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Discriminating between Commercial and Residual Hydrocarbon Saturation Integrating Pre-stack Seismic and CSEM

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Summary

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, which allows us to discriminate between commercial and non-commercial (residual) hydrocarbon saturation. 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 modelling 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 saturations. 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.
Introduction
The integration of pre-stack seismic inversion attributes with controlled source electromagnetic (CSEM) attributes using a rock physics framework constitutes one of the most modern and complete methodologies to carry out geophysical reservoir characterization. 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 and lithology, however, the seismic data cannot distinguish between low- and high-saturated hydrocarbon saturation due to their similar AVO responses. In contrast, 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 allowing the separation between commercial and non-commercial hydrocarbon accumulations.

This paper presents a case study in which the integration of seismic, CSEM and well-log data has been applied to distinguished between these two scenarios. This separation would not be possible to achieve if only seismic reservoir characterization approaches were applied. The study area is located in the Hoop area of the Barents Sea, Norway.

Location, data sets and workflow
The area in question covers a significant oil discovery in the Hoop Fault Complex on the Bjarmeland Platform in the Barents Sea, Norway. A densely-sampled dataset consisting of six lines of 2D GeoStreamer® seismic and towed streamer EM data were acquired concurrently in 2015 by PGS, using the system depicted in Figure 1a (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 (residual saturation). The results from these wells were used to validate and corroborate the accuracy of the reservoir property predictions (Figure 1b).

The workflow used to carry out the quantitative interpretation of well-log, seismic and CSEM data 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 honours all the geophysical measurements.
Seismic Reservoir Characterization
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. The resultant litho-fluid facies, clay content and total porosity sections for the line 5001P1009 (see Figure 1b), along with the corresponding well log information for the Central and Alternative wells is shown in Figure 2. 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 (only found residual saturation). 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 2. For line 5001P1009 (Figure 1b), sections of litho-fluid facies (top), clay content (middle) and total porosity (bottom) along wells Central and Alternative derived after apply the MARS analysis to 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
To resolve the interpretation ambiguity in the seismic interpretation, we used resistivity information derived from CSEM data. A 2.5D inversion approach, in which the earth structure is 2D and the source is a 3D point dipole, was therefore applied. The CSEM data for six frequencies (0.2Hz, 0.8Hz, 1Hz, 1.4Hz, 2.2Hz, and 2.6Hz) were inverted using an Occam approach (Constable et al., 1987; Key, 2016). 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 to examine the resistivity structure obtained in the absence of any a priori information. Seismic data were then 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. Figure 3 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. 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 1b).

**Figure 3.** For line 5001P1009 (Figure 1b), sections 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.

**Water saturation prediction**
The input data for this analysis was the seismically-derived porosity, clay content and litho-fluid facies section shown in Figure 2, and CSEM-derived transverse resistance along the CSEM line (Figure 3). 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 4).

**Figure 4.** Methodology used to estimate Sw from seismically-derived rock properties volumes and CSEM derived resistivity.
It is important to mention that only potential reservoir rocks as indicated by the seismic litho-fluid facies (green facies in Figure 2 to the top), 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.

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 5). 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 indicate the presence of hydrocarbon bearing sands, the integrated interpretation result again predicts correctly that this well was unsuccessful.

Figure 5. For line 5001P1009 (Figure 1b), sections of hydrocarbon saturation obtained from a joint interpretation of CSEM, seismic and well-log data, with hydrocarbon saturation curves overlaid. Notice that the seismic data alone cannot distinguish between commercial and non-commercial (residual) 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 resulting in an excellent correlation with known well results.

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Reference