

Towed Streamer EM data density and target recoverability

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Summary

Towed Streamer EM is a recently introduced marine CSEM data acquisition system. The use of the towed system facilitates dense subsurface data sampling, which improves the signal-to-noise (S/N) ratio, lateral and vertical resolution, thus provides the data quality required for imaging challenging targets in a shallow water environment. In this study, we investigate the image recoverability issue of the CSEM inversion using different source and receiver space distributions. It is evident that the fine-scale resistive structures can only be recovered from inverting the dense dataset. By adopting a staged integration workflow, where seismic, well log and Towed Streamer EM technologies make contributions with their individual strengths, we demonstrate that such an integration workflow provides a powerful tool for reservoir characterization, discriminating between lithology and fluid properties. It can serve as veritable inputs for reservoir volumetric analysis i.e. to estimate the volume of hydrocarbon in place.

Introduction

The controlled-source electromagnetic (CSEM) method has been extensively used to search for hydrocarbons given that accumulation of oil and gas can be charged by high resistivity. By using a Towed Streamer EM system, the CSEM data acquisition becomes easy and it is possible to carry efficient operations at both prospect and regional scales. The towed system has also facilitated the simultaneous acquisition of both seismic and EM data by the same vessel, which significantly reduces the operation cost.

One of the key technical features of the Towed Streamer EM systems is the dense in-line sampling of the electric field. For a typical towed acquisition the spatial data density is more than ~4 times denser than a conventional seafloor node CSEM acquisition (Key, et al, 2014). The inversion of the towed streamer EM dataset is therefore computationally much more intensive and challenging. However, the extra cost is offset by benefits such as improved signal-to-noise (S/N) and lateral and vertical resolution, which will translate into values and turn out of the resistivity models with improved resolution.

The solution of the geophysical inverse problem is non-unique. This applies to the interpretation of Towed streamer EM data. Effects due to bathymetric variations, shallow subsea electromagnetic variations, as well as

anisotropic geological formations all contribute to form an electromagnetically complex environments from where a solution needs to be sought. When assessing the prospectivity in a complex geological region, the most reliable answer is obtained by a combination of tools within an integrated framework. By integrating seismic and CSEM data in a staged workflow, limitations of each method can be over-come and the strength of each exploited. Where seismic provides a high-resolution structural image of the subsurface, EM estimates the resistivity distribution. To integrate Towed Streamer EM and dual-sensor seismic data, we have introduced a seismic guided EM inversion (Du and Hosseinzadeh, 2014). The inversion workflow is initiated by adopting a sparse-layer depth model defined by the 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, more importantly, the fact that a reservoir can be hydrocarbon-charged to an unknown degree, corresponding to the spill-point or less. Where the anisotropic resistivity variations within the layers are accommodated by the lower and upper boundaries, estimated by the unconstrained 2.5D anisotropic inversions.

The BBK Towed Streamer EM

The Bressay, Bentley and Kraken (BBK) heavy oil (11-12 API; viscosity of 1000 centipoise) reservoirs are located on the western edge of the Viking Graben in UK Quadrant 9 of the North Sea (Figure 1). The BBK discoveries are considered to pose several challenges to conventional CSEM surveying. The very shallow depth of water, 90 - 130 m, dampen the EM anomalies due to airwave coupling. The formation within the block consists of coarse clastics, which lead to the further formation of a prograding delta compound. The reservoirs are to a large extent injectites, located in close depth proximity to other high resistivity settings, such as the regional Balder Tuff, and granite intrusions. The geology in the region is thus complex, resulting in challenging imaging issues. The heavy oil charge means there is no direct hydrocarbon indication in the seismic data due to the low acoustic impedance contrast between the reservoir and its surrounding shale.

The BBK Towed Streamer EM survey was carried out by using a ~7.7 km receiver cable deployed at 50 -100 m depth, and a powerful (1,500 A) 800 m long bipole source towed at 10 m depth. Towing speed was 4 knots, source spacing 250 m, with 44 unique receiver positions for each source point. The highly sensitive receiver electrodes housed in the streamer were able to densely sample the

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subsurface with an average offset interval of ~160 m over offset ranges from ~800 to 7595 m. The Towed Streamer EM system thus provided the dense sampling, data quality and signal-to-noise ratio required for imaging challenging targets in such a shallow water and complex geological environment.

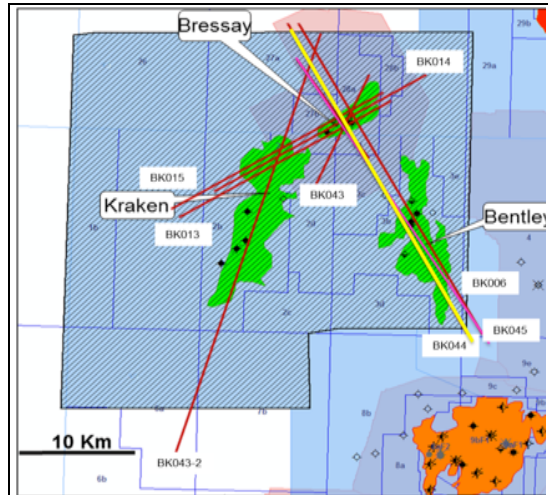


Figure 1: Map of Bressay, Bentley and Kraken (BBK) area. The red lines show the Towed Streamer EM BBK survey lines. BK045 line is indicated by yellow.

Seismic guided EM inversion

The seismic guided inversion (Du and Hosseinzadeh, 2014) aims to facilitate an optimal procedure to combine the complementary information from dual-sensor seismic data and the Towed Streamer EM. The seismic data is best at constraining structure, and the EM data is best at constraining the reservoir strength. The inversions are guided by the seismic to find the stratigraphic boundaries, whereas the resistivity variations within the overburden layers are accommodated by plausible lower and upper boundaries suggested by unconstrained EM inversions.

We use line BK045 as a data example. The seismic guided inversion was set up to have an isotropic 1 Ω m half-space background, as shown in Figure 2. While the boundaries between the intra-bedded sands and shales in the overburden were suggested by the post-stack dual-sensor seismic data, the anisotropic resistivity variations within these layers above the top reservoir (indicated by the star) were accommodated by the lower and upper boundaries, the lowest and highest average anisotropic resistivities, constrained by the unconstrained inversions, whilst the remaining regions are all set as free parameter space for inversion. Note the seismic boundaries adopted here are free parameters and have been adopted only for the purpose of ‘guiding’ and to inform the EM inversion these

geological interfaces mapped by seismic may be also be potential EM boundaries. In this way the inversion-searching domain is maximized to ensure the use of both the seismic structure and the results of the unconstrained inversion all as the guiders, whilst still employing the appropriate regularization that the inversion required.

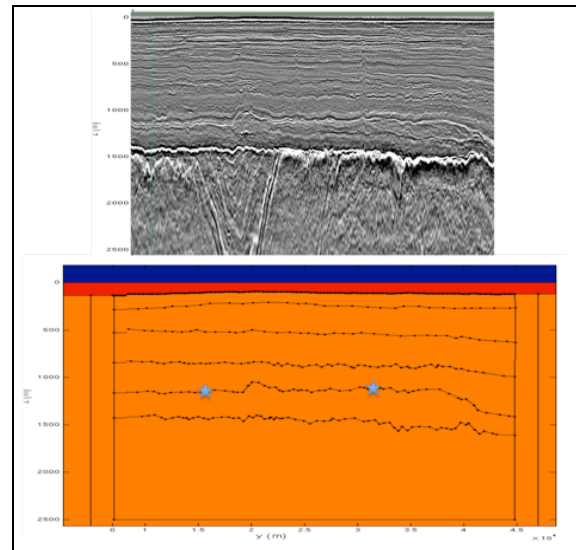


Figure 2: The setup for conducting Line BK045 seismic guided inversion. The Top panel shows the coincident broadband dual-sensor seismic section in depth; the bottom panel shows the interpreted seismic horizons extracted from the top and adopted for guiding the inversion. The stars indicate the seismically defined top reservoir interface. Note that inversion starts from a 1 Ohm m half-space.

The Towed Streamer EM dataset was inverted using the MARE2DEM codes, an Occam based 2.5D inversion, build around a parallel adaptive finite element algorithm (Key, 2012). The line BK045 is ~45 km long. The towed EM data consists of 172 source-receiver gathers (so called ‘shorts’), with source and receiver spacing of 250 m and 160 m, respectively. Each of the gathers consist of frequency responses from 44 offsets, between ~800 – 7600 m, from six frequencies from 0.2 to 1.2 Hz with the step of 0.2. The inversion thus need to deal with in total of ~90800 input data.

Case 1: We parameterized the model domain with a dense triangular grid of around 20,100 with 40200 unknown (anisotropic) resistivity parameters from the seafloor to a depth of 2.5 km. It would have been computationally too expensive to invert for every source-receiver offset. In order to alleviate computation burden, in particular to fit within the available computer memory, we pre-processed the data by decimating the dataset, re-sampling the source positions by a factor of 2 and the receiver positions by 3,

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respectively. After the pre-processing, the new dataset consists of ~15490 data points. We set a 3% error floor to the data.

Figure 3 shows the EM Line BK045 inversion result (for brevity, only vertical resistivity is shown). After 15 iterations, the data was fit to a root-mean-squared (RMS) misfit of about 6.2%. The inversion result matches the reservoir depths and geometries of Bressay and Bentley. The resistivity magnitudes reflect the reservoir strength, showing as the prominent EM anomalies, coincident with the positions of the main target structures indicated by seismic.

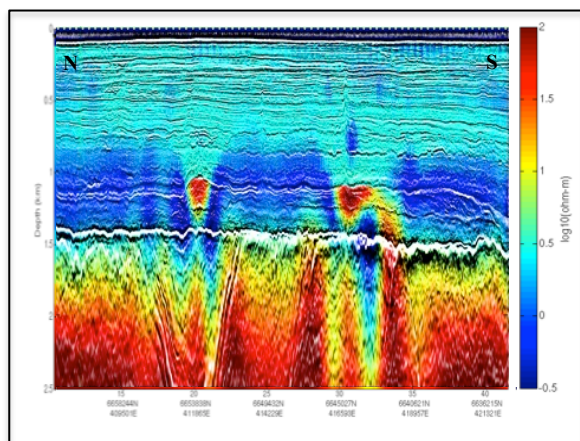


Figure 3: Seismic guided inversion for line BK045 by Case 1. The vertical resistivities are co-rendered with the coincident depth converted seismic section.

While the inversion clearly recovered the targets at the depth and lateral location of the known reservoirs of Bressay and Bentley, it has also created a few ‘holes’ in the basement that presented no plausible geological scenario. This is probably due to in-completed data coverage (a cost from the heavy re-sampling of the dataset). In a vertical sense for the southern part of Bentley the resistive features have not been recovered, but are partially merged into the basement. For the case of a 2D structure, MacGregor (2014) and Tshering et al. (2014) have done independent studies for the issue of the ‘recoverability’, using synthetic data from the node and towed acquisition system, respectively. One of the important features revealed by these studies, regardless of the acquisition system, is that ‘recoverability’ depends heavily on the data density or spatial sampling, and more fine-scale resistive structures could only be recovered from the dense dataset.

Case 2: To investigate the result further, we chose to invert only half-length of line BK045. The purpose is to

understand how the Towed Streamer denser spatial sampling is going to translate into values for the resistivity models that would possibly improve resolution and precision in comparison to those derived from coarser data (Case 1). We re-parameterized the model domain for the portion of the line covering only Bentley with a denser triangular grid of ~23,200 with 46400 (anisotropic) unknown resistivity parameters from the seafloor to a depth of 2.5 km. This setup halves the size of the inversion grid used in Case 1. The inversion domain is now only ~20 km long (covering line between ~25 – 45 km), which allows us to invert the data for every source-receiver offset, and to process the full recorded dataset for the segment of line.

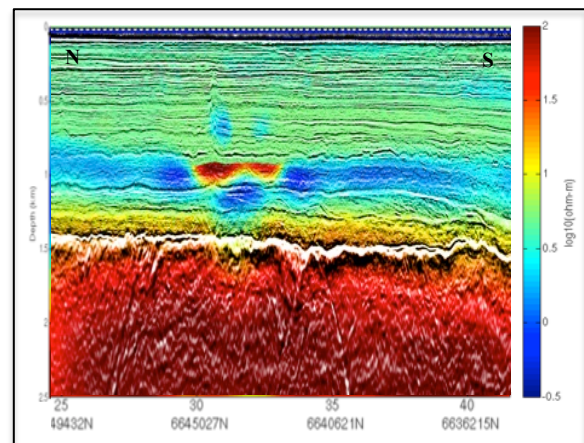


Figure 4: Seismic guided inversion for line BK045 by Case 2. The vertical resistivities are co-rendered with the coincident depth converted seismic section.

Figure 4 shows the final retrieved vertical resistivity model after fit to a root-mean-squared (RMS) misfit of about 4.5%. By comparing the results obtained in Case 1, shown in Figure 3, more fine-scale resistive structures have been revealed. The denser data inversion was able to vertically separate the reservoir from the basement, while retrieving the basement boundary with lateral resistivity variations following closely the amplitude of seismic reflections. Compared to Case 1 it is also worth to note the reservoir of Bentley, as shown in Figure 4, was imaged as a vertically more compacted (ref. to Figure 3) resistivity anomaly centrally hooked by two displaced high anomalies, side by side, forming a ‘w’ shape of the bottom.

Integrated analysis

Hydrocarbons are found in geologic traps, a geological structure that will keep oil and gas from migrating either vertically or laterally. The knowledge of reservoir dimension is an important factor in quantifying recoverable

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hydrocarbon resources. This includes the thickness and area extent of the reservoir. These parameters serve as veritable inputs for reservoir volumetric analysis i.e. the volume of hydrocarbons in place.

In this study, we use the mapped reservoir area from seismic interpretation. Figure 5a shows, in a plane view, the reservoir top horizon (in green), and on the top, the boundaries of the Bentley lateral extent (denoted by a polygon) from seismic interpretation. Line BK045 crosses the long axis of Bentley from north to south (thin yellow line). The seismic interpreted outline of the reservoir is shown in the plane view together with the vertical 2D profile of resistivity distribution, obtained by the Case 2 high data density inversion. In Figure 5a it is evident that the strong resistivity anomalies (in red) is restricted within the boundaries of the seismic delineated reservoir. In addition, it also explains the 'w' shaped Bentley 2D resistivity distribution: that central image is concave (indicated by the red arrow) due to the fact that part of the survey line passes quite near to reservoir boundary (less resistive).

In our integrated analysis, we have also gathered and used information from a number of available exploration wells (Figure 5b). The oil-water-contact (OWC) determined by these wells is located at depths ~ 1136 – 1138 m. We may, therefore, reasonably assume that the OWC is flat in the northern Bentley, whereas we may expand this assumption to the southern. It is most likely that sand bodies below OWC (indicated by the grey plane) are water saturated. However, note here that the resistivity anomalies (denoted by red dots, Figure 5b) are overlain with those major sand bodies above the OWC.

From Figure 5b, we observe good agreement between seismic reservoir interpretation, well logs and the EM inversion. The high resistivity anomalies not only map the reservoir strength but also delineate the possible hydrocarbon charged sand bodies within the reservoir. By using the staged integration, where seismic, well log and Towed Streamer EM technologies make selectively contributions with their own individual strengths. Such an integration workflow provides a useful tool for reservoir characterization, discriminating between lithology and fluid properties. It can serve as veritable inputs to distinguish water saturated from hydrocarbon charged volumes in a reservoir.

Conclusions

We studied the image recoverability issue of the CSEM inversion, by using the Towed Streamer EM data acquired over BBK, North Sea. We demonstrated that the complex and fine-scale resistive structures could only be recovered

from inverting the dense dataset. By using a staged data integration workflow where seismic, well log and Towed Streamer EM technologies make selectively contributions with their individual strengths, we demonstrated that such an integrated analysis provides a powerful tool for reservoir characterization and can serve as veritable inputs for reservoir volumetric analysis, i.e. to estimate the volume of hydrocarbon in place.

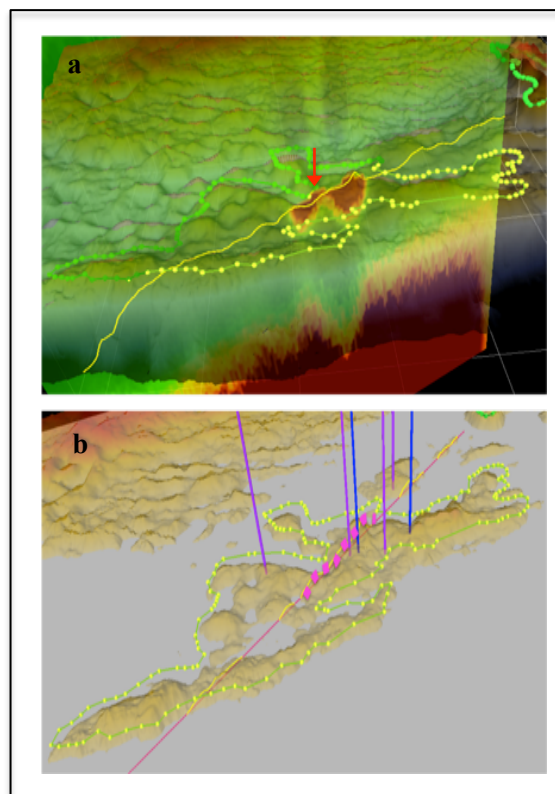


Figure 5: (a), Vertical plane shows inverted Line BK045 (thin yellow line) vertical resistivity (in red), whereas in plane view shows the reservoir top horizon (in green), plotted on the top is the outlet of Bentley reservoir (yellow & shallow green dot lines), determined by seismic interpretation. (b), Reservoir top horizon (in yellow & red) overlain on the OWC (grey plane). A thin red line indicates the footprint of Line BK045, whereas the red dots denote those highest resistivities, as shown in (a). Vertical lines indicate well locations.

Acknowledgements

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2015 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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