Chalk lithology-fluid characterization using regional broadband elastic attributes: an integrated study from the North Sea Central Graben

Noémie Pernin[1*], Cyrille Reiser[1], Tim Bird[1] and Lucile Goswami[1] demonstrate how reliable regional broadband pre-stack elastic attributes integrated with depth dependent rock physics analysis enable porosity and fluid characterization of challenging chalk reservoirs.

Introduction

The chalk play of the North Sea Central Graben spans the Norwegian, Danish and UK sectors and its reserves approach 10 billion barrels of liquids and almost 5 billion boe of gas.

As opposed to clastic reservoirs, the quantitative interpretation of carbonates and chalk reservoirs requires careful rock physics analysis integrated with reliable pre-stack elastic attributes. Such attributes need to be correctly calibrated with well log information to understand the variability of the chalk reservoir facies.

The acoustic impedance attribute correlates well with porosity in carbonates, low acoustic impedance equating to high porosity (Landrø et al., 1995; Santoso et al., 1995; D'Angelo et al., 1997; Li and Downtown, 2000; Abramovitz et al., 2011). However, a number of recent wells drilled in Norwegian waters have encountered high porosity in dry, non-hydrocarbon-bearing chalk reservoirs (Gennaro and Wonham, 2014) which contradicts the well-established mechanism of porosity preservation through the presence of hydrocarbons. This has triggered the development of new theories (Oxnevad and Taylor, 1999; Mork et al., 2018) and highlights the importance of having additional independent attributes such as Vp/Vs to improve the detection of hydrocarbons and to optimize well placement and derisking in near-field exploration.

A large regional GeoStreamer multi-sensor dataset covering 18.000 km² in the central North Sea Central Graben has recently

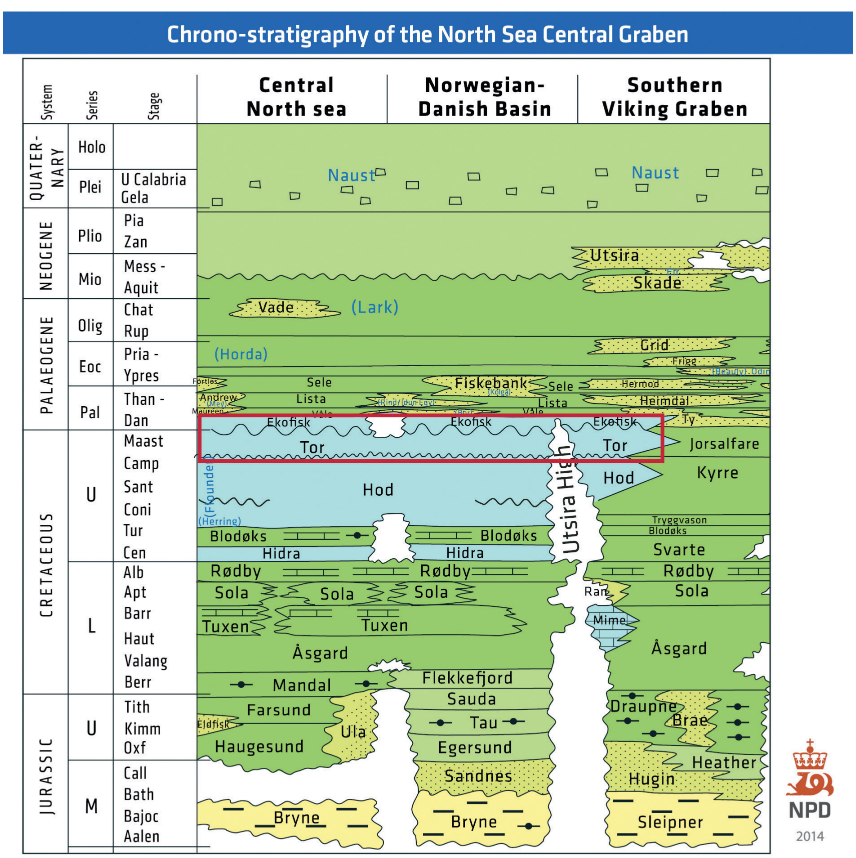

Figure 1 Chrono-stratigraphy of the North Sea Central Graben, showing the formations of interest from the Chalk Group (Ekofisk and Tor highlighted in the red box), adapted from the Norwegian Petroleum Directorate (NPD) chart.

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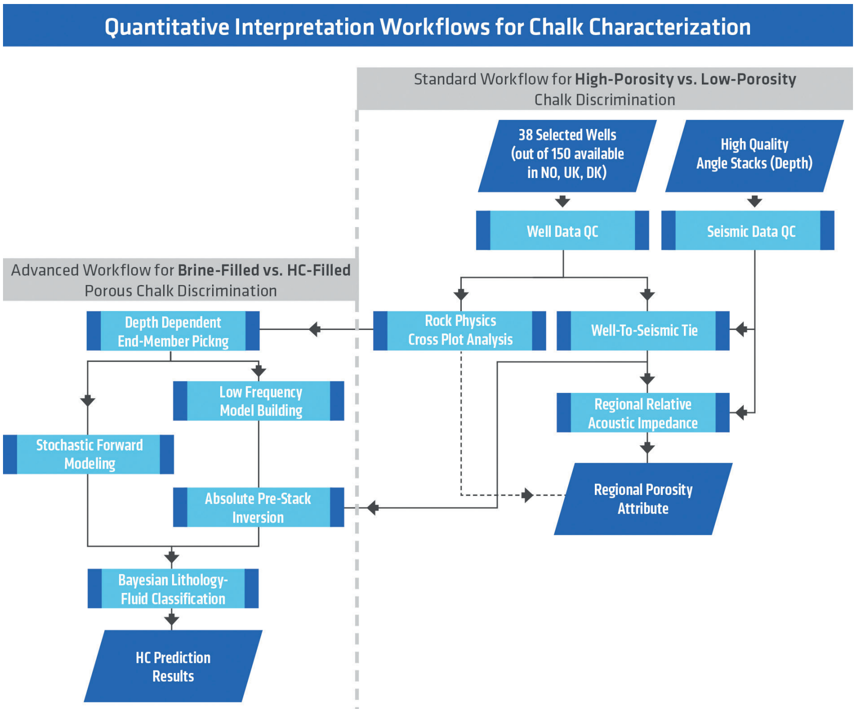

Figure 2 Standard and advanced quantitative interpretation workflows for chalk characterization.

been depth processed as a contiguous dataset (GeoStreamer PURE). One of the main objectives of the reprocessing was to better image the main producing chalk fields in the Upper Maastrichtian and Danian layers (Ekofisk and Tor Formations) such as Ekofisk, Eldfisk, Valhall, Dan-HalfDan, Tyra and Gorm, using advanced depth imaging techniques.

A bespoke Quantitative Interpretation (QI) workflow for chalk characterization has been developed and implemented, demonstrating the value of high-quality pre-stack broadband seismic data integrated with extensive well data analysis for the mapping of porosity variations and for predicting hydrocarbon accumulations in these very challenging chalk reservoirs.

Summary of geological settings for chalk deposition and facies variability

The Chalk Group started to accumulate in the North Sea Basin during the Late Cretaceous and Early Tertiary (100 to 61 Ma) period after several rifting phases that occurred during the Triassic and the Jurassic period (Figure 1). The post-rift thermal relaxation created subsidence and a eustatic sea level rise that caused a transgression in Northwest Europe. The warm waters were suitable for coccolith development in large quantities and their skeletons are the main component of the chalk sediments. Their deposition ended with the continental collision that formed the Alps in the Danian (Early Tertiary) when the influx of erosional material into the oceans increased and siliciclastic sediments were accumulated (Ziegler, 1990).

The chalk facies are not only linked with the regional sedimentology and deposition but also with the deformation history and the possibility of re-working (though mass transport deposit for example). Structural deformation associated with inversions and salt diapirism and hydrocarbon entrapment has also modified the original rock properties. This variability within the chalk leads to a wide range of reservoir properties such as porosity ranging from 20% to over 50% and permeability (1 mD to 1000 mD) (Megson, 1992). These lateral facies changes and depth-related variations contribute to a broad range of elastic properties.

Advanced quantitative interpretation workflow for chalk characterization

Figure 2 shows an overview of the integrated workflow used in this study. The standard workflow (right) focuses on the prediction of porosity (mainly using relative acoustic impedance) whereas the more advanced workflow (left) focuses on hydrocarbon prediction (combining absolute acoustic impedance and absolute Vp/Vs).

The main processes of the advanced workflow included:

- advanced depth imaging processing sequence for broadband seismic data
- detailed end-member picking and depth dependent rock physics analysis
- Monte Carlo simulation and stochastic forward modeling based on the previous step
- pre-stack well-to-seismic tie
- absolute sparse spike inversion
- Bayesian lithology-fluid classification integrating the well expectations (depth dependent rock physics analysis) and seismic derived elastic attributes

Regional rock physics analysis and stochastic forward modeling: understanding the regional elastic response of the chalk with well data

The North Sea Central Graben chalk play lies around 3 km below mudline (bml) in Norwegian and UK waters in the north and becomes gradually shallower towards the south reaching an average of 2 km bml for the chalk fields in the Danish sector (Figure 3).

The aim of robust regional statistical rock physics analysis is to guide the seismic QI analysis by better understanding the population behaviour of key lithologies and fluid combinations as a function of rock type, fluid content, reservoir quality and depth.

The depth trend analysis of elastic rock properties is based on well information and is a standard part of the rock physics workflow. This analysis is achieved through a detailed interpretation of well log data where end-member intervals are picked, up-scaled and cross-plotted. End-members are defined as the cleanest examples of the lithologies present in the wells, based on an interpretation of all relevant well logs. Thirty eight wells out of around 150 were selected for this analysis based on the quality and coverage of the available log suites (mainly Vp, Vs and density). Five lithology-fluid classes were discriminated from in-situ data only: Tertiary shales (above the chalk interval), brine-filled high-porosity chalk, hydrocarbon-saturated high-porosity chalk, and low-porosity Ekofisk and Tor chalks. A 20% porosity cut-off was used to discriminate high porosity from low-porosity chalk. If no petrophysical information was available the neutron porosity log was used as a proxy for porosity estimation in the chalk interval.

Depth dependent end-member trends capturing the mean and inherent scatter (probability distribution) of the elastic properties of each of the five classes were based directly from the different cross-plots (Figure 4). These trends were then used for stochastic forward modelling of different lithology and fluid combinations through a Monte-Carlo simulation scheme, testing the sensitivity of important variables and assessing discrimination (unique separation) in both the rock properties and elastic attributes. The use of end-members and a depth-dependent model from the wells is essential to understand the range of seismic responses and elastic properties that may be observed in the inversion results. Depth dependent changes are also important when dealing with such large regional seismic coverage, as the interpretation of high-porosity vs. low-porosity and brine-filled vs. HC-bearing porous chalk is expected to be different in the Danish and the Norwegian sectors.

The acoustic impedance attribute shows a clear decrease as the porosity increases and corroborates previous published studies that it can be used as a proxy for porosity estimation in the chalk layers (Figure 4). However, any hydrocarbon presence seems to decrease the acoustic impedance values even further and in addition also decreases the value of Vp/Vs. Including Vp/Vs in the analysis offers the potential to discriminate between high-porosity brine-filled chalk reservoirs and high-porosity hydrocarbon-bearing chalk reservoirs.

Note that the discrimination between the five classes appears clearer at greater depth rather than in the shallow area where less separation between the elastic properties (acoustic impedance and Vp/Vs) can be observed. This might be in part driven by the fact that there are fewer wells to constrain the rock physics analysis for shallower burial depth (mainly the Danish sector) which increases the uncertainties in the analysis here.

Regional pre-stack broadband relative seismic inversion results: mapping the vertical and lateral porosity changes in the chalk interval

Most of the 38 wells are located inside the seismic survey outline and were tied to the angle stacks. The regional depth dependent rock physics analysis was therefore used in conjunction with the

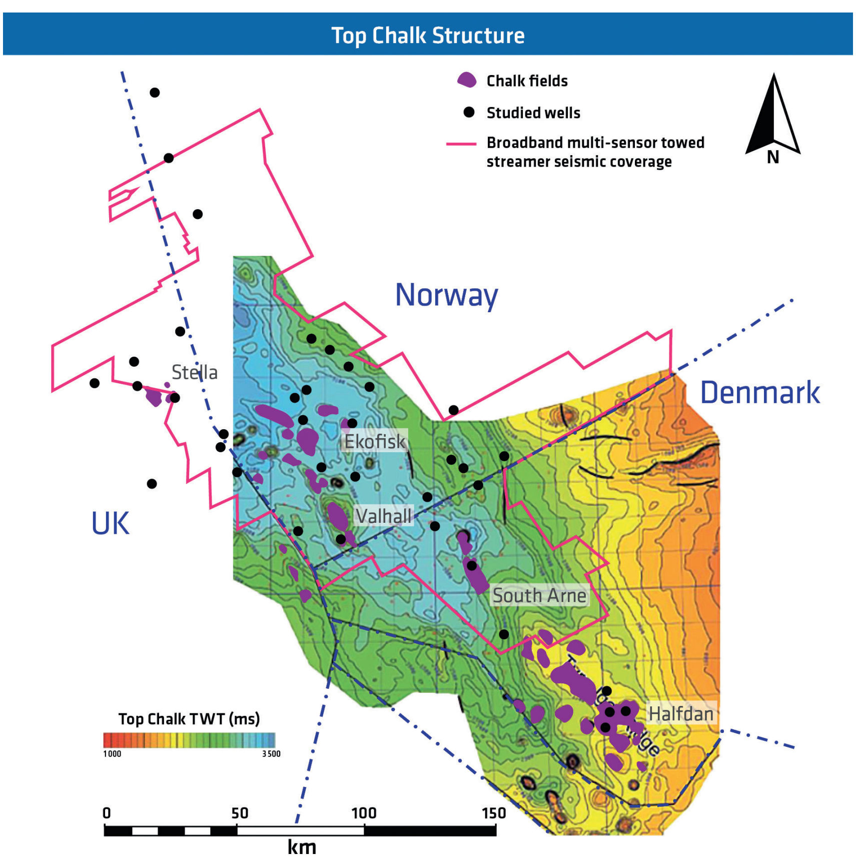

Figure 3 Base map of the studied area showing top chalk depth variation from north (deeper) to south (shallower). The seismic dataset is outlined in pink, the main chalk fields in purple. The well locations used in the rock physics analysis are shown as black dots (structure map adapted from Mork et al., 2018).

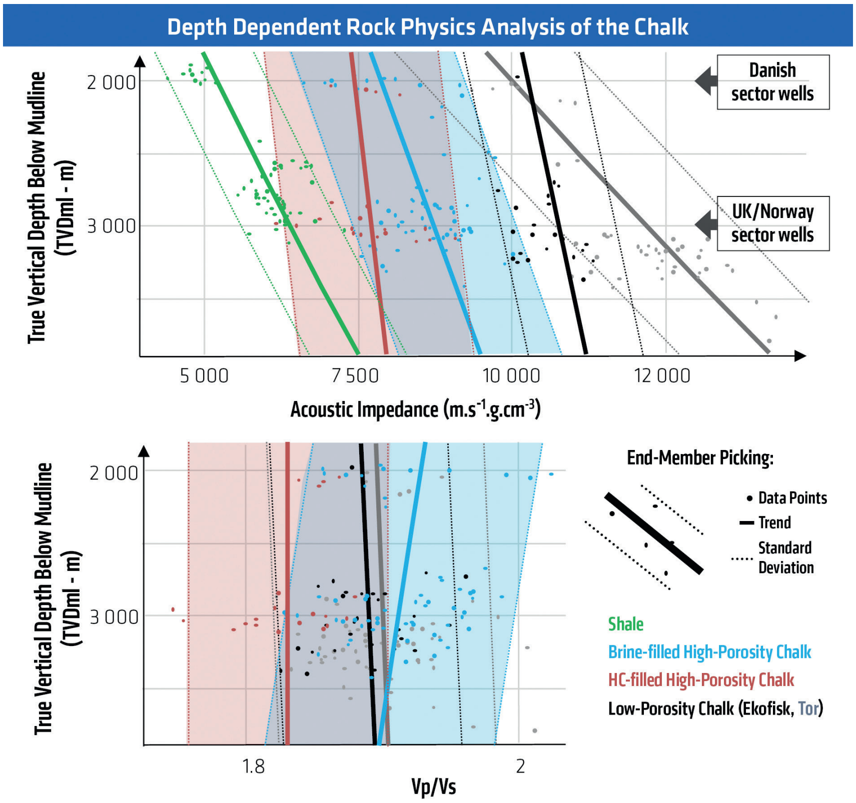

Figure 4 Rock physics depth dependent trends derived using end-member picking. Top: chalk is harder (or higher acoustic impedance) than shale above. High-porosity chalk is softer (or lower acoustic impedance) than low-porosity chalk. Based on this analysis, the acoustic impedance is a good attribute for porosity prediction. Bottom: chalk has much lower Vp/Vs than the shale above (not represented on the graph as the average value for the Vp/Vs is 2.3). Good discrimination seen between the high-porosity brine-filled with the HC-bearing high-porosity chalk showing the lowest Vp/Vs values. No discrimination is possible between brine-filled high-porosity chalk and low-porosity chalk in this domain.

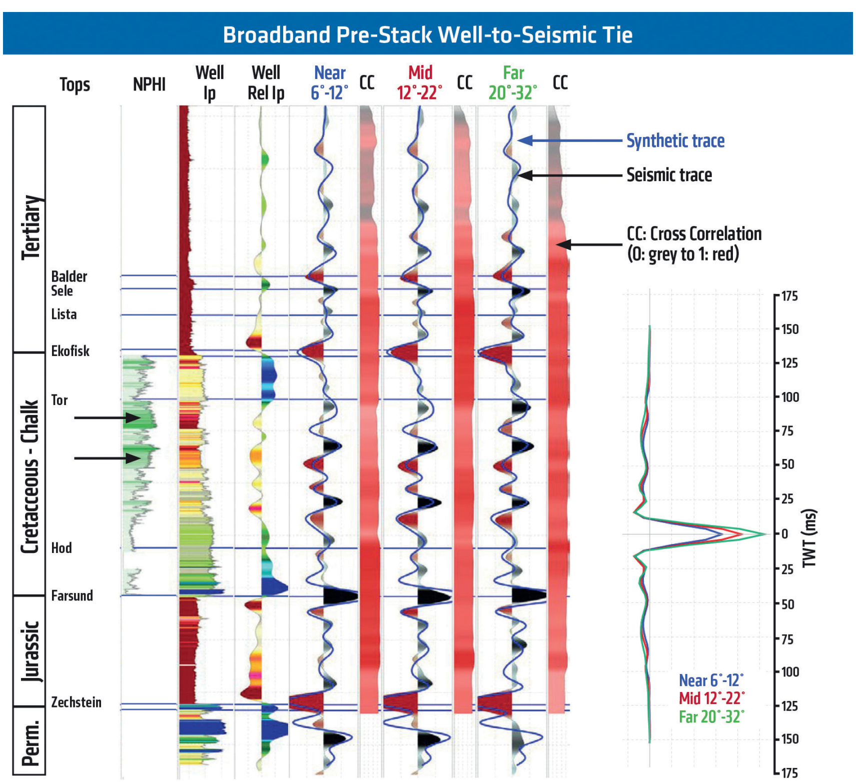

Figure 5 Example of a pre-stack well-to-seismic tie using broadband seismic data. The length of this well log is close to one second of continuous logged section, which is necessary for a wavelet extraction using broadband seismic data with a low frequency down to 3-4 Hz. The wavelets are relatively long (~300 ms) for capturing this low seismic frequency information. It can be noted that the well-to-seismic tie is of very good quality (high cross-correlation between the synthetic trace and the seismic trace represented by the red colour tracks). Two high-porosity intra-chalk layers are observed in the Tor Formation (position of the two arrows) and correspond to a low acoustic impedance response.

pre-stack seismic data. This unique 18,000 km^2 dataset has been built up over several years and consists of contiguous broadband GeoStreamer data. Recently, the data has been reprocessed using a modern Kirchhoff pre-stack depth migration workflow including dual-sensor wavefield separation and P-UP generation (upgoing wavefield), 3D surface-related multiple elimination, tomographic velocity model building (using the well information) and high-resolution Radon demultiple. This consistent processing allows for a unified interpretation approach throughout the entire regional volume.

Figure 5 displays an example of a pre-stack well-to-seismic tie focusing on the Upper Cretaceous chalk interval. The AVO compliance (amplitude and phase) of the pre-stack dual-sensor data provides reliable elastic attributes as demonstrated by the good quality of the well-to-seismic ties. A good correlation is observed between low acoustic impedance high-porosity intra-chalk layers (red) with the elastic logs computed from the wells and also with the neutron porosity log. The relative acoustic impedance estimated from this dataset has a vertical resolution at the target of 15-19 m (thanks to the high frequency present in the broadband data up to 45 Hz) allowing detection and characterization of the various intra-chalk units (Ekofisk and Tor chalk units).

A regional relative acoustic impedance volume of 18,000 km^2 was computed from this newly depth migrated regional broadband data. The rich low-frequency content allowed a confident and reliable pre-stack inversion from 5 Hz (Ozdemir, 2009; ten Kroode et al., 2012; Reiser et al., 2012; Whaley et al., 2013). A regional horizon of Top Chalk was used to extract the relative acoustic impedance over the shallowest Ekofisk intervals. Results are displayed in Figure 6. As predicted by the wells, high porosity zones correspond to low relative acoustic impedance (red). These anomalies match all the main

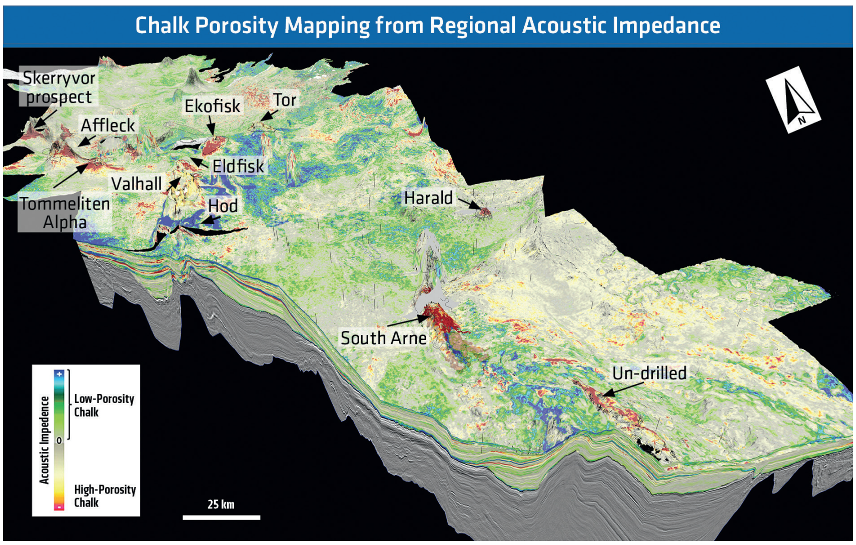

Figure 6 Regional acoustic impedance amplitude extraction below top chalk horizon from regional dataset (18.000 km^2). Low acoustic impedance (red) is expected to highlight high-porosity chalk intervals based on findings from the rock physics analysis. High-porosity anomalies correlate very well with chalk fields and highlight some undrilled prospects at this particular stratigraphic interval (e.g. in the south of the dataset).

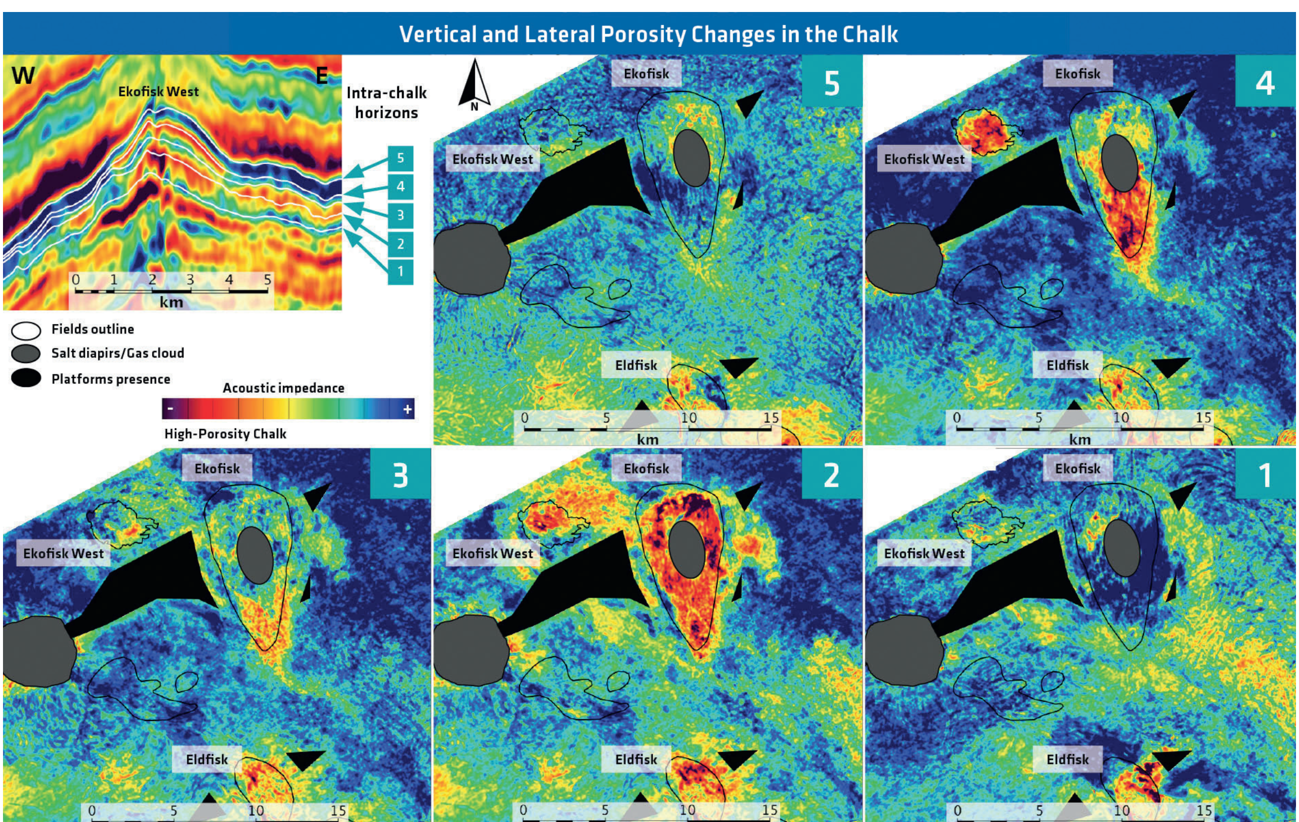

Figure 7 Amplitude extraction of relative acoustic impedance performed on five intra-Ekofisk horizons. Abrupt changes of chalk porosity, vertically and spatially, are well imaged by the broadband dual-sensor data. Observe the good match of low acoustic impedance (red)/high-porosity/chalk with field outlines.

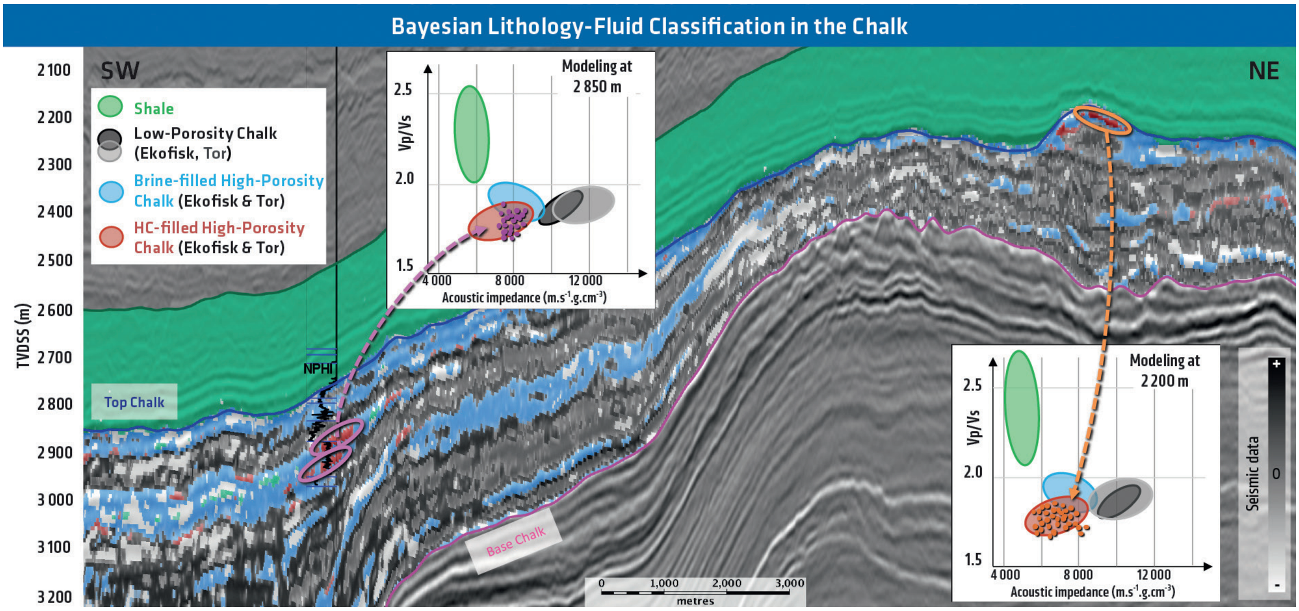

Figure 8 A promising first-pass porosity and hydrocarbon presence prediction through Bayesian lithology-fluid classification. The various colours correspond to the most likely class from the five lithology-fluid classes established during the depth-dependent rock physics analysis. As part of this Bayesian lithology-fluid classification it is possible to get access to the individual class probability, i.e. probability to be either brine, hydrocarbon-filled or shale or low-porosity chalk.

fields in the region and help to identify and derisk near-field exploration opportunities by demonstrating the lateral variations of the chalk properties.

This same attribute was also used to map the vertical variations of the chalk properties indicating the challenges but also the strength of stacked intra-chalk high-porosity layers for hydrocarbon production. An example of abrupt porosity changes in the Ekofisk Formation both spatially and vertically is illustrated in Figure 7 around the Norwegian Ekofisk field area.

Extracting more: Bayesian lithology-fluid prediction

To directly relate the seismic inversion results with the well measurements, the elastic attributes have to be absolute properties. This allows the statistical distribution of elastic properties derived from the well data to be used to understand and predict the likely lithology and fluid types from the seismic inversion attributes and the uncertainty in these predictions.

The quantitative interpretation workflow has been pushed towards a Bayesian lithology-fluid classification for a more detailed investigation of a focus area near the South Arne field. This requires the inversion to be in the absolute domain. Input into the absolute pre-stack seismic inversion were: the three angle stacks from 5 Hz to 45 Hz, their corresponding broadband wavelets, and a low-frequency model (to fill the gap between the 0 Hz and the lowest useable seismic frequency) built from the well data krigged in a layered geology-conformable model.

The depth dependent end-member picking described previously was used as the 'a-priori' model for the Bayesian lithology-fluid classification in the absolute acoustic impedance vs. absolute Vp/Vs domain. One of the outputs of the process is the 'most likely' lithology-fluid predicted out of the five classes and an example is displayed along a line in Figure 8.

The classification predicted high-porosity chalk (either blue or red) and low-porosity chalk (either grey or black) that matched closely with the neutron porosity log in the vicinity of the well.

Two hydrocarbon-filled features are predicted:

- In the pink ellipse areas around the well – although the well is reported as dry with no hydrocarbons. After back projection of the seismic elastic attributes on to the stochastic forward modelling of the cross-plot at the corresponding depth (2850 m bml), the pink points appear to plot near the overlap area between brine-filled and hydrocarbon-filled high-porosity chalk ellipses, but still slightly closer to the hydrocarbon distribution hence a higher probability of being hydrocarbon than brine. This observation shows the remaining uncertainties and challenges of the fluid prediction in the chalk reservoirs.
- In the orange ellipse area: after back projection of the seismic elastic attributes on to the stochastic forward modelling cross-plot at the corresponding depth (2250 m bml), the orange points appear to plot clearly on the hydrocarbon-filled high-porosity chalk ellipse with some values plotting on the bottom-left hand side of the ellipse, away from any overlap with other lithology-fluid classes. This observation shows much more confidence and encouraging results in terms of hydrocarbon prediction. The integrated seismic and well data Bayesian classification workflow predicts that at this particular location there is a higher probability and greater confidence of encountering hydrocarbon-charged high-porosity chalk.

The encouraging shallow anomaly predicted as HC-filled high-porosity chalk presented in Figure 8 has been further investigated in 3D to estimate the spatial extent and nature of the feature and its relation with nearby discoveries.

The outcomes of the prospectivity analysis are promising, demonstrating the value of quantitative interpretation studies with advanced workflows using reliable pre-stack broadband data to characterize challenging reservoirs such as the chalk and to identify remaining near-field opportunities.

Conclusions

The regional rock physics analysis with end-member picking and stochastic forward modelling has been fundamental for fully understanding the expected petro-elastic behaviour of the different intra-chalk layers (porosity and fluid effect) with depth. Understanding the depth component in the rock physics analysis allows for better definition of the expected reservoir properties and their probability distribution – which is essential for derisking challenging reservoirs such as the chalk.

The high-quality broadband seismic depth data used in the pre-stack inversion workflow has proved to be of high fidelity and enabled the differentiation of the intra-chalk layering highlighting both lateral and vertical changes away from the wells. The acoustic impedance has been demonstrated to be effective as an initial porosity estimator in the chalk – with low acoustic impedance correlating to the high-porosity chalk encountered in known hydrocarbon discoveries and fields and revealing untested anomalies.

Moreover, the rock physics results presented here demonstrate that a combination of robust elastic attributes (here acoustic impedance and Vp/Vs) from broadband multi-sensor seismic data have the potential to distinguish hydrocarbon-filled high-porosity chalk from water-wet anomalies. To enable such separation a tailored QI workflow was implemented to integrate the end-member picking with the seismic pre-stack absolute inversion results through a Bayesian lithology-fluid classification process.

This study has demonstrated clear improvements in the characterization of the chalk at a regional scale using a combination of a regional rock physics model and AVO-compliant broadband pre-stack seismic data. The QI workflows presented have improved the mapping of porosity changes both vertically and spatially and enabled better prediction of fluids in the chalk through the depth-dependent Bayesian lithology fluid classification. This approach can be effective for right-risking/right-sizing/derisking of remaining opportunities in the North Sea Central Graben chalk fairway.

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