Reservoir properties prediction using CSEM, pre-stack seismic and well log data: Case Study in the Hoop Area, Barents Sea, Norway

ABSTRACT

We present an example from the Hoop area of the Barents Sea showing a sequential quantitative integration approach to integrate seismic and CSEM attributes using a rock physics framework. The example illustrates a workflow to address the challenges of multi-physics and multi-scale data integration for reservoir characterization purposes.

A dataset consisting of 2D GeoStreamer® seismic and towed streamer electromagnetic data that were acquired concurrently in 2015 by PGS provide the surface geophysical measurements used in this study. Two wells in the area: Wisting Central (7324/8-1) and Wisting Alternative (7324/7-1S) provide calibration for the rock physics modeling and the quantitative integrated analysis.

In the first stage of the analysis, we invert pre-stack seismic and CSEM data separately for impedance and anisotropic resistivity respectively. We then apply the multi-attribute rotation scheme (MARS) to estimate rock properties from seismic data. This analysis verified that the seismic data alone cannot distinguish between commercial and non-commercial hydrocarbon saturation. Therefore in the final stage of the analysis we invert the seismic and CSEM-derived properties within a rock physics framework. The inclusion of the CSEM-derived resistivity information within the inversion approach allows for the separation of these two possible scenarios. Result show excellent correlation with known well outcomes. The integration of seismic, CSEM, and well data predicts very high hydrocarbon saturations at Wisting Central, and no significant saturation at Wisting Alternative, consistent with the findings of each well. Two further wells were drilled in the area and used as blind tests in this case: The slightly lower saturation predicted at Hanssen (7324/7-2) is related to 3D effects in the CSEM data, but the positive outcome of the well is correctly predicted. At Bjaaland (7324/8-2), although the seismic indications are good, the integrated interpretation result predicts correctly that this well was unsuccessful.
**INTRODUCTION**

Rock-property estimation (fluid saturation, porosity, and lithology) is the ultimate goal for geologists, geophysicists, and reservoir engineers. All seek to combine well and surface measurements to generate a model of rock properties that can be used to generate an exploration, appraisal, or exploitation plan and quantify the hydrocarbon resources available. Since hydrocarbon exploration began in the 19th century, technology and innovation have driven the process of subsurface rock-property prediction from exploration, solely based on surface geology, to the progressive inclusion of 2D seismic (early 1920s), gravity, magnetic, 3D seismic (late 1960s), AVO analysis (Ostrander, 1984) and, most recently, controlled source electromagnetic (CSEM) data (Ellingsrud et al., 2002).

Nowadays the integration of pre-stack seismic inversion attributes with CSEM attributes using a rock physics framework constitutes one of the most modern and robust methodologies to carry out geophysical reservoir characterization (see for example Harris et al., 2009; MacGregor, 2012; Gao et al., 2012). Each method provides independent physical measurements of the subsurface that complement each other and can be validated by well log measurements and forward modeled at different reservoir conditions through the application of rock physics principles. Seismic provides the structural framework and, from AVO information, the possibility to derive P- and S-wave impedance volumes. These two valuable, independent measurements can be linked to porosity, lithology, geomechanical properties, and, under certain conditions and limitations, to fluid saturation prediction. On the other hand, CSEM data provide a lower resolution measure of resistivity, which, when constrained with the structural framework and seismically-derived volumes of porosity and lithology, can be linked to fluid saturation, overcoming seismic ambiguity related to similar AVO responses in both low- and high-saturated hydrocarbon reservoirs.

However, there are a number of challenges to be overcome when putting seismic and CSEM data together. Electric and elastic properties must be coupled through a single earth model that accurately and consistently describes each. There must be overlap in sensitivity of the methods applied to the properties within the intervals of interest. Finally, seismic, CSEM and well log data sample the earth at very different scales, which must be reconciled in an integrated interpretation.

The integration process itself can take many forms (Figure 1). The simplest qualitative techniques, such as co-rendering, are applicable everywhere and provide a first-look approach to data combination. However, they can be misleading since they fail to address the underlying cause of variations observed. Full quantitative joint inversion of seismic and CSEM data is in principle possible (for example Chen & Hoverston, 2012; Du & MacGregor, 2010), but is complex and applicable in a far narrower range of circumstances. An intermediate approach, based on a sequential quantitative integrated interpretation workflow, which seeks to integrate elastic and electric attributes-derived from inversion of seismic and CSEM data respectively, provides in many circumstances an effective way of addressing the challenges of data integration.

This paper presents a case study in which the latter integration approach has been applied to overcome the challenges of the integration of seismic and CSEM data and successfully predicts a seismic-resolution fluid saturation volume that helps characterize the reservoir and diminish the risk related to the exploration and appraisal of the prospects in the study area. The area in question covers a significant oil discovery in the Hoop Fault Complex on the Bjarmeland Platform in the Barents Sea, Norway (Figure 2a).
Figure 1. Approaches for multi-physics integration. Simple qualitative approaches are applicable in almost every circumstance. The requirements for applicability become more stringent as approaches become more quantitative.

Figure 2. a) Structural elements of the Barents Sea showing with a red box the location of the studied area (modified from Halland et al. 2013). b) Detailed view of the studied area showing the location of the 2D GeoStreamer® seismic and towed streamer CSEM data (blue lines), as well as the calibration wells (Central and Alternative) and the validation wells (Hanssen and Bjaaland). The green outlines show the location of the proven reservoirs in the area (data courtesy NPD), which were discovered by the Central and Hanssen wells.
**Seismic, CSEM and well log data sets**

A densely sampled dataset consisting of six lines of 2D seismic and towed streamer CSEM data were acquired concurrently in 2015 by PGS using the system depicted in Figure 3 (Englemark et al., 2014). The survey area lies in water depths of approximately 400m. Two public domain wells in the area provide calibration for the integrated analysis. Oil bearing sands were encountered in the Realgrunnen interval at well 7324/8-1 (Wisting Central), whereas the same interval was dry in nearby well 7324/7-1S (Wisting Alternative). Two additional wells have been drilled in the immediate vicinity: 7324/7-2 (Hanssen) yielded a small oil discovery, and 7324/8-2 (Bjaaland) was dry. The results from these wells were used to validate and corroborate the accuracy of the reservoir property predictions (Figure 2b).

![Diagram of seismic and CSEM acquisition](image)

**Figure 3.** CSEM and 2D seismic data used in this project were acquired simultaneously using a towed source and receiver system. Further details of this acquisition approach can be found in Englemark et al, 2014.

In general, the 2D seismic data quality is good but varies significantly in different parts of the survey. The velocity fields obtained from the fast track migration of the data available at the time of this study were not sufficiently accurate to completely flatten and position events properly. The data were therefore conditioned before use in the workflow described here following the approach described by Singleton, 2009.

For the CSEM data acquisition, a towed streamer consisting of 72 receivers collected data at source-receiver offsets ranging from 31 to 7755m. Overall, quality of the data used in the study was excellent, with good signal to noise ratios over a wide range of frequencies between 0.2Hz to over 3Hz.
The remainder of this case study will address the analysis of the data from line 5001P1009, which provides the best calibration with the well information available in the area (Figure 2b).

**METHODODOLOGY**

The workflow used to carry out the quantitative interpretation of well log, seismic and CSEM data is illustrated in Figure 4. The methodology involves as a first stage the inversion of pre-stack seismic data and then the quantitative estimation of rock property and facies volumes by combining well log data and seismic inversion attributes. Resistivity volumes are then estimated from the seismically-derived properties at different fluid saturations by applying rock physics relationships calibrated at the wells. In the next step, the CSEM data are inverted and the transverse resistance calculated from the resulting resistivity by vertically integrating the resulting resistivity volumes across the interval of interest. The seismically and CSEM-derived electrical properties can then be compared to infer areas that may be hydrocarbon charged. Finally, a global search inversion algorithm is applied to estimate a hydrocarbon saturation volume that honors all the geophysical measurements. These steps will be described in more detail below.

![Figure 4. Methodology used to carry out the quantitative interpretation of well log, seismic and CSEM. So is the oil saturation and is 1-Sw (the water saturation) in this case.](image)
**GEOLOGICAL SETTING**

Several sedimentary basins and platform areas make up the Norwegian sector of the Barents Sea. The general structural configuration in the area of interest is to a large extent dominated by the Hoop Fault Complex on the Bjarmeland Platform (see Figure 2a). The area of interest is positioned on the hanging wall of the Hoop Fault Complex to the east and on the footwall of the Maud Basin. Figure 5 shows a seismic cross-section illustrating the general nature and structure of the area. The Realgrunnen Subgroup of the Kapp Toscana Group provides some of the best reservoirs in the Barents Sea. It is subdivided into four formations: Fruholmen, Tubåen, Nordmela and Stø. The Nordmela Formation (Sinemurian-Late Pliensbachian) consists of interbedded siltstones, sandstones, shale and mudstones with minor coals. Sandstones become more common towards the top. The formation represents deposits in a tidal flat to flood-plain environment. Individual sandstones represent estuarine and tidal channels. The Stø Formation (Late Pliensbachian to Bajocian) is defined with the appearance of sandy sequences above the shale-dominated sediments of the Nordmela Formation. The dominant lithology of the Stø Formation is mineralogically mature and well sorted sandstone. The sands in the Stø Formation were deposited in prograding coastal regimes, and a variety of linear clastic coast lithofacies are represented. Marked shale and siltstone intervals represent regional transgressive pulses in the late Toarcian and late Aalenian. Overlying the Stø Formation is the Fuglen Formation, which belongs to the Adventdalen Group. The group is dominated by dark marine mudstones, locally including deltaic and shelf sandstones as well as carbonate. The Fuglen Formation constitutes the cap rocks of the reservoir facies. (Halland et al. 2013)

The study area is significantly uplifted, and characterized by high background resistivity and high electrical anisotropies. Target intervals exist in a wide range of depths, ranging from about 250m below mudline to nearly 2000m below mudline. The reservoir encountered in well 7324/8-1(Wisting Central) consists of the Stø and Nordmela Formations, overlying the Snadd Fm. of upper Triassic age. The Stø Fm. is marked by a sharp contact with the overlying Fuglen Fm., seen both on logs and on drilling parameters. The Stø Fm. consists of 20m clean and homogenous sand, with very good reservoir properties. This is confirmed both by wireline log data and core measurements.
Integration of well-logs, seismic and CSEM

Case Study in the Hoop Area

Figure 5. Seismic cross-section through the wells Alternative and Central. The top Stø horizon marks the top of the reservoir interval encountered in the Wisting Central well (7324/8-1).

ELASTIC AND ELECTRIC ROCK PHYSICS AND PETROPHYSICAL OBSERVATIONS

Detailed petrophysical evaluation and rock physics analysis was carried out for the Wisting Central and Wisting Alternative wells. Lithology and fluid sensitivity of the elastic attributes were addressed in the rock physics analysis and the main results obtained are illustrated in Figure 6. This figure shows a cross-plot of the elastic attributes Poisson’s ratio versus acoustic impedance, color coded by four different fluid substituted saturations: 100% water, 80% oil, 80% gas, 20% gas (fizz saturation). Also shown is the in-situ saturation for the Stø Fm., which is a clean, blocky shallow-marine shoreface sandstone, as well as for the underlying Nordmela Fm, which is a coarsening upwards shaly sand.

Two important observations can be extracted from these plots. The first is the well-known inability of the seismic data alone to discriminate between commercial and non-commercial gas saturation: The 20% and 80% gas cases plot on top of each other, which is not the case for the combination of elastic and electric attributes (see Figure 7). The second observation is the unexpected high Poisson’s ratio (or higher Vp/Vs) in the Stø Fm. compared to that observed in Nordmela Fm. for the same fluid saturation. It is worthwhile mentioning that the same observation was found in both the Wisting Central and Wisting Alternative wells, which suggests this unusual response is not a measurement problem. Moreover, the fact that the AVO inversion produced a Poisson’s ratio solution that also honors these slightly unusual well log observations of Poisson’s ratio for the Stø and Nordmela Fms. (Figure 9) validates these measurements.
There is significant variation between the resistivity measurements made with different tools in the well. In order to calibrate the saturation model we have chosen to use the LWD P40H curve. This is from a phase shift induction tool, logged while drilling (which has the added benefit of reducing the impact of mud invasion). This tool has returned results that are closer in amplitude to the CSEM-derived resistivity values, when compared to the wireline HRLT laterolog results (with resistivities in the tens of thousands Ωm). With the chosen induction curve resistivity values in the Stø Fm. at Wisting Central are in the 700-900 Ωm range. The water saturation was calculated from this using the rock physics model represented by the Simandoux equation (Simandoux, 1963), (equations 1), due to the overall simplicity of the model and increased accuracy over Archie in shaly-sand systems. This gives predicted hydrocarbon saturations in excess of 90%.

\[
\frac{1}{R_t} = \frac{\phi_e^m \times S_w^n}{a \times R_w} + \frac{V_{sh} \times S_w}{R_{sh}}
\]  

(1)

where \(R_t\) is the horizontal resistivity, \(S_w\) is the water saturation, \(m\) is the cementation exponent, \(n\) is the saturation exponent, \(a\) is the tortuosity exponent, \(R_w\) is the water resistivity at formation temperature, \(V_{sh}\) is the shale content, \(R_{sh}\) is the resistivity of the shale, and \(\phi_e\) is the effective porosity defined as

\[
\phi_e = \phi_T \times (1 - V_{sh})
\]

(2)

where \(\phi_T\) is the total porosity. The parameters used in the Simandoux equation were calibrated to the measured data and are summarized in Table 1.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<tr>
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<td>1.7</td>
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<tr>
<td>$R_{sh}$</td>
<td>6 Ωm</td>
</tr>
<tr>
<td>$R_w$</td>
<td>0.18 Ωm</td>
</tr>
</tbody>
</table>

**Table 1.** Parameters used in the Simandoux equation

![Figure 7](image)

**Figure 7:** a) For the Sto Fm., multi-well cross-plot of acoustic impedance versus resistivity color coded by fluid saturation with background colored by volume of clay for the full well. b) For the Nordmela Fm., multi-well cross-plot of acoustic impedance versus resistivity color coded by fluid saturation with background colored by volume of clay for the full well. The induction *in situ* resistivity in Central is clipped at 1,000 Ωm in the Sto sands, for reference the laterolog shows a similar shape in this zone, but is clipped at 100,000 Ωm.

In the context of a CSEM analysis, the background resistivity and the contrast between background and reservoir is also important to understand. Figures 8a and 8b show the resistivity variation with saturation calculated at the Wisting Central and Alternative wells using the Simandoux parameters from Table 1. For each case, the calibrated Simandoux equation is used to calculate the resistivity at log scale for a range of values of $S_w$ (Figure 8c). The log scale values are then up-scaled using an arithmetic average to give the bulk vertical resistivity (as would be measured by a CSEM survey) across the reservoir interval. The shaded area corresponds to the region of the curve where the resistivity is equal to or lower than the observed background vertical resistivity in the area (around 20-30 Ωm). Only when the reservoir resistivity lies outside the shaded region is there a contrast between it and the background, allowing it to be detected by a CSEM survey. Figure 8c shows that this condition is met for values of $S_w$ less than 30%. This provides a practical limit on the sensitivity to $S_w$, i.e. values greater than this will not be resolved.
Figure 8: a) Well log suite from the Wisting Alternative well, showing porosity, lithology, Sw and resistivity. b) Well log suite from the Wisting Central well, showing porosity, lithology, Sw and resistivity. c) The variation of resistivity with water saturation calculated from the Wisting Central and Alternative wells using the Simandoux equation. The shaded region shows the area in which the resistivity of the reservoir is less than the resistivity of the background structure, and will not be detected by a CSEM survey. Water saturations less than about 30% are required for the reservoir to be detected.

PRE-STACK SIMULTANEOUS SEISMIC INVERSION

The ultimate quality of any inversion depends on the quality of the input data, and to ensure a robust result, data must be optimally conditioned for the workflow to be applied. In this example, the input seismic offset gathers were pre-conditioned prior to inversion to increase the overall signal-to-noise ratio and avoid any remaining noise having a high impact on the inversion results. The pre-conditioning also corrected for offset dependent frequency loss and ensured that the gathers were aligned. Since data pre-conditioning, if not applied carefully, could significantly affect AVO behavior of target reflectors, the sensitivity of inversion results to the pre-conditioning approaches applied has been thoroughly tested and analyzed. It is important to note that all conditioning steps were parameterized keeping in mind the need to preserve amplitude behavior, and the minimum possible pre-conditioning was undertaken. The processes applied are summarized in Singleton (2009).

During the pre-stack seismic inversion, a global objective function is minimized in order to compute an optimal model for P- and S-impedance, which best explains the input angle stacks and is consistent with the geological knowledge introduced through a priori information (Tonellot, 2001). Initial low frequency models of P- and S-impedance were created based on seismic velocity and well data. These models exclude any reservoir signature and mix the lateral variations from the velocity field and vertical resolution from well logs filtered at 5Hz. Wavelets were extracted per angle stack per well and later combined to obtain the most representative wavelet for each angle stack. Additional parameters such as the scale factor between wavelets and actual amplitude sections, confidence in seismic amplitude angle stack data, number of iterations and allowed low frequency model standard deviations were also customized based on iterative tests performed per set of lines. Final results were then extracted along well trajectories and compared to actual well log data in order to ensure a good representation of the earth model. Also, percentage of differences between input and synthetic angle stacks were calculated to ensure that they were less than 20% of the original seismic amplitude. In this case, where the P- and S-impedance models were allowed to change 2000 [m/s gr/cc] from the initial model, after 25 iterations, the
seismic inversion results represent very well both the earth model from the well log data and the actual partial angle stacks. (Figure 9)

**Figure 9.** Initial model, P-wave impedance and Poisson’s ratio from seismic inversion (left), tracks of P-wave impedance, Poisson’s ratio, volume of clay and water saturation extracted along the projection of the well 7324/8-1 (right).

**Rock property estimation from well log and seismic data**

The multi-attribute rotation scheme (MARS) (Alvarez et al. 2015), was used to estimate rock properties and facies volumes from well log and seismic inversion attributes. This workflow uses a numerical solution to estimate a transform to predict petrophysical properties from elastic attributes. The transform is computed from well log-derived elastic attributes and petrophysical properties, and posteriorly applied to seismically-derived elastic attributes. MARS estimates a new attribute, \( \tau \), in the direction of maximum change of a target property in an \( n \)-dimensional Euclidean space formed by \( n \) attributes. The method sequentially searches for the maximum correlation between the target property and all of the possible attributes that can be estimated via an axis rotation of the basis that forms the aforementioned space.

Multiple elastic attributes such as P-wave impedance \( l_p \), S-wave impedance \( l_s \), P-to-S velocity ratio \( (V_p/V_s) \), the product of density and Lamé’s parameters \( \lambda \rho \) and \( \mu \rho \) (Goodway et al. 1997), Poisson’s ratio \( \nu \), the product of density by bulk modulus \( K \rho \), the product of density and Young’s modulus \( E \rho \), Poisson dampening factor (PDF) (Mazumdar, 2007), etc., can be used in the MARS assessment. For this case study, for each target petrophysical property, MARS was run for a 2D combination of the 64 elastic attributes shown in Table 2, which can be derived from IP and IS, resulting in the evaluation of 2016 independent bi-dimensional spaces. In this table, each number represents a single attribute, which is obtained after applying the mathematical operation shown in the leftmost column to the elastic attribute shown in the uppermost row. For example, the number 21 represents...
the attribute $\frac{1}{\lambda\rho}$. The purpose of applying a mathematical operation (such as square root, power, inverse, logarithm, etc.) to attributes is to be able to model physical phenomena that exhibit nonlinear behavior. This is a mathematical strategy to linearize potential nonlinear relationship between the elastic attributes and the petrophysical properties, used with the goal of improving the correlation between the attribute $\tau$ and the target petrophysical property.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>$I_p$</th>
<th>$I_s$</th>
<th>$V_p/V_s$</th>
<th>$\lambda\rho$</th>
<th>$\mu\rho$</th>
<th>$\lambda/\mu$</th>
<th>$(\lambda-\mu)\rho$</th>
<th>$\sigma$</th>
<th>$E_p$</th>
<th>$K_p$</th>
<th>$PDF$</th>
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<tr>
<td>$\sqrt{\text{Attribute}}$</td>
<td>6</td>
<td>11</td>
<td>17</td>
<td>23</td>
<td>--</td>
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<td>46</td>
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<td>58</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 2. Matrix of attributes used in MARS. Each number represents a single attribute, which is obtained after applying the mathematical operation shown in the leftmost column to the uppermost row. For example, the number 21 represents the attribute $\frac{1}{\lambda\rho}$.

The MARS approach was applied in two different depth windows, given the different rock physics relationships between the elastic attributes and the petrophysical properties in the Stø and Nordmela Fms. (see Figure 6). The first window comprises the Fuglen and Stø Formations and the second window the Nordmela Formation. The rock properties that were estimated using the MARS approach were total porosity ($\Phi_T$), volume of clay ($V_{clay}$) and the hybrid petrophysical property water saturation plus volume of clay ($S_w+V_{clay}$).

This last property, which can take values between zero and two, was used as input to build a litho-fluid facies volume based on the cut-off values shown in Table 3. Three litho-fluid facies were defined. The green facies denotes zones where clean hydrocarbon bearing sands with thickness above seismic resolution are expected to be found, including both commercial and residual saturation given the inability of the elastic measurements to distinguish between these two. The blue facies represents clean wet sand or shaly hydrocarbon bearing sand or thin hydrocarbon bearing sand that cannot be resolved at seismic resolution. These three configurations of rock and fluid properties present a high degree of overlap in the elastic domain, in consequence cannot be separated using seismic data. The last litho-fluid facies (brown) represents the background trend that are composed of shales or thin wet sand.
<table>
<thead>
<tr>
<th>Litho-fluid-facies Definition</th>
<th>Sw+Vclay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean hydrocarbon bearing sand (commercial and residual saturation) with thickness above seismic resolution</td>
<td>&lt; 0.85</td>
</tr>
<tr>
<td>Clean wet sand / Shaly hydrocarbon bearing sand / Thin clean hydrocarbon bearing sand</td>
<td>0.85 – 1.5</td>
</tr>
<tr>
<td>Shales / Thin wet sand</td>
<td>&gt; 1.5</td>
</tr>
</tbody>
</table>

**Table 3.** Litho-fluid facies definition based on the hybrid petrophysical property Sw+Vclay

**Figure 10.** Comparison of the actual (upper) and predicted (middle) target property log upscaled to seismic resolution for the Central and Alternative wells in the optimal cross-plot space estimated from the MARS analysis for the Fuglen and Stø Formations. Gray arrows, orthogonal to the blue lines, indicate the direction of maximum change of target petrophysical property in the optimal attribute space. The lower plots show a crossplot of the correlation coefficients between the target property log and the set of attributes estimated via axis rotation, versus the rotation angle (θ). The black arrow highlights the angle where the maximum cross correlation was found.
The results obtained after applying MARS to well log information from the Central and Alternative wells is shown in Figure 10 for the Fuglen and Stø Formations and Figure 11 for the Nordmela Formation. These plots show a comparison between the actual and predicted target petrophysical property using MARS in the optimal elastic attribute space determined by a global search algorithm. The lower plots show a crossplot of the correlation coefficient between the derived set of attributes (estimated via axis rotation) and the target petrophysical log, versus the angle of rotation ($\theta$). These plots show for all the cases a fair to good maximum cross correlation that supports the application of the MARS-derived transform to seismically-derived elastic attributes to estimate sections of the target petrophysical properties along the 2D seismic lines analyzed.

**Figure 11.** Comparison of the actual (upper) and predicted (middle) target property log upscaled to seismic resolution for the Central and Alternative wells in the optimal cross-plot space estimated from the MARS analysis for the Nordmela Formation. Gray arrows, orthogonal to the blue lines, indicate the direction of maximum change of target petrophysical property in the optimal attribute space. The lower plots show a crossplot of the correlation coefficients between target property log and the set of attributes estimated via axis rotation, versus the rotation angle ($\theta$). The black arrow highlights the angle where the maximum cross correlation was found.

Once the transform to predict petrophysical properties from elastic attributes was found for each window using well log data, the resulting relationships were applied over the seismically-derived elastic attributes per window using the seismic horizons (upper window: from top Fuglen to base Stø, and bottom window: from base Stø to top Snadd), with the goal of estimating a single 2D section of total porosity, clay content and litho-fluid facies per 2D seismic line. The litho-fluid facies section was estimated after applying the cut-off presented in Table 3 to the seismically-derived section of $Sw+Vclay$. The resultant litho-fluid facies, clay content and total porosity sections for the line 5001P1009, along with the corresponding well log information for the Central and Alternative wells is...
shown in Figure 12. Notice the good match between the seismic and well log-derived petrophysical property in the calibration wells demonstrating that both were correctly predicted. In addition, the well trajectory of the Hanssen and Bjaaland wells are also shown (no log information is available for these wells). The former was catalogued as a discovery well and the latter as a dry well. The litho-fluid facies section suggests that hydrocarbon fluid is present in both locations, and highlights the fact that seismic data alone cannot distinguish between commercial and non-commercial hydrocarbon saturations, leaving a significant ambiguity in prospect de-risking.

**Figure 12.** For line 5001P1009, sections along A-A’ (Figure 5) of litho-fluid facies (top), clay content (middle) and total porosity (bottom) along wells Central and Alternative-derived from MARS analysis of elastic attributes. The curves overlaid in the top panel are Vclay (left) and Sw (right) and in the middle and bottom panels are volume of clay (left) and total porosity (right).

**DERIVATION OF RESISTIVITY FROM CSEM DATA**

In order to resolve the interpretation ambiguity inherent when only seismic data are considered, we used resistivity information-derived from controlled source electromagnetic (CSEM) data. CSEM has been used successfully as an offshore hydrocarbon exploration tool for over a decade (Constable 2010). The data for this study has been collected in a relatively new way; using a towed source and array of electric field receivers (Englemark et al, 2014; Key et al. 2014). MacGregor and Tomlinson (2014) provides an overview to the offshore CSEM method and the various acquisition methods that can be applied.

In common with the seismic analysis, the CSEM analysis was focused on line 5001. A 2.5D inversion approach, in which the earth structure is 2D and the source is a 3D point dipole, was therefore applied. Although this does
not take into account the full 3D structure of the earth, in many circumstances it provides a good approximation to the resistivity structure along the line inverted. The effect of this approximation on the results is discussed in more detail below. Figure 13 shows an example of the CSEM acquired along line 5001, in the form of source gathers at 1Hz. A significant response to the accumulation encountered at Wisting Central can be clearly seen in the CSEM data, particularly in the phase response (lower panel of Figure 13 around 611km Easting). This is observed across a wide band of frequencies. It should be noted that it is somewhat unusual to see such a large reservoir response in the data directly. In this case the oil accumulation at Wisting is both extremely resistive (several thousand $\Omega$m) and at a relatively shallow depth below mudline (about 300m) leading to the large response observed.

![Figure 13. CSEM Amplitude (top) and phase (bottom) data collected at 1Hz along line 5001. The effect of the oil accumulation at Wisting Central (around 611km Eastings) is clear, especially in the phase data.](image)

The CSEM data for six frequencies (0.2Hz, 0.8Hz, 1Hz, 1.4Hz, 2.2Hz, 2.6Hz) were inverted using an Occam approach (Constable et al 1987; Key, 2016) to derive anisotropic resistivity models that are smooth in a first derivative sense, and therefore as close to a uniform halfspace as possible, while honoring the data. A layered seawater conductivity structure based on measurements throughout the water column and 1D modeling was used. Nineteen to twenty-three source-receiver pairs per frequency were included in inversion.

The inversion was performed in stages. Firstly, an unconstrained inversion was run in order to examine the resistivity structure obtained in the absence of any a priori information. However unconstrained inversions in general have poor resolution. Resolution can be improved by including structural information from the seismic data. This also ensures consistency between seismic and CSEM-derived results, which is important for subsequent integrated interpretation. Following unconstrained 2.5D inversion therefore, seismic data were used to condition...
the inversion of the CSEM data by adding structural constraint in the form of breaks in the smoothness requirement at selected seismic horizons, thereby improving the resolution of the CSEM result. Two versions of constrained inversion were run, one with a regularization break at reservoir level (top Stø) only, and one with regularization breaks at both top Stø and the Intra-Snadd horizon. After initial constrained inversion testing, the resistivity was limited between 0.1 to 40Ωm from seafloor to top Stø for both horizontal and vertical resistivity.

Figure 14 shows the vertical (upper panel) and horizontal (lower panel) resistivity resulting from the final constrained inversion that were carried using depth-converted seismic horizons top Stø horizon and Intra-Snadd horizon. In figure 15 the RMS residual per source gather as a function of position along the line is plotted. A normalized misfit of less than 1 indicates a fit (on average across the gather) to within the error bar defined. Good fits were achieved across the survey line.

Background resistivity is extremely high in the area with vertical resistivity of 25-30 Ωm. Background anisotropy is also extremely high with factors of five or more observed. This high overburden resistivity and anisotropy is the result of the significant uplift in the area. A significant increase in vertical resistivity was recovered in the lower Snadd, with localized variations contained within a regional feature. This regional feature also exhibits extremely high electrical anisotropy.

A localized resistive feature coincident with the structure penetrated at Wisting Central is clearly recovered in the vertical resistivity. A more subtle increase in resistivity is observed at the Hanssen well location. No localized resistive feature is recovered in the Stø at the location of the Wisting Alternative or Bjaaland wells.

Figure 14. Vertical resistivity (top) and horizontal resistivity (bottom) models recovered by 2.5D inversion for line 5001P1009 CSEM data. The inversion was constrained with regularization breaks at Top Stø and Intra Snadd. The Hanssen, Alternative, and Central well locations are marked by the white lines.
Figure 15. RMS residual per source gather for the final inversion result shown in figure 14, plotted as a function of distance along the line. A good fit to the data is achieved by the inversion.

Figure 16 shows the CSEM-derived vertical resistivity in the same windows of analysis used in the seismic quantitative interpretation, for the unconstrained and constrained inversions run: The top one corresponding to the unconstrained inversion, and the bottom image shows the results of the constrained inversion previously shown in the Figure 14.

A qualitative interpretation of the CSEM inversion results supports the outcome of the Alternative, Central and Bjaaland wells. A prominent resistivity anomaly is recovered at Central, in which there was a significant oil discovery, which is in agreement with the high resistivity values measured at the reservoir location. On the other hand, the Realgrunnen structures penetrated at Alternative and Bjaaland, two dry wells, are related to low resistivity values that support the petrophysical outcome.

At the location of the Hanssen discovery well, a subtle high resistivity anomaly is observed. The relatively small magnitude of this feature is the product of a 3D effect in the CSEM data, a consequence of the location of the CSEM line with respect to the location and the size of the reservoir (see Figure 2b). Although in many circumstances the 2.5D approximation is a good one, if the resistive reservoir is relatively small, or the 2D line being inverted is close to the edge of the reservoir, then the effect of the of the reservoir on the CSEM data is diminished, and consequently the resistivity recovered by a 2.5D inversion is reduced from its true value. Loseth et al. illustrate this with a synthetic modelling study in which they demonstrate the reduction in inverted resistivity with width of the target reservoir and proximity of the CSEM line to the reservoir edge. In the case of Hanssen, the reservoir is both relatively small and the line is close to the edge of the body, leading to the lower resistivity at this location. The effect of this on the quantitative interpretation is discussed in later sections.

Having analysed the seismic and CSEM data in isolation the next stage is to combine the results. A quantitative approach that integrates the resistivity measurements with the seismic results is necessary to evaluate in more detail the CSEM results and corroborate and/or validate the petrophysical outcome of the wells.
Figure 16. Cross-sections along A-A’ (Figure 5) of CSEM-derived vertical resistivity for (top) unconstrained inversion, and (bottom) inversion constrained by the top Stø horizon and Intra-Snadd horizon. The Intra-Snadd horizon (a deeper horizon that is outside the area of interest for the remainder of the analysis not shown in the Figure) is about 500 m. deeper than the Snadd horizon.

**ROCK PROPERTY ESTIMATION FROM WELL LOG, SEISMIC AND CSEM DATA**

The final stage of the workflow is to combine the seismically-derived properties, with the electrical information-derived from the CSEM data. The goal of this stage is to reduce the uncertainty in fluid saturation that is observed in the seismic-only results. In order to do this, electric and elastic properties must be combined in a common domain and at a common scale so that direct comparison, and ultimately quantitative integration is possible.

*Seismically-derived resistivity estimation and transverse resistance (TR) calibration*

In order to allow direct comparison between seismic and CSEM results, the next step in the methodology (figure 16) is the estimation of resistivity models from seismically-derived properties for different fluid saturation scenarios. With this goal in mind, we used the seismically-derived litho-fluid facies, clay content and total porosity sections with a calibrated rock physics model to transform these petrophysical properties into the electrical domain. The calibrated rock physics model used was the Simandoux equation (equation 1, Simandoux, 1963). This rock physics model represents the same one used in the petrophysical evaluation of the Central and Alternative wells to estimate water saturation (Sw) from the horizontal resistivity log and was calibrated in the early stage of the study. The procedure used to estimate the seismically-derived resistivity sections at different fluid scenarios consisted of applying directly Equations 1 and 2 to the total porosity and volume of clay sections (Figure 12) for different values of Sw that were modified only in those areas were the seismic indicates the presence of clean hydrocarbon bearing sand, i.e. green facies in the litho-fluid facies section (Figure 12). The results are shown in Figure 17 b, c, and d, for values of Sw equal to 0.1, 0.5 and 1 respectively.
As a quality control of the results for the case of Sw=0.1 (90% hydrocarbon saturation, which is a saturation close to that obtained from the petrophysical evaluation at the Central well), the measured resistivity curve was overlaid. An excellent match with the modeled resistivity is obtained. One important observation that can be made from the comparison of the three seismically-derived results is the low resistivity contrasts between the reservoir and non-reservoir facies for the case of Sw=0.5. This demonstrates that this level of water saturation (or higher) cannot be identified using CSEM data in this particular geological setting due to the high values of the background resistivity.

At this stage in the workflow, results have all been transformed to the electrical domain. However, there is one further step required before a direct comparison can be made. It is noticeable that the seismic results in figure 16 are significantly higher resolution than the CSEM results in figure 16, even when the CSEM inversion is constrained. This difference must be resolved before the results can be compared or combined in a quantitative fashion.

The simplest approach to achieving this is to upscale both seismic and CSEM results. The reservoir parameter that is best constrained by the CSEM method is the transverse resistance (vertically integrated resistivity). By calculating the transverse resistance from the seismically and CSEM-derived resistivity, the difference in vertical resolution between the two methods can be overcome, albeit at the expense of the higher resolution of the seismic result. Transverse resistances based on CSEM and seismic results are compared in figure 17a. Note that when the resistivity is calculated from the seismic data using the Simandoux relationship, which is calibrated to horizontal resistivity at the well, the result is most closely related to the horizontal resistivity of the sub-surface. The CSEM measurements, in contrast, provide a measure of both horizontal and vertical resistivity however reservoir related structure manifests in the vertical resistivity. To address this difference, an empirical calibration factor of three, based on CSEM analysis of background anisotropy, was applied to the seismically-derived transverse resistance to compensate for the electrical anisotropy observed.

An analysis of figure 17a offers important information about the hydrocarbon saturation levels of the reservoirs and potential reservoirs along the section. A good agreement is seen between the CSEM and seismic transverse resistance curves at the end member positions represented by the Central well location (Sw=0.1 - magenta curve) and for the Alternative well location (Sw=1 - blue curve) that corroborate the validity of the rock physics model used and the calibration factor applied to the data. For the case of the Bjaaland well, the CSEM-derived transverse resistance most closely agrees with the lower saturation seismically-derived curves, indicating, in a semi-quantitative way, the absence of a commercial hydrocarbon saturation at this location. Finally, for the Hanssen well, the separation between the CSEM transverse resistance curve and that for the wet case seismically-derived curve (blue curve) indicates the presence of hydrocarbon saturation at least higher than 50%. However, it is important to have in mind that a diminished CSEM-derived resistivity value is expected to be found in this area due to the 3D effects discussed previously. As a consequence of this the hydrocarbon saturation will be underestimated in this case.
Figure 17. a) Comparison between the seismically- and CSEM-derived transverse resistance estimates. b) Cross-sections along A-A' (Figure 5) of seismically-derived resistivity for Sw=0.1, c) Sw=0.5 and d) Sw=1. Note the good match between the measured and modeled resistivity in the Central well at the (b) section. So is the oil saturation and is 1-Sw in this case.

**Water saturation prediction**

Although the semi-quantitative comparison of transverse resistance presented above provides valuable information on reservoir properties, it is often desirable to derive a quantitative estimate of rock and fluid properties. The last step in the workflow (Figure 4), is therefore the quantitative prediction of the Sw. The input data for this analysis was the seismically-derived porosity, clay content and litho-fluid facies section shown in Figure 12, and CSEM-derived transverse resistance along the CSEM line (Figure 17a). These datasets were inverted using the Simandoux equation calibrated at the Central and Alternative wells, and a global search inversion method. This method seeks the value of Sw that provides the minimum misfit between seismically and CSEM-derived transverse resistance, using a grid search algorithm (see Figure 18). It is important to mention that only potential reservoir rocks as indicated by the seismic litho-fluid facies (green facies in figure 12 to the top panel), were considered to have variable Sw during the inversion process.
In this way the quantitative seismic interpretation result not only provides information about the clay content and total porosity of the rocks, necessary for the Simandoux equation, but also about the location and thickness of the potential pay sand, thus maintaining seismic resolution in the final result. However, note that since only Sw varies during the inversion, it is implicitly assumed that the porosity and Vclay as defined by the seismic data are correct.

Figure 18. Methodology used to estimate Sw from seismically-derived rock properties volumes and CSEM-derived resistivity.

The result of this inversion is shown in figure 19. The top panel shows the profile of the misfit obtained as a function of the Sw. This information can be interpreted as a measurement of the robustness of the Sw estimation. The middle panel shows how the optimal Sw is linked to the lowest misfit value. Note that in areas where no hydrocarbons are indicated by the seismic litho-fluid classification shown in the bottom panel for reference (i.e. outside the green facies), Sw is set to 1. Around Wisting Central, the inversion result shows a well constrained low Sw value, with a narrow inversion minimum. This is as expected since at low water saturations, a small change in Sw results in a relatively large change in resistivity. Around the Hanssen well, the inversion minimum is wider, a result of the lower predicted saturation. At Bjaaland, the results predict a minimum water saturation of about 50%, consistent with the sensitivity limit suggested by well log analysis.

Finally, the resulting Sw profile was mapped back in its correct position using the seismically-derived litho-fluid facies volume to generate a hydrocarbon saturation section along the line (Figure 20). Excellent correlation with known well results was achieved. The integration of seismic, CSEM, and well data predicts very high hydrocarbon saturations at Wisting Central, consistent with the findings of the well. The slightly lower saturation at Hanssen is related to 3D effects in the CSEM data, but the outcome of the well is predicted correctly. There is no significant saturation at Wisting Alternative, again consistent with the findings of the well. At Bjaaland, although the seismic data indicate the presence of hydrocarbon bearing sands, the integrated interpretation result again predicts correctly that this well was unsuccessful.
Figure 19. Misfit as a function of $S_w$ between the CSEM-derived transverse resistance and the set of seismically-derived transverse resistance computed for different $S_w$ values (top). Optimal $S_w$ estimation linked to the minimum misfit value (middle). Cross-sections along A-A’ (Figure 5) of seismically-derived litho-fluid facies (bottom).

Figure 20. Cross-sections along A-A’ (Figure 5) of hydrocarbon saturation obtained from a joint interpretation of CSEM, seismic and well log data, with hydrocarbon saturation and Vclay curves overlaid. Notice that the seismic data alone cannot distinguish between commercial and non-commercial hydrocarbon saturation. The inclusion of the CSEM resistivity information within the inversion approach allows for the separation of these two possible scenarios.
CONCLUSIONS

This case study shows successful inversion of the seismic and CSEM-derived properties within a rock physics framework. The well and seismic data were integrated to produce a litho-fluid facies volume identifying areas of clean oil or fizz gas sand; however, the seismic data cannot distinguish between commercial and non-commercial hydrocarbon saturation. The inclusion of the CSEM resistivity information allows for the separation of these two possible scenarios. Excellent correlation with known well results was achieved.

Multi-physics integration is not straightforward. There are a number of technical challenges that were identified for consideration in future work. For example, in the case study presented here, the reservoir interval was relatively simple, comprising a single sand interval. Mapping the resistivity into this layer was therefore relatively straightforward. However, in more complex settings with multiple reservoir layers, that cannot be independently resolved using the CSEM data, mapping from a low resolution resistivity image into multiple layers is not straightforward. A workflow for dealing with this situation must be developed. Rock physics strategies for correctly accounting for anisotropy when linking electric and elastic measurements must also be considered. However, despite this, the results demonstrate the value of combining multiple geophysical data types to improve interpretation robustness.

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