Integrated analysis of Towed streamer EM and dual-sensor seismic data: Application to the Bressay and Bentley heavy oil fields, North Sea

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Summary

We introduce a method for integrating Towed Streamer EM and dual-sensor seismic data referred to as seismic guided EM inversion. The inversion workflow is initiated by adopting a sparse-layer depth model defined by dual-sensor seismic data to suggest resistivity boundaries without a rigid constraint. This makes good sense when considering the uncertainties in the seismic data from 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. The anisotropic resistivity variations within the layers are accommodated by the lower and upper boundaries, which can be estimated by the unconstrained 2.5D anisotropic inversions. We describe in detail the workflow by applying it to a dataset example resulted from a complex geological region where the heavy oil fields known as Bressay and Bentley are located in the North Sea. Seismic imaging over these fields is challenging since they are rich in injectites, having steep and irregular features. There are also other resistive features such as the Balder tuff, granite intrusions and the basement that can interfere with a fully unconstrained EM inversion. The method introduced here is applicable for exploring complex geological regions, in particular in a frontier exploration, where CSEM and seismic data co-exist.

Introduction

In 2012 PGS conducted a challenging survey in a complex geological region over Bressay, Bentley and Kraken (BBK) heavy oil fields in the North Sea (Figure 1), with the newly developed controlled source Towed Streamer EM acquisition system. The towed system deploys a ~7.7 km receiver cable at 50 -100 m water depth, and a powerful (1,500 A) 800 m long bi-pole source at 10 m depth. Towed at a speed of 4 knots, 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. The Towed Streamer EM system is thus able to provide the dense sampling, data quality and SNR (signal-to-noise ratio) required to image challenging targets in a shallow water environment.

The ideal companion to high quality marine EM data is the dual-sensor broadband seismic data, and the application of integrated analysis of seismic and marine EM in de-risking exploration prospects has led to a significant number of success stories since 2000 (e.g. Karman, et al., 2013). When assessing the prospectivity in complex geological environments, where seismic provides a high resolution structural image of the subsurface, marine EM estimates the resistivity of assumed reservoirs, and as such is more sensitive to the presence of hydrocarbons. The integration of seismic with CSEM data can thus provide subsurface information that is either unreliable or simply unavailable when only a single data type is used. We propose here a method for integrating towed streamer EM and dual-sensor seismic data, referred to it as seismic guided CSEM inversion. We show the workflow by applying the method to an area with complex geology resulting in challenging imaging issues of the Bressay and Bentley fields. The two heavy oil reservoirs are rich in injectites, located in close proximity to other high resistivity settings, such as the regional Balder Tuff and a few granite intrusions.

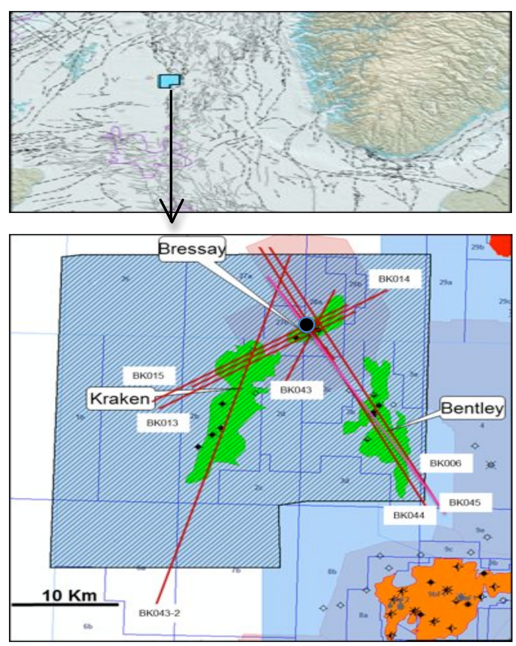

Figure 1: Map showing the Towed Streamer EM BBK survey area, where the thick red lines indicate EM survey lines. The well log: 3/28A-06, is located approximately at the center of Bressay, as indicated by the large black dot.

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Seismic and well log data

Located at the western edge of the Viking Graben, Bentley and Bressay are situated in UK Quadrant 9, North Sea, within a depth range of ~1,100-1,300 m, beneath a shallow water column of ~ 90 - 130 m (Figure 1). Both fields are found in the Dornoch Formation of late Palaeocene age. The formation within the block consists of coarse clastics, transitioning to the formation of a prograding delta compound across the eastern boundary of the Shetland Platform. The main source-rock is the Kimmeridge Clay Formation (Upper Jurassic) encountered within Viking Graben to the east of the block, whereas the targets are the Heimdal sands within the Lista formation, which consist of a complex, disrupted channel system of unconsolidated and uncemented sands and remobilized injectites (Figure 2). Discovered in 1976 and 1977, respectively, Bressay and Bentley contain ~200 – 300 million barrels of recoverable oil. Velocity information from seismic processing shows that the channels/injectites are filled with high-velocity material. This has also been confirmed by the appraisal wells that found the in situ heavy oil (11 – 12 API) with a viscosity of 1,000 cp. The Heimdal heavy oil sands are difficult to image with seismic data alone due to the low acoustic impedance (AI) contrast with the surrounding shale (Figure 2), despite the fact the well logs show a clear trend for the sands (Figure 3).

Unconstrained EM inversion

The BBK Towed Streamer EM survey, as shown in Figure 1, consists of two parallel survey lines in the NNW to SSE directions over the Bressay, Bentley and Kraken fields. The CSEM data consist of a wide range of offsets, 743 – 7,457 m, and 6 frequencies from 0.2 to 1.2 Hz with an increment of 0.2 Hz. The data quality is good, with a low noise level, and the overall uncertainties of the data are ~ 5%. The attribute maps of the amplitude and phase show large EM anomalies over the reservoirs that persist from line to line (Bhuiyan et al., 2013).

The length of the 3 acquisition towlines over Bressay and Bentley are approximately 30 – 45 km long. We parameterized the model domain with a dense grid of around 20,000 unknown resistivity parameters (depending on the profile length) from the seafloor to a depth of 2 km. Because of the huge number of transmitter and receiver positions produced by the moving towed streamer system, the inversion of the towed streamer EM dataset is computationally challenging, and a pre-data processing procedure is thus required.

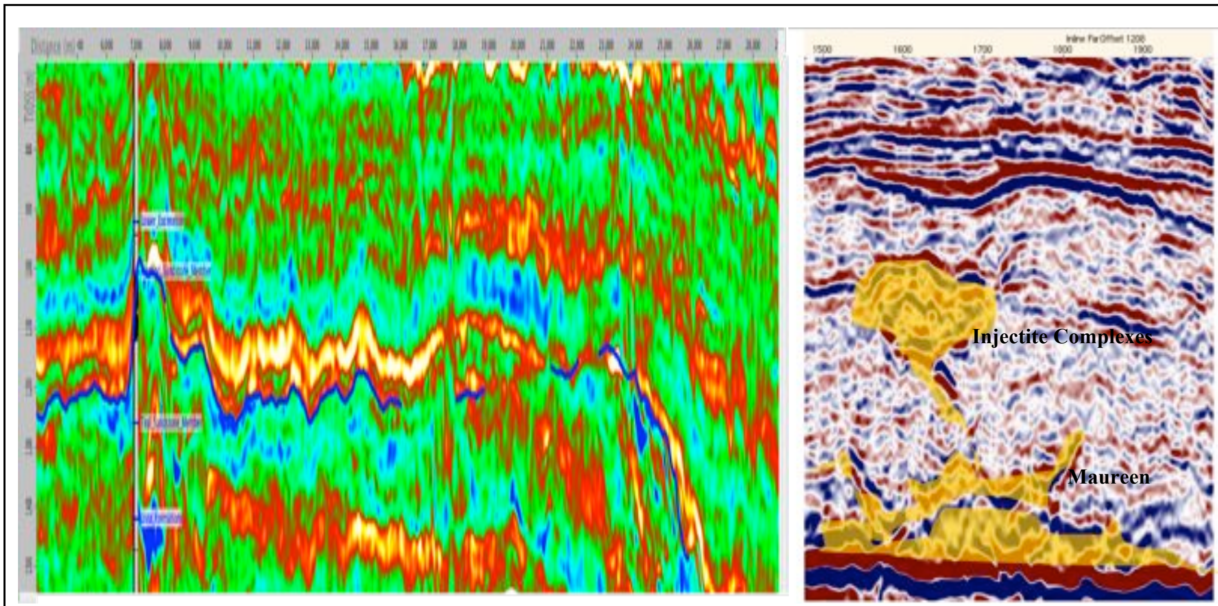

Figure 2: Left shows a seismic AI (low value in blue) section along the EM line BK006 (pink line in Figure 1), and the resistivity log for well 3/28A-06 (thin black line). The thick blue line indicates a seismic horizon picked at the top of Bressay and Bentley. Right: The injectites are highlighted in yellow to enhance their irregular shapes.

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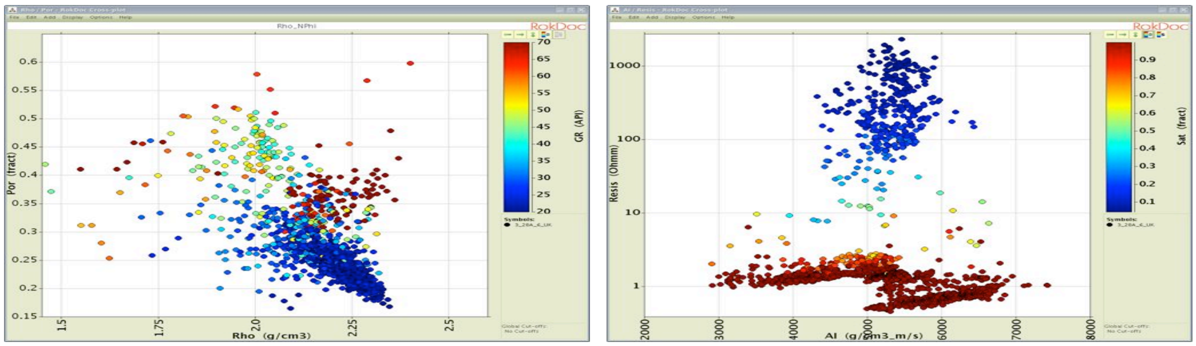

Figure 3: Well log 3/28A-06 rock physics analysis. Left: Density versus Neutron porosity, color coded by GR (Gamma Ray), displays a clear sand trend (blue) for the reservoir section, whereas the surrounding shales are more dispersed (yellow, green and red circles). Right: AI versus resistivity cross-plot with S_w (water saturation) in color, the surrounding shales are similar to the sands in AI, and the reservoir sand (blue) displays significant hydrocarbon charge with a low S_w.

It will be computationally very expensive if we invert for every source - receiver offset. This is because for a typical towed acquisition, e.g. BBK dataset, the data density is 4 times denser than a conventional node CSEM acquisition (Key, et al, 2014). The computational burden of the increased data density is further compounded by the fact that we need to use a bi-pole source and receiver (no more dipole approximation) and that using reciprocity to lighten the computational load is not possible since the towed receivers move with the transmitter (Key et al, 2014). In order to alleviate computation burden in this study, we have decimated the BBK dataset by de-sampling the source positions by a factor 2 and the receiver positions by 3, respectively, and the re-processed dataset consists of about 10k data points for each towline inversion.

By focusing on the seismically constrained sub-surface structures of interest, Key et al. (2014) has conducted 2.5D anisotropic inversions with above described data and model configuration, by adopting a parallel adaptive finite element (FE) algorithm, to retrieve a total EM field (Key, 2012). The unconstrained inversions recovered a resistive basement at a depth of ~1.5 km, and showed thin high resistivity features at the expected two reservoir locations. The inversion also revealed significant anisotropy in the overburden.

Seismic guided CSEM inversion

The seismic guided EM integration is aiming to provide a possible way to make inversion-based EM and seismic structural integration process more data and information-driven and less *a priori* model driven. We describe here the workflow for integrating the Towed EM and dual-sensor seismic data by applying the method to illuminate the heavy oil reservoirs of Bressay and Bentley, located in a complex geological area.

We setup line BK006 (pink line in Figure 1) seismic guided inversion to have an isotropic 1Ωm half space background, as shown in Figure 4. The first step of the seismic guided inversion is to perform an unconstrained (blind without considering field geology) anisotropic inversion of the Towed EM data. 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). Although the unconstrained inversion takes no account for complex or higher dimensional structures, it allows the class of structures to which the data are most sensitive, and variations in these structures across the area to be assessed. One of the prominent features that unconstrained inversion shows is a conductive and anisotropic overburden, while it recovers an isotropic resistive basement at the depths of ~1.5 km (The unconstrained inversion results are not shown for brevity, refer Key et.al, 2014 for detail).

Based on the results of unconstrained anisotropic inversion, the seismic guided EM inversion attempts to facilitate an optimal procedure to combine the complementary information from the Towed EM and dual-sensor seismic data. As shown in Figure 4 (top), the boundaries between the inter-bedded sands and shales in the overburden of Bressay and Bentley were defined by the post-stack dual-sensor seismic data, the anisotropic resistivity variations within the layers above the top reservoir (indicated by the star) were accommodated by the lower and upper boundaries, i.e. the lowest and highest average resistivities, as constrained by the previous step of the unconstrained anisotropic 2.5D inversions, whilst the remaining regions are all set as free parameter space for inversion. Note the seismic boundaries adopted here are inversion free (not fixed) parameters, and been adopted only for the purpose of 'guiding' and to inform the EM inversion these geological interfaces seen by seismic may be also the potential EM boundaries. The seismic guided inversion started from an isotropic 1Ωm half space, includes no assumptions at all

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about the background resistivity distribution, and no a priori information about the existence, size and shape of the reservoirs were given. The anisotropy shown by unconstrained inversion in the overburden is most likely caused by the inter-bedding of shale with brine sand, as shown by rock physics analysis at the well location (Figure 2). In practice, we further enlarge the inversion boundaries, as estimated from the unconstrained anisotropic inversion. We used the smallest and the largest values between the horizontal and vertical boundaries in each layer to form only one set of the lower and upper boundaries for both vertical and horizontal resistivity inversions. In this way, we maximize the inversion-searching domain to ensure the use of the seismic and the unconstrained inversion results as a guide, which, at the mean time, provide the appropriate regularization that the inversion requires.

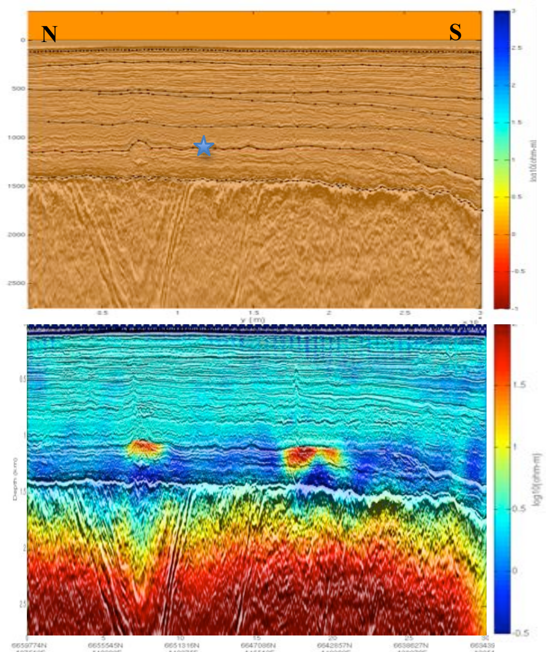

Figure 4: Top shows the seismic horizons (thin black lines) used for guiding line BK006 inversion, where the star indicates the seismically defined the top of the reservoirs. Bottom shows the vertical resistivities of the 2.5D seismic guided EM inversion for the BK006, co-rendered with the coincident depth converted seismic section (top). The inversion was started from a simple isotropic 1Ωm half-space model.

In Figure 4, the inversion result (for brevity, only vertical resistivity is shown) of the seismic guided EM inversion for the EM Line BK006, after 15 iterations (misfit reached 6.2%), is shown. The inversion result matches the reservoir depths and geometries of Bressay and Bentley and faithfully reflect the resistivity magnitudes by showing the prominent EM anomalies, strikingly coincident with the positions of the main target structures as shown by seismic (Figure 2). Similar consistent results were also obtained by inversion of the other two EM towlines, BK044 & 045 (ref. Figure 1).

The EM anomalies, shown in Figure 4, map the strength of the possible hydrocarbon charge spatial distribution of Bressay and Bentley. Since they are rich in injectites having steep and irregular features, compounded by the fact that the heavy oil means the low acoustic impedance contrast with the surrounding shale, seismic imaging over these fields is challenging and was only able to delimitate the major geological interfaces, as shown in Figure 2. The result obtained from this study has thus provided the important information for Bressay and Bentley reservoir characterization.

As revealed by the unconstrained inversions, the seismic guided EM inversions confirm the same degree of anisotropy in the overburden, which persists from line to line, whereas the basement is shown to be isotropic (Key et al., 2014). While anisotropic inversion clearly recovered these shallow anisotropic resistors in the overburden, isotropic inversion resulted in some strong artificial alternating stripes of resistive and conductive layers creating a final meaningless model that presented no plausible geological scenario. Key et al. (2014) have thus concluded that in the BBK region anisotropic inversion is mandatory.

More fine-scale resistive structures might possibly be revealed by the seismic guided EM inversions when the full dataset were inverted. To further improve the towed streamer EM data processing workflow is challenging but is our current focus of study.

Conclusions

We have presented the seismic guided EM inversion method, and it has been applied in the inversion of a Towed Streamer EM dataset acquired over a complex geological area of the BBK to illuminate the Bressay and Bentley heavy oil reservoirs. The data processing examples shown here demonstrate the seismic guided EM inversion can be used for exploring complex geological regions, and is applicable in a frontier exploration where CSEM and 3D seismic data co-exist.

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EDITED REFERENCES

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