Seismic stratigraphy of the Lower Cretaceous Valhall Formation (Danish Graben, North Sea)

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Abstract
Detailed seismic stratigraphic analysis of a 3D seismic survey covering the southern part of the Danish Central Graben in the North Sea has revealed a complex stratigraphic basin infill pattern controlled by eustacy and local tectonics in the Lower Cretaceous Valhall Formation. The understanding of the stratigraphic architecture of this mudstone formation is critical for the development of the overlying chalk reservoirs of the Tuxen and Sola Formations.

The applied workflow included an application of flattening in order to approximate the Lower Cretaceous basin morphology, the attenuation of multiples generated by the overlying chalk deposits, a systematic use of both 2D transects and horizon slices in the analysis of the depositional geometries and the application of a Relative Geological Time (RGT) model interpretation technology. The results show an asymmetrical infill of the Lower Cretaceous consisting of westward prograding, mud-dominated clinoforms. The overall progradational pattern is clearly expressed in the most southern part of the basin by coast-parallel features interpreted as shelf margin breaks. The asymmetrical paleotopography, created by the muddy shelf of the Valhall Formation, formed subsequently the substratum for the deposition of the chalks of the Tuxen and Sola Formations, and controlled their facies distribution.

Introduction
The current petroleum-geological interest in the Lower Cretaceous Valhall Formation of the Danish Central Graben is twofold, firstly as an analogue for time-equivalent deposits in the UKCS (UK Continental Shelf), which contain sandstone reservoirs with a strong stratigraphic trap component (McGann et al., 1991), and secondly as the substratum for the oil-bearing Tuxen and Sola formations and its control on the distribution of these carbonate reservoirs (Ineson, 1993).

Until recently, the Valhall Formation has attracted relatively little attention due to the poor seismic expression, which was practically transparent on standard seismic sections, except for the presence of multiples of the overlying Chalk deposits. On a newly acquired and processed 3D seismic survey it has now become possible to recognize geologically interpretable internal structures in this unit. In addition, the utilization of a seismic interpretation application (Pauget et al., 2009; Schmidt et al., 2010; Lacaze et al., 2011) allowed a Relative Geological Time (RGT) model interpretation technology. The results show an asymmetrical infill of the Lower Cretaceous consisting of westward prograding, mud-dominated clinoforms. The overall progradational pattern is clearly expressed in the most southern part of the basin by coast-parallel features interpreted as shelf margin breaks. The asymmetrical paleotopography, created by the muddy shelf of the Valhall Formation, formed subsequently the substratum for the deposition of the chalks of the Tuxen and Sola Formations, and controlled their facies distribution.

Geological context
The Danish Central Graben is located in the westernmost part of the Danish offshore sector about 250 km from the mainland (Figure 1). It consists of a system of generally NNW-SSE trending half-grabens bounded by the Coffee Soil Fault to the east, and by the Mid North Sea High to the west (Figure 1). It is the southern extension of a complex system of grabens which together form the North Sea Central Graben (Japsen et al., 2003). The Danish Central Graben was initiated during the Late Jurassic extensional rifting phase, which started at the end of the Callovian and continued till the mid-Valanginian in the Early Cretaceous (Møller and Rasmussen, 2003). The inherited Late Jurassic basin morphology persisted during the Lower Cretaceous, and was inverted during the Late Cretaceous (Vejbæk and Andersen, 1987).

During the Late Jurassic–Early Cretaceous, the Danish Central Graben area was characterized by regional extension with sinistral transtensional strike-slip movements along NNW–SSE trending faults (Vejbæk and Andersen, 1987). Towards the end of the Early Cretaceous, the regional tectonic regime changed. Inversion from NE–SW oriented extension to NNE–SSW oriented compression started during the late Hauterivian resulting in several Late Cretaceous–Palaeogene inversion phases of increasing intensity (Vejbæk and Andersen, 2002). Lower Cretaceous sediments were widely deposited in an extensional tectonic regime apart from on a few minor structural highs (Vejbæk, 1986; Korstgård et al., 1993).

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Figure 1 A) Regional map showing the structural elements of the Danish Central Graben during the Lower Cretaceous and the study area. The well section is presented in Figure 10 (Modified from Vejbæk, 1986). B) Regional seismic cross-section (from N-Jens-1 to Deep-Adda-1).

Figure 2 A) Lower Cretaceous Lithostratigraphy column in the Danish North Sea (modified from Copestake, 2003); B) Gamma Ray, Acoustic Impedance and Synthetic logs for Adda-2 well with the Lower Cretaceous well tops.
The Lower Cretaceous succession of the Danish Central Graben consists, in stratigraphic order, of the Vyl, Valhall, Tuxen, Sola and Rødby Formations (Figure 2a). The Vyl Formation is a thin unit overlaying the ‘Base Cretaceous Unconformity’ (BCU), and consists of siltstones and fine-grained sandstones (Figure 2B). The Valhall Formation is composed of grey calcareous claystone with an upward-increasing content of marlstone, and is of Valanginian and Hauterivian age. The overlaying Tuxen Formation is mainly composed of clean chalks, with locally a more marly facies, and is of late Hauterivian to Barremian age. The Sola Formation, aged from latest Barremian to Early Aptian age, also contains chalk-rich intervals, but is generally speaking much more argillaceous, and includes the organic-matter-rich Fischschiefer Member. And finally, the Albian age Rødby Formation is predominantly argillaceous, but can locally be carbonate rich (Jakobsen et al., 2005; Ineson, 1993).

The paleogeographic evolution of the North Sea region during the Early Cretaceous reflects an overall rise in relative sea-level. The Central Graben during most of the Lower Cretaceous was closed towards the south, and only opened towards the ocean in the north (Figure 3). The first establishment of a direct connection towards the south, with the chalk basins in Northern France and Southern England, occurred during the Early Aptian transgression (Copestake et al., 2003).

Material and workflow
This study was performed using a regional 3D seismic survey acquired in 2005 with a 6-km streamer length in order to properly image structures below chalk. The seismic processing was aimed towards the best possible resolution and imaging. The processing applied to the seismic dataset used in this study thus included Pre-Stack Time Migration with modern multiple removal. The bin size of the processed dataset was 25 x 25 m.

The following workflow was applied in this study:

(a) Flattening on a geological meaningful datum
The main purpose of the flattening was to reconstruct the Lower Cretaceous basin morphology. This was achieved by choosing the base Chalk seismic marker as a flattening horizon, since it represents a reasonable approximation of a flat surface at its time of deposition, and it permits the elimination of the effects of compressional inversion tectonics that occurred during Chalk deposition causing the uplift of the former depocenters (Vejbæk 1986; Vejbæk and Andersen, 2002).

(b) Multiple attenuation from the overlaying Chalk deposits
The seismic velocity of the Lower Cretaceous mudstones and chalks is lower than that in the overlying interval (Upper Cretaceous Chalks). This velocity reversal causes severe chalk-generated multiple contamination in the lower Cretaceous layers despite the multiple removal methods applied in the seismic processing. Therefore, further post-stack multiple removal was needed in order to be able to reliably interpret the Lower Cretaceous basin morphology. Post-stack multiple removal tests applying several potential multiple generators have been performed, and is further described below.

(c) Seismic interpretation software
In order to efficiently map in 3D the stratigraphic architecture of the Valhall Formation, a geo-model interpretation technology was used, based on an optimization technique that was applied to this seismic volume (Pauget et al., 2009).
A Relative Geological Time (RGT) model was computed directly from the seismic volume. A regular grid is computed where each node of the model is an elementary horizon patch with a limited size (Lacaze et al., 2011; Schmidt et al., 2013). The patch size and the polarity parameters defined the spatial and vertical resolution of the model grid. The nodes are automatically linked by propagation of the horizon patches. This propagation process is constrained by using a ‘cost function minimization’ algorithm that establishes a relationship between every seismic sample according to their distances and similarity (Schmidt et al., 2010; Lacaze et al., 2011).

A relative geological time is then computed for every node of the grid and, by interpolation, populated continuously over the entire seismic volume. The seismic interpreter can refine the model by verifying and modifying relationships between the nodes until an optimum solution is obtained.

This technique is particularly powerful in illustrating the basin architecture. The RGT model that is generated is constrained by a relatively limited number of handpicked surfaces, and is thus significantly more time-efficient than a traditional interpretation approach.

**Seismic stratigraphy**

**Basin morphology**

The base Chalk flattening allowed the evaluation of the Lower Cretaceous basin morphology: time slices of the flattened seismic data (also referred to as horizon slices) highlighted geological patterns. In an approximately W-E transect (Figure 4), the Lower Cretaceous is delineated by the strong reflector of the BCU at the base, and the base Chalk at the top. It is apparent, from the underlying Jurassic strata, that the Lower Cretaceous fills a basin topography that was inherited from the Upper Jurassic, but which was contracted due to uplift of the margins during the formation of the BCU. This phenomenon was also observed in the UK sector (McGann et al., 1991). A horizon slice through the flattened cube clearly delineates the contours of the Lower Cretaceous basin, which was closed towards the south and open towards the north (Figure 4).

The presence of an inherited, Late Jurassic, underfilled rift-basin morphology at the beginning of the Valhall Formation deposition is proven by the presence of a number of basinward-dipping surfaces, which are interpreted as large-scale clinoforms, prograding towards the basin centre (Figure 4). The maximum depth at the time of deposition is estimated at approximately 400 m (360 ms TWT). In map view (horizon slice), the foresets of the prograding clinoforms are intersected, and these appear to form a remarkably continuous pattern of NW/SE-oriented ridges, representing the westward migrating sequences of the Valhall shelf. After deposition of the Valhall Formation, the western part of the basin remains underfilled.
Figure 5 Comparison before and after multiple attenuation. Base chalk was selected as multiple generator, and the multiple attenuation was only applied within the Valhall Formation. A) Inline before multiple removal; B) Inline after multiple removal; C) Multiple model: difference between A and B; D) Horizon slice before multiple removal; E) Horizon slice after multiple removal.

Figure 6 Horizon slice at -2184 ms: A and A'). Large scale: showing the lithostratigraphic units; B') Medium scale: sequences defined within the Valhall Formation; C and C') Small scale: parasequences observed within the medium scale sequences.
This basin topography, a relatively shallower shelf in the east and a basin depocentre in the west, subsequently controlled the facies distribution in the Tuxen, Sola and Rødby Formations.

**Basin infill pattern**

Figure 5a and 5d illustrate how the multiples remaining in the seismic data overprint the geological features in the layers. The demultiple technique employed here is a...
post-stack algorithm using pattern recognition that accounts for lateral amplitude variation and the structural context of the targeted multiple. A model of the multiples is built by using interpreted horizons of the primary events that generate the multiples. The events that match this model are then removed using a targeted spatial-temporal gate whose size is determined by structural complexity, signal-to-noise of the data, multiple period and number of bounces.

Several post-stack multiple removal tests were performed by using different multiple generators (Base Chalk or Top Valhall) and applied either below base Chalk or Top Valhall. The results, obtained from multiple attenuation, were evaluated based on the preservation of characteristic geological features. The preferred images (Figures 5b and 5e) were obtained by using the Base Chalk horizon as the multiple generator and thereafter applying the predicted multiple attenuation only below the Top Valhall surface. Figure 5c shows the multiples removed by the applied methodology. Traces of potential multiples parallel to the removed multiples can still be seen in Figure 5b. Figures 5b and 5e clearly illustrate how the continuity of the internal structures in the Valhall Formation have been enhanced by the selected multiple removal methodology. Figure 5b clearly shows a different dip angle of the primaries compared to the dip angle of the removed multiples shown in Figure 5c.

The Lower Cretaceous deposits are organised at three scales (Figure 6): at the large scale, the formations are distinguished, with the Valhall Formation characterised by relatively weak internal reflectors and best developed in the eastern part of the basin. The Tuxen, Sola and Rodby Formations are characterised by strong reflectors and fill in the western part of the basin (Figure 6a). At the medium scale, six depositional sequences have been defined within the Valhall Formation based on seismic geometries (Figure 6b). These can be further subdivided into smaller scale parasequences, notably by using horizon slices (Figure 6c).

Figure 7 shows the aggrading and prograding nature of the basin infill over a distance of approximately 10 km in a south-westerly direction, which can be traced by the offlap break points. The estimated dip of the clinoforms (without decompaction) is low (1-2 degrees). In the horizon slices taken from the flattened volume, a remarkable lateral continuity (approx 20 km) of these large-scale prograding sequences is observed in the southern part of the basin. In addition, two lowstand packages were mapped which occur at the base of the clinoforms and onlap against the toe and foresets (Figure 8). These lowstand systems tracts may potentially act as stratigraphic traps.

In the northern part of the study area the regular progradational pattern is interrupted, and an offset is observed towards the east in the horizon slices (Figure 7). A regional 2D line (northern inline in Figure 9) shows that there is evidence for syn-sedimentary tectonic subsidence, controlled by a half-graben along a W-E-oriented major normal fault system, which created more local accommodation space. The tectonic deformation may have been active slightly earlier, but clearly post-dates the formation of the BCU seismic marker. The vertical throw can reach a magnitude of about 120 m (northern inline in Figure 9).

The stratigraphic and structural architecture of the Lower Cretaceous is summarized in a 3D image using a combination of the seismic data and the geo-model constructed with interpretation technology (Figure 10).
Well ties
Wireline logs through the Valhall Formation show a consistent high gamma ray (GR) signature, attributable to the high clay content (confirmed by cuttings and core observations). The homogenous lithological composition explains the transparent nature of the seismic reflectivity. The detected, subtle reflectors are probably caused by a combination of thin hardgrounds and possible differential compaction within the claystone package. Strong reflectors observed in the overlying formations can be linked to lithological (and associated acoustic) contrasts between chalks, marls and claystones.

Biostratigraphic information available for several wells (Figure 11) shows that the seismically observed thickness variation occurs in the Valanginian, with the thick shelf wedge present in the eastern part of the basin, and the thin, time-equivalent basinal sediments in the western part.

Discussion
This study confirmed earlier work on the Valhall Formation (Ineson, 1993; Copestake et al., 2003), which suggested a progradational infill architecture based on wireline log picks. The seismic stratigraphic analysis of this study did, however, significantly refine the earlier work in a number of ways. After application of a carefully selected flattening horizon, the basin contours are visible, suggesting an embayment, closed towards the south. The embayment is surrounded by areas where no Lower Cretaceous (Valanginian – Albian) sediments have been recorded. Evidence for uplift and erosion has so far only been observed around the BCU, suggesting that the surrounding area may have been an area of either subaereal exposure and/or sediment bypass for most of the Lower Cretaceous. In addition, the identification of laterally continuous, large scale, westerly prograding clinoforms composed of smaller scale parasequences suggests a gradual basin infill during the Valanginian and Hauterivian during a period of general tectonic quiescence, with only a local tectonic overprint. Eustatic sea level fluctuations, in combination with variations in the sediment supply were thus the primary factors controlling sedimentation at this time. These detailed insights into the architecture and depositional history of the Valhall Formation are critical to an ongoing re-evaluation of the depositional models of the overlying and hydrocarbon-bearing Tuxen and Sola Formations (Ineson, 1993; Copestake et al., 2003).

The origin of the clays of the Valhall Formation is not clear. With the absence of evidence for channels in the prograding shelf, a sediment supply from the eastern Ringkøbing/Funen High seems unlikely. As an alternative hypothesis we favour longshore currents, which came in along the eastern margin and deposited their sediment, leaving the embayment along the western margin. This was an area where sedimentation was limited, and some erosion may have occurred, thus causing an asymmetrical infill of the basin. Similar patterns of prograding clay-rich depositional systems with a high coast-parallel lateral continuity have

Figure 9 Tectonic and eustatic control. The northern inline section from the RGT model (A-A’) reflects greater accommodation space caused by tectonic subsidence. The southern inline section from the RGT model (B-B’) displays an infill pattern dominated by eustacy.
been observed in other basins and stratigraphic intervals. A good analogue is the Late Aptian in the Bab Basin in Oman and the UAE, where similar clay-dominated prograding clinoforms have been observed (Droste, 2010; Pierson et al., 2010). With the absence of a siliciclastic source area in the hinterland, the origin of these clinoforms is attributed to longshore currents. A present-day analogue of a similar system occurs in the Adriatic Sea, where longshore currents transport sediment from the Po Delta southward along the eastern Italian coastline (Cattaneo et al., 2003; Cattaneo et al., 2004).

Conclusions
The present study, which is the first one with a detailed seismic stratigraphic analysis of the Valhall Formation, was made possible because of the recent reprocessing of the
regional 3D seismic dataset and the application of a systematic workflow, including a dedicated reprocessing effort, a targeted multiple attenuation, flattening on geologically-meaningful horizons, and the application of the RGT model interpretation technology. The following is concluded:

- A distinct asymmetrical, infill pattern of westward prograding and aggrading clinoforms is observed in 3D in the southern part of the Danish Central Graben. These geometries confirm the basin morphology, which is estimated to have had a maximum depth of approximately 400 m. In total, six well-expressed clinoform surfaces have been mapped, each one of which can be further subdivided into higher order cycles. In addition, two lowstand packages were observed. This sedimentation pattern is interpreted as an effect of dominantly eustatically driven variations in relative sea level.

- In the northern part of the study area, this systematic sedimentation pattern is interrupted and shows variations in both thickness and rate of progradation, locally causing a more irregular shelf break. This is interpreted as an effect of local tectonic subsidence in E-W-oriented half-graben structures.

- Based on the observed sediment infill pattern and absence of Lower Cretaceous rocks in the surrounding areas it is suggested that the Danish Central Graben was a land-surrounded embayment that opened up towards the North.

- The identification of an inherited Late-Jurassic basin morphology that guided the Lower Cretaceous sedimentation and the asymmetrical infill pattern of the Valhall Formation have significant implications for the interpretation of the paleogeography and lateral facies changes that can be expected in the overlying oil and gas-bearing Tuxen and Sola formations.

Acknowledgements
We would like to thank Maersk Oil and DUC partners Shell and Chevron for permission to publish this paper.

References


Received 13 December 2013, accepted 18 April 2014.
doi: 10.3997/1365-2397.2014008