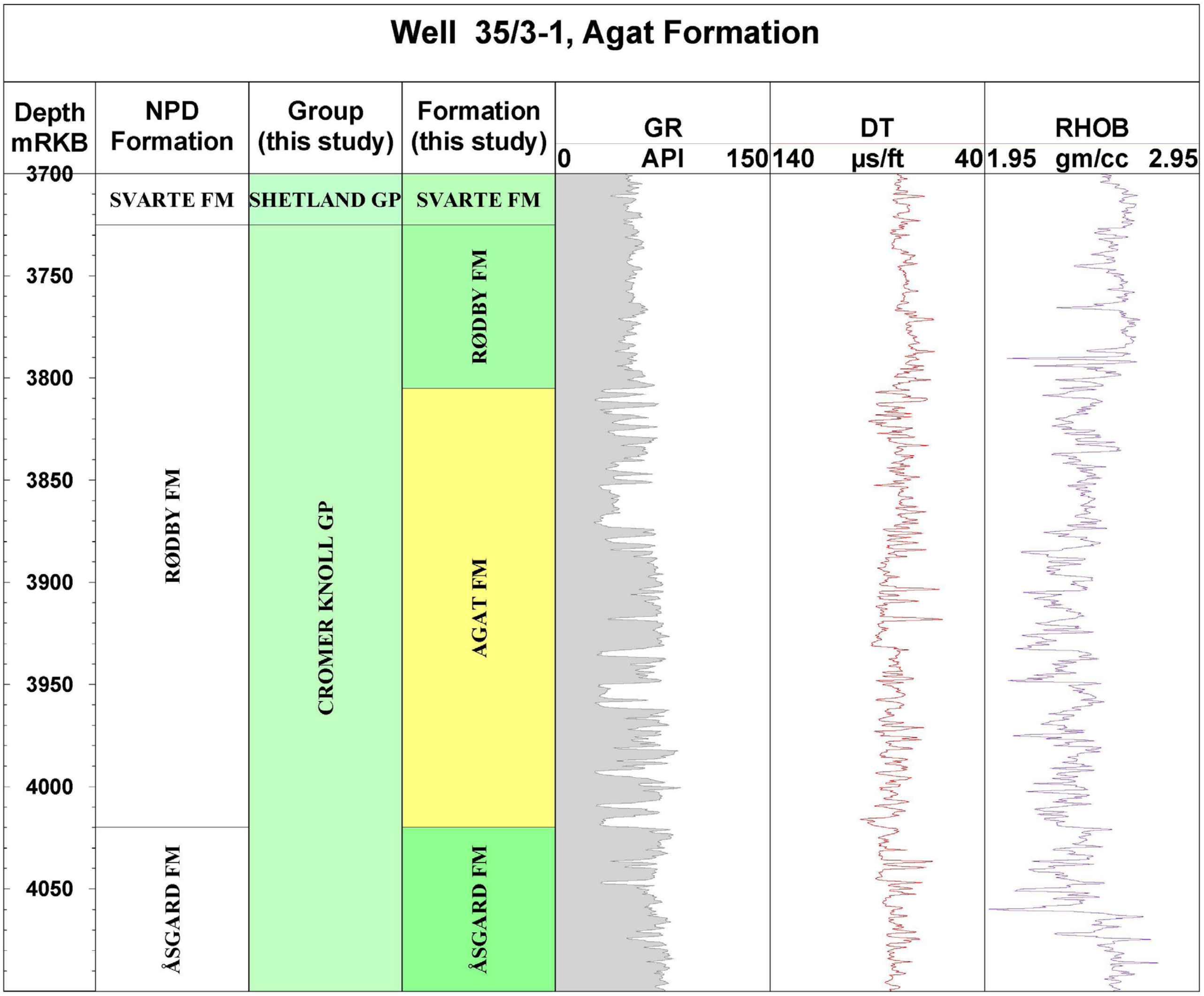


Figure 4.10. Principal well logs of the Agat Formation in well 35/3-1 north Viking Graben.

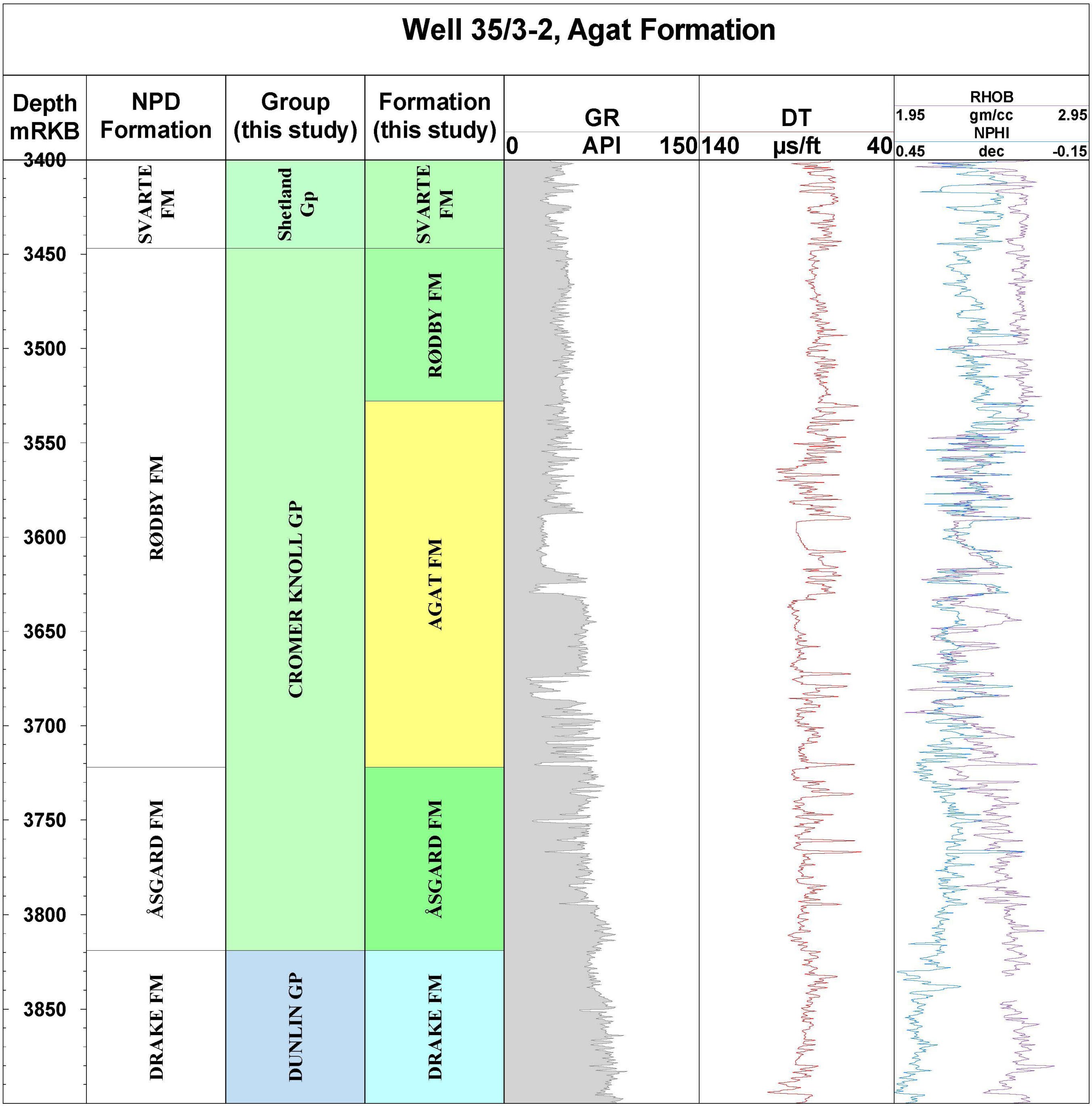


Figure 4.11. Principal well logs of the Agat Formation in well 35/3-2, north Viking Graben.

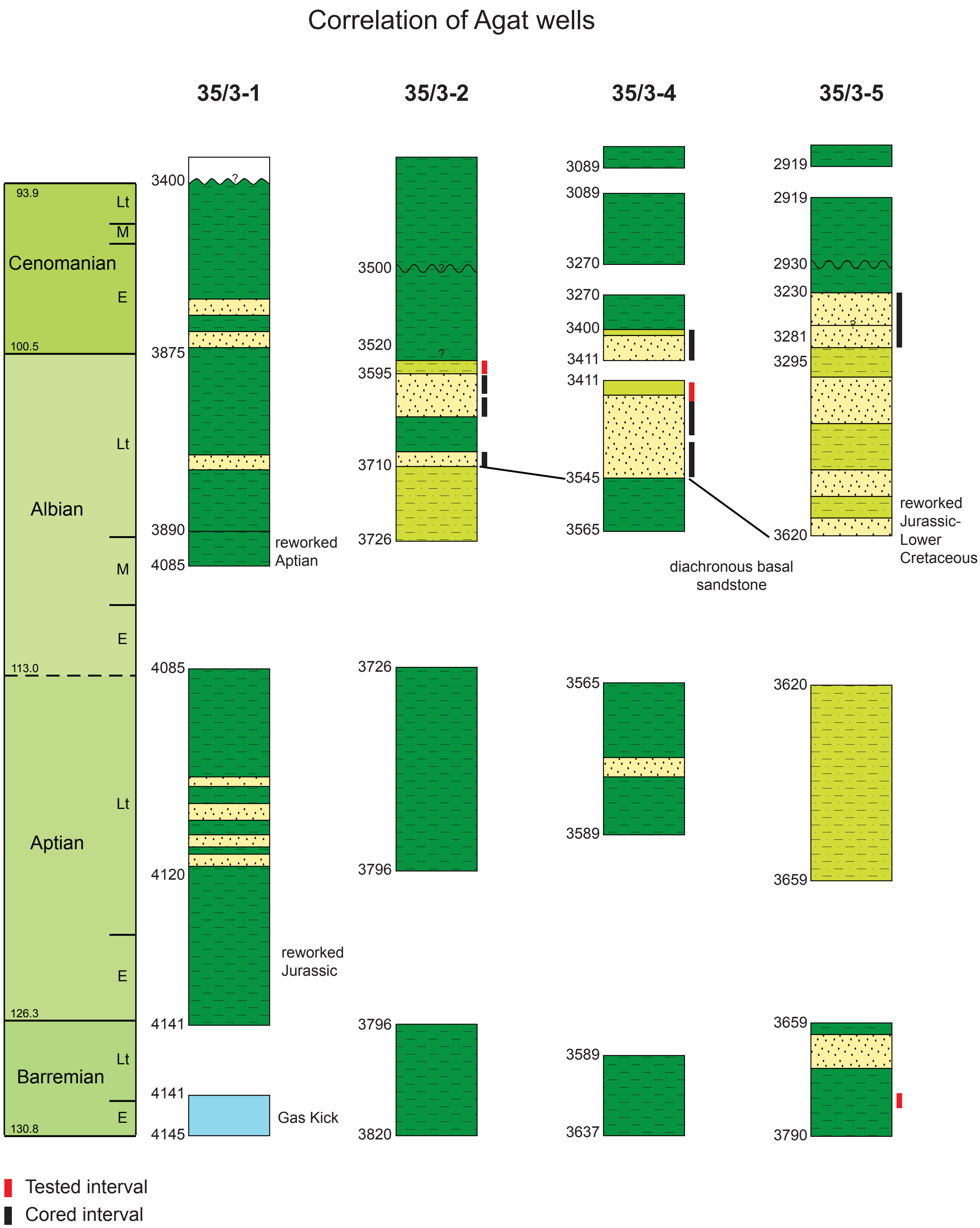


Figure 4.12. Chronogram and principal correlations in time of the Agat Formation in key wells, north Viking Graben.

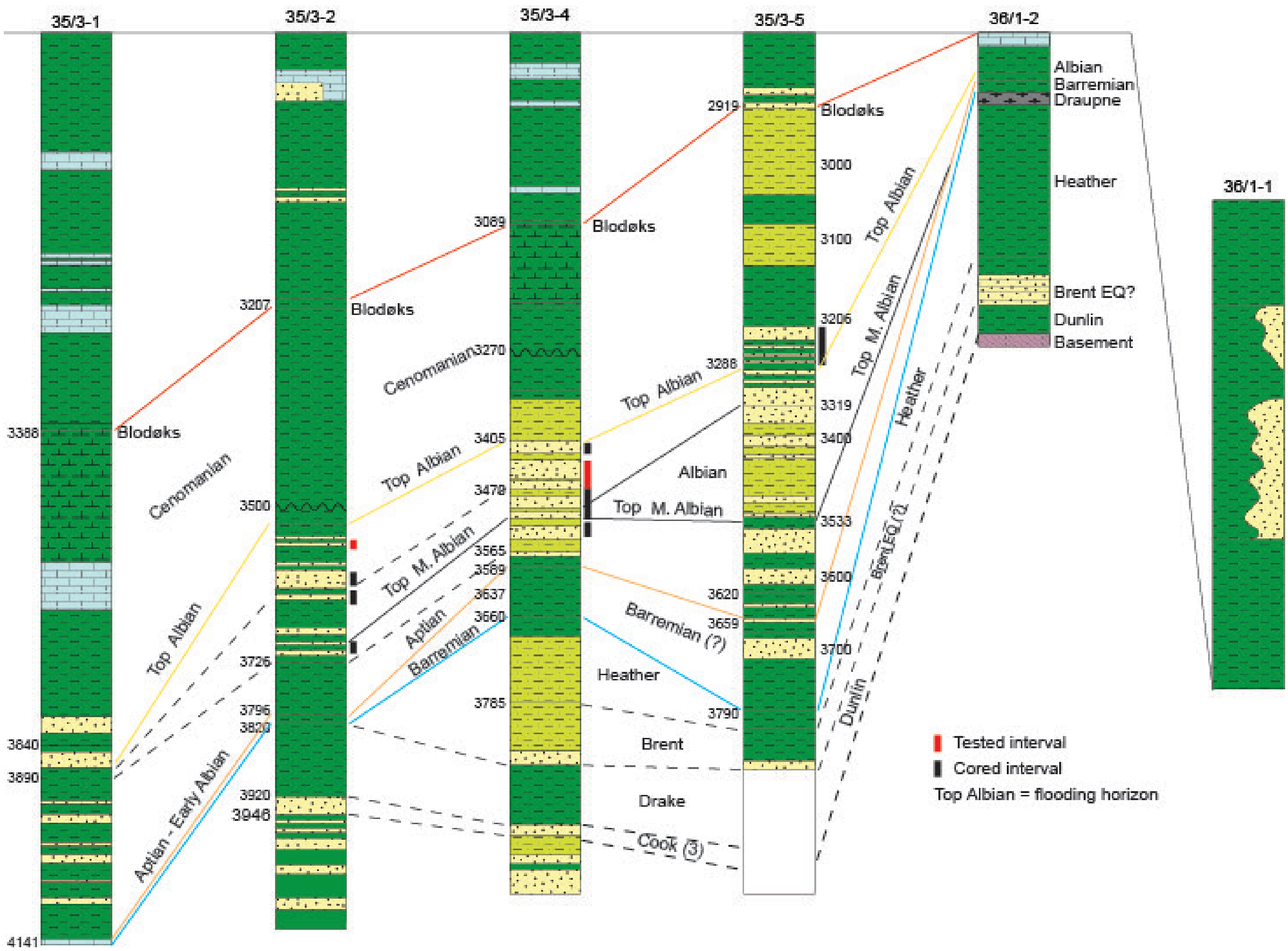


Figure 4.13. Detailed correlation of microfossil levels in the Agat Formation below Blødoks and above Jurassic (shown a bit). Top Albian is a flooding (condensation) horizon with microfossil acmes. For details see text in Chapter 2.

Rødby Formation (Cromer Knoll Group)

Introduction
The definition of the Rødby Formation follows that described in Isaksen & Tonstad (1989) for the Norwegian Sector. In the UK Sector the definition is set out by Johnson & Lott (1993) for the Central and Northern North Sea, which follows that of Larsen (1966) and Deegan & Scull (1977). Because of the ease with which this unit may be correlated into the Southern North Sea Basin, the usage of the term Rødby Formation was extended by Lott & Knox (1994) and replaces the term Red Chalk Formation formerly used for this unit by Rhys (1974). The Rødby Formation generally forms the topmost unit of the Cromer Knoll Group (Table 4.4).

Name
From the town of Rødby on the island of Lolland in southern Denmark (Larsen, 1966).

Lithology
Norway Central Graben and Viking Graben (Isaksen &Tonstad 1989): Mainly red-brown marlstones, but green and grey colours may occur. Glauconite and pyrite may be present. Sandstones and siltstones are known to be present locally.

UK Central to Northern North Sea (Johnson & Lott, 1993): Mudstones (calcareous and chalky) with sporadic thin beds of argillaceous limestone. Mudstones are soft to hard, blocky to fissile, micaceous, glauconitic and sometimes silty. They are mainly pale to dark grey, but often red-brown, brick red, olive grey and dark brown. The red coloration is more often developed in the lower and upper parts of the formation and used for informal subdivision. The interbedded limestones are white to pale grey, tan and re-brown to pink, firm, argillaceous and microcrystalline.

UK Southern North Sea (Lott & Knox, 1994): Calcareous mudstones, chalky mudstones and chalky limestones. They range in colour from pink, pale red, red-brown to brown-grey and often show a variegated, colour-mottled appearance. The mudstones are firm to hard and become increasingly calcareous upwards before passing into the overlying pelagic white to pale grey chalks of the Chalk Group.

The Rødby Formation is characterized by high gamma-ray values (Andrews *et al.*, 1990).

Thickness
In the well type section in the Danish Sector, the thickness is 23 m.

Norway Central Graben and Viking Graben (Isaksen & Tonstad, 1989): The thicknesses in the reference sections are 23 m in well 2/11-1, and 18 m in well 2/7-15. The formation generally ranges in thickness between 15 and 30 m. In the Viking Graben it may become 200 m or more thick (Deegan & Scull, 1977).

UK Sector: The Rødby Formation is generally about 80-180 m thick in the Outer Moray Firth, up to about 90 m thick over the Halibut Shelf (e.g. 13/14-1) and up to about 100 m in the South Viking Graben (e.g. 16/12b-6) and Central Graben (Johnson & Lott, 1993). In the Northern North Sea the formation is typically only a few metres thick (e.g., 211/27-10 comprises 8 m of reddish brown to pale green or grey claystone, calcareous claystone and limestone (Johnson *et al.*, 1993). However, in the Magnus Trough, an exceptionally thick development, 731 m thick, is recorded in well 210/15-4 (Johnson *et al.*, 1993). In the Southern North Sea the formation is generally between 20 and 30 m in thickness but exceptionally may reach 50 m in thickness (e.g. 53/4-6, Lott & Knox, 1994).

Geographical distribution
The Rødby Formation is widely correlatable throughout much of the North Sea Basin. However, it is locally absent on the Utsira-, Jæren-, and Mandal Highs, Tampen Spur and Horda Platform. Formation tops in wells may be obtained from a routine on the Norlex website under this formation.

In the UK Sector it is present in the Central North Sea, South Viking Graben, Moray Firth, Central Graben, Southern North Sea (as far south as approx. 52 degrees 30 minutes N) and off the coast of Yorkshire, Lincolnshire and Norfolk. In the Southern North Sea the Rødby Formation occurs throughout the basinal areas but may be absent over some intra-basinal highs (e.g. 53/2-5, Panel 1, Lott & Knox, 1994).

Type well
Well name: Rødby No.1

Interval of type section and thickness in type well: 459-469 m (1506-1539 ft) below ground level (Larsen, 1966).

Norway Reference wells
Norwegian well 2/11-1: 2910 to 2887 m
Lat. 56°14'16.98"N Long. 03°27'07.05"E
(Figure 12 in Isaksen & Tonstad (1989)). No cores.

Norwegian well 2/7-15: 3419 to 3401 m
Lat. 56°23'46.82"N Long. 03°18'54.63"E
(Figure 22 in Isaksen & Tonstad (1989)). No cores.

UK Reference wells
Central and Northern North Sea (Johnson & Lott, 1993)
14/4-1: 1219-1279 m (3999-4196 ft)
Lat. 58°59'52"N Long. 00°23'44"W
14/20-8: 2530.5-2670.5 m (8302-8762 ft)
Lat. 58°24'41.3"N Long. 00°06'20.9"W
16/12b-6: 3977.5-4087.5 m (13050-13411 ft)
Lat. 58°37'23.076"N Long. 01°20'57.813"E
29/2a-2: 3464-3511 m (11381-11519 ft)
Lat. 56°51'25.18"N Long. 01°17'59.64"E

Southern North Sea (Lott & Knox, 1994)
44/24-1: 1365-1393 m (4478-4570 ft)
Lat. 54°15'0.98"N Long. 02°40'46.2"E
48/22-3: 397.5-420.5 m (1304-1380 ft)
Lat. 53°17'31.3"N Long. 01°15'58.9"E
49/24-1: 1292.5-1325 m (4240-4347 ft)
Lat. 53°16'49.5"N Long. 02°41'30.4"E type section for Red Chalk Formation of Rhys (1974); see Crittenden (1984) for description of the foraminifera present in this well.
53/4-6: 1184-1236 m (3886-4055 ft)
Lat. 52°59'06.71"N Long. 02°44'11.75"E

Upper and lower boundaries

Upper boundary

Norwegian Sector: The upper boundary can be seen as an upward decrease in gamma-ray response, and an increase in velocity into the more calcareous sediments of the Svarte Formation (Figures 33-36 in Isaksen & Tonstad (1989)). On the Horda Platform the Rødby Formation is more calcareous; it also has a lower gamma-ray response, and a higher velocity than the overlying unspecified unit of the Shetland Group (Figure 37 in Isaksen & Tonstad (1989)). Where the chalk facies of the Shetland Group is present, the upper boundary is characterised by a distinct upward drop in gamma-ray readings and a marked increase in velocity (Figures 12, 15 and 22-28 in Isaksen & Tonstad (1989)).

UK Sector: In the Central and Northern North Sea there is a subtle downward change from interbedded pale to dark grey and pink limestones, argillaceous chalks and calcareous mudstones (Hidra Formation, Chalk Group) to less calcareous mudstones and chalky mudstones with interbedded limestones (Rødby Formation). In the Southern North Sea the boundary is less subtle and corresponds to the change from grey and white chalk (Hidra Formation) to red-brown chalky mudstones (Rødby Formation). The upper boundary of the formation corresponds to a moderately sharp downward increase in gamma-ray values and a downward decrease in sonic velocity (Johnson & Lott, 1993; Lott & Knox, 1994).

Lower boundary

Norwegian Sector: The lower boundary is placed on the Sola and Åsgard Formations and on the Ran Member; it represents an upward decrease in gamma-ray response and usually an increase in velocity into the Rødby Formation (Figures 12, 22 and 23 in Isaksen & Tonstad (1989)).

UK Sector: In the Central to Northern North Sea, the base of the Rødby Formation is taken at a transitional downward change from grey and red brown chalky mudstones and calcareous mudstones with interbedded limestones to dark grey, non-calcareous mudstones of the Carrack Formation (Johnson & Lott, 1993). Locally, where the basal beds are absent, the boundary is sharp (e.g. Well 16/12b-6 in the southern Viking Graben) and in some areas of the Inner Moray Firth the boundary is a downward change to sandstone (Wick Sandstone Formation).

In the Southern North Sea, the base of the Rødby Formation is taken at a change from reddened mudstones and chalky limestones to the mudstones of the Carrack Formation. In some wells sited over structural highs the formation may rest directly on thin sandy sediments of Jurassic or older strata. (e.g., 49/9-1, Lott & Knox, 1994).

The lower boundary is defined by a moderately sharp downward increase in gamma-ray values and a sharp decrease in velocity.

Biostratigraphy

In the UK Sector long-ranging planktonic foraminifera, particularly species of *Hedbergella*, are abundant in the Rødby Formation, accompanied by the *Osangularia schloenbachi* biomarker. The top of the formation is characterized by the FDO of *Arenobulimina chapmani* and the ostracod *Isocythereis fissicostis.* The following microfaunal biomarkers can be recognised within the formation: the *Globigerinelloides bentonensis* biomarker, the *Neocythere ventrocostata* biomarker and the *Arenobulimina macfadyeni* biomarker. The *Globigerinelloides gyroidinaeformis* biomarker, is at the base of the Rødby Formation (Crittenden *et al.*, 1991). Two calcareous nannofossil biomarkers are recognised in the middle of the Rødby Formation, based on the FDOs of *Hemipodorhabdus gorkae* and *Gartnerago praeobliquum*. The dinoflagellate cyst floras of the Rødby Formation are diverse and generally well preserved (Crittenden *et al.*, 1991), and by analogy with the Central North Sea and onshore areas, the *Ovoidinium scabrosum* and *Apteodinium maculatum* subsp. grande biomarkers occur at the top of the formation and *Protoellipsodinium spinosum* and *Systematophora cretacea* in the middle unit.

Age

Mainly mid to late Albian (Table 4.4). It is locally early Cenomanian in the Danish Sector (Jensen *et al.*, 1986).

Correlation

In eastern England in the onshore succession of East Anglia, the Rødby Formation equates for the most part with the Hunstanton Formation (formerly the Red Chalk) (Rawson, 1992).

Depositional environment

The Rødby Formation is a highly condensed sequence of sediments which were deposited in a well-oxygenated shallow-marine environment with limited supply of clastics and which have a rich faunal assemblage. The microfauna in Unit R2 is dominated by agglutinating foraminifera indicating a phase of more restricted water circulation (Johnson & Lott, 1993). The formation marks a transitional phase of sedimentation between the hemipelagic mudstone dominated lithologies of the underlying early Cretaceous into the pelagic chalk-dominated lithologies of the overlying late Cretaceous. The characteristic red to red-brown coloration of much of the formation has been attributed to a variety of processes ranging from weathering of reddened lateritic soils to diagenetic changes (e.g. Jeans, 1980).

Subdivision

The Rødby Formation in the Central and Northern North Sea is commonly divisible into three informal units R1 to R3 upwards (Johnson & Lott, 1993). In some wells within the Southern North Sea Basin (e.g. 53/4-6) these three divisions can be recognized but in the majority where the sequence is commonly much thinner and more condensed, only the basal R1 unit may be apparent (e.g. 49/24-1, Lott & Knox, 1994). Consequently the application of these subdivisions is not considered to be appropriate at present for most wells the Southern North Sea area.

Shetland Group (Updated) (Shetlandsgruppen)

Introduction

The term Shetland Group was introduced by Deegan & Scull (1977) for a unit of mudstone with relatively minor interbedded argillaceous limestones lying between the Cromer Knoll and Montrose groups in the Northern North Sea. They did not define formations within the Shetland Group, but recognized six informal subdivisions and designated these 'Formations' A to F (Table 4.3).

The original definitions in the Norwegian Sector of the North Sea are in Dalland *et al.* (1988) and Isaksen & Tonstad (1989). Here the original definition is updated. The Shetland Group has been extended in the Norwegian Sea such that it has a similar stratigraphic duration and boundaries to the original definition in the North Sea by Deegan & Scull (1977), (Table 4.3).

In the UK Sector Northern North Sea Johnson & Lott (1993) followed Deegan & Scull (1977) in recognizing both the Chalk and Shetland groups, albeit with modified definitions (Table 4.2). The Shetland Group now includes all formations dominated by mudstone facies and the Chalk Group all formations dominated by chalky limestone facies. The differentiation of mudstone-dominated and limestone-dominated facies is achieved on the basis of gamma-values. Average values for the Chalk formations range up to about 30 API units, whereas those for the mudstone formations generally exceed 35 API units. In the South Viking Graben and northern parts of the Central North Sea, the Chalk and Shetland groups, as defined in this study, interdigitate.

Many of the Shetland Group mudstone formations named by Isaksen & Tonstad (1989) are adopted for the UK Sector in this report. However, mudstone equivalents of the Herring Formation (as redefined by Johnson & Lott, 1993) are included within a single formation, the Macbeth Formation, rather than the two formations recognized by Isaksen & Tonstad in the Norwegian Sector (the Blodøks and Tryggvason formations).

Isaksen & Tonstad (1989, fig.6, p. 10), showed the base of the Jorsalfare Formation to be time-equivalent to the base of the Tor Formation. However, the Tor Formation was redefined by Johnson & Lott (1993) restricting it to relatively 'clean', lowgamma chalk. This conforms to current usage and provides a more consistently definable formation boundary. However, it necessitates raising the base of the Tor Formation in Deegan & Scull's UK reference section (22/1- 2A), so that the bases of the Tor and Jorsalfare formations are no longer time equivalent (Tables 4.1-4.4). King *et al.* (1989) indicate that the base of Jorsalfare Formation is in the earliest Late Campanian, whereas the base of the Tor Formation as here redefined is believed, in most sections, to lie in the earliest Maastrichtian.

Name

Named from the Shetland Islands off the north coast of Scotland (Deegan & Scull, 1977). The group was expanded in Isaksen & Tonstad (1989) to include the formational units of the former Chalk Group.

Type area

The group is typically developed as a siliclastic facies in the Northern North Sea and as a chalk facies in the Central North Sea. UK well 22/1-2A illustrates a section in the transition zone between the two facies (Johnson & Lott, 1993). A typical section of the chalk facies in the central area is represented by Norwegian well 1/3-1 (Figure 24 in Isaksen & Tonstad, 1989), while Norwegian well 25/1-1 (Figure 33 in Isaksen & Tonstad, 1989) provides a typical section of the siliciclastic facies in the northern area. UK well 22/1-2A illustrates a section in the transition zone between the two facies (Figures 5 and 25 in Isaksen & Tonstad, 1989).

Thickness

In Norwegian well 1/3-1 the group is 1183 m thick, and in well 25/1-1 it measures 1284 m. Seismic interpretation and well data indicate that the thickness of the group ranges between 1000 and 2000 m in graben areas within the Norwegian Sector. The group shows considerable thinning towards and in the platform areas.

The Shetland Group in the UK Sector is up to 2000 m thick (Figure 4.3) in the Viking Graben, Beryl Embayment, East Shetland Basin and Magnus Trough (Johnson & Lott 1993).

A regional isopach of the Shetland Group thickness in the Norwegian Sea based on released well

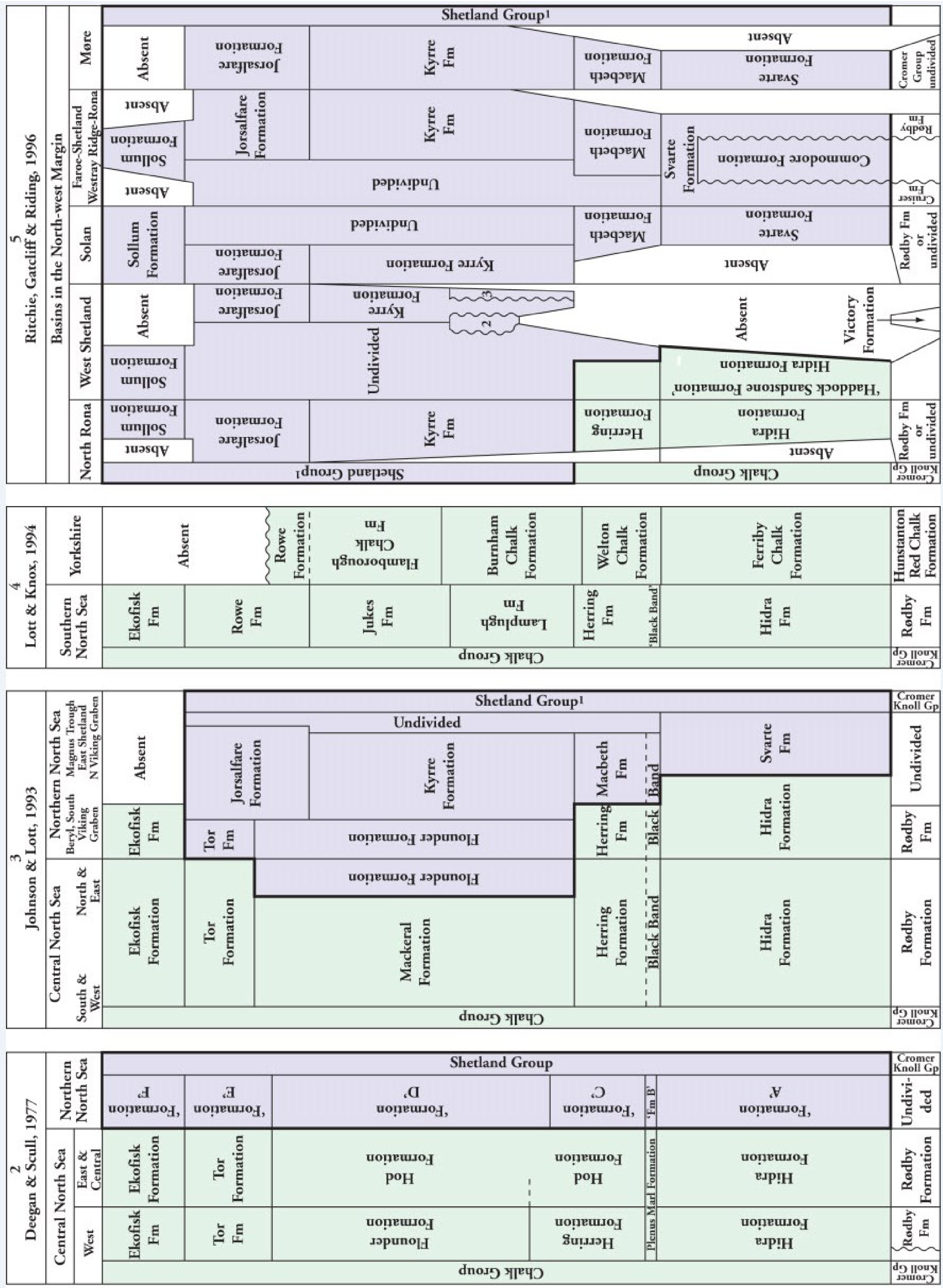


Table 4.3 Historical development of the Upper Cretaceous lithostratigraphical nomenclature for the offshore UK Sector (from Hopson, 2005). The nomenclature used in this study is derived from columns 3, 4 and 5.

data is in Figure 3.11, and on the Norlex website. The isochore map is generated from Norlex data using thin plate splines (thickness constrained to original range). Thicknesses in metres. Circled well contain both top and base horizons. In the case of the Shetland Group this includes wells with a well TD within the group. The red wells have Norlex biostratigraphy. Note that this map is only a regional interpretation and the user can generate more specific, local area isochore maps interactively within the Norlex website, using a dedicated link.

Lithology

The group consists of the chalk facies of chalky limestones, limestones, marls, and calcareous shales and mudstones. Chert (flint) occurs throughout the facies. The siliciclastic facies consists of mudstones and shales, partly interbedded with limestones (Johnson & Lott, 1993). In the Norwegian Sector sandstones are present in the lower part in the Agat Field area (block 35/3). The shales and sandstones are slightly calcareous to very calcareous. In the Maastrichtian age part of the unit the quantity of limestones is generally higher on the Horda Platform than in the Viking Graben.

Figure 3.12 is the well log and lithology section of our reference well 6506/12-1, where the Shetland Group extends from the clear log break at 2279 m with lower Maastrichtian fossil taxa to the log break at 3705 m, just above the top of Albian index taxa (see below) in the Cromer Knoll Group.

Figure 3.13 is the well log and lithology section of our reference well 6506/12-4, where the Shetland group extends from the clear log break at 2211 m with upper Maastrichtian fossil taxa to the log break at 3738 m, just above the top of Albian index taxa (see below) in the Cromer Knoll Group.

Characteristics of the lower boundary

Typically, in the Norwegian Sector, the lower boundary is the contact with the calcareous mudstones or marlstones of the Cromer Knoll Group. On structural highs like the Horda Platform, Tampen Spur, Sørvestlandet and Mandal Highs the lower part of the group is occasionally absent, and the remainder rests unconformably on the Cromer Knoll Group, Jurassic or even older rocks.

In the Northern North Sea (UK Sector) the lower boundary is taken at the base of the essentially non--calcareous mudstones (Black Band) of the Macbeth Formation where it rests upon white to pale grey chalky limestones of the Hidra Formation (Chalk Group), or where the Chalk Group is absent, at the base of the calcareous mudstones or argillaceous chalky limestones of the Svarte Formation where it rests upon the less calcareous mudstones and chalky mudstones with interbedded limestones of the Rødby Formation (Cromer Knoll Group).

In the Central North Sea (UK Sector) the lower boundary is taken at the base of the mudstones with argillaceous chalky limestones of the Flounder Formation, where it rests upon cleaner limestones of the Herring Formation (Chalk Group).

Characteristics of the upper boundary

In the Norwegian Sector the group is overlain by Paleocene mudstones, marls or sandstones of the Rogaland Group. In the Northern North Sea (UK Sector) the upper boundary is taken at the base of the argillaceous chalky limestones and interbedded calcareous mudstones of the Ekofisk Formation (Chalk Group) where it rests upon cleaner limestones of the Jorsalfare Formation. In the Central North Sea the upper boundary is taken at the base of the hard chalky limestones of the Tor Formation (Chalk Group), where it rests upon the argillaceous mudstones with argillaceous chalky limestones of the Flounder Formation.

Distribution

The group is present throughout the Norwegian North Sea, being absent only locally on highs (e.g. in the 16/5-1 and 31/2-9 wells) and a few salt diapirs (e.g. in well 2/7-12). A transition between the chalk and siliciclastic facies of the group occurs relatively abruptly in the Norwegian Sector along the Utsira High and more gradually in the graben areas. The interactive decription of the Shetland Group on the Norlex website has a function to generate formation tops in wells. In the UK Sector the Shetland Group occurs in the Viking Graben, Beryl Embayment, East Shetland Basin and Magnus Trough (Figure 4.1).

Biostratigraphy and Age

The Shetland Group ranges in age from Cenomanian

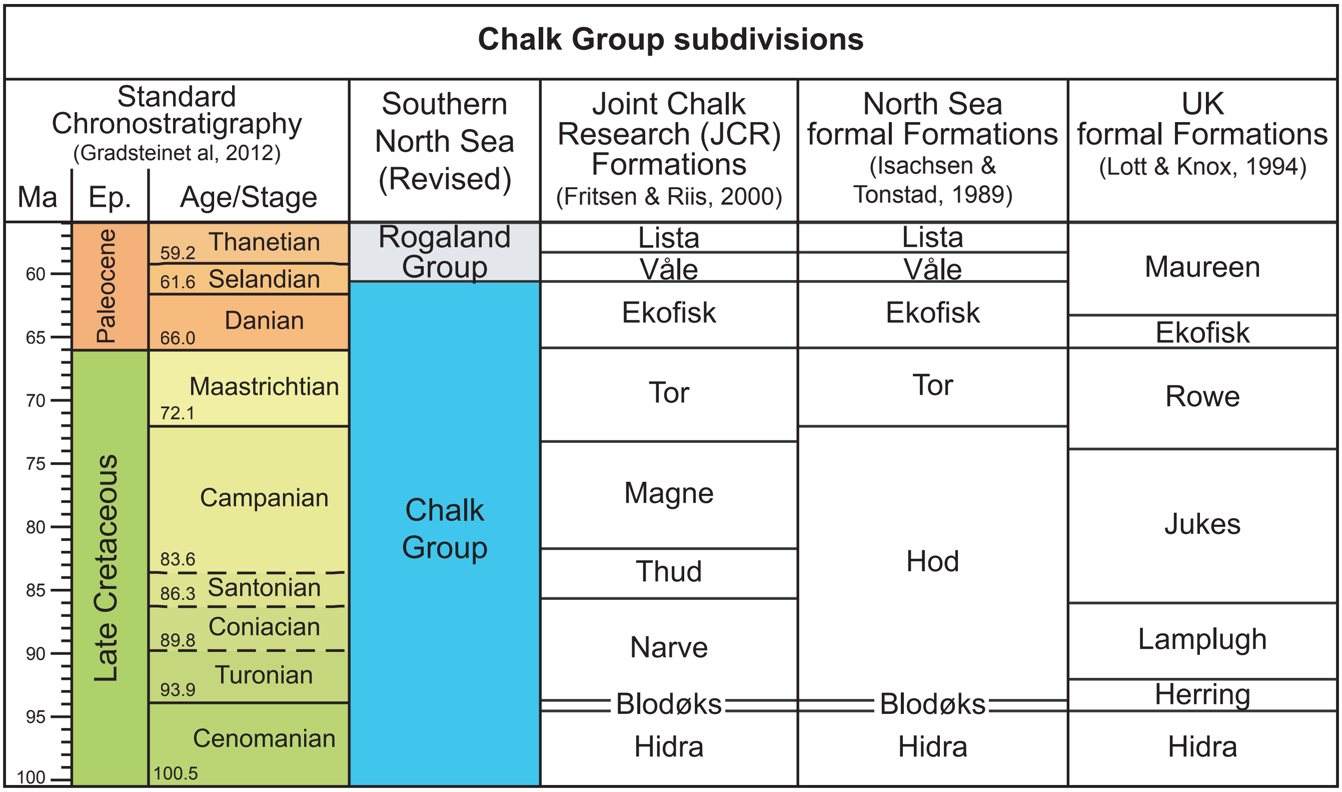


Table 4.4 Chalk Group subdivisions in the offshore Norwegian Sector North Sea compared with the UK Sector.

to Danian. The siliciclastic facies is restricted in age to the Late Cretaceous. In the UK Sector the group is restricted in age to the Late Cretaceous, ranging from Turonian to Maastrichtian (Table 4.1).

In well 6506/12-1, the upper part of the Shetland Group just below 2279 m contains *G.michelinianus, O.costata, O.operculata, L.cooksonia* and *S.delitiense*, belonging in Zone NCF18 of an Early Maastrichtian age. Just below the base of the group in this well near 3710 m, in the uppermost Cromer Knoll Group, occur *A.grande*, common *H.planispira* and *O.schloenbachi* of our Zone NCF8, Late Albian (see Figure 2.7b).

In well 6506/12-4, the upper part of the Shetland Group at 2220 m contains *T.utinensis* of Late Maastrichtian age, and just below the base at 3738 m common *H.planispira* and *A.grande* of Zone NCF8, Late Albian.

Depositional environment

The Upper Cretaceous sequence in the North Sea was deposited in an open marine environment during a general rise in sea level. On the basis of microfossil assemblages, King *et al.* (1989) suggested that the Shetland Group was deposited as a deeper water (bathyal) facies compared to the Chalk Group. Hancock (1990) noted a northward increase in the proportion of silt in the Shetland Group and postulated a northern provenance for the mudstones, with Greenland as a possible source area. The chalk facies formations were deposited as coccolith debris and other carbonate grains and sequences often show a cyclic pelagic sedimentation pattern termed periodite. In the Central Graben, extensive subsidence resulted in the chalk facies being dominated by allochthonous, redeposited chalks which were transported downslope as major slides, slumps, debris flows, and proximal and distal turbidites. The siliciclastic facies in the northern North Sea is less well studied. The influx of siliciclastic mud was higher, and carbonate production lower than in the area with chalk facies.

Subdivision

The Shetland Group in the Norwegian Sea is subdivided from older to younger in the Blålange Formation (new) and Kvitnos, Nise and Springar Formations (Table 3.2).

In the northern North Sea the Shetland Group is represented by six siliciclastic facies units: the Svarte, Blodøks, Tryggvason, Kyrre, Jorsalfare and Hardråde Formations (Table 4.4; all erected by Isaksen & Tonstad, 1989). In the southern North Sea the Shetland Group is now replaced by the Chalk Group and represented by the typically siliciclastic Blodøks Formation and six chalk facies units: the Hidra, Narve (new), Thud (new) and Magne (new), Tor and Ekofisk Formations (Table 4.4). The Narve, Thud and Magne units were informally described by Fritsen & Riis (2000), subdividing the original Hod unit of Deegan & Scull (1977). The latter authors described the Blodøks, Hidra, Tor and Ekofisk units.

The Shetland Group in the Northern North Sea (UK Sector) is represented by three siliciclastic facies formations, in ascending order: the Macbeth, Kyrre and Jorsalfare formations (Johnson & Lott, 1993; Tables 4.1 and 4.3). In northern parts of the Central Graben, the Shetland Group is represented by a single formation, the Flounder Formation, which occurs between the chalky limestones of the Tor and Herring formations (Chalk Group). The lateral boundary with the Herring Formation (to the west, south and east) is transitional. The boundary with the Kyrre Formation and the lower part of the Jorsalfare Formation (to the north) is similarly transitional, but the limit of the Flounder Formation is more or less defined by the limit of the chalky limestones of the Tor Formation. The Herring and Flounder Formations in the UK Sector (Deegan & Scull, 1977) are regarded as equivalents of the Macbeth Formation and of the Kyrre Formation, respectively (Tables 4.1 and 4.3).

When traced northwards of the Central Graben, the formations of the Shetland Group become increasingly difficult to differentiate in the UK Sector, only the Svarte Formation being consistently recognizable. The characteristic limestones of the Macbeth Formation do not extend into the East Shetland Basin, so that the boundary with the overlying Kyrre can no longer be recognized with certainty. Similarly, the Jorsalfare Formation, cannot be traced through the Northern North Sea area. Where the formations cannot be recognized, the mudstones are classed as undivided Shetland Group.

Shetland Group (UK Sector)

Svarte Formation (Shetland Group)

The definition of this lowermost formation of the group in the UK Sector is provided in the description below of the Shetland Group (Norwegian Sector- Viking Graben).

Macbeth Formation (Shetland Group)

Introduction

The term Macbeth Formation was introduced Johnson & Lott (1993) for a unit of interbedded mudstones and argillaceous chalky limestones that lies between the Svarte and Kyrre formations in the UK Viking Graben and East Shetland Basin (Table 4.1). The Macbeth Formation comprised the informal 'Formations' B and C of the Shetland Group (Table 4.3) as defined by Deegan & Scull (1977). In the Norwegian North Viking Graben, Isaksen & Tonstad (1989) included laterally equivalent strata in the Blodøks and Tryggvason formations (Table 4.2).

Name

After the 10th century Scottish king.

Lithology

The Macbeth Formation consists of mudstones with interbedded limestones. The mudstones are pale to dark grey, calcareous to non-calcareous and occasionally very silty, micaceous, glauconitic and pyritic. The limestones are chalky and argillaceous, white to pale grey or brownish grey, and locally glauconitic. In the Viking Graben and East Shetland Basin, the limestone units are up to about 60 m thick (e.g. 9/10c-2, Panel 2, Johnson & Lott, 1993), but both the proportion of limestone and the thickness of individual limestone beds tend to decrease northwards and away from contemporary structural highs (e.g. 3/10b-I, Panel 1, Johnson & Lott, 1993). In the Beryl Embayment and Viking Graben, the formation displays an overall 'barrel-shaped' wireline log signature, with a more calcareous middle section underlain and overlain by more argillaceous deposits (e.g. 9/10c-2, Panel 2, Johnson & Lott, 1993).

Thickness

The Macbeth Formation is up to 175 m thick in the UK North Viking Graben (Johnson & Lott, 1993).

Geographical distribution

The Macbeth Formation occurs in the UK Viking Graben, Beryl Embayment and the south and west of the East Shetland Basin. It is, however, absent over contemporary structural highs. Seismic evidence suggests onlap of the formation onto these structures, but condensation and intra-Cretaceous erosion may also be a limiting factor (Johnson *et al.*, 1993).

Type well

Well name: 3/29-1

WGS84 coordinates:

Lat. 60°06'46.5"N Long. 01°44'21.9"E

UTM coordinates:

UTM zone: 31

Drilling operator name: BP Exploration Operating Company Limited

Completion date: 31.08.1973

Status: P & A

Interval of type section and thickness in type well: 3603 - 3778 m (11821-12395 ft) below KB (Johnson & Lott, 1993).

UK Reference well

3/10b-1: 3586-3840 m (11765-12598 ft)

Lat. 57°40'51.5"N Long. 00°08'50.4"W

Upper and lower boundaries

Upper boundary

The top of the Macbeth Formation is normally marked by a downward change from mudstones of the Kyrre Formation to argillaceous chalky limestones and interbedded mudstones (Johnson & Lott, 1993).

Lower boundary

The base of the Macbeth Formation is normally marked by a downward change from essentially non-calcareous mudstones (Black Band) to calcareous mudstones and argillaceous chalky limestones of the Svarte Formation (e.g. 3/29-1 & 9/10c-2, Panel 2, Johnson & Lott, 1993). Over some structural highs, the Macbeth Formation rests unconformably on very condensed sections of the Cromer Knoll Group or on pre-Cretaceous rocks (e.g. Kimmeridge Clay Formation in 9/19-7Z, Panel 2, Johnson & Lott, 1993). In the Beryl Embayment and South Viking Graben, the Macbeth Formation overlies the Hidra Formation (Johnson & Lott, 1993).

Well log characteristics

The upper boundary is marked on wireline logs by a downward decrease in gamma values and an increase in velocity into the Macbeth Formation. The lower boundary is marked on wireline logs by a decrease in gamma values and an increase in velocity. Commonly, the Black Band is difficult to recognize (e.g. 3/12-2, Panel 2, Johnson & Lott, 1993).

Biostratigraphy

Calcareous benthonic foraminifera such as *Ivulineria gracillima, Stensioeina pokornyi* and *Gavelinella intermedia* are common. Planktonic taxa are less common, but provide the *Praeglobotruncana stephani* biomarker; other taxa present include the long-ranging taxa *Dicarinella hagni* and *Praeglobotruncana gibba*. The *Litosphaeridium siphoniphorum* dinoflagellate cyst biomarker occurs in the lower part of the formation, immediately above the Black Band. Acme occurrences of *Heterosphaeridium difficile* arecharacteristic of the formation (Costa & Davey, 1992).

Age

?Early to mid Turonian (Tables 4.1 and 4.3).

Correlation

The Macbeth Formation is laterally equivalent to the Herring Formation of the South Viking Graben and Central North Sea (Tables 4.1 and 4.3).

Depositional environment

According to King *et al.* (1989), the foraminiferal assemblages in the Macbeth Formation (zone FCN 14a) are dominated by non-calcareous agglutinates, indicating a relatively restricted, sublittoral and bathyal, marine environment.

Subdivision

A unit of relatively high-gamma mudstones at the base of the Macbeth Formation is formally designated the Black Band (Johnson & Lott, 1993). In the East Shetland Basin, the upper part of the Macbeth Formation has been informally designated the 'Basal Shetland Limestone' in several published accounts describing oilfields in the East Shetland Basin (see Abbotts, 1991).

Kyrre Formation

The definition of this formation of the Shetland Group in the Northern North Sea (UK Sector) is provided in the description below of the Shetland Group (Norwegian Sector- Viking Graben).

Jorsalfare Formation

The definition of this formation of the Shetland Group in the Northern North Sea (UK Sector) is provided in the description below of the Shetland Group (Norwegian Sector- Viking Graben).

Flounder Formation (Shetland Group)

Introduction

The term Flounder Formation was introduced by Deegan & Scull (1977) for a unit of mudstones and interbedded limestones that lay between the Herring Formation and the Tor Formation (Table 4.3). This definition was adopted by Johnson & Lott (1993) except that, in contrast to Deegan & Scull (1977), the Flounder Formation is included in the Shetland Group.

Name

From the salt-water flat-fish.

Lithology

The Flounder Formation consists of pale to dark grey, occasionally pink to red, very calcareous mudstones, grading into pale to dark grey argillaceous chalky limestones. Thin beds of white brittle cryptocrystalline limestone are also present (Johnson & Lott, 1993).

Thickness

The Flounder Formation is up to 500 m in thickness in the Fisher Bank Basin, but is absent over the crest of the Forties-Montrose High (Gatliff et al., 1994). Seismic evidence suggests that it broadly onlaps, and becomes very thin over, contemporary structural highs (Gatliff *et al.*, 1994). Andrews *et al.* (1990) interpreted a significant unconformity or hiatus within the Flounder Formation.

Geographical distribution

The Flounder Formation is confined to the southern part of the South Viking Graben and the extreme north of the Central North Sea

Type well

Well name: 22/l-2A

WGS84 coordinates:
Lat. 57°56'12.2"N Long. 01°02'55.8"E
UTM coordinates:
UTM zone: 31
Drilling operator name: BP Exploration Operating Company Limited
Completion date: 13.04.1974
Status: P & A G/C W
Interval of type section & thickness in type well: 3198-3605 m (10492-11827 ft) below KB (Deegan & Scull, 1977, p.27, fig.28) (revised depths by Johnson & Lott, 1993). Highly argillaceous chalky limestones and mudstones that were placed within the Tor Formation by Deegan & Scull were included within the Flounder Formation by Johnson & Lott (1993).

UK Reference well

16/17-6: 3249 - 3590.5 m (10660-11779 ft)
Lat. 58°25'55.6"N Long. 01°18'26.0"E

Upper and lower boundaries

Upper boundary

The top of the Flounder Formation is normally marked by a relatively abrupt downward change from the hard chalky limestones of the Tor Formation to calcareous mudstones with interbedded argillaceous chalky limestones, which are commonly stained pink or red.

Lower boundary

The base of the Flounder Formation is usually taken at a downward change from mudstones with interbedded argillaceous chalky limestones to cleaner, higher velocity limestones of the Herring Formation. On intrabasinal highs, the Flounder Formation locally rests unconformably on Jurassic or older rocks (e.g. Pentland Formation in 15/26a-2).

Well log characteristics

The Flounder Formation has a similar wireline-log signature to the more argillaceous developments of the Mackerel Formation, but is distinguished on the basis of its higher overall gamma values (generally over 30-35 API units, Johnson & Lott, 1993). The top of the Flounder Formation corresponds to a downward increase in gamma values and decrease in velocity on wireline logs. The base of the Flounder Formation corresponds to a downward decrease in gamma values and an increase in velocity

Biostratigraphy

The top of the Flounder Formation is marked by the *Reussella szajnochae* acme foraminiferal biomarker, which in the Central North Sea is accompanied by the FDO of *Tritaxia capitosa*. In some areas, this biomarker occurs at the top of the formation; in others it is just below the top (this is also implied in King *et al.*, 1989, fig.8.4). Long-ranging planktonic foraminifera, particularly species of *Rugoglobigerina*, are common. The *Cenosphaera* sp. radiolarian biomarker is present in the middle part of the formation. The *Stensioeina granulata polonica* and *S. granulata granulata* biomarkers also occur within the formation.

Three key calcareous nannofossil biomarkers occur: the *Reinhardtites anthophorus* biomarker, at the top of the formation, the *Broinsonia enormis* biomarker, at the top of the early Santonian, and *Watznaueria barnesae* acme biomarker, which marks the mid/early Santonian boundary, in the middle part of the formation. The *Helicolithus trabeculatus* biomarker and *H. valhallensis* acme biomarker also occur within the formation.

The S*enoniasphaera protrusa, Callaiosphaeridium assymetricum, Cassiculosphaeridia reticulata, Heterosphaeridium difficile, Endoscrinium campanula, Florentinia deanei* and *Stephodinium coronatum* dinoflagellate cysts biomarkers all occur within the formation (Johnson & Lott, 1993). *Spiniferites* spp. (especially *S. ramosus*) dominates and *Chatangiella* spp. are locally common in the Coniacian.

Age

Mid Turonian to early Maastrichtian (Table 4.1 and 4.3).

Correlation

In the Central North Sea, the Flounder Formation grades laterally into the Mackerel Formation (Tables 4.1 and 4.3). In the South Viking Graben, the Flounder Formation passes northwards into the Kyrre Formation and the lower part of the Jorsalfare Formation (J1 and the basal part of J2) (see Panel 3 of Johnson & Lott, 1993). Red coloration in the unit of interbedded argillaceous chalky limestone and mudstone near the top of the formation in well 22/l -2A supports a wireline-log correlation with the characteristically red, calcareous unit (J1) at the base of the Jorsalfare Formation.

Depositional environment

The Flounder Formation comprises marine hemipelagic mudstones and pelagic limestones that accumulated in low-energy shelf to upper bathyal conditions. Phases of more open marine circulation are indicated by a higher proportion of planktonic foraminifera in the Coniacian and Upper Campanian (King *et al.*, 1989).

Subdivision

King *et al.* (1989) informally divided the Flounder Formation into three units of pale grey mudstone with argillaceous limestone, and three intervening units of red-stained, and generally more argillaceous mudstone. On the basis of wireline-log signatures, Andrews et al. (1991) recognized four chalk-marl cycles, each up to about 100 m thick in the Flounder Formation of the Moray Firth and subdivided it into four informal units (designated F1 to F4). The Flounder Formation was not formally subdivided by Johnson & Lott (1993), although informal subdivisions are recognized and correlated locally.

Shetland Group (Norwegian Sector)

Svarte Formation (Updated) (Svarteformasjonen)

Introduction
The term Svarte Formation was introduced by Isaksen & Tonstad (1989) for a unit of calcareous mudstones with interbedded argillaceous chalky limestones lying between the Rødby and Blodøks formations in the Norwegian Northern North Sea (Table 4.2). The Svarte Formation was extended into the UK North Viking Graben, East Shetland Basin and Magnus Trough by Johnson & Lott (1993; Table 4.1). The Svarte Formation was informally designated 'Formation' A of the Shetland Group by Deegan & Scull (1977; Table 4.3).

Name
After Halvdan Svarte, King of Ringerike, Norway, c. A.D. 850 (Isaksen & Tonstad, 1989, p.27).

Lithology
Norwegian Sector: The formation generally consists of mudstones interbedded with limestones. Sandstones occur in the Agat region. The content of limestones relative to mudstones is generally lower in the northern than in the southern part of the Viking Graben. The mudstones are medium to light grey, often calcareous, occasionally micaceous, glauconitic and pyritic. The limestones are mainly white to medium grey, argillaceous or sandy. The sandstones are clear to light grey and often cemented by calcite.

UK Sector: The Svarte Formation consists of calcareous mudstones with interbedded argillaceous chalky limestones (Johnson & Lott, 1993). In the North Viking Graben and East Shetland Basin, the proportion of limestone within the formation generally decreases northwards and away from contemporary high structures. The mudstones are typically medium to pale grey and occasionally micaceous, glauconitic and pyritic. The argillaceous chalky limestones are mainly white to medium grey and locally sandy.

Thickness
Norwegian Sector: In the type well 25/1-1, in the Viking Graben, the formation is 188 m thick. In the reference sections the thickness is 240 m in well 35/3-2, and 188 m in well 24/9-1.

UK Sector: The formation ranges up to about 250 m thick (e.g. 210/15b-4, Johnson & Lott, 1993). The formation can be over 57 m thick in the Magnus Trough of the Northern North Sea, thinning and pinching out over the basin-margin highs (Johnson *et al.*, 1993).

Geographical distribution
Norwegian Sector: The formation is present in the Viking Graben, and north of the Tampen Spur towards the Marulk Basin. It is, however, lacking on structural highs such as the Lomre Terrace (e.g. Norwegian wells 35/8-1 and 35/8-2).

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

UK Sector: The Svarte Formation occurs in the North Viking Graben, East Shetland Basin and Magnus Trough (Johnson & Lott, 1993). It is, however, absent over contemporary structural highs. Although seismic evidence suggests onlap of the formation onto these structures, condensation and intra-Cretaceous erosion may also be a limiting factor (Johnson *et al.*, 1993).

Type well
Well name: N25/l -1 (Norwegian Sector)
WGS84 coordinates:
Lat. 59°53'17.5"N Long. 02°04'42.7"E
UTM coordinates: 6639470.41 N 448427.57 E
UTM zone: 31
Drilling operator name: Elf Petroleum Norge AS
Completion date: 22.07.1971
Status: P & A
Interval of type section and thickness in type well: 3807 - 3995 m (12490-13107 ft) below KB (Isaksen & Tonstad, 1989, p.27, fig.33). No cores.

Norwegian Reference well
35/3-2: 3447 to 3207 m
Lat. 61°50'05.98"N Long. 03°46'28.22"E
(Figure 34 in Isaksen & Tonstad (1989)). No cores.
24/9-1: 3992 to 3804 m
Lat. 59°16'09.48"N Long.01°47'31.18"N

(Figure 35 in Isaksen & Tonstad (1989)). No cores.

UK Reference well

3/29-1: 3778-3932 m (12395-12900 ft)
Lat. 60°06'46.5"N Long. 01°44'21.9"E
3/1-1: 3081.5-3176.5 m (10110-10421 ft)
Lat. 60°56'43.5"N Long. 01°09'31.9"E

Upper and lower boundaries

Upper boundary

Norwegian Sector: The upper boundary is generally easily located, and is characterised by an increase in gamma-ray intensity and a distinct decrease in velocity from the Svarte Formation up into the Blodøks Formation (Figure 33 in Isaksen & Tonstad (1989)). This is caused by lower carbonate content in the Blodøks Formation.

UK Sector: The top of the Svarte Formation is marked by a downward change from mudstones of the Macbeth Formation (Black Band) to argillaceous chalky limestones or calcareous mudstones (e.g. 3/29-1 & 9/10c-2 Johnson & Lott, 1993). In the north of the East Shetland Basin, the Svarte Formation is overlain by undivided Shetland Group mudstones (e.g. 211/26-4).

Lower boundary

Norwegian Sector: The lower boundary shows a general upward decrease in gamma-ray intensity, and an increase in velocity from the Cromer Knoll Group into the Svarte Formation (Figure 34 in Isaksen & Tonstad (1989)). This is due to a higher content of carbonate in the Svarte Formation.

UK Sector: The base of the Svarte Formation is normally marked by a downward change from calcareous mudstones or argillaceous chalky limestones to less calcareous sediments of the undifferentiated Cromer Knoll Group (Johnson & Lott, 1993).

Well log characteristics

The upper boundary in the UK Sector is marked on wireline logs by a decrease in gamma values and an increase in velocity into the Svarte Formation. Where the Black Band is not easily distinguished, the log break associated with the boundary is not as conspicuous (e.g. 3/8b-10). The base of the formation corresponds to a downward increase in gamma values and a decrease in velocity (Johnson & Lott, 1993).

Biostratigraphy

The calcareous microfauna in the UK Sector is dominated by planktonic foraminifera (over 90%), particularly species of *Hedbergella*. The *Rotalipora cushmani* biomarker is well represented in the south, but becomes increasingly difficult to recognise to the north. The *Lingulogavelinella ciryi inflata* / *Rotalipora reicheli* biomarker is present in the middle part of the formation. The *Axopodorhabus albianus* nannofossil biomarker occurs at the top of the formation, with the *Gartnerago theta, G. nanum* and *Biscutum constans* acme biomarkers occurring lower down in the formation (Johnson & Lott, 1993).

The *Apteodinium granulatum* dinoflagellate cyst biomarker occurs at the top of the formation, with the *Epelidosphaeridia spinosa* and *Ovoidinium verrucosum* subsp. *verrucosum* biomarkers occurring lower down. A downward influx of peridiniacean (deflandroid) dinoflagellate cysts occurs in the upper part of the formation, including *Chatangiella* spp., *Isabelidinium magnum* and *Trithyrodinium suspectum* (Costa & Davey, 1992).

Age

Cenomanian (Tables 4.1 and 4.3).

Correlation

The Svarte Formation is laterally equivalent to the Hidra Formation in the Central Graben and Central North Sea and with the informal "formation A" of Deegan & Scull (1977; Table 4.3), (Figure 6 in Isaksen & Tonstad (1989)).

Depositional environment

The microfossil assemblages in the Svarte Formation are rich in planktonic foraminifera and indicate marine, sublittoral and bathyal conditions with access to open oceanic circulation (King *et al.*, 1989).

Subdivision

None in UK and Norwegian waters.

Blodøks Formation (Updated) (Blodøksformasjonen)

Central and Viking Grabens, Norwegian Sector

Name

Named after Eirik Haraldson Blodøks, a Norwegian king who reigned in Norway (A.D. 930-934) and in Northumberland (A.D. -954).

Lithology

The formation consists of red, green, grey and black shales and mudstones, which are non-calcareous to moderately calcareous. In the Central North Sea the formation may show a varied influx of marls, limestones and chalky limestones.

Thickness

The formation is 17 m thick in the type well (25/1-1), 17 m in well 35/3-2, 28 m in well 1/3-1 and 7 m in well BO-1. It rarely exceeds 20 m in thickness.

Geographical distribution

The formation is present throughout the North Sea, lacking only on local highs such as the Sørvestlandet High, the Utsira, Mandal, Jæren and Sele highs and the Grensen Ridge as well as above many salt diapirs.

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

Type well

Well name: 25/1-1 (Norwegian Sector)

25/1-1: 3807 to 3790 m

Lat. 59°53'17.40"N Long. 02°04'42.70"E. No cores.

Norwegian reference wells

35/3-2: 3207 to 3190 m

Lat. 61°51'05.98"N Long. 03°46'28.22"E. No cores.

1/3-1: 4371 to 4343 m

Lat. 56°51'21.00"N Long. 02°51'05.00"E. No cores.

Danish reference well

BO-1: 2220 to 2213 m

Lat. 55°48'02.22"N Long. 04°34'18.66"E. Cored throughout.

Upper and lower boundaries

Upper boundary

The upper boundary shows a decrease in gamma-ray intensity and an increase in velocity from the Blodøks Formation upwards into the more calcareous Tryggvason Formation, or the chalky Narve Formation (Table 4.2).

Lower boundary

The lower boundary is generally characterised by a distinct log break with an upward increase in gamma--ray intensity and a distinct decrease in velocity from the Svarte Formation (Figure 33 in Isaksen & Tonstad (1989)), or Hidra Formation (Figure 24 in Isaksen & Tonstad (1989)), into the Blodøks Formation. This is due to lower carbonate content in the Blodøks Formation.es.

Age

Latest Cenomanian to early Turonian (Table 4.2).

Depositional environment

The formation was deposited during a period characterised by anoxic bottom conditions (e.g. Hart & Leary, 1989). Presence of carbonates may indicate periods of more oxic conditions or supply of allochthonous limestones and chalks (e.g. Norwegian wells 1/3-1 and 2/5-1).

Tryggvason Formation (Updated) (Tryggvasonformasjonen)

Shetland Group, Viking Graben, North Sea.

Name

Named after Olav Trygvason, a Norwegian king (A.D 995-1000).

Lithology

The Tryggvason Formation consists generally of mudstones with interbedded limestones. Interbedded sandstones are common in the Agat area. The content of limestones relative to mudstones is generally lower in the northern part of the Viking Graben (from blocks 30/2 and 30/3 northwards) than in the southern part. At the transition between the Viking Graben and the Horda Platform (e.g. block 30/11;

Fig. 36 of Isaksen&Tonstad, 1989) the formation consists of limestone.

The mudstones are light to dark grey, often calcareous, occasionally micaceous, glauconitic and pyritic. The limestones are white to light grey or brownish grey and argillaceous. The sandstones are clear to light grey, very fine- to fine-grained and cemented by calcite.

Thickness

In the Viking Graben, the formation is 208 m thick in the type well (25/5-1), 326 m in well 35/3-2, and 145 m in well 24/9-1. It is 45 m thick in well 30/11-3 on the western margin of the Horda Platform.

Geographical distribution

The formation is present in the Viking Graben and northern Tampen Spur area, towards the Marulk Basin.

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

Type well

Well name: 25/1-1 (Norwegian Sector)

25/1-1: 3790 to 3582 m

Lat. 59°53'17.40"N Long. 02°04'42.70"E (Figure 33 in Isaksen & Tonstad (1989)). No cores.

Norwegian reference wells

35/3-2: 3190 to 2864 m

Lat. 61°51'05.98"N Long. 03°46'28.22"E (Figure 34 in Isaksen & Tonstad (1989)). No cores.

24/9-1: 3783 to 3638 m

Lat. 59°16'09.48"N Long. 01°41'31.18"E (Figure 35 in Isaksen & Tonstad (1989)). No cores.

30/11-3: 3207 to 3162 m

Lat. 60°02'38.59"N Long. 02°32'15.47"E (Figure 36 in Isaksen & Tonstad (1989)). No cores.

Upper and lower boundaries

Upper boundary

The upper boundary shows an increase in gamma-ray intensity and a decrease in velocity from the Tryggvason Formation upwards into the Kyrre Formation (Figure 33 in Isaksen & Tonstad (1989)). This log change is due to the lower carbonate content of the Kyrre Formation.

Lower boundary

The lower boundary is defined by a decrease in gamma-ray intensity, and an increase in velocity from the Blodøks Formation into the Tryggvason Formation (Figures 33 and 34 in Isaksen & Tonstad (1989)). This is due to the difference in carbonate content.

Age

Early to middle Turonian (Table 4.2).

Correlation

The Tryggvason Formation is time-equivalent with the Herring Formation in the Central North Sea and the Macbeth Formation in the Northern North Sea, and also with the informal "formation C" of Deegan & Scull (1977; Table 4.3) (Figure 6 in Isaksen & Tonstad (1989)).

Depositional environment

Open marine.

Kyrre Formation (Updated) (Kyrreformasjonen)

Introduction

The term Kyrre Formation was introduced by Isaksen & Tonstad (1989) for a thick, monotonous unit of marine mudstones with sporadic limestone stringers that lay between the Tryggvason and Jorsalfare formations in the Norwegian Northern North Sea in the Viking Graben. The Kyrre Formation was extended into the UK Northern North Sea by Johnson & Lott (1993; Table 4.1). It was informally designated 'Formation' D of the Shetland Group by Deegan & Scull (1977; Table 4.3). It has also been informally designated the 'Shetland Clay' in several published accounts describing oilfields in the East Shetland Basin (see Abbotts, 1991).

Name

After Olav "Kyrre" Haraldson, a Norwegian king (A.D. 1067-1093) (Isaksen & Tonstad, 1989, p.29).

Lithology

Norwegian Sector: The formation consists of mudstones with occasional limestone beds. Some sandstone beds are found in the Agat region. The mudstones are medium grey to grey, silty to calcareous, occasionally pyritic, glauconitic or micaceous. The sandstones are clear to white, and very fine- to fine-grained.

UK Sector: The Kyrre Formation typically comprises a thick, monotonous sequence of mudstones with sporadic limestone stringers. The mudstones are grey, silty, slightly calcareous and occasionally pyritic, glauconitic and micaceous. The limestones are off-white to pale brown, argillaceous, chalky and locally dolomitic (Johnson & Lott, 1993).

Thickness

Norwegian Sector: The formation is 585 m thick in the type well (25/1-1), 1199 m in well 35/3-2, 521 m in well 24/9-1 and 270 m in well 30/11-3.

UK Sector: The formation reaches a thickness of about 1100 m; 1200 m is recorded in the Magnus Trough (Johnson *et al.*, 1993). Seismic data suggest that it thins by onlap over contemporaneous highs, but condensed basal sections may also occur (Johnson *et al.*, 1993).

Geographical distribution

Norwegian Sector: With the exception of the Gullfaks area, the formation is present in the Viking Graben, on the Tartipen Spur and the western margin of the Horda Platform.

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

UK Sector: The Kyrre Formation is widely distributed across the Viking Graben, Beryl Embayment and East Shetland Basin, covering intrabasinal highs (Johnson & Lott, 1993).

Type well

Well name: N25/1- l (Norwegian Sector)
WGS84 coordinates: 59°53'17.4" N 02°04'42.7" E
UTM coordinates: 6639470.41 N 448427.57 E
UTM zone: 31
Drilling operator name: Elf Petroleum Norge AS
Completion date: 22.07.1971
Status: P & A
Interval of type section and thickness in type well: 2997 - 3582 m (9832.5-11752 ft) below KB (Isaksen & Tonstad, 1989, p.29, fig.33). Part of one core (0.5 m), including the upper boundary.

Norwegian reference wells

35/3-2: 2864 to 1665 m
Lat. 61°51'105.98"N Long. 03°46'28.22"E (Figure 34 in Isaksen & Tonstad (1989)). No cores.
24/9-1: 3638 to 3117 m
Lat. 59°16'09.48"N Long. 01°41'31.18"E (Figure 35 in Isaksen & Tonstad (1989)). No cores.
30/11-3: 3162 to 2892 m
Lat. 60°02'38.59"N Long. 02°31'15.47"E (Figure 36 in Isaksen & Tonstad (1989)). No cores.

UK reference wells

3/29-1: 2925-3603 m (9596-11821 ft)
Lat. 60°06'46.5"N Long. 01°44'21.9"E
3/10b-1: 2528-3586 m (8294-11765 ft)
Lat. 57°40'51.5"N Long. 00°08'50.4"W

Upper and lower boundaries

Upper boundary

Norwegian Sector: The upper boundary shows a decrease in gamma-ray intensity and an increase in velocity from the Kyrre Formation upwards into the Jorsalfare Formation (Figures 33 and 34 in Isaksen & Tonstad (1989)). This log change is also a result of the higher carbonate content and the presence of basal limestone beds in the Jorsalfare Formation. In the Horda Platform the Kyrre Formation passes up into the Hardråde Formation (Table 4.2).

UK Sector: The top of the Kyrre Formation is usually marked by a downward change from pale grey and commonly red-brown calcareous mudstones and argillaceous chalky limestones of the Jorsalfare Formation (unit J1) to darker grey mudstones.

Lower boundary

Norwegian Sector: The lower boundary is defined by an increase in gamma-ray intensity and a decrease in velocity from the Tryggvason Formation into the Kyrre Formation (Figure 33 in Isaksen & Tonstad (1989)) due to changes in carbonate content. The boundary is unconformable on structural highs, usually above the Cromer Knoll Group.

UK Sector: The base of the Kyrre Formation is normally marked by a downward change from mudstones to argillaceous chalky limestones and interbedded mudstones of the Macbeth Formation. On intrabasinal highs, the Kyrre Formation locally rests unconformably on pre-Cretaceous rocks. In the South Viking Graben, the Kyrre Formation locally rests on the Herring Formation of the Chalk Group (e.g. 16/3-1).

Well log characteristics

The top of the Kyrre Formation is marked on wireline logs by a downward increase in gamma values and a decrease in velocity. The base of the formation is marked on wireline logs by a downward decrease in gamma values and an increase in velocity. Locally, the basal sediments of the Kyrre Formation display a progressive downward decrease in gamma values and an increase in velocity (e.g. 3/10b-1, Panel 1, Johnson & Lott, 1993), which is similar to the log signatures displayed by the basal Flounder and Mackerel formations.

Biostratigraphy

In the UK Sector microfaunas in the upper part of the Kyrre Formation are dominated by noncalcareous agglutinated foraminifera, with only sparse calcareous microfaunas. The upper part of the formation includes the *Cenosphaera* sp. radiolarian biomarker. In the middle part of the formation, calcareous benthonic foraminifera become more common. Planktonic species are consistently present (e.g. *Globotruncana* and *Whiteinella*) and the *Stensioeina granulata polonica* and *S. granulata granulata* biomarkers may be recognized. Two calcareous nannofossil biomarkers occur: the *Broinsonia enormis* biomarker and the *Watznaueria barnesae* acme biomarker.

Dinoflagellate cyst associations in the Kyrre Formation are dominated by peridiniacean taxa (e.g. *Chatangiella* spp., *Isabelidinium magnum, Laciniadinium* spp., *Palaeoperidinium pyrophorum* and *Trithyrodinium suspectum*. The following dinoflagellate cyst biomarkers are recognized: *Callaiosphaeridium assymetricum, Cassiculosphaeridia reticulata, Heterosphaeridiumdifficile, Endoscrinium campanula, Florentinia deanei* and *Stephodinium coronatum.*

Age

Late Turonian to mid Campanian (Tables 4.1 and 4.2).

Correlation

In the South Viking Graben, the Kyrre Formation passes laterally into the lower part of the Flounder Formation (Tables 4.1 and 4.3). In the East Shetland Basin, the Kyrre Formation passes northwards into undifferentiated mudstones of the Shetland Group (Johnson & Lott 1993). It is also equivalent with the informal "formation D" of Deegan & Scull (1977; Table 4.3) (Figure 6 in Isaksen & Tonstad (1989)).

Depositional environment

The foraminiferal assemblages in the upper part of the Kyrre Formation are dominated by non-calcareous agglutinated foraminifera and indicate relatively restricted bathyal, marine environments. However, planktonic foraminifera are dominant in the lower part of the formation, indicating phases of more 'open' marine conditions (King *et al.*, 1989).

Subdivision
None in UK or Norwegian waters.

Hardråde Formation (Hardrådeformasjonen)

Name
Named after Harald "Hardråde" Sigurdsson, a Norwegian King (A.D. 1046-1066).

Lithology
The formation consists generally of interbedded limestones and mudstones, except in the Troll area where it is thin and consists of a single limestone bed. The limestones are white or pale, moderately hard to very hard. The mudstones are medium to light grey, often silty and calcareous.

Thickness
The formation is 291 m thick in the type well (30/11-3), and 10 m in well 31/6-2. It is absent on tilted fault blocks in the Troll area (e.g. well 31/2-9).

Geographical distribution
The formation is present on the Horda Platform (Figure 32b in Isaksen & Tonstad (1989)).

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

Type well
Well name: 30/11-3 (Norwegian Sector)

30/11-3: 2892 to 2601 m

Lat. 60°02'38.59"N Long. 02°32'15.47"E (Figure 36 in Isaksen & Tonstad (1989)). No cores.

Norwegian reference wells
31/6-2: 968 to 978 m

Lat. 60°34'58.24"N Long. 03°54'55.76"E (Figure 37 in NPD Bulletin 5). Cored through the formation.

Upper and lower boundaries
Upper boundary

The upper boundary is towards the Rogaland Group. When it is towards the Lista Formation it is characterised by an upward increase in gamma-ray intensi ty and a distinct drop in velocity due to a transition from limestones to mudstones (Figure 36 in Isaksen & Tonstad (1989)). An upper boundary towards the Våle Formation lacks the distinct drop in velocity. This is due to the presence of limestones and a more marly facies in the Våle Formation. An upper boundary towards the Ty Formation is shown by a change to sandstone.

Lower boundary

The lower boundary is towards the Kyrre Formation, or an unconformity above older rocks. The boundary above the Kyrre Formation is identified by the absence of relatively thick limestone beds within the Kyrre Formation and a lower content of calcareous material in the mudstone. This results in a decrease in gamma-ray intensity and an increase in velocity from the Kyrre Formation into the Hardråde Formation (Figure 36 in Isaksen & Tonstad (1989)). The formation has an unconformable lower boundary in the Troll area.

Age
Late Campanian to Maastrichtian (Table 4.2).

Correlation
The Hardråde Formation is time-equivalent with the Jorsalfare and Tor Formations of the Shetland Group (Table 4.2; Figure 6 in Isaksen & Tonstad (1989)).

Depositional environment
Open marine.

Jorsalfare Formation (Updated) (Jorsalfareformasjonen)

Shetland Group, Northern North Sea

Introduction

The term Jorsalfare Formation was introduced by Isaksen & Tonstad (1989) for a unit of calcareous mudstones with interbedded argillaceous limestones that lay between the Kyrre Formation and the Ekofisk, Lista, Vale, Maurren & Ty formations. The Jorsalfare Formation was extended into the UK Sector by Johnson & Lott (1993; Table 4.1). The Jorsalfare Formation was informally designated 'Formation' E of the Shetland Group by Deegan & Scull (1977; Table 4.3). It has also been informally designated the 'Shetland Marl' in several published accounts describing oilfields in the East Shetland Basin (Abbotts, 1991).

Name

After Sigurd 'Jorsalfare' Magnusson, a Norwegian king (AD 1103-1130) (Isaksen & Tonstad, 1989, p.30).

Lithology

Norwegian Sector: The formation generally consists of mudstones interbedded with thin limestone beds. The mudstones are light to medium grey, often calcareous. The limestones are white to light grey, fine-grained, occasionally sandy and dolomitic.

UK Sector: The Jorsalfare Formation consists of mudstones with interbedded argillaceous chalky limestones. The mudstones are pale grey to grey and usually calcareous. The limestones are argillaceous, chalky, white to pale grey, but locally red brown, fine-grained and occasionally sandy and dolomitic. In the East Shetland Basin, the proportion of limestone relative to mudstone generally decreases to the north and east (Johnson & Lott, 1993).

Thickness

Norwegian Sector: The formation is 286 m thick in the type well (25/1-1), 145 m in well 35/3-2 and 365 m in well 24/9-1.

UK Sector: In contrast to the underlying formations of the Shetland Group, the Jorsalfare Formation displays only minor lateral thickness variation, and forms a blanket-like layer generally about 300-400 m thick, but up to 580 m in the Magnus Trough (Johnson *et al.*, 1993).

Geographical distribution

Norwegian Sector: The formation is present in the Viking Graben and on the Tampen Spur. Its boundaries towards the Jorsalfare Formation in the Viking Graben, the Hardråde Formation on the Horda Platform and the Tor Formation on the Utsira High are illustrated in Figure 32b of Isaksen & Tonstad (1989).

The main characteristics that can be used to distinguish the three formations are:

a. The Jorsalfare Formation contains shales with thin limestone beds, which are usually no thicker than 5 m.
b. The Tor Formation is dominated by limestones, and has a negligible shale content.
c. The Hardråde Formation contains thick limestone beds (10-60 m), as well as shales, except in the Troll area where it is thin and may consist of only a single bed of limestone or marly limestone. Separation of these three formations may be difficult in transitional areas.

On the Norlex website under this formation is a button to find the occurrence of formation tops in wells, and a relative thickness map.

UK Sector: The Jorsalfare Formation is widely distributed in the Viking Graben, Beryl Embayment and East Shetland Basin.

Type well

Well name: N25/1- 1 (Norwegian Sector)
WGS84 coordinates: 59°53'17.40"N 02°04'42.70" E
UTM coordinates: 6639470.41 N 448427.57 E
UTM zone: 31
Drilling operator name: Elf Petroleum Norge AS
Completion date: 22.07.1971
Status: P & A
Interval of type section and thickness in type well: 2711-2997 m (8894-9832.5 ft) below KB (Isaksen & Tonstad, 1989, p.30, fig.33). One core (17 m) in the middle of the formation and another (4 m) at the base.

Norwegian reference wells

35/3-2: 1665 to 1520 m
Lat. 61°51'05.98"N Long. 03°46'28.22"E (Figure 34 in Isaksen & Tonstad (1989)). No cores.
24/9-1: 3117 to 2752 m
Lat. 59°16'09.48"N Long. 01°47'31.18"E (Figure 35 in Isaksen & Tonstad (1989)). No cores.

UK Reference wells

3/12-2: 2134 - 2448.5 m (7002-8033 ft)
Lat. 60°39'27.6"N Long. 01°20'31.5"E
3/29-1: 2628 - 2925 m (8622-9596 ft)
Lat. 60°06'46.5"N Long. 01°44'21.9"E
16/3a-1: 2847 - 3251.5 m (9340-10668 ft)
Lat. 58°52'53.2"N Long. 01°31'29.4"E
211/13-7: 1809.5 - 2126 m (5936-6975 ft)
Lat. 61°31'17.1"N Long. 01°33'25.8"E

Upper and lower boundaries

Upper boundary

Norwegian Sector: The upper boundary may be towards the Våle, Lista or Ty Formations of the Rogaland Group. When the upper boundary is towards the shale of the Lista Formation it is usually characterised by an upward increase in gamma-ray intensity and a distinct drop in velocity (Figure 34 in Isaksen & Tonstad (1989)). When it is towards the Våle Formation it does not show the same distinct drop in velocity and increase in gamma-ray intensity, because the overlying lithology consists of limestones or calcareous mudstones (Figure 35 in Isaksen & Tonstad (1989)). Where the upper boundary is towards the Ty Formation it is identified as a change to sandstone (Figure 33 in Isaksen & Tonstad (1989)).

UK Sector: In the Beryl Embayment, North Viking Graben and East Shetland Basin, the top of the Jorsalfare Formation is usually marked by a downward passage from calcareous mudstones of the Maureen Formation to increasingly calcareous mudstones (e.g. 211/13-7, 3/12-2). In some sections the basal mudstones of the Maureen Formation are replaced by thinly bedded sandstone or reworked limestone (e.g. 9/19-7Z, Panel 2, Johnson & Lott, 1993).

In the South Viking Graben, the top of the Jorsalfare Formation is normally characterized by a downward change from argillaceous chalky limestones and interbedded calcareous mudstones of the Ekofisk Formation to cleaner limestones. It is marked by a downward decrease in gamma values and an increase in velocity (e.g. 16/3a-1).

Lower boundary

Norwegian Sector: The lower boundary is defined by a decrease in gamma-ray intensity and an increase in velocity, reflecting an increase in calcareous content from the Kyrre Formation into the Jorsalfare Formation (Figures 33 and 34 in Isaksen & Tonstad (1989)). In the Tampen Spur area, however, the boundary may be difficult to identify due to small differences in calcareous content. The lower boundary may be unconformable above the Jurassic sequences (e.g. in the Gullfaks area).

UK Sector: The base of the Jorsalfare Formation is normally characterized by a downward change from argillaceous chalky limestones and calcareous mudstones, which are characteristically red brown, to grey mudstones of the Kyrre Formation.

Well log characteristics

The top of the Jorsalfare Formation in the UK Sector is usually marked on wireline logs by a downward increase in velocity (Johnson & Lott, 1993). Where thinly bedded sandstone or reworked limestone occurs at the base of the Maureen Formation the boundary is usually marked by a downward change from more variable to more consistent gamma and sonic responses. Where relatively pure reworked limestone rests unconformably on calcareous mudstones of the Jorsalfare Formation (e.g. 3/29-1) a downward increase in gamma values and a decrease in velocity is recorded.

The base of the Jorsalfare Formation is normally characterized on wireline logs by a downward increase in gamma values and a decrease in velocity.

Biostratigraphy

In the UK Sector the *Pseudotextularia* elegans biomarker is present at the top of the formation. Here planktonic species such as *Globigerinelloides* spp., *Heterohelix* spp. and *Rugoglobigerina* spp. dominate (over 90% of the fauna). The *Reussella szajnochae* biomarker may be recognized, although it is rare and patchily distributed in the upper part of its range.

Towards the middle part of the formation, assemblages dominated by non-calcareous agglutinated foraminifera replace those dominated by planktonic taxa. This occurs at a level equivalent to the *Gavelinella* spp. / *B. miliaris* biomarker in the Chalk facies. The *R. szajnochae* acme biomarker is present at the J1 / J2 boundary, where it is accompanied by the FDO of *Tritaxia capitosa*. King *et al.* (1989) considered this to be within the uppermost part of Formation 'D' (sensu Deegan & Scull, 1977), but the definition used here places it in the basal part of the Jorsalfare Formation.

The following dinoflagellate cyst biomarkers occur within the Jorsalfare Formation: *Palynodinium grallator, Odontochitina operculata* and *Senoniasphaera protrusa*. The FDOs of *Trithryrodinium suspectum* and several species of *Chatangiella* and *Isabelidinium* mark the Campanian/Maastrichtian boundary within the Shetland Group (Costa & Davey, 1992).

Age

Late Campanian to Maastrichtian in the Norwegian Sector (Table 4.2) and Mid Campanian to Maastrichtian in the UK Sector (Tables 4.1 and 4.3).

Correlation

The Jorsalfare Formation is laterally equivalent to the uppermost Flounder Formation (Shetland Group) and Tor Formation (Chalk Group) of the Central North Sea and South Viking Graben (Table 4.1) and is time-equivalent with the Hardråde Formation of the Shetland Group (Table 4.2; Figure 6 in Isaksen & Tonstad (1989)).

Depositional environment

Foraminiferal assemblages in the Jorsalfare Formation are mainly dominated by planktonic forms, indicating outer sublittoral and bathyal environments with open marine circulation. However, non-calcareous agglutinants are dominant in the lower and middle parts of the formation (early Maastrichtian) indicating a phase of more restricted circulation (King *et al.,* 1989).

Subdivision

An informal two-fold subdivision of the Jorsalfare Formation was recognized by Johnson & Lott (1993). At the base of the formation, Jorsalfare unit 1 (J1) is a thin unit of relatively low gamma, high velocity, calcareous mudstones and argillaceous chalky limestones, which are characteristically reddened. Jorsalfare unit 2 (J2) comprises the bulk of the formation and consists of pale grey mudstones with interbedded argillaceous chalky lim estones. Usually, unit J2 displays an upward increase in calcareous content (3/12-2, Panel 2, Johnson & Lott 1993).

Chalk Group (UK Sector)

Introduction

The term Chalk Group was introduced by Rhys (1974) in the UK Southern North Sea (Tables 4.1, 4.3 and 4.4) for a unit of Upper Cretaceous chalky limestones of Cenomanian to Maastrichtian age, lying between the Cromer Knoll Group below and a then undivided succession of Tertiary sediments above (now known as the Montrose Group). Subsequent drilling has shown that these chalky limestone lithologies in some areas do extend into the Danian (Ekofisk Formation). Deegan and Scull (1977) extended the definition of the group to include the Central and Northern North Sea (east of the Shetland Islands and southwards).

The term Chalk Group has subsequently been formally defined as an onshore lithostratigraphical unit by Hopson (2005). The definition provided by Hopson (2005) makes mention of the offshore successions, but are not an intrinsic part of that definition. The following account reflects a distinct description of the offshore successions, as defined by Johnson & Lott (1993) and Lott & Knox (1994).

In the thicker Chalk succession present in the Southern North Sea, the same units can be recognised as on land though a different nomenclature is used; the Hidra, Herring, Lamplugh and Jukes Formations correspond approximately with the Ferriby Chalk, Welton Chalk, Burnham Chalk and Flamborough Chalk Formations onshore (Lott & Knox, 1994; Table 4.3), and the Rowe Formation is fully developed (note that the Chalk Group as defined in Lott & Knox, 1994, also includes the Ekofisk Formation of basal Paleogene age throughout the North Sea).

Name

From the characteristic chalky limestone lithology (Rhys, 1974, fig.7. p.9).

Type area

The Chalk Group in the offshore has a type area in the Southern North Sea, with Rhys (1974) using well 49/24-1 as a typical section of the group. The group is divided onshore into provincial areas (Southern, Transitional and Northern). The most complete onshore exposure is in the near vertically inclined, cliff sections on the Isle of Wight where the greater part of the known Southern Province sequence can be seen. The sea-cliffs of Sussex and Kent afford many of the individual formation stratotype sections for the Southern Province, whilst the sea-cliffs and extensive inland exposures in Yorkshire and Lincolnshire provide the stratotypes for the constituent Northern Province formations. The Transitional Province is represented in the Chiltern Hills and their extension northward to the coast at Hunstanton and widely spaced inliers within the Quaternary cover of East Anglia.

Thickness

The group varies greatly in thickness, locally reaching over 1200 m in rim synclines adjacent to major salt diapir developments east of the Sole Pit Inversion (Figure 4.3).

It thins northwards over the Mid North Sea High (Figure 4.3), before thickening into the Erskine Basin of the Central Graben, where it is up to 1500 m thick (Johnson & Lott, 1993, Gatliff *et al.*, 1994). It also thins southwards across the London-Brabant High into the eastern English Channel (Cameron *et al.*, 1992). It reaches over 1000 m thick in the Outer Moray Firth (Andrews *et al.*, 1990; Johnson & Lott, 1993). Thinning, condensation and onlap relationships over some diapiric structures and tectonic highs are apparent from some wells (e.g. Block 23/26a, Foster & Rattey, 1993) and thins to a few metres or is entirely absent over the Fladen Ground Spur and Halibut Horst in the Outer Moray Firth (Andrews *et al.*, 1990).

Lithology

The Chalk Group is dominated by chalky coccolithic limestone, with or without flint and discrete marl, sponge, calcarenite, phosphatic, hardground and fossil-rich beds (Hopson, 2005). The division into limestone- and mudstone-dominated facies in the Central North Sea is evident in gamma-ray logs, with the chalky limestone formations on average up to 30 API units, whereas the mudstones are typically significantly greater than 35 API units (Johnson & Lott, 1993). Irregularities in the sonic logs are probably the result of alternations of soft and hard chalk and also the presence of chert (flint). The Central Graben primary pelagic chalks are interdigitated with large volumes of allochthonous chalk transported from the flanks of the graben by submarine slides, slumps, debris flows and turbidites during the Maastrichtian and Danian (Kennedy, 1987). The primary chalks are bioturbated and typically have low porosity (Kennedy, 1987), whereas the allochthonous deposits have higher porosity (Taylor & Lapré, 1987). Glauconitic sandstone is present in the Inner Moray Firth Basin, typical of the onshore Greensand facies (Andrews *et al.*, 1990). Although sedimentation of the Chalk Group appears to be almost continuous in the North Sea during the Upper Cretaceous, stratigraphic breaks are recorded in the Moray Firth in late Albian/early Cenomanian, late Cenomanian/early Turonian, late Turonian, intra-Santonian, late Campanian and late Maastrichtian (Andrews *et al.*, 1990).

Characteristics of the lower boundary

The base of the Chalk Group occurs at a downward change from interbedded pale to dark grey and pink chalky, argillaceous limestones (Hidra Formation) to red-brown chalky mudstones of the Rødby Formation (Cromer Knoll Group). The boundary is marked on the wireline log responses by an increase in gamma ray values and decrease in velocity (Lott & Knox, 1994).

Characteristics of the upper boundary

Conformable beneath Danian age Maureen Formation in parts of the North Sea. The group is evident at depth in seismic sections as an often featureless package with a top marked by strong continuous reflections traceable over much of the North Sea (Andrews *et al.* 1990).

Distribution

The Chalk Group is widely distributed over the Central North Sea and extends into the South Viking Graben and East Shetland Platform (Johnson & Lott, 1993; Figures 4.1 and 4.3). Erosion following Cenozoic uplift completely removed the Chalk Group from onshore Scotland and a zone from 20 to 100 km east of the coastline (Gatliff *et al.*, 1994). Eastward from its outcrop, drilling has proved the Chalk Group to be buried at progressively deeper levels beneath up to 3500 m of Cenozoic and Quaternary deposits in the eastern part of the UK Sector (Gatliff *et al.*, 1994). The group also extends across much of the Southern North Sea area, subcropping thin Pleistocene sediments west of the Sole Pit Inversion but lying beneath a thick Tertiary and Pleistocene cover in the Cleaver Bank basinal area east of the structure (Figure 4.2).

Over the stable East Midland Shelf the youngest chalk units are of Campanian or early Maastrictian age, with Maastrichtian (early only) chalk demonstrated in the south east of the area, adjacent to the North Norfolk coast (e.g. Peak & Hancock, 1970). The Chalk Group is absent through erosion over much of the Sole Pit Inversion structure but thickens eastwards into the Cleaver Bank Basin (Figures 4.2 and 4.3), where Maastrichtian chalks are widely present and some Danian chalky limestone units also occur sporadically. Further eastwards the Chalk Group continues to increase in thickness into the Dutch Sector (Hancock, 1986).

Age

Cenomanian to Danian (Tables 4.1-4.4).

Depositional environment

The chalks of the Southern North Sea were generally deposited in somewhat shallower water than those of the Central Graben (shelf and bathyal 'facies' of King *et al.* 1989; Cameron *et al.* 1992, p.90) and, in contrast to those to the north of the Mid North Sea High, contain abundant cherts. They have also undergone a shallower though much more varied burial history, associated with the extensive salt tectonics and inversion phases that have occurred in the basin. Consequently their sonic velocity profiles, in particular, appear very different from those developed in the deeply buried chalks of the Central Graben. The glauconitic sandstones present in the Inner Moray Firth Basin mark deposition in a shallow marine environment close to the contemporary shoreline (Andrews *et al.,* 1990).

Subdivision

Rhys (1974) did not formally subdivide the Chalk Group but noted that a thin bed of dark mudstones commonly occurred about 30 m above the base of the group in many wells. On some composites and in a few published papers (e.g. Crittenden, 1982), this bed has been referred to as the Plenus Marl; however in this report the unit has been informally termed the Black Band bed following the terminology introduced by Johnson & Lott (1993, p.95) and continued in the Southern North Sea by Lott & Knox (1994) (Table 4.3).

In the Central North Sea the Chalk Group comprises in ascending order: the Hidra, Herring, Lamplugh, Mackerel, Tor and Ekofisk formations (see Tables 4.1 and 4.3). The Ekofisk Formation, the uppermost unit of the group is entirely of Danian age and is also found in the Southern North Sea, though relatively poorly developed.

On some company logs there has been an extension of the usage of the terminologies used for the Central North Sea Chalk Group into the southern basin (Deegan & Scull, 1977; Johnson & Lott, 1993). In particular, where the Black Band is recognisable, the chalky and argillaceous limestones below have commonly been referred to the Hidra Formation and the beds immediately overlying the Black Band to the Herring Formation. Mackerel and Tor formations are, however, difficult to recognise south of the Mid North Sea High because of a marked change in log character, particularly of the sonic log response. Three new formation names were therefore introduced by Lott & Knox (1994). In ascending order these are the Lamplugh, Jukes and Rowe formations which are stratigraphically largely equivalent to the Mackerel and Tor formations (Tables 4.1 and 4.3) but differ somewhat in their lithologies and log responses.

In the Northern North Sea, only the lowermost and uppermost units, the Hidra and Ekofisk formations, respectively, are present. The Hidra Formation shows a transition to the Svarte Formation (Table 4.1).

Hidra Formation (Chalk Group)

The definition of this lowermost formation of the group in the UK Sector is provided in the description below of the Chalk Group (Norwegian Sector- Central Graben).

Herring Formation (Chalk Group)

Southern and Central North Sea

Introduction

The term Herring Formation was introduced by Deegan & Scull (1977), in the Central North Sea area (Table 4.3), to describe a unit of hard, chalky limestones and interbedded calcareous mudstones lying between a thin mudstone unit, the Plenus Marl Formation, and the overlying chalks of the Flounder Formation. These terms were subsequently revised by Johnston & Lott (1993) for the Central North Sea and as the unit is recognizable into the Southern North Sea Basin the definition was also followed by Lott & Knox (1994). The Herring Formation now includes the thin mudstone unit at the base of the formation, the Black Band (refer to Johnson & Lott, 1993; p.95), formerly known as the Plenus Marl Formation (Table 4.3), and the lower sequence of high-velocity harder, thinly bedded Turonian limestones and chalks, formerly included within the Hod Formation (Gatliff *et al.*, 1994).

Name

The Herring Formation is named after the fish (Deegan & Scull, 1977).

Lithology

The Herring Formation consists of hard to very hard, dense, chalky limestones with interbedded argillaceous chalks and mudstones (Johnson & Lott, 1993; Lott & Knox, 1994). Chert is abundant in the unit. The limestones are white to pale grey, occasionally medium grey and buff, glauconitic and occasionally pyritic. The interbedded mudstones, including the Black Band, are soft to hard, dark grey to black or variegated red-brown, carbonaceous, micaceous non-calcareous to calcareous and pyritic. In the South Viking Graben, thin, glauconitic, quartzose sandstones are present in the lower part of the formation (e.g. 16/28-7, Panel 3, Johnson & Lott, 1993).

Thickness

In the Central North Sea the formation ranges from 25 to 75 m, but locally reaches over 120 m (e.g., 22/3a-1, Panel 7, Johnson & Lott, 1993) and over 140 m in the Fisher Bank Basin (e.g., 22/1-2A, Gatliff *et al.*, 1994, fig. 48). In the Peterhead sub-basins and south-east part of the Witch Ground Graben of the Outer Moray Firth, the formation, including the 'Plenus Marls', is up to 285 m thick, but is virtually absent in the Inner Moray Firth (Andrews *et al.*, 1990). The formation is up to 60 m thick in the Southern North Sea Basin (Lott & Knox, 1994).

Geographical distribution

The Herring Formation can be recognized throughout the Central North Sea and extends into the South Viking Graben. It is absent, however, over some contemporary structural highs (Johnson & Lott, 1993).

The Herring Formation can be recognized over most of the Southern North Sea Basin (Lott & Knox, 1994). The unit is absent over the Sole Pit Basin because of subsequent inversion and erosion, and is also missing over some contemporary tectonic highs and salt diapirs (e.g. 48/10-1, 52/5-3).

Type well

Well name: 22/1-2A

WGS84 coordinates:
Lat. 57° 56'12.2"N Long. 01°02'55.8"E
UTM coordinates:
UTM zone: 31
Drilling operator name: BP Exploration Operating Company Limited
Completion date: 13.04.1974
Status: P & A
Interval of type section and thickness in type well: 3605-3738.5 m (11827-12265 ft) below KB (Deegan & Scull, 1977) (revised depths).

UK Reference wells

Central and Northern North Sea (Johnson & Lott, 1993)
13/28-2: 1405.5-1468.5 m (4611-4818 ft)
Lat. 58°06'59.3"N Long. 01°25'27.0"W
16/12b-10: 3679.5-3792.5 m (12072-12442 ft)
Lat. 58°39'17.7"N Long. 01°23'59.0"E
29/5a-1: 3878-4056 m (12723-13306 ft)
Lat. 56°50'18.6"N Long. 01°48'52.5"E

Southern North Sea (Lott & Knox, 1994)
49/20-1: 1433-1495 m (4701-4905 ft)
Lat. 53°24'07.0"N Long. 02°51'52.0"E
53/4-2: 1515-1573 m (4970-5161 ft)
Lat. 52°52'50.0"N Long. 02°47'16.0"E

Upper and lower boundaries

Upper boundary

In the Central North Sea the top of the Herring Formation is normally marked by a downward change from argillaceous chalky limestones of the Mackerel Formation, or calcareous mudstones of the Flounder Formation, to cleaner, harder chalky limestones (Johnson & Lott 1993). In the South Viking Graben, the Herring Formation is locally overlain by the Kyrre Formation (e.g. 16/3-1).

In the Southern North Sea the top of the Herring Formation is normally marked by a downward change from softer, more argillaceous chalks of the Lamplugh Formation to cleaner, harder chalky limestones (Lott & Knox, 1994).

Lower boundary

The base of the Herring Formation is normally marked by a sharp downward change from dark coloured mudstones (Black Band) to chalky limestones of the Hidra Formation (Johnson & Lott, 1993; Lott & Knox, 1994). The Black Band forms a key log marker throughout much of the basin (refer to Panel 1, Lott & Knox, 1994). Where the Black Band mudstones are poorly developed the boundary is often more difficult to identify without biostratigraphic control. Where the Black Band is absent, limestones of the Herring Formation disconformably overlie the Hidra Formation (e.g. 21/1-7ST, Burnhill & Ramsay, 1981 and 14/26-1). On intrabasinal highs, the Herring Formation locally rests unconformably on Lower Cretaceous or older rocks (e.g. 14/13-1, 16/28-4 and 16/23-4, Johnson & Lott, 1993).

The Plenus Marl Formation and/or Black Band at the base of the Herring Formation marks the base of the onshore White Chalk Subgroup (Hopson, 2005). However, this author noted that the use of the two terms Plenus Marl Formation and/or Black Band were not necessarily mutually exclusive offshore.

Well log characteristics

In the Central North Sea, the top of the formation is marked on the downhole log responses by a downward increase in velocity accompanied by a decrease in the gamma ray values (e.g. 16/28-7 and 15/28a-3, Johnson & Lott, 1993). In the Southern North Sea, this upper boundary is marked on the downhole log responses by an increase in velocity sometimes accompanied by a slight decrease in the gamma-ray values (e.g. 49/24-1, Lott & Knox, 1994). The lower boundary of the formation is marked by a sharp downward decrease in gamma-ray values and increase in velocity. The Black Band, commonly present at the base of the formation, usually has characteristic high gamma-ray and low velocity spikes. Gamma-ray values may be expressed as a single peak (e.g. 13/17-1, Panel 4 Johnson & Lott, 1993) or two peaks (e.g. 29/1b-1, 29/3-1, Panel 10 Johnson & Lott, 1993), although, occasionally the gamma spike is not well developed (e.g. 49/24-1, Panel 2 Lott & Knox, 1994). The low velocity Black Band generates a high-amplitude seismic reflector present across much of the Central North Sea (Gatliff *et al.*, 1994).

Biostratigraphy

The *Praeglobotruncana stephani* biomarker can be recognized towards the middle of the formation, together with other common planktonic foraminifera such as *Dicarinella hagni, Praeglobotruncana gibba, Dicarinella imbricata* and *Marginotruncana renzi* (Johnson & Lott, 1993; Lott & Knox, 1994). Calcareous benthonic foraminifera are rare, but *Lingulogavelinella globosa* and *Stensioeina granulata humilis* are occasionally found within the formation. The *Eprolithus* spp. nannofossil biomarker is situated in the middle part of the formation. Palynological recovery in the Herring Formation is generally rather low, but by analogy with the Central North Sea and onshore areas, the *Litosphaeridium siphoniphorum* dinoflagellate cysts biomarker should be present immediately above the top of the Black Bed (Johnson & Lott, 1993). The dinoflagellate cyst *Heterosphaeridium difficile* is typically common to abundant (Costa & Davey, 1992).

Age

Early to mid Turonian (Tables 4.1 and 4.3).

Correlation

The Herring Formation is the lateral equivalent, in part, of the Welton Chalk Formation of Eastern England which includes the Black Band bed (Wood & Smith, 1978; Table 4.3). The Black Band bed is widely recognized in Eastern England (Hart & Bigg, 1981). It is also the lateral equivalent of the more argillaceous Macbeth Formation in the Viking Graben and East Shetland Basin.

Depositional environment

The micritic, chalky limestones of the Herring Formation are pelagic sediments deposited as nannofossil-rich oozes in a well-oxygenated sea of moderate depth (Johnson & Lott, 1993; Lott & Knox, 1994). The Black Band mudstones, in contrast, were deposited during a phase of bottom-water stagnation and is dominated by planktonic foraminifera and impoverished benthonic faunas (Gatliff *et al.*, 1994). It represents a widely documented global marine transgression and phase of anoxia close to the CenomanianTuronian boundary (e.g. Hart & Leary, 1989).

Subdivision

The four informal sub-units of the Herring Formation (G1-G4) were recognized by Burnhill & Ramsay (1981) in the Outer Moray Firth based upon wireline-log responses. G1 and G3/4 comprise high velocity, thin-bedded, often hard chalk commonly topped by a 'hot shale' band, with G2 dominated by calcareous mudstone and thin interbedded chalk. Johnson & Lott (1993) extended recognition of these units into the Central Graben and South Viking Graben, with an additional G0 unit to substitute the Plenus Marl Formation of Deegan & Scull (1977). These informal sub-units are not, with the exception of the Black Band, readily apparent in the wells south of the Mid-North Sea High (Lott & Knox, 1994).

The Black Band (of bed status, formerly the lower part of the Plenus Marl Formation of Deegan & Scull, 1977 and Plenus Marl Formation unit A of Crittenden *et al.*, 1991) consists of up to 40 m of dark grey to black, fissile, carbonaceous and non-calcareous mudstones (Johnson & Lott, 1993; Lott & Knox, 1994). The base of the Black Band is defined by a sharp downward change from black mudstones to argillaceous, white, chalky limestones of the Hidra Formation.

Lamplugh Formation (Chalk Group)

Southern North Sea

Introduction

The term Lamplugh Formation was introduced for a unit of argillaceous, chert-bearing, chalky limestones which underlie harder relatively chert-free chalks of the Jukes Formation and overlie hard, chalky limestones of the Herring Formation (Lott & Knox, 1994; Table 4.1).

Name

After the eminent geologist G.W. Lamplugh (1859-1926) who carried out detailed studies of the Cretaceous successions in Yorkshire in the late 19th century.

Lithology

The Lamplugh Formation consists of chalky limestones which are typically white to grey, soft to moderately hard, commonly argillaceous and characteristically chert-bearing. The presence of chert (flint) bands throughout the unit is a characteristic feature (Lott & Knox, 1994).

Thickness

The Lamplugh Formation ranges up to 200 m (e.g. well 49/25-1), but may vary in thickness due to intra-basinal tectonic controls and post-Cretaceous erosion.

Geographical distribution

The Lamplugh Formation is widely distributed throughout the Southern North Sea Basin.

Type well

Well name: 49/24-1

WGS84 coordinates:

Lat. 53°16'49.5"N Long. 02°41'30.4"E

UTM coordinates:

UTM zone: 31

Drilling operator name: Shell UK Exploration and Production Ltd

Completion date: 30.04.1972

Status: Suspended

Interval of type section and thickness in type well: 1060-1242 m (3478-4075 ft)

UK Reference wells

38/24-1: 1585.5-1670.5 m (5202-5481 ft)
Lat. 55°12'35.3"N Long. 02°37'33.1"E
43/8a-2: 948-1189 m (3110-3901 ft)
Lat. 54°45'11.3"N Long. 01°33'07.8"E
49/5-1: 1679.5-1987 m (5510-6519 ft)
Lat. 53°52'05.0"N Long. 02°49'04.0"E

Upper and lower boundaries

Upper boundary

The upper boundary of the Lamplugh Formation is marked by a downward change from the chalky limestones of the Jukes Formation into harder, more argillaceous chalks (Lott & Knox, 1994).

Lower boundary

The lower boundary of the Lamplugh Formation is characterized by a downward change from moderately hard, chalky limestones to the harder, clean, micritic limestones of the Herring Formation (Lott & Knox, 1994).

Well log characteristics

The top of the Lamplugh Formation is marked by a sharp downward increase in velocity accompanied in some sections by a slight increase in gamma-ray values e.g. 49/24-1. In some wells the mid-part of the Lamplugh Formation is particularly argillaceous (e.g. well 42/29-C01 Panel 1; 53/4-2 Panel 2, Lott & Knox, 1994) giving the log profiles a 'waisted' appearance. At the base of the formation there is a corresponding downhole decrease in gamma ray and increase in sonic velocity responses (Lott & Knox, 1994).

Biostratigraphy

The FDO of *Stensioeina granulata granulata* marks the top of the formation and two intraformational biomarkers are *S. granulata levis* and *S. granulata kelleri*. Palynomorph recovery in the Lamplugh Formation is generally relatively low.

Age

Late Turonian to Coniacian (Tables 4.1 and 4.3).

Correlation

The Lamplugh Formation passes northwards into the lower part of the Mackerel Formation of the Central North Sea (Table 4.1). Onshore, in eastern

England the formation equates largely with the Burnham Chalk Formation (Table 4.2) of Wood & Smith (1978; refer also to Whitham, 1991).

Depositional environment

The chalky limestones of the Lamplugh Formation were deposited in an open marine setting as pelagic carbonates and consist primarily of fine bioclastic skeletal debris (dominated by coccolith plates). Terriginous clay is present as thin beds and seams (Lott & Knox, 1994).

Subdivision

None in UK waters.

Jukes Formation (Chalk Group)

Southern North Sea

Introduction

The term Jukes Formation was introduced for a unit of hard, comparatively chert-free chalky limestones which underlie the Rowe Formation and overlie the more argillaceous chalks of the Lamplugh Formation (Lott & Knox, 1994; Tables 4.1 and 4.3).

Name

After the eminent survey geologist A. J. Jukes-Browne (1851-1914) who carried out extensive studies of the Cretaceous rocks of Britain.

Lithology

The Jukes Formation typically consists of moderately hard, white, occasionally greyish white, variably argillaceous, chalky limestones. Occasional harder limestone bands occur together with comparatively few nodular chert developments (Lott & Knox, 1994).

Thickness

The Jukes Formation ranges up to 500 m (Panel 2, Lott & Knox, 1994), but may vary in thickness due to intra-basinal tectonic controls and post-Cretaceous erosion.

Geographical distribution

The Jukes Formation is widely distributed throughout the Southern North Sea Basin.

Type well

Well name: 49/24-1

WGS84 coordinates:

Lat. 53°16’49.5”N Long. 02°41’30.4”E

UTM coordinates:

UTM zone: 31

Drilling operator name: Shell UK Exploration and Production Ltd

Completion date: 30.04.1972

Status: Suspended

Interval of type section and thickness in type well:
840 -1060 m (2756-3478 ft)

UK Reference wells

38/24-1: 1448 -1585.5 m (4751-5202 ft)

Lat. 55°12’35.3”N Long. 02°37’33.1”E
43/8a-2: 810-948 m (2657-3110 ft)
Lat. 54°45’11.3”N Long. 01°33’07.8”E
49/5-1: 1265.5-1679.5 m (4152-5510 ft)
Lat. 53°52’05.0”N Long. 02°49’04.0”E

Upper and lower boundaries

Upper boundary

The upper boundary of the Jukes Formation is characterized by a downward change from relatively soft chert-bearing argillaceous chalks to harder white chalks with fewer cherts. The top of the unit is often marked by a thin, hard chalk unit (e.g. well 49/5-1 Lott & Knox, 1994).

Lower boundary

The base of the Jukes Formation is defined by a downward change from moderately hard, relatively chert-free chalks, to darker, consistently harder, argillaceous, cherty chalks of the Lamplugh Formation

Well log characteristics

The top of the Jukes Formation is marked by a slight downward decrease in gamma-ray values and a more marked increase in sonic velocity. There is considerable variability in the sonic response over the formation as a whole as a result of the cyclic interbedding of thin argillaceous units, hard chalks and occasional hard chert-rich bands. The lower boundary of the formation corresponds to a consistent increase in sonic velocity, sometimes accompanied by a slight downward increase in gamma values (Lott & Knox, 1994).

Biostratigraphy

The FDOs of a number of taxa form good biomarkers within the formation: *Stensioeina granulata incondita* and *Bolivinoides strigillatus* in the mid Campanian; the radiolarian *Cenosphaera* sp. at the top of the Santonian (where *Stensioeina exsculpta exsculpta* is also found); and *Stensioeina granulata polonica*. The key calcareous nannofossil biomarkers within the formation are the FDOs of *Broinsonia enormis*, at the top of the early Santonian; and *Watznaueria barnesae* acme, which marks the mid/early Santonian boundary. Palynomorph recovery in the Jukes Formation is generally relatively low.

Age

Santonian to early Campanian (Tables 4.1 and 4.3).

Correlation

The Jukes Formation passes northwards into the middle part of the Mackerel Formation of the Central North Sea (Table 4.1). In the UK onshore area the formation equates largely with the Flamborough Chalk Formation (Table 4.3) of Wood & Smith (1978; refer also to Whitham, 1993).

Depositional environment

The chalky limestones of the Jukes Formation were deposited in an open marine setting as pelagic carbonates and consist primarily of fine bioclastic skeletal debris (dominated by coccolith plates). Thin more argillaceous beds present represent increased terrigenous input into the basin (Lott & Knox, 1994).

Subdivision

None in UK waters.

Rowe Formation (Chalk Group)

Southern North Sea

Introduction

Lott & Knox (1994, fig.7/4) working in the Southern North Sea introduced the term Rowe Chalk Formation to cover the very highest Chalk concealed beneath Quaternary deposits in the Hornsea area and immediately offshore.

Name

After the eminent geologist A.W. Rowe who carried out extensive studies of the English Chalk successions in the early 1900s.

Lithology

The Rowe Formation consists of chalky limestones which are typically white to greyish white, friable to moderately hard, commonly argillaceous and chert-bearing (Lott & Knox, 1994). The presence of abundant chert (flint) bands throughout the unit is a characteristic feature. Terrigenous clay is present as darker coloured thin beds and seams. The formations both above and below the Rowe Formation, i.e the Ekofisk and Jukes formations respectively, are generally chert-free.

Thickness

The Rowe Formation ranges up to 380 m in thickness (e.g. well 49/25-1, Lott & Knox, 1994). However, it may vary significantly in thickness due to intra-basinal tectonic controls and post-Cretaceous erosion notably around the Sole Pit Inversion structure.

Sumbler (1999) described these beds, based on geophysical logs from boreholes, as 70m or so of flint--bearing chalks characterised by the inferred presence of *Belemnitella mucronata* and also indicated that still younger beds were present offshore.

Geographical distribution

The Rowe Formation is widely distributed throughout the Southern North Sea Basin. In eastern England the formation is known only in the subsurface where it overlies the Flamborough Chalk Formation of Wood & Smith (1978; refer also to Whitham, 1993). In the Trunch borehole, on the north Norfolk coast, the base of the formation probably equates with the hardground development marking the base of the Basal Mucronata Chalk (base *Belemnitella mucronata* Zone) (McArthur *et al.*, 1993).

Type well

Well name: 49/24-1

WGS84 coordinates:

Lat. 53°16'49.5"N Long. 02°41'30.4"E

UTM coordinates:

UTM zone: 31

Drilling operator name: Shell UK Exploration and Production Ltd

Completion date: 30.04.1972

Status: Suspended

Interval of type section and thickness in type well: 635-840 m (2083-2756 ft) (Panel 2, Lott & Knox, 1994).

UK Reference wells

44/28-1: 1651.5 - 1918.5 m (5418-6294 ft)
Lat. 54°03'42.0"N Long. 02°26'52.6"E
49/5-1: 1041.5 - 1265.5 m (3417-4152 ft)
Lat. 53°52'05.0"N Long. 02°49'04.0"E
47/10-1: 635 - 840 m (2083-2756 ft)
Lat. 53°43'51.6"N Long. 00°48'17.1"E
53/4-2: 858.5 - 1125.5 m (2817-3693 ft)
Lat. 52°52'50.0"N Long. 02°47'16.0"E

Upper and lower boundaries

Upper boundary

The top of the Rowe Formation is overlain by Danian chalky limestones (Ekofisk Formation), with the boundary usually being marked by a downward into chalk with a lower clay content. Where the Ekofisk Formation is absent, the Rowe Formation is overlain by Paleocene mudstones (Lott & Knox, 1994).

Lower boundary

The base of the Rowe Formation is marked by a downward conformable passage from chert-bearing and argillaceous chalks resting upon of the moderately hard, white, chalky limestones of the Jukes Formation.

Well log characteristics

The character of the log responses for the top of the Rowe Formation is variable, depending on whether the unit is overlain by Paleogene or younger Cenozoic or Pleistocene sequences. In a few wells the formation is overlain by Danian chalky limestones (Ekofisk Formation), with the boundary usually being marked by a downward decrease in gamma-ray values, reflecting a lower clay content. The sonic log signature is, however, variable, with some sections showing a downward decrease in velocity (e.g. 44/28-1) and others a downward increase (e.g. 39/7-1, Panel 1 Lott & Knox, 1994). Where the Ekofisk Formation is absent, the Rowe Formation is overlain by Paleocene mudstones and there is a corresponding sharp downward decrease in gamma ray values and increase in velocity (e.g. 44/28-1: Panel 2, Lott & Knox, 1994).

The base of the Rowe Formation is defined by a marked downward increase in velocity but only shows a slight downward decrease in gamma-ray values. The sharp increase in velocity is probably related to a significant basinwide regressive hardground surface (Lott & Knox, 1994).

Biostratigraphy

The top of the Rowe Formation is marked by the *Pseudotextularia elegans* foraminiferal biomarker and the *Nephrolithus elegans* calcareous nannofossil biomarker (Lott & Knox, 1994). In the middle part of the formation, *Reussella szajnochae* has its FDO, but it is rare and patchily distributed in the upper part of its range. However, within the formation the *Reussella szajnochae* acme biomarker, which may be accompanied by *Tritaxia capitosa*, is biostratigraphically important. In the lower part of the formation, the FDO of a number of species of *Gavelinella* and *Bolivinoides miliaris* forms a characteristic biomarker. At approximately the same horizon as the FDO of *R. szajnochae*, the FDO of *Reinhardtites levis* forms a key nannofossil biomarker at the early/late Maastrichtian boundary. The FDO of *Reinhardtites anthophorus* is within the early Maastrichtian. Palynomorph recovery in the Rowe Formation is generally relatively low.

Age

Late Campanian to Maastrictian (Table 4.3).

Correlation

The Rowe Formation passes northwards into the upper part of the Mackerel Formation and the Tor Formation of the Central North Sea (Tables 4.1 and 4.3).

Depositional environment

The chalky limestones of the Rowe Formation were deposited in an open marine setting as pelagic carbonates and consist primarily of fine bioclastic skeletal debris (dominated by coccolith plates). Microfaunas are dominated by planktonic foraminifera (Lott & Knox, 1994).

Subdivision

None in UK waters.

Mackerel Formation (Chalk Group)

Southern North Sea

Introduction

The Mackerel Formation was introduced by Johnson & Lott (1993) for a unit of limestones and argillaceous chalky limestones with interbedded mudstones that lies between the Herring Formation and the Tor Formation (Table 4.1). The strata were included in the Hod Formation (Table 4.3) by Deegan and Scull (1977) and Gatliff *et al.* (1994), which was abandoned again by Johnson & Lott (1993).

Name

After the salt-water fish.

Lithology

The Mackerel Formation consists of white, pale grey, and occasionally pink or red, fine-grained, and commonly argillaceous chalky limestones (Johnson & Lott, 1993). Sections with relatively high amounts of detrital clay are reflected in higher gamma values and lower velocity. The formation becomes more argillaceous towards the South Viking Graben, where it grades laterally into the Flounder Formation (Shetland Group). The northward passage into the mudstone-dominated Flounder Formation is reflected in an increasing proportion of argillaceous limestone intercalations in the Mackerel Formation of the Outer Moray Firth.

Thickness

In depocentres the Mackerel Formation is between 200 and 500 m thick (Panels 4 and 13W, Johnson & Lott, 1993).

Geographical distribution

The Mackerel Formation is present over much of the Central North Sea. It onlaps and covers the intrabasinal ridges, such as the Jaeren High, but is absent from the higher parts of the Forties-Montrose High and the Western Platform, where it borders the Central Graben (Johnson & Lott, 1993).

Type well

Well name: 30/19-1

WGS84 coordinates:
Lat. 56°26'48.2"N Long. 02°42'15.3"E
UTM coordinates:
UTM zone: 31
Drilling operator name: Shell UK Exploration and Production Ltd
Completion date: 25.07.1970
Status: P & A
Interval of type section and thickness in type well: 3322 - 3577 m (10899-11735 ft) below KB.

UK Reference wells

13/28-2: 1212.5 - 1405.5 m (3978-4611 ft)
Lat. 58°06'59.3"N Long. 01°25'27.0"W
14/20-6A: 2324 - 2751 m (7624-9025 ft)
Lat. 58°28'11.2"N Long. 00°03'07.8"W
29/4a-1A: 3605 - 3801 m (11827-12470 ft)
Lat. 56°50'37.0"N Long. 01°45'14.4"E

Upper and lower boundaries

Upper boundary

The top of the Mackerel Formation is normally marked by a relatively abrupt downward change from the hard chalky limestones of the Tor Formation to the interbedded argillaceous chalky limestones, which are commonly stained pink or red (Johnson & Lott, 1993).

Lower boundary

The base of the Mackerel Formation is taken at a downward change from the argillaceous chalky limestones to cleaner, higher velocity limestones of the Herring Formation (Johnson & Lott, 1993).

Well log characteristics

On wireline logs, the upper boundary of the Mackerel Formation corresponds to a downward increase in gamma values and decrease in velocity. Commonly, the basal part of the Mackerel Formation displays a downward decrease in gamma values and increase in velocity immediately above the Herring Formation (e.g. 14/20-6A, Panel 4; 21/4-1, Panel 6, Johnson & Lott, 1993).

Biostratigraphy

The top of the Mackerel Formation is marked in the *Reussella szajnochae* acme foraminiferal biomarker, which in the Central North Sea is accompanied by the

FDO of *Tritaxia capitosa*. In some areas this biomarker occurs at or just below the top of the formation (King *et al.*, 1989, fig. 8.4). Long-ranging planktonic foraminfera, particularly species of *Rugoglobigerina*, are common (Johnson & Lott, 1993). The *Cenosphaera* sp. radiolarian biomarker is present in the middle part of the formation. The *Stensioeina granulata polonica* and *S. granulata granulata* biomarkers also occur within the formation.

Three key nannofossil biomarkers are present (Johnson & Lott, 1993): the *Reinhardtites anthophorus* biomarker occurs at the top of the formation, the *Broinsonia enormis* biomarker, at the top of the early Santonian, and the *Watznaueria barnesae* acme biomarker, which marks the mid/early Santonian boundary, in the middle of the formation. The *Helicolithus trabeculatus* biomarker and *H. valhallensis* acme biomarker are also present.

The *Senoniasphaera protrusa, Callaiosphaeridium assymetricum, Cassiculosphaeridia reticulata, Heterosphaeridium difficile, Endoscrinium campanula, Florentinia deanei* and *Stephodinium coronatum* dinoflagellate cysts biomarkers all occur within the formation (Johnson & Lott, 1993). *Spiniferites* spp. (especially *S. ramosus*) dominates and *Chatangiella* spp. are locally common in the Coniacian.

Age
Mid Turonian to early Maastrichtian (Tables 4.1 and 4.3).

Correlation
The Mackerel Formation becomes more argillaceous towards the South Viking Graben, where it grades laterally into the Flounder Formation (Tables 4.1 and 4.3).

Depositional environment
The Mackerel Formation consists of dominantly pelagic chalky, coccolith-rich limestones that accumulated in marine, low-energy shelf to upper bathyal conditions (Johnson & Lott, 1993). Phases of more open marine circulation are indicated by a higher proportion of planktonic foraminifera in the Coniacian and Upper Campanian (King *et al.*, 1989).

Subdivision
Undivided.

Two informal subdivision schemes have been applied to beds assigned to the Mackerel Formation. King *et al.* (1989) recognized a sub-unit of pink-stained chalks at the top of the formation, and in the Moray Firth, Andrews *et al.* (1990) recognized four chalk-marl cycles (designated units F1 to F4), each up to about 100 m thick. The Mackerel Formation was not subdivided by Johnson & Lott (1993).

Tor Formation (Chalk Group)

The definition of this formation in the UK Sector is provided in the description below of the Chalk Group (Norwegian Sector- Central Graben).

Ekofisk Formation (Chalk Group)

The definition of this uppermost formation of the group in the UK Sector is provided in the description below of the Chalk Group (Norwegian Sector- Central Graben).

Chalk Group (Norwegian Sector- Central Graben)

The stratigraphic history of the Chalk Group is discussed at the beginning of this chapter, introducing the UK chalk units. Figure 4.14 provides a very schematic sequence stratigraphic figure of the units in chalk type well 1/3-1 (Tor Formation; Hidra Fm; the latter not shown near base of figure below Blodøks Fm). Tables 4.2-4.4 provide insight in stratigraphic subdivisions.

Hidra Formation (Hidraformasjonen)

(After NPD Bulletin no. 5)

Introduction

The term Hidra Formation was introduced by Deegan & Scull (1977), in the Central North Sea area (Table 4.3), for the unit of chalky limestones with interbedded argillaceous chalks lying between the Cromer Knoll Group below and the Plenus Marl Formation above (since renamed the Black Band by Johnson & Lott (1993). This same unit is recognizable in the wells of the Southern North Sea Basin and it was recommended by Lott & Knox (1994) that the usage of the term Hidra Formation was therefore extended. The formation is defined formally in the Central Graben (Norwegian Sector) by Isaksen & Tonstad (1989).

Name

From the Hidra High in Norwegian blocks 1/3 and 2/1, which was named after an island of Hidra off the southwest coast of Norway.

Lithology

Norwegian Sector: In the type well the Hidra Formation consists of white to light grey, hard chalks with thin interbeds of grey to black shale in the lower part of the formation. Locally, the formation is more marly with interbedded marly chalk and marl. The chalks are occasionally softer with abundant glauconite and pyrite. The colour may be white, grey, green, brown or pink. Traces of pink waxy tuff occur in places. The formation is generally highly bioturbated.

UK Sector: The Hidra Formation consists of micritic chalky limestones with interbedded argillaceous chalks and mudstones (Johnson & Lott, 1993; Lott & Knox, 1994). The unit becomes increasingly argillaceous in its lower part in the Southern North Sea, with thin beds of detrital clay become increasingly common towards the base of the formation. At the base of the formation in UK well 22/1-2A, hard, black, carbonaceous and argillaceous limestones are present. It also becomes more argillaceous to the north, where in the North Viking Graben it passes laterally into the Svarte Formation (Shetland Group). The chalky limestones are white to pale grey and occasionally pink, red-brown or green. The argillaceous chalks and mudstones are pale to dark grey or red-brown. Chert is only rarely recorded. Thin, pale grey, glauconitic and calcareous, quartzose sandstones are locally present in the Inner Moray Firth (Andrews *et al.*, 1990) and South Viking Graben (Johnson & Lott, 1993). Pink, waxy, tuffaceous beds have been recorded in the Central North Sea (Deegan & Scull, 1977).

Thickness

Norwegian Sector: The formation is 70 m thick in the type well, and 55.5 m in BO-1 in the Danish Sector. Seismic interpretation suggests that the formation reaches a maximum thickness of about 150 m in the northwestern part of the Central Trough in the Norwegian Sector.

UK Sector: In the Central North Sea the formation is typically 30-70 m thick, 45 m in well 22/1-2A and 30.5 m in well 29/25-1. However, is up to about 160 m in the Erskine and Fisher Bank basins of the Central Graben (Johnson & Lott, 1993; Gatliff *et al.*, 1994) and up to 120m in the southern and eastern parts of the Moray Firth (Andrews *et al.*, 1990). The formation onlaps the flanks of the Forties-Montrose and Jaeren highs and is absent from the western flanks of the Central Graben, on the West Central Ridge and Argyll Shelf (Gatliff *et al.*, 1994). The Hidra Formation ranges up to c.40 m in thickness in the Southern North Sea (Lott & Knox, 1994).

Geographical distribution

The Hidra Formation occurs throughout most of the Central North Sea and South Viking Graben, but is locally absent over some contemporary structural highs (30/1c-2A, Panel 12S, Johnson & Lott, 1993). The Hidra Formation occurs throughout most of the

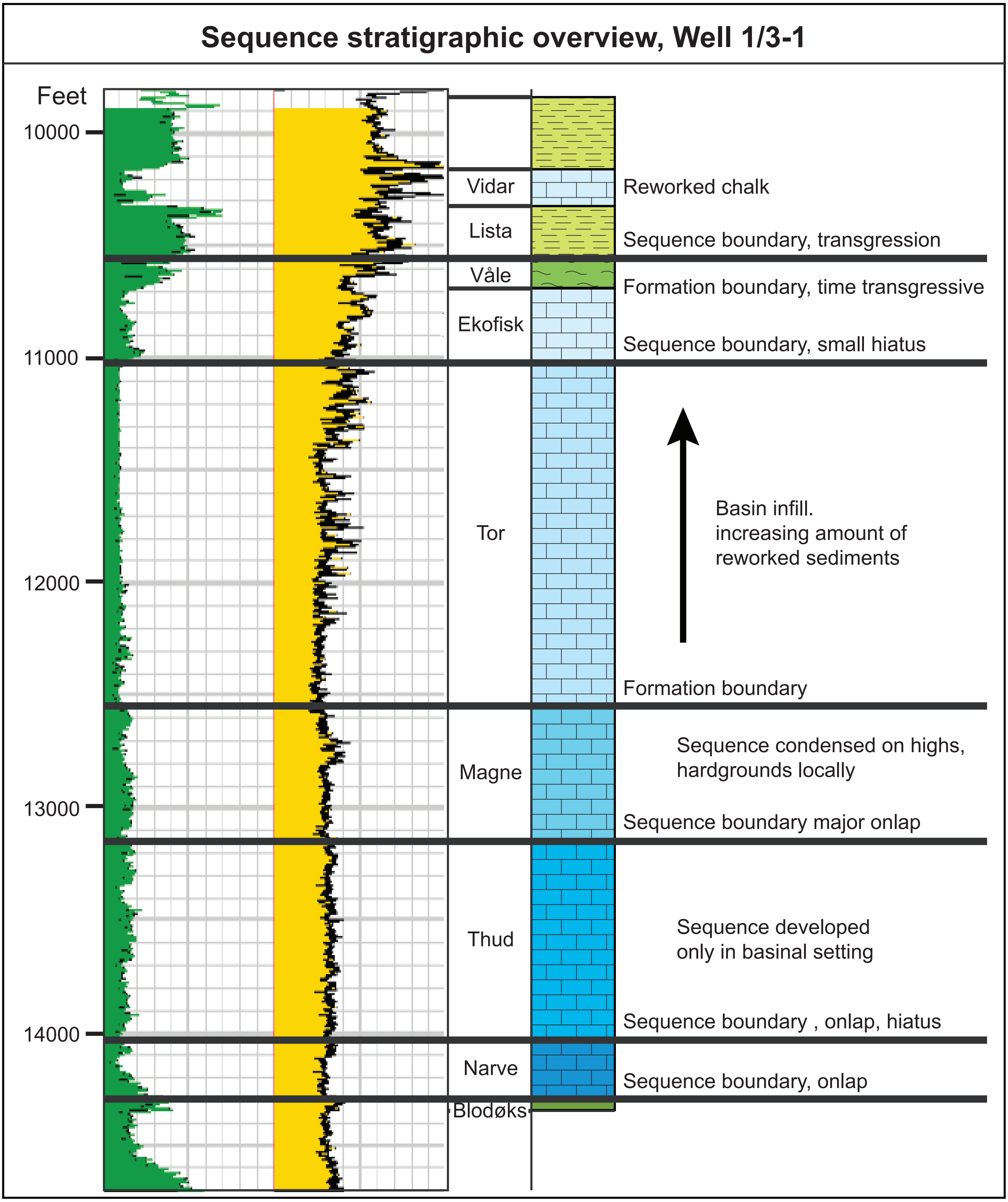


Figure 4.14. Schematic sequence stratigraphic overview of Chalk units (in blue) in Norwegian well 1/3-1 (redrafted after Joint Chalk Research document , 2000; unpublished)

Southern North Sea area but is absent, due to subsequent inversion and erosion over the Sole Pit Basin and over some contemporary structural highs and salt diapirs (Lott & Knox, 1994). In the Norwegian Sector, it is missing above highs such as the Sørvestlandet, Mandal, Jæren, Utsira and Sele Highs, the Grensen Ridge, as well as many of the salt diapirs.

The Norlex internet site (*www.nhm2.uio.no/norlex*) provides occurrences of formation tops in wells and relative thickness maps.

Type well

Well name: 1/3-1 (Norwegian Sector)
WGS84 coordinates:
Lat. 56°51'21"N Long. 02°51'05"E
UTM coordinates: 6301488.86 N 490936.87 E
UTM zone: 31
Drilling operator name: A/S Norske Shell
Completion date: 11.11.1968
Status: P & A
Interval of type section and thickness in type well:
4371 - 4441 m (14340-14570 ft) below KB (Deegan & Scull, 1977, p.26, fig. 30) (metric conversion slightly amended). No cores.

UK Reference wells

Central and Northern North Sea (Johnson & Lott, 1993)
15/22-4: 3115 - 3266.5 m (10219-10717 ft)
Lat. 58°15'52.3"N Long. 00°13'49.2"E
16/7-5: 3456.5 - 3528 m (11340-11575 ft)
Lat. 58°48'27.0"N Long. 01°16'44.5"E
22/1-2A: 3738.5 - 3782.5 m (12265-12410 ft)
Lat. 57°56'12.2"N Long. 01°02'55.8"E
29/9a-1: 3791 - 3907 m (12438-12819 ft)
Lat. 56°49'51.95"N Long.01°43'20.37"E
29/25-1: 2258.5 - 2228 m
Lat. 56°18'10.00"N Long. 01°51'48.80"N. No cores.

Southern North Sea (Lott & Knox, 1994)
43/8a-2: 1261.5 - 1295.5 m (4139-4250 ft)
Lat. 54°45'11.3"N Long. 01°33'07.8"E
49/25-2: 1949 - 1989.5 m (6394-6527 ft)
Lat. 53°11'51.2"N Long. 02°51'19.49"E

Danish well
BO-1: 2275.5 - 2220 m
Lat. 55°48'8.22"N Long. 04°34'18.66"E.
Cored through the upper 35 m.

Upper and lower boundaries

Upper boundary

Norwegian and Danish Sectors: The upper boundary is defined by the Blodøks Formation. The boundary is characterised by a change from the chalk lithology to mainly mudstone. This is seen as an abrupt change to higher gamma-ray response and a decrease in velocity in the Blodøks Formation. The boundary shows as a glauconitised hardground in the core from Danish well BO-1.

UK Sector: The top of the Hidra Formation is normally marked by a sharp downward change from the basal black mudstone of the Herring Formation (Black Band) to white to pale grey chalky limestones (Johnson & Lott, 1993; Lott & Knox, 1994).

Lower boundary

Norwegian Sector: The formation usually shows a gamma-ray response that has constant low values and high velocities. These contrast sharply at the lower boundary with the higher gamma-ray response and lower velocity of the Åsgard and Sola Formations. The lower boundary is more gradational when the carbonate rich facies of the Rødby Formation is present beneath the Hidra Formation.

UK Sector: The base of the Hidra Formation is normally defined by a downward change from interbedded pale to dark grey and pink chalky, argillaceous limestones to red-brown chalky mudstones of the Rødby Formation. In the Central North Sea, this boundary is commonly represented by a minor unconformity, although locally the formation rests unconformably upon Jurassic or older rocks (Gatliff *et al.*, 1994).

Well log characteristics

The variable proportion of interbedded mudstone in the Hidra Formation of the Central North Sea provides a typically uneven geophysical log character (Gatliff *et al.*, 1994), whereas in the Southern North Sea there is a lower proportion of mudstones and less uneven signature. The top of the Hidra Formation is characterized on wireline log responses by a sharp downward decrease in gamma-ray values and increase in sonic velocity response. Where the Black Band is absent or poorly developed the boundary is much more difficult to pick and biostratigraphic data may be required to define the boundary (e.g. 49/5-1, Lott & Knox, 1994). The lower boundary of the formation is marked on the wireline log responses by a downward increase in gamma-ray values and decrease in velocity into the underlying Rødby Formation (Lott & Knox, 1994). In the Moray Firth, the base of the formation is commonly taken at the top Lower Cretaceous seismic event. This is marked in wells by a relatively undistinguished log break of variable amplitude associated with a thin chalk bed that interrupts the progressive change in gamma-ray and velocity values (Andrews *et al.,* 1990).

Biostratigraphy

In the Central North Sea (Johnson & Lott, 1993) and Southern North Sea (Lott & Knox, 1994) the *Rotalipora cushmani* foraminiferal biomarker occurs near the top of the Hidra Formation where there is a major influx of planktonic foraminifera, notably *Rotalipora cushmani, R. greenhornensis, Hedbergella brittonensis* and *H. delrioensis*. The *Lingulogavelinella ciryi inflata/ Rotalipora reicheli* biomarker occurs in the middle part of the formation and consistent and common *Hedbergella planispira* and *Quinqueloculina antiqua* have their FDOs immediately above the base of the Hidra Formation at a similar horizon as the FDO of the ostracod *Neocythere steghausi.* Of the nannofossil biomarkers, the following occur within the Hidra Formation: *Axopodorhabdus albianus*, which forms a good marker for the top of the formation, *Gartnerago theta, Gartnerago nanum* and *Biscutum constans* acme. Palynological recovery in the Hidra Formation is variable, but generally low. The *Apteodinium granulatum* dinoflagellate cyst biomarker marks the top of the formation and the *Epelidosphaeridia spinosa* biomarker is present within the formation (Costa & Davey, 1992).

Age

Cenomanian (Table 4.4); the base of the unit is taken at the base of UC1, base of Cenomanian at 100.5 Ma. However, in the Erskine Basin (UK Sector), boreholes suggest chalk sedimentation commenced earlier in the basinal areas of the Central Graben (Gatliff *et al.*, 1994).

Correlation

The Rowe Formation passes northwards into the upper part of the Mackerel Formation and the Tor Formation of the Central North Sea (Tables 4.1 and 4.3).

Depositional environment

The Hidra Formation is laterally equivalent to the upper part of the flintless, grey occasionally pink, argillaceous chalks of the Ferriby Chalk Formation of eastern England (Wood & Smith, 1978; Table 4.3). The Hidra Formation and its lateral equivalent Svarte Formation (Shetland Group) correlate approximately with the Grey Chalk Subgroup of the onshore southern England province (Hopson, 2005).

Depositional environment

The bioturbated chalky limestones of the Hidra Formation were deposited in open marine environments as fine-grained pelagic carbonate, containing abundant bioclastic, skeletal debris (dominated by coccolith plates) (Johnson & Lott, 1993; Lott & Knox, 1994). Beds of terrigenous mudstone are common towards the base of the formation in the Central North Sea (Johnson & Lott, 1993). Thin calcarenite turbidite beds may be present within the Central Graben (Kennedy, 1987). The upward change from dominantly benthonic to planktonic foraminiferal faunas in the middle of the formation reflects the development of good open-ocean connections in the late Cenomanian (Crittenden *et al.*, 1991).

Subdivision

Four sub-units (H1H4) are recognized informally by Burnhill & Ramsay (1981), Crittenden *et al.* (1991) and Johnson & Lott (1993) based upon wireline log signatures. H1 and H3 are dominated by thin beds of chalk interbedded with mudstone and marl, whereas H2 and H4 comprise thick massive chalk with uniformly high velocity. They are best developed in the Moray Firth; they are not widely recognizable in Southern North Sea wells and the units are not, therefore, used in this area.

Narve Formation (Narveformasjonen) - Chalk Group

Introduction

The definition of the Narve Formation in the Central Graben is after Fritsen & Riis (2000: 'A revised chalk lithostratigraphic nomenclature'; NPD Report, unpublished) (see Table 4.4).

Name

After the Norse god Narve, who was the son of Loke and Sigyn.

Lithology

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 difficult, for which high-resolution study is desirable of the paleobathymetry of 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.

Thickness

The thickness of this formation ranges from zero to a few hundred metres in the study wells. It is thin (typically less than 100 m 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.

Geographical distribution

The formation is present in the Central Graben in the Norwegian and Danish Sectors. It is absent in the 2/2 wells in the Norwegian Sector and in the Lulu-1 well in the Danish Sector. The formation is eroded on crests of structures.

The Norlex internet site (*www.nhm2.uio.no/norlex*) provides occurrences of formation tops in wells and relative thickness maps.

Type well

Well name: 1/3-8 (Norwegian Sector)

4520 - 4337 m MD.

Reference wells

2/8-A-1, 2581.5 - 2501.5 m MD.

Upper and lower boundaries

Upper boundary

Picked primarily on seismic and biostratigraphic criteria. The seismic criterion is an onlap surface. The biostratigraphic criterion is penetration of local nannozone UC11.

Lower boundary

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

Log pattern or seismic characteristics

The Narve Formation has been penetrated in 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 BP) 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.

Biostratigraphy and Stage/Age

Latest Cenomanian-earliest Santonian (for practical purposes, Turonian-Coniacian). Microzones FCS-14-FCS18pp; nannozones UC4-UC11. The base is taken near 94 Ma.

Depositional environment
Variable "shallow water" and "deep water" pelagic environments are listed in well completion reports.

Thud Formation (Thudformasjonen) - Chalk Group

Introduction
The definition of the Thud Formation in the Central Graben is after Fritsen & Riis (2000; A revised chalk lithostratigraphic nomenclature; NPD Report, unpublished), (see Table 4.4).

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

Lithology
Poorly constrained owing to the lack of core coverage. Relatively argillaceous chalks appear to alternate with clean chalks.

Thickness
The thickness of this formation ranges from zero to a few hundred metres in the study wells. 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.

Geographical distribution
The formation is confined to the Central Graben of the Norwegian and Danish Sectors. 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.

Type well
Well name: 1/3-8 (Norwegian Sector)
4337-4125 m MD

Reference wells
Not assigned.

Upper and lower boundaries
Upper boundary
Picked primarily on a seismic criterion (onlap surface), corresponding to the original informal middle Hod sequence boundary.

Lower boundary
Picked primarily on seismic and biostratigraphic criteria. The seismic criterion is an onlap surface. The biostratigraphic criterion is penetration of nannozone UC11. The formation laps on to the Narve formation on the flanks of structures.

Well log charactertistics
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.

Biostratigraphy and Stage/Age
Late early Santonian to earliest Campanian (for practical purposes, Santonian). Microzones FCS18pp-FCS20pp; nannozones UC12-UC14 pp.

Depositional environment
Biofacies in cuttings samples from some wells are characterised by moderately abundant and diverse planktonic foraminifera and radiolaria and generally rarer carbonate agglutinated and calcareous benthonic foraminifera. This indicates affinity with the open marine platform or "shallow water" pelagic biofacies of the Valhall structure.

Magne Formation (Magneformasjonen)- Chalk Group

Introduction
The definition of the Narve Formation in the Central Graben is after Fritsen & Riis, (2000; A revised chalk lithostratigraphic nomenclature; NPD Report, unpublished), (see Table 4.4).

Name
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).

Lithology
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.

Thickness
The thickness of this formation ranges from zero to a few hundred metres in the study wells.

Geographical distribution
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. The Norlex internet site (*www.nhm2.uio.no/norlex*) provides occurrences of formation tops in wells and relative thickness maps

Type well
Well name: 1/3-8 (Norwegian Sector)
4125 - 3952 m MD.

Reference wells
Well 2/11-A-2 T2
3486 - 3427.4 m MD.

Upper and lower boundaries
Upper boundary
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).

Lower boundary
Picked primarily on a seismic criterion (onlap surface). The formation onlaps the Thud Formation and oversteps on to the Narve (?) Formation on flanks of structures.

Biostratigraphy and Stage/Age
Late early to early late Campanian (for practical purposes, Campanian). Microzones intraFCS20pp-intraFCS22; nannozones intraUC14pp-intraUC16pp. The base is taken near 81 Ma, using the criterion of 40% up in UC14.

Depositional environment
The formation is variably associated with the open marine platform, high productivity upper slope and basinal environments, locally eutrophic.

Tor Formation (Torformasjonen) - Chalk Group

Introduction
The term Tor Formation was introduced by Deegan & Scull (1977) and retained in the Central North Sea by Johnson & Lott (1993), with modification of the definition of the base (Tables 4.3 and 4.4). The definition in the type area of the Central Graben (Norwegian Sector) is after Fritsen & Riis, (2000; A revised chalk lithostratigraphic nomenclature; NPD Report, unpublished). For earlier definition, see NPD Bulletin no. 5.

Name

After the Tor Field in Norwegian blocks 2/4 and 2/5 (Deegan & Scull, 1977, p.27). Tor was a son of Odin, and one of the principal Gods of Norse mythology.

Lithology

Norwegian Sector: 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 of 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 paleo-topography, 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.

UK Sector: The Tor Formation typically consists of homogeneous, white or pale grey, tan or pink chalky limestones. Locally, however, softer argillaceous chalky limestones are interbedded with harder, purer limestones (e.g. 16/28-7). Beds of relatively porous, slumped and chaotically bedded chalky limestone are common (Kennedy, 1980).

Thickness

Norwegian Sector: Tor thicknesses in the study wells vary from 0 m in Baron-2 to 472 m 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.

UK Sector: On intra-basinal and graben-marginal ridges the formation is generally less than 150 m thick. However, the formation is more than 250 m thick in depocentres within the Central Graben, locally reaching over 500 m (Johnson & Lott, 1993). In the Outer Moray Firth the formation is typically about 200 m thick, up to 500 m thick in the Wick Sub-basin (Andrews *et al.*, 1990).

Geographical distribution

Norwegian Sector: 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 (Ziegler, 1990). This general observation has an overprint of local east or west depocentres going from north to southeast along the Graben axis. This pattern is confirmed by the study wells also for the Tor Formation alone. The Norlex internet site (*www.nhm2.uio.no/norlex*) provides occurrences of formation tops in wells and relative thickness maps

UK Sector: The Tor Formation is the most widespread of the Chalk Group formations, and occurs throughout the Central North Sea, including the Forties-Montrose High. It also extends into the South Viking Graben and onto the East Shetland Platform, where it rests on Jurassic and older rocks. It is absent from the graben margin of the Western Platform and parts of the Halibut Horst (Johnson & Lott, 1993).

Type well

Well name: 1/3-1 (Norwegian Sector)

WGS84 coordinates:

Lat. 56°51'21"N Long. 02°51'05"E

UTM coordinates: 6301488.86 N 490936.87 E

UTM zone: 31

Drilling operator name: A/S Norske Shell

Completion date: 11.11.1968

Status: P & A

Interval of type section and thickness in type well: 3354-3827.5 m (11004-12558 ft) below KB, (Figure 4.14).

(Deegan & Scull, 1977, p.27, fig.30; Tonstad & Isaksen, 1989). No cores.

Danish Reference wells

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.

UK Reference wells

16/17-6: 2964 - 3249 m (9724-10660 ft)
Lat. 58°25'55.6"N Long. 01°18'26.0"E
22/1-2A: 2982 - 3198 m (9783-10492 ft) revised depths Lat. 57°56'12.2"N Long. 01°02'55.8"E
29/4a-1A: 3176 - 3604 m (10420-11824 ft)
Lat. 56°50'37.0"N Long. 01°45'14.4"E
29/25-1:1869 - 1995 m (6132-6542 ft)
Lat. 56°18'10.023"N Long.01°51'48.758"E
(see Bigg, 1981 for foraminifera found in the Tor Formation in this well).

Upper and lower boundaries

Upper boundary

Norwegian Sector: 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 Formation is missing in 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 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 Formation 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).

UK Sector: The top of the formation is marked by a downward change from relatively argillaceous chalky limestones of the Ekofisk Formation to relatively clean limestones. Thin argillaceous units are present locally and, in the northern parts of the Central Graben, expansion of these argillaceous units leads to uncertainty as to the correct pick for the upper boundary (Johnson & Lott, 1993).

Lower boundary

Norwegian Sector: 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 the Magne Formation 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.

UK Sector: The base of the Tor Formation is normally marked by a relatively abrupt downward change from the hard chalky limestones to the interbedded argillaceous chalky limestones, which are commonly stained pink or red top of the Mackerel Formation (Johnson & Lott, 1993). Over intrabasinal and graben-margin ridges, the Tor Formation overlies Lower Cretaceous and older sediments (e.g. 29/23-1).

Well log or seismic characteristics

Norwegian Sector: 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.

UK Sector: The top of the formation is marked by a downward decrease in gamma-ray values and forms a strong, regionally developed seismic reflector (Andrews *et al.*, 1990). The formation is characterized by an almost featureless log response and high, uniform velocity values (Deegan & Scull, 1977). Beds of relatively porous, slumped and chaotically bedded chalky limestone are marked by low velocity peaks and distinctive porosity and dipmeter log responses (Johnson & Lott, 1993). On wireline logs, the lower boundary of the formation corresponds to a downward increase in gamma-ray values and decrease in velocity.

Biostratigraphy

Norwegian Sector: 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 foram zones FCS22 through FCS23. The base of the Formation is in the middle of zone UC16 near 74 Ma.

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 and 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. There is considerable biostratigraphic evidence for intra-formational reworking within the Tor Formation throughout the study region. Several wells contain sections where late Campanian and early Maastrichtian Tor sediments have been re-deposited during late Maastrichtian. There is also evidence of reworking within late Maastrichtian. Despite the frequent presence of stacked allochthonous chalk units within the Tor Formation, 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.

UK Sector: The top of the Tor Formation is marked by the *Pseudotextularia elegans* foraminiferal biomarker and the *Nephrolithus frequens* calcareous nannofossil biomarker (Johnson & Lott, 1993). The FDO of *Reussella szajnochae* is present in the middle part of the formation, but is rare. The *Gavelinella* spp. / *Bolivinoides miliaris* biomarker occurs in the lower part of the formation. The *Reinhardtites levis* nannofossil biomarker is an important marker for the early/late Maastrichtian boundary, at about the same level as the FDO for *R. szajnochae*. The *Gatnerago obliquum, Tranolithus orionatus* and *Broinsonia parca* biomarkers also occur within the formation. The presence of the *Reinhardtites anthophorus* biomarker in some wells suggests the base of the formation locally extends into the latest Campanian (Johnson & Lott, 1993). The *Palynodinium grallator* and *Odontochitina operculata* dinoflagellate cysts biomarkers are present in the formation, the former dominating in the uppermost part (Costa & Davey, 1992).

Age

Early Maastrichtian, locally latest Campanian, to latest Maastrichtian (Tables 4.1-4.4).
(Deegan & Scull, 1977, p.27, fig.30; Tonstad & Isaksen, 1989). No cores.

Correlation

The formation is laterally equivalent to the upper part of the Jorsalfare Formation (Shetland Group) of the Northern North Sea and

North Viking Graben, and the upper part of the Rowe Formation of the Southern North Sea (Tables 4.3-4.4).

Depositional environment

The chalky limestones occur as two facies: 1) pelagic chalky, coccolith-rich limestones with varying proportions of detrital clay (Johnson & Lott, 1993), with phases of more open marine circulation indicated by a higher proportion of planktonic foraminifera in the latest Maastrichtian (King *et al.*, 1989); and 2) an allochthonous facies formed of sediments originating from the redeposition of slumped sediments derived from the flanks of the graben (Johnson & Lott, 1993). Gennaro & Wonham (2014) provide a detailed description of a long (~30 km) submarine channel in the Tor Formation, developed in WNW-ESE direction by submarine bottom currents. It interacted with downslope mass flow deposits.

Subdivision

No formal subdivisions are recognized in UK or Norwegian waters. On the basis of lithological and porosity characteristic the Tor Formation in the Central North Sea is divided in sixteen single, or multiple, high-porosity allochthonous chalk units (Hatton, 1986).

Ekofisk Formation (Ekofiskformasjonen) - Chalk Group

Introduction

The term Ekofisk Formation was introduced by Deegan & Scull (1977). The definition in Norwegian waters is updated from Fritsen & Riis (2000), with an earlier definition by Isaksen and Tonstad (1989; see NPD Bulletin no. 5). It was formally redefined in the UK Sector by Knox & Holloway (1992); (see Tables 4.1-4.4).

Name

From the Ekofisk Field in Norwegian block 2/4 (Deegan & Scull, 1977, p.27).

Lithology

Norwegian Sector: 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. 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 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 & 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).

Danish Sector: 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. 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 nannofossil zone (NNTp1) are reported from Lulu-1.

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 seems to 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.

UK Sector: The Ekofisk Formation typically consists of variably cemented white, pale grey, tan and beige chalky limestone, composed largely of the remains of coccoliths and calcareous microfossils (Knox & Holloway, 1992; Gatliff *et al.*, 1994). Grey, argillaceous chalky limestone, calcareous mudstone and shale units, indicated by higher gamma responses, are also present; these appear to consist of limestone with thin, discrete, clay layers. Fine to medium grained, moderately to well sorted sandstones are present locally; they are distinguished from the associated limestones by their higher gamma values and generally by lower velocity and resistivity. Units of reworked chalk occur locally within the Ekofisk Formation in Central Graben (Hatton, 1986; Kennedy, 1987). The formation is typically chert-free, although chert may be present in southernmost sections of the Southern North Sea (Lott & Knox, 1994).

Thickness

The thickness of the Ekofisk Formation varies throughout central North Sea. In the southern end of the Danish Sector, the thickness is some 30 to 40 m 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 m 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.

In UK waters the formation reaches over 100 m in the Central and Northern North Sea, with up to 120 m preserved in the basinal depocentres of the Central Graben and between 10 and 60 m over its intra-basinal high (Gatliff *et al.*, 1994). In the Moray Firth the formation is between 50 and 80 m thick (Andrews *et al.*, 1990). Typically, the formation is between 10 and 30 m in the Southern North Sea, but is c. 55 m in the north-east in well 39/2-1 (Lott & Knox, 1994).

Geographical distribution

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. The Norlex internet site (*www.nhm2.uio.no/norlex*) provides occurrences of formation tops in wells and relative thickness maps.

UK Sector: The Ekofisk Formation extends throughout the basinal areas of the Central Graben, Outer Moray Firth and South Viking Graben (Knox & Holloway, 1992) and the Southern North Sea around the quadrant boundary of 44/49 and in the north of quadrant 53 (Lott & Knox, 1994). The limit of the Ekofisk Formation appears to be erosional throughout the UK Sector.

Type well

Well name: 2/4-5 (Norwegian Sector)
WGS84 coordinates:
Lat. 56°34'27.24"N Long. 03°12'11.82"E
UTM coordinates: 6270151.28 N 512490.31 E
UTM zone: 31
Drilling operator name: Phillips Petroleum
Completion date: 01.08.1970
Status: P & A
Interval of type section and thickness in type well: 3037 - 3164 m (9964-10380 ft) below KB (Deegan & Scull, 1977, p.27, fig.31). The top of the Ekofisk Formation as defined below (for UK sections) would be taken at c. 3043 m. No cores.

Norwegian Reference wells

1/3-1, 3354 - 3257 m MD
Lat. 56°5'21.00"N Long. 02°51'05.00"E. No cores.
2/5-1, 3132 - 3041 m
Lat. 56°38'19.95"N 03°21'07.94"E. Cored through the upper 78 m. (This well was added by Isaksen & Tonstad, 1989).

UK Reference wells

Central and Northern North Sea (Knox & Holloway, 1992)
14/30-1: 1932 - 2009 m (6371-6591 ft).
Lat. 58°07'52.6"N Long. 00°10'45.4"W
16/23-3: 2727 - 2776 m (8946-9107 ft).
Lat. 58°12'32.6"N Long. 01°33'14.0"E
21/10-1: 2859.5 - 29445 m (9382-9660 ft).
Lat. 57°43'50.2"N Long. 00°58'29.5"E
22/1-2A, 2982.5 - 2935 m MD
Lat. 57°56'12.20"N Long. 01°02'55.80"E. No cores.
29/15-1: 3082.5 - 3148 m (10113-10328 ft).
Lat. 56°34'10.4"N Long. 01°58'33.3"E

Southern North Sea (Lott & Knox, 1994)
49/9-1: 810 - 820 m (2658-2690 ft)
Lat. 53°44'32.2"N Long. 02°44'23.1"E

Upper and lower boundaries

Upper boundary

Norwegian and Danish Sectors: 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 Sectors, 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.

UK Sector: The top of the Ekofisk Formation is generally marked by a rapid downward transition from chalky marl of the Maureen Formation to limestone. In some sections, the basal Maureen marl is replaced by sandstone or reworked limestone (e.g. 14/19-9; 22/11-2).

Lower boundary

Norwegian and Danish Sectors: 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. 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 occurs.

UK Sector: The base of the Ekofisk Formation is normally marked by a downward change from the basal marly limestone to the relatively clean, limestone of the Tor Formation (Knox & Holloway, 1992). Thin marly limestone units are locally present in the underlying limestone (e.g. 16/23-3), and in some areas expansion of these marly units leads to uncertainty as to the correct pick. Thus the base of the Ekofisk Formation in well 21/1-5 may be stratigraphically slightly lower than in more typical sections. In the Southern North Sea, the lower boundary is defined by a downward change from chert-free to chert-rich chalky limestone (Lott & Knox, 1994).

Well log or seismic characteristics

Norwegian and Danish Sectors: 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.

UK Sector: On wireline logs the upper boundary of the Ekofisk Formation is taken at the top of a section of consistently low gamma limestone; a downhole increase in sonic velocity commonly occurs at the same intra-basinal high (Gatliff *et al.*, 1994). In the Moray Firth the formation is between 50 and 80 m thick (Andrews *et al.*, 1990). Typically, the formation is between 10 and 30 m in the Southern North Sea, but is c. 55 m in the north-east in well 39/2-1 (Lott & Knox, 1994).

Geographical distribution

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. The Norlex internet site (www.nhm2.uio.no/norlex) provides occurrences of formation tops in wells and relative thickness maps.

UK Sector: The Ekofisk Formation extends throughout the basinal areas of the Central Graben, Outer Moray Firth and South Viking Graben (Knox & Holloway, 1992) and the Southern North Sea around the quadrant boundary of 44/49 and in the north of quadrant 53 (Lott & Knox, 1994). The limit of the Ekofisk Formation appears to be erosional throughout the UK Sector.

Type well

Well name: 2/4-5 (Norwegian Sector)

WGS84 coordinates:

Lat. 56°34'27.24"N Long. 03°12'11.82"E

UTM coordinates: 6270151.28 N 512490.31 E

UTM zone: 31

Drilling operator name: Phillips Petroleum

Completion date: 01.08.1970

Status: P & A

Interval of type section and thickness in type well: 3037 - 3164 m (9964-10380 ft) below KB (Deegan & Scull, 1977, p.27, fig.31). The top of the Ekofisk Formation as defined below (for UK sections) would be taken at c. 3043 m. No cores.

Norwegian Reference wells

1/3-1, 3354-3257 m MD

Lat. 56°5'21.00"N Long. 02°51'05.00"E. No cores.

2/5-1, 3132 - 3041 m

Lat. 56°38'19.95"N 03°21'07.94"E. Cored through the upper 78 m. (This well was added by Isaksen & Tonstad, 1989).

UK Reference wells

Central and Northern North Sea (Knox & Holloway, 1992)

14/30-1: 1932 - 2009 m (6371-6591 ft).

Lat. 58°07'52.6"N Long. 00°10'45.4"W

16/23-3: 2727 - 2776 m (8946-9107 ft).

Lat. 58°12'32.6"N Long. 01°33'14.0"E

21/10-1: 2859.5 - 2944.5 m (9382-9660 ft).

Lat. 57°43'50.2"N Long. 00°58'29.5"E

22/1-2A, 2982.5 - 2935 m MD

Lat. 57°56'12.20"N Long. 01°02'55.80"E. No cores.

29/15-1: 3082.5 - 3148 m (10113-10328 ft).

Lat. 56°34'10.4"N Long. 01°58'33.3"E

Southern North Sea (Lott & Knox, 1994)

49/9-1: 810 - 820 m (2658-2690 ft)

Lat. 53°44'32.2"N Long. 02°44'23.1"E

Upper and lower boundaries

Upper boundary

Norwegian and Danish Sectors: 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 Sectors, 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.

level. Where the gamma and sonic markers do not coincide, the boundary is picked on the gamma log (e.g. 14/30-1). Commonly, coarser clastic units present in the Maureen Formation are distinguished from the underlying Ekofisk Formation by their more erratic gamma and sonic log character, reflecting greater lithological variability (e.g. 22/16-1). Where relatively pure reworked limestones rest directly on Ekofisk limestone (e.g. 22/11-2) the boundary may be revealed by a downhole change from scattered to consistent dips. The lower boundary is taken at a marked decrease in gamma-ray values.

Biostratigraphy

Norwegian and Danish Sectors: Nannoplankton zones NNTp1-NNTp5B. 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. 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. [SEE: Extensive details in Fritsen & Riis, 2000.]

UK Sector: The top of the formation is poorly characterized biostratigraphically, although there is a downhole decrease in the abundance and diversity on benthonic microfossils at this level. The dinoflagellate cyst *Senoniasphaera inornata* biomarker occurs within the formation (Knox & Holloway, 1992).

Age

Danian (Tables 4.1-4.4), with the base of the Ekofisk unit at 66 Ma.

Correlation

The Ekofisk Formation has not been identified in the East Shetland Basin, although it is possibly represented in condensed form at the base of the marl unit here assigned to the Maureen Formation. The Ekofisk is not represented onshore in southern England (Table 4.3).

Depositional environment

The chalky limestones of the Ekofisk Formation mostly represent pelagic nannofossil oozes, deposited in an outer shelf to basinal setting, probably in water depths of over 200 m. Units of resedimented chalk, are present as calcareous debris flows, turbidites and autochthonous periodites, locally in the Central Graben (Skovbro, 1983, d'Heur, 1986, Hatton, 1986; Kennedy, 1987). Bioturbation is common, indicating that the bottom waters were mostly well oxygenated (Knox & Holloway, 1992).

Subdivision

No formal subdivision, but the Ekofisk Formation displays a characteristic stratigraphical variation in gamma-ray values in the UK Sector (e.g. well 14/30-1). The lower unit of high-gamma, argillaceous chalky limestone or calcareous mudstone may also locally include sandstones (e.g. 21/1-5), whereas the upper unit comprises low-gamma, often high-velocity, clean chalky limestones (Knox & Holloway, 1992). Two zones of the formation are readily correlatable within the Central Trough area (Hatton, 1986, Figs. 24, 29, 30 and 31).

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Appendix 1

Genus: *Uvigerinammina*
Species: *Uvigerinammina una* Gradstein and Kaminski
Reference: Appendix B and Plate 3 in Gradstein *et al.* (1999).
Illustrations: Plate 1, figures 4a,b and 5.
Synonymy: 1981 - *Uvigerinammina* sp. 1 Burnhill and Ramsay
Derivation of name: Latinisation of the original open nomenclature name *Uvigerinammina* sp. 1 Burnhill and Ramsay 1981.
Diagnosis: Test rounded triserial, rapidly expanding in width, with last whorl occupying most of test.
Holotype: Housed in the Micropaleontology Collection of the British Museum of Natural History, London.
Material, localities and horizons: The type level is the interval of 3040 - 3130 m in greenish mudstones in well 6507/6-2, offshore mid Norway. The species is known from the *Uvigerinammina una* zone, late middle Albian to early late Albian. Auxiliary material is in the UK North Sea well 21/1A-10 at 2765 m, assigned by Burnhill and Ramsay (1981) to upper Albian.

Additional occurrences of this new taxon, offshore Norway are in wells 6507/2-1 at 3580 m, 6507/2-3 at 3450 m, 6506/12-5 at 3727.50 m, 6406/2-2 at 4260m, 6406/2-3 at 4578 m, 6506/12-4 at 3784 m; 35/3-2 at 3639.10 m, 35/3-4 at 3542.10 m, 35/12-1 at 2310 m, 35/11-2 at 2712 m, and 34/7-21A at 2852 m.
Description: Test triserially coiled, with three whorls, the last one of which occupies most of the test and widens rapidly; the geatest width of the semicircular test is halfway up the last whorl. Sutures slightly depressed. Test smooth, shiny, fine grained agglutinated with organic cement. Aperture an elongate opening, bordered by a rim, at the top of last chamber.
Dimensions: Specimens range between 150 and 300 micrometer in size.
Remarks: The nominate taxon, *Uvigerinammina una*, apparently is a boreal mid-Cretaceous species restricted to the Norwegian and North Sea regions. It appears not to possess calcareous cement, therefore it cannot be assigned to the genus *Falsogaudryinella.* Most likely it belongs in the genus *Uvigerinammina,* as originally reported by Burnhill & Ramsay (1981). It has not been found in the Albian of the Kirchrode-1 Borehole, NW Germany (Jaroslaw Tyszka, personal communication), or in deep-sea deposits. The acme of *Uvigerinammina una* itself often forms a narrow zone, but the species also is found in low numbers in both the immediately overlying and immediately underlying zones.

The species differs from co-occurring *Uvigerinammina alta* in its much wider test; *U. alta* is relatively long and slender.

Genus: *Ammoanita*
Species: *Ammoanita globorotaliaeformis* Gradstein & Kaminski
Illustrations: Plate 1, figures 6, 7 and 8.
Derivation of name: Based on resemblance of the *Ammoanita* specimens to a high conical, many chambered planktonic foraminifer of the genus *Globorotalia.*
Diagnosis: Planoconical, high spired with 9 or more chambers in last whorl; chambers strongly overlap; sutures swing backward.
Holotype: Housed in the Micropaleontology Collection of the British Museum of Natural History, London. The holotype is registered in slide PF66923.
Material, localities and horizons: The type level is the interval of 3040 - 3140 m in greenish mudstones in well 6507/6-2, offshore mid Norway. This interval belongs in the *Uvigerinammina una* zone, late middle Albian to early late Albian. The species appears to be restricted to this zone. Additional occurrences of this new taxon, offshore Norway are in wells 6507/2-3 at 3450 m, 6406/2-2 at 4280 m, 35/3-5 at 3476 m, and 34/7-21A at 2852.22 m.
Description: Test trochospirally coiled, with two to four whorls; spiral side flat; umbilical side highly convex, with no or only a narrow umbilical depression; periphery acute. Outline circular to slightly lo-

bate. Chambers are numerous, increasing rapidly in height, 9 or more in the last whorl; last chamber may tower over previous ones. Sutures limbate, and can be slightly depressed or smooth; on the umbilical side the sutures are curved backward; on the spiral side the sutures are tangentially situated. Wall aggutinated, silicified. Aperture extraumbilical, poorly visible, a slit at the base of the final chamber.

Dimensions: Specimens range between 125 and 300 micrometer in diameter.

Remarks: We place this species in the genus *Ammoanita* Seiglie & Baker, 1987, rather than in *Trochammina* because of its angular chambers and acute periphery. According to our observations *Ammoanita globorotaliaeformis* has a tighter coil than the Paleocene *A. ingerlisae* Gradstein & Kaminski, with chambers increasing more rapidly in height, and more chambers in the last whorl. In local well completion reports such specimens are referred to as Trochammina 'globorotaliaformis', and constitute a useful mid- -upper Albian index.

Charnock & Jones (1990) mention occasional specimens of their *Trochammina subvesicularis* in Albian mudstones, offshore mid Norway, which probably belong in the new taxon *Ammoanita globorotaliaeformis. Trochammina abrupta* Geroch of the middle Cretaceous Verovice Beds of Poland is less planoconvex, has more radial sutures, far fewer and wider chambers and a wider spire than *A.globorotaliaeformis.*

T. subvesicularis Hanzlikova, of the Albian of Czechoslovakia has fewer chambers in the last whorl and is more strongly planoconvex, with a lobate periphery. Its chambers increase more rapidly in height than *A. globorotaliaeformis* (see Gradstein & Kaminski, 1997).

Genus: *Fenestrella*

Species: *Fenestrella bellii* Gradstein and Kaminski

Reference: Appendix B in Gradstein *et al.* (1999) and Plate 3 in Earth-Science Reviews 50/200, p.135-136 (Erratum); not Plate 3 in Gradstein *et al.*,1999.

Illustrations: Plate 1, figures 1, 2 and 3.

Synonymies: Unpublished well completion reports, offshore Norway refer to this taxon either as Diatom sp. *H Stratlab*, or as Diatom sp. 17 Robertson Research.

Derivation of name: Named after Dr. Graham Bell, in recognition of his stratigraphic palynology, offshore Norway.

Diagnosis: A small and always pyritized diatom test that is disk shaped with sharp periphery.

Holotype: Housed in the Micropaleontology Collection, Department of Botany of the British Museum of Natural History, London. The holotype is registered in slide BM 100179.

Material, localities and horizons: The type level is in mudstones at 2320 m in well 6507/6-2. Additional types are from 2330 m in well 34/7-7, also offshore Norway. The type level is the *Fenestrella bellii* zone, lower Campanian. Additional occurrences of this taxon, widespread and common offshore Norway are in wells 6610/3-1 at 2245 m, 6607/5-2 at 4134 m, 6607/5-1 at 3172 m, 6507/2-2 at 2220 m, 6507/2-3 at 2400 m, 6507/7-1 at 2330 m, 6507/7-2 at 2091 m, 6506/12-4 at 2449 m, 6406/2-1 at 2700 m, and 34/7-24s at 2630 m.

Description: Test small, always pyritized (due to depth of burial below the stability level of siliceous tests) and shiny. The tests are disk shaped, with a circular equatorial outline, a rather sharp periphery, and a low conical side view, giving rise to the distinctive oval or low-conical cross-section when viewed perpendicular to the equatorial plane. Some specimens show a small dimple in the cone as in the type illustrations.

Dimensions: Specimens range between 80 and 150 micrometer in diameter.

Remarks: This species also occurs stratigraphically in lower zones than the *F. bellii* zone. Its total stratigraphic range has not been determined, but it may range down from the *F. bellii* zone into the *Marginotruncana* zone. The last occurrence and last common occurrence are stratigraphically distinct and key indicators for the *F. bellii* zone, assigned to lower Campanian.

F.bellii should not be confused with a slightly larger, unequally convex and silicified pillbox diatom with a blunt periphery, that extends into younger Campanian strata. The latter has no dimple !. This morphotype has not been formally described; it is of limited regional utility for linking younger Campanian strata.