Introduction

The reservoir potential within the Lower Cretaceous succession in the Danish North Sea has received relatively little attention due to its complex and heterogeneous geology. Yet, wells in the Valdemar Field (see Figure 1) have successfully been extracting hydrocarbons from reservoirs within the Lower Cretaceous during the last decade. The Valdemar field is characterized as a low-relief marly chalk structure, sealed by calcareous shales. However, its seismic response is recognized for being highly ambiguous and challenging to understand, and there are limited quantitative seismic interpretation (QSI) studies. We present an initial rock physics feasibility study based on well log data covering the Lower Cretaceous unit in the Valdemar Field. The objective is to investigate the possibilities for utilizing QSI methods for improved reservoir characterisation of the Lower Cretaceous when moving laterally away from well locations.

Figure 1 Left: Map showing the thickness of the Sola and Tuxen Formation in the Danish sector of the North Sea. The Valdemar Field is marked by the red rectangle. Right: Enhanced area of investigation showing the top Tuxen depth. Not all wells in the area are indicated on the map. From Jakobsen et. al. (2004).

This paper presents the following steps: 1. pore stiffness interpretation, 2. lithofacies classification and 3. rock physics modelling. Well log data from BO-2X are used for demonstration, focusing on a depth interval covering the oil saturated Tuxen reservoir formation.

1. Pore stiffness interpretation

The reservoir target in this study is the Tuxen Formation in the BO-2X well (depth interval: 2370-2430 m). To check whether the well log data yields geologically and physically consistent data, the elastic dry rock properties were investigated. Figure 2 shows a normalized bulk modulus ($K/K_0$) vs. porosity, computed for various normalized pore-space stiffness ($K_\phi/K_0$) plotted on top of data from the main Tuxen reservoir (Mavko et al., 2009). The dry (circles) and water (diamonds) properties are derived from a Gassmann fluid substitution. In this process, we can make interpretations of which fluid and solid constituent properties and mixing theories that yields reasonable elastic properties. We see that the data clusters approximately around similar pore-space stiffness curves for varying porosity, which indicate that the pore-stiffness is approximately the same for the formation and that no drill mud invasion issues are present. Furthermore, the high-porosity data (40%) are separated by around three contours between the dry and water saturated fluid states, whereas for porosities around 20%, we count around four contours. This implies that the pore-stiffness for the lower porosity data is larger, resulting in lower fluid sensitivities. As such, the pore-stiffness tends to somewhat vary internally within the Tuxen interval due to reservoir heterogeneity.
2. Lithofacies classification

Figure 3a-b shows the petrophysical logs in BO-2X in an interval covering the primary Tuxen reservoir Formation as well as the Sola and Valhall Formations. Figure 3c-d shows the corresponding acoustic impedance (AI) and P-to-S velocity ratio ($V_p/V_s$) logs, representing seismic parameters that can be inverted from seismic pre-stack data. To test if the lithofacies can be discriminated based on AI and $V_p/V_s$ data, a Bayesian classification approach was performed (Doyen 2007). First, we create a reference facies classification by a linear discriminant classifier using petrophysical logs as input (Figure 3e), where four lithofacies groups are classified as shown by the legend. The upper and middle part of the Tuxen Formation is dominated by high porosity, oil saturated chalks, whereas in the lower part, more interchanging lithofacies are revealed. The Sola and Valhall Formations consist more of low-porous, water saturated chalks, marly chalks and shales. Then, a Bayesian classification model is conditioned by the AI and $V_p/V_s$ training data to estimate multivariate PDFs (i.e. the model likelihoods, see Figure 3g), with prior probabilities set by the volume fractions of each lithofacies within the depth interval in Figure 3.

Figure 3f shows the resulting Bayesian classified (or predicted) lithofacies profile, with a good match to the reference lithofacies profile. This implies that the AI and $V_p/V_s$ properties are sensitive to the specific lithofacies variations in BO-2X, and seismically inverted AI and $V_p/V_s$ data can in principle be used for lithofacies discrimination, given sufficient seismic data quality and resolution. However, also note that several lithofacies exhibit overlapping AI and $V_p/V_s$ properties, which highlight the non-uniqueness of the problem. For instance, there is a certain chance that some of the marly chalk and shales have similar seismic properties as high porosity, oil saturated chalks. The PDFs are however only based on the BO-2X data, but a rock physics model could be used to predict other possible reservoir scenarios as well.
3. Rock physics modelling

Changes in the seismic response of the Tuxen Formation as function of varying reservoir properties have been investigated based on rock physics modelling. From previous studies, Fabricius (2005, 2007) tested a so-called iso-frame (IF) model based on well data covering the Lower Cretaceous unit in the Valdemar field as well as other areas in the Danish sector of the North Sea. The model was implemented using calcite, quartz and clay as the solid components for the frame and suspended pore material. The volume fractions of the various solid constituents were guided by log data and X-ray diffraction analysis of core plugs.

Figure 4a and Figure 4b shows respectively cross-plots of porosity vs. the bulk and shear moduli with model trends of various IF values plotted on top of the well log data. The data is fluid substituted to 100% brine to eliminate hydrocarbon effects. The data is colorized according to the reservoir zones as illustrated in Figure 3. Most of the Tuxen data plots in between IF values between 0.4-0.6, which specifies the volume fraction of the calcite in the pore space that contributes to effective stiffening of the framework. The varying IF values reflects the lithological heterogeneity within the Tuxen Formation. Furthermore, Figure 4c shows rock physics templates (RPT) (Ødegaard and Aavseth, 2004) based on the same rock physics model where we assume a 100% calcite lithology and an IF-value of 0.4, and we let the porosity and water saturation vary. We observe a reasonably good agreement between the model trends and the porosity and water saturation observations from BO-2X. These RPTs can further be used to make interpretations of porosity, lithology and pore fluid saturation from seismic inversion data away from well locations.
Figure 4 Porosity vs. (a) bulk modulus and (b) shear modulus cross-plots with the IF model for different IF values plotted on top of Tuxen data, which is subdivided into various reservoir zones. (c) Rock physics templates plotted on top of data as function of porosity $\phi$ and water saturation $S_w$.

Conclusions

We have performed a rock physics feasibility study of the Lower Cretaceous unit in the Valdemar field, in the Danish North Sea, based on well log data covering the Tuxen Formation. The analysis shows that there is a promising potential for subsequent QSI when seismic attributes are available, such as inversion results and AVO data. The results demonstrate that the Tuxen Formation segregates into various zones with different elastic behaviour, and that the reservoir can be distinguished from the Sola and Valhall Formations based on elastic properties. Furthermore, a rock physics model was calibrated to the Tuxen Formation as a tool for interpreting the elastic and seismic response of various reservoir scenarios.

References


