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North Sea case study: Heavy oil reservoir characterization from integrated analysis of Towed Streamer EM and dual-sensor seismic data

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SUMMARY

Integrated analysis of geophysical data can provide valuable information on reservoir properties, on the basis of which exploration, appraisal, and development decisions can be made. Hence, we have introduced a quantitative interpretation workflow that integrates dual-sensor seismic and Towed Streamer controlled-source electromagnetic (CSEM) data. The workflow was designed to facilitate a reliable extraction of the complementary information from the two datasets. The seismic contribution starts with a depth-converted sparse horizon model to initialize the EM inversion, but it is not placed rigidly. This makes good sense when taking into account the uncertainties in seismic data, in the time to depth conversion, and more importantly, the fact that a reservoir can be hydrocarbon-charged to an unknown degree corresponding to the spill-point or less. We show how this approach enables a robust and reliable workflow for integrating EM and 3D seismic data with data examples acquired in an area with the complex geology of the Bressay, Bentley and Kraken (BBK) fields in the North Sea. The three heavy oil reservoirs are injectites, located in close proximity to other high resistivity settings, such as the shallow gas in the overburden, regional Balder Tuff and granite intrusions, resulting in challenging imaging issues.

Key words: seismic, CSEM, inversion, integration.

INTRODUCTION

The integrated analysis of seismic and marine CSEM in de-risking exploration prospects has led to a significant number of success stories since 2000 (e.g. Karman, et al., 2013), indicating that the ideal companion to high quality marine EM data is 3D seismic data. When assessing the prospectivity in a complex geological region, seismic data can provide a high-resolution structural image of the subsurface while marine EM estimates the resistivity of assumed reservoirs since EM data are more sensitive to the presence of hydrocarbons. The integration of seismic data with EM data can thus provide a more accurate image of the subsurface than is possible when only a single data type is used.

Several methods for joint interpretation of multiple geophysical data exist and have been applied with varying degrees of success. These can be broadly classified into two approaches: 1. cooperative methods that involve the use of structural attributes, i.e. boundaries of geological features, as a common factor between seismic and resistivity models, and 2. collaborative methods that involve the use of petrophysical characteristics to relate the two datasets, relying on the rock physics models forming the link between the elastic and electrical rock properties measured respectively by seismic and EM data.

We have introduced a method to make the inversion-based EM and seismic integration process more data and information-driven and less *a priori* model driven (Du and Hosseinzadeh, 2014). The workflow is based on the cooperative approach, however, it uses the seismic image to guide the EM inversion rather than constrain it. This approach is initiated by adopting a sparse-layer depth model defined by a high-resolution seismic image to suggest resistivity boundaries for the EM inversion, whereas the previously proposed cooperative inversion approaches adopt this model to prejudice the EM inversion's roughness penalty to force resistivity variations to follow these major seismic boundaries. In this study we use the workflow by integrating the towed streamer EM and dual-sensor seismic data acquired in an area with complex geology, showing how it can be used for reservoir characterization of the heavy oil reservoirs Kraken, Bressay and Bentley (BBK) in the North Sea.

THE BBK REGION AND TOWED STREAMER EM DATA

Using the newly developed controlled-source Towed Streamer EM acquisition system, PGS conducted a survey in 2012 over the Bressay, Bentley and Kraken (BBK) heavy oil fields in the North Sea (Figure 1). The BBK discoveries were considered to pose several challenges to conventional CSEM surveying. The very shallow water depth of 90-130 m, dampen the EM anomalies due to airwave coupling. The reservoir within the block consists of coarse clastics, forming a prograding delta compound. The reservoirs are to a large extent injectites, having steep and irregular features. The geology in the region is complex, resulting in challenging imaging issues. The heavy oil charge means there is no direct hydrocarbon indicator in the seismic data due to the low acoustic impedance contrast between the oil-charged reservoir and the brine-charged reservoir below.

The Towed Streamer EM acquisition system for the BBK surveys consisted of a ~7.7 km receiver cable deployed at 50-100 m water depth, and a 1,500 A, 800 m long bipole source towed at 10 m depth. With a 4 kt towing speed, the acquisition pattern was based on a source signal every 250 m and 44 unique receiver positions for each "shot". Compared to a conventional node-based marine CSEM system where the receivers are very sparsely placed on the seafloor in a line or areal pattern, approximately 1 km apart, the highly sensitive receiver electrodes housed in the streamer of the towed EM system are able to densely sample the subsurface with an average offset interval of ~160 m over offset ranges of ~800-7,595 m. Additionally, whereas conventional seafloor CSEM receivers uses 10 m dipole sensors, the towed system uses receiver bipoles of 200 to 1100 m length, resulting in high sensitivity measurements. The Towed Streamer EM system thus provides the dense sampling, data quality, and signal-to-noise ratio required for imaging challenging targets in a shallow water environment.

INTEGRATED ANALYSIS

The workflow for integrating the Towed Streamer EM and dual-sensor (GeoStreamer®) seismic data was applied to illuminate the heavy oil reservoirs of Kraken, Bressay and Bentley, located in a complex geological area, in the North Sea.

The unconstrained anisotropic inversion

The unconstrained blind (without considering field geology) inversion for anisotropic resistivities started from an isotropic 1.0 Ωm half space. Figures 2a, b and c show the inversion results (vertical resistivity only, for the sake of brevity) from the selected three towed streamer EM lines that cross over Kraken, Bressay and Bentley, BK043, BK014 and BK006, respectively (orange lines in Figure 1).

The Towed Streamer EM data were inverted using the MARE2DEM code, which is an Occam-based 2.5D inversion built around a parallel adaptive finite element algorithm (Key and Ovall, 2011; Key, 2012). We parameterized the model domain with a dense grid of around 15,000-20,000 unknown resistivity parameters (depending on the profile length) from the seafloor to a depth of 2.5 km. We set a 1% error floor to the data and found that all three survey profiles could be fit to a root-mean-squared (RMS) misfit of about 1.0 to 1.5 percent within 10-15 Occam iterations.

The unconstrained inversion seeks the best model to fit the data that is also the smoothest model in the first derivative sense (Constable et al., 1987). The unconstrained inversion does not take into account complex or higher dimensional structures, but allows the class of structures to which the data are most sensitive, and variations in these structures across the area to be assessed. The inversions have faithfully recovered the resistive basement since it has the largest impact on the data responses. It has also revealed several large size bodies with significantly increased resistivity in the overburden (Figures 2a, b and c). While these increases are located at the lateral positions of BBK reservoirs, their depths are inconsistent with the known reservoirs.

The seismic guided inversion

The seismic guided inversion (Du and Hosseinzadeh, 2014) is aiming to facilitate an optimal procedure to combine the complementary information from dual-sensor seismic data and the Towed Streamer EM, with the seismic data best at constraining structure, and the EM data best at constraining the reservoir strength. In some detail, the inversions are guided by the seismic to find the stratigraphic boundaries, whereas the resistivity variations within the overburden layers are set by plausible lower and upper boundaries suggested by the previous step of unconstrained inversions. Further technical details of the seismic guided inversion are given in Du and Hosseinzadeh (2014). Here we apply the workflow and demonstrate how it incorporates the geological information constrained by seismic data into an inversion of EM, showing how it helps substantially to raise the resolution of the EM inversions.

Bressay. Figure 2e shows the vertical resistivity of the final result of the seismic guided inversion for line BK014. Compared to the unconstrained inversion (Figure 2b) where the thin Bressay reservoir was not resolved, the seismic-guided inversion has retrieved a prominent high resistivity anomaly at the depth and lateral position of the known reservoir location. By comparing it to the result obtained by the unconstrained inversion (Figure 2b), both inversions have also consistently revealed a laterally extending large shallow resistive body in the overburden, in the depth range of ~500 800 m. The body looks like a chimney-like intrusion that is cross-cutting the primary reflections, and is possibly formed by gas leakage from the top of the reservoir (Figures 2b and 2e).

Kraken. In the seismic guided inversion for line BK043, we have adopted a seismic horizon that define the top of the Heimdal sand as a 'cut" to break the Occam smooth regularization at the top of the reservoir (a sharp contrast in resistivity is allowed here). Figure 2d shows the final inversion model, indicating that the cut is helpful for constraining the reservoir, but has no adverse effect on other parts of the horizon where the cut was applied along the surface of the body seismically defined as sand. The cut also has little effect on the inversion for retrieving the background structure, as evidenced by comparing the unconstrained (Figure 2a) to the seismic guided inversion (Figure 2d).

The inversion result displays a localized strong EM anomaly coincident with the location of the known Kraken reservoir (Figure 2d). The seismic-guided inversion was able to vertically separate the reservoir from the basement, while the basement boundary exhibits lateral resistivity variations that follow the seismic amplitudes closely.

Bentley. The seismic guided inversion result for Line BK006 is shown in Figure 2f. The result significantly improves the vertical resolution compared to the unconstrained inversion (Figure 2c). The inversion result matches the reservoir depths and geometries of Bressay and Bentley, and faithfully reflects the resistivity magnitudes by showing the prominent EM anomalies, perfectly coinciding with the positions of the main target structures as shown by the seismic data.

By adopting the same model parameterization built from the unconstrained inversion, the above three seismic-guided inversions were able to fit the data to a root-mean-squared

(RMS) misfit of about 1.1 to 1.4 after 14-17 Occam iterations, requiring a few hours of run-time on 320 processors.

From the integrated analysis of BBK outlined above, based on Towed Streamer EM and seismic data, we can summarize some of the BBK main regional structural features. One of the prominent features is the existence of the overburden anisotropy (Key et al. 2014). Seismic imaging for hydrocarbon in such a structurally complicated region is challenging, due to the fact that the reservoirs consists to a large extent of injectites. The properties of the heavy oil mean there is no direct hydrocarbon indicator in the seismic data due to the low acoustic impedance contrast between the charged and the non-charged reservoir below. The existence of shallow gas in the overburden, and the regional Balder Tuff and granite intrusions, have also resulted in challenging imaging issues for the unconstrained EM inversion. However, the CSEM images over the BBK area, obtained by the seismic-guided inversion, have successfully delimited these heavy oil reservoirs. The result obtained from this study has thus provided important information for the BBK reservoir characterization, forming the basis for which appraisal and development decisions can be made.

CONCLUSIONS

In this abstract, we showed the successful application of a newly developed seismic and EM data integration workflow to the inversion of towed streamer EM data from a complex geological area, illuminating the Bressay, Bentley and Kraken heavy oil reservoirs. The study shows that the integrated analysis of seismic and EM is a powerful tool, which can be used for exploring complex geological regions. It clearly demonstrates the value of acquiring Towed Streamer EM data in addition to 3D seismic data for frontier exploration.

ACKNOWLEDGMENTS

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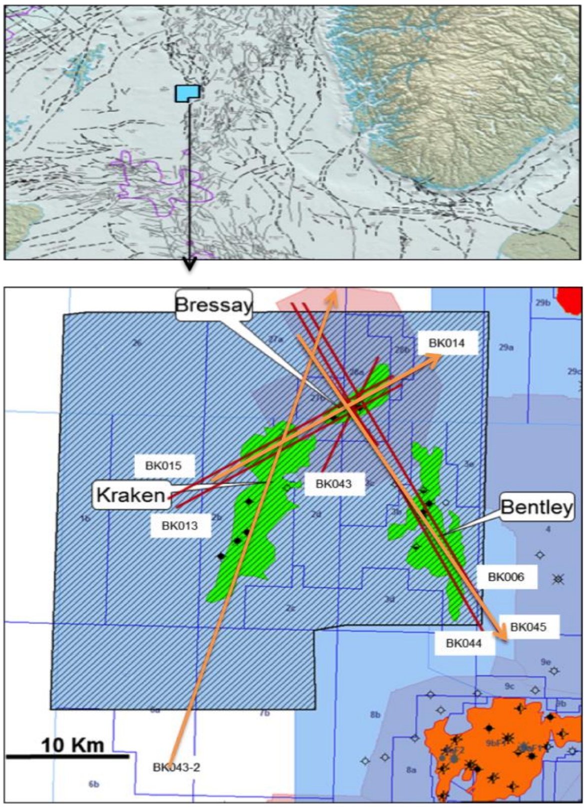

Figure 1. The Towed Streamer EM BBK survey area, where the lines show the EM acquisition lines. The lines BK043, BK014 and BK006 are indicated in orange.

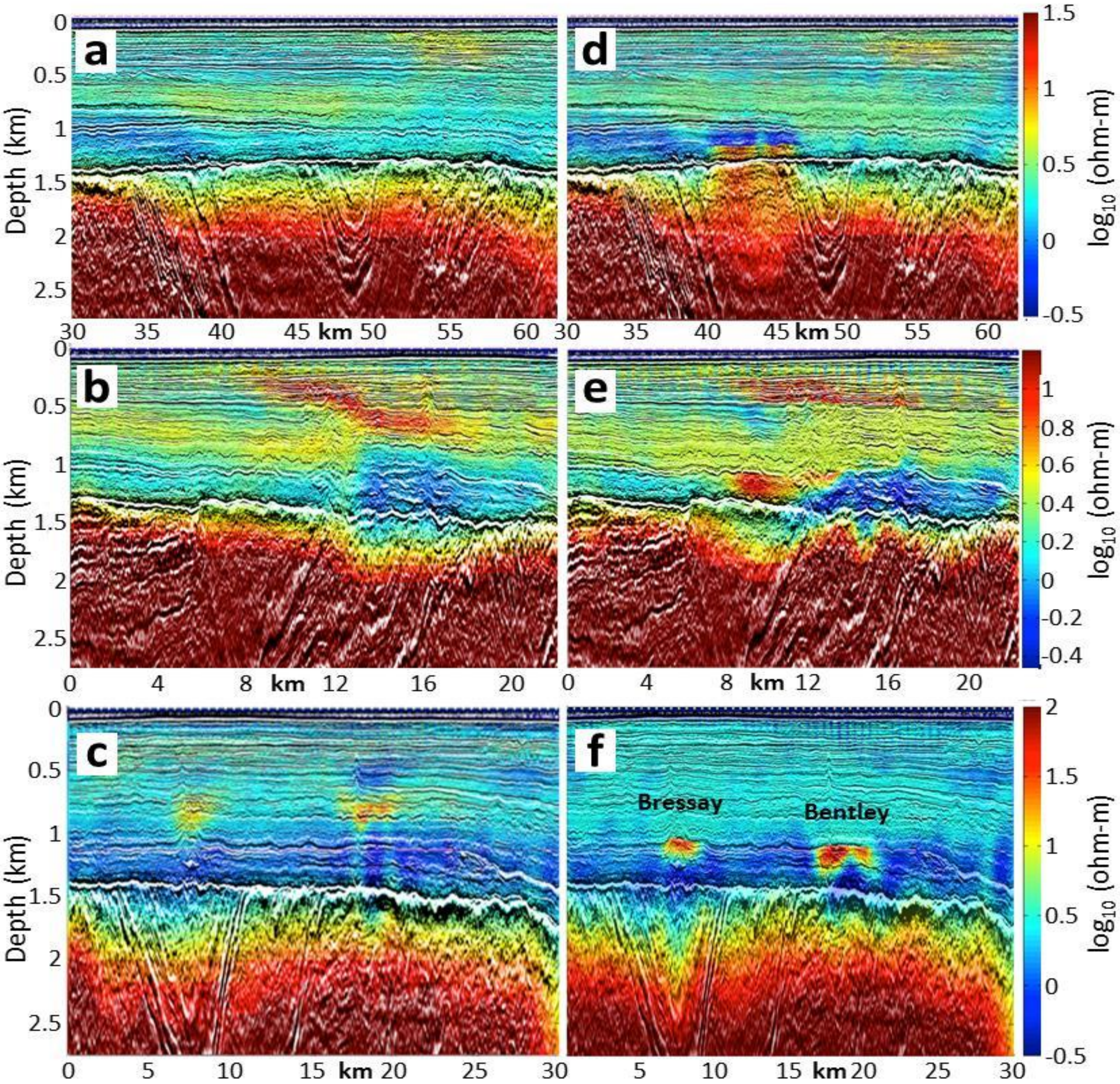

Figure 2. The vertical resistivity from the 2.5D EM anisotropic inversion of line BK043, Kraken (top), line BK014, Bressay (middle), and line BK006, Bressay (left anomaly), and Bentley (right anomaly) (bottom). The inverted vertical resistivity is co-rendered with the coincident depth converted seismic sections. On the left are the unconstrained inversions (a, b and c), and on the right are the seismic guided inversions (d, e and f).