

Seismic Guided EM Inversion in Complex Geology - Application to the Bressay and Bentley heavy Oil Discoveries, North Sea

Z. Du* (PGS) & S. Hosseinzadeh (PGS)

SUMMARY

A novel method for integrating Towed Streamer EM and dual-sensor seismic data is introduced. The method is referred to as seismic guided EM inversion, where a sparse-layer depth model defined by seismic is used to suggest resistivity boundaries without a rigid constraint. This makes good sense since a reservoir can be hydrocarbon-charged to an unknown degree corresponding to the spill-point or less, and the final EM model boundaries do not have to be exactly identical to the seismic determined ones. The inversion workflow is described in detail as applied to 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 deployed a ~7.7 km receiver cable at 50 -100 m water depth, and a powerful (1,500 A) 800 m long bipole 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 for imaging 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 joint interpretation of seismic and marine EM in de-risking exploration prospects has led to a significant number of success stories since 2000. 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 introduce here a new method of integrating EM and seismic data and refer to it as seismic guided CSEM inversion, with a data example from an area with complex geology resulting in challenging imaging issues of the Bressay and Bentley fields. The two heavy oil reservoirs are injectites, located in close proximity to other high resistivity settings, such as the regional Balder Tuff and a few granite intrusions.

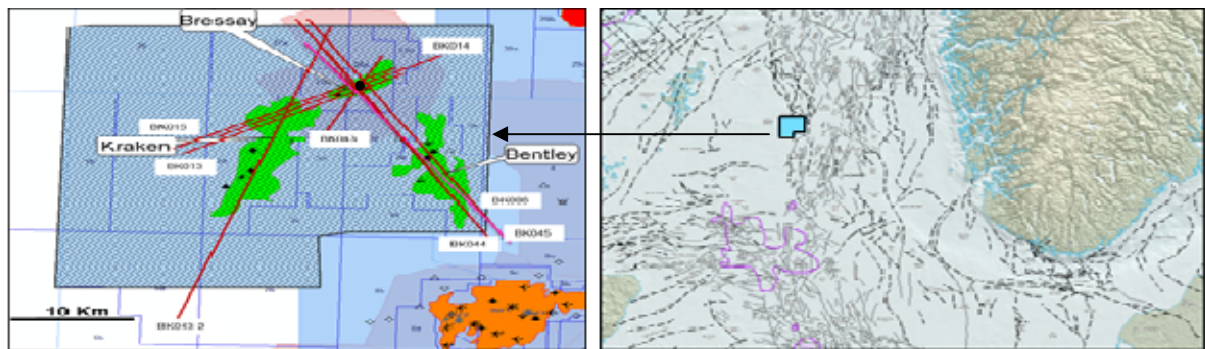


Figure 1 The Towed Streamer EM BBK survey area (red lines indicate EM survey lines). The well log: 3/28A-06, is located approximately at the center of Bressay, as indicated by the large black dot.

Seismic and well log interpretation

Located on the western edge of the Viking Graben, Bentley and Bressay are situated in UK Quadrant 9, North Sea, within a depth range of 1,000-1,300 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 shale, 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 contrast with the surrounding shale (Figure 2), despite the fact the well logs show a clear trend for the sands (Figure 3).

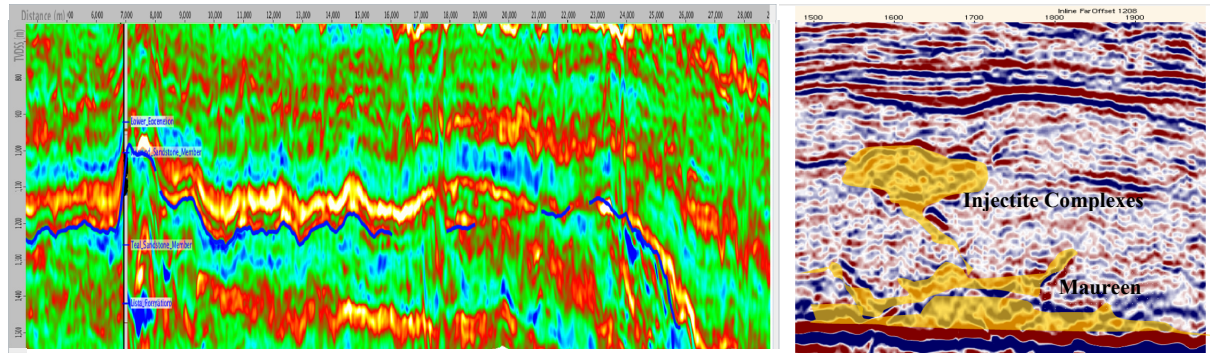


Figure 2 Left shows a seismic P-Impedance section along the EM line BK006, and the resistivity log for well 3/28A-06, (low value in blue). The thick blue line indicates a seismic horizon picked at the top of Bressay. Right: The injectites are highlighted in yellow to enhance their irregular shapes.

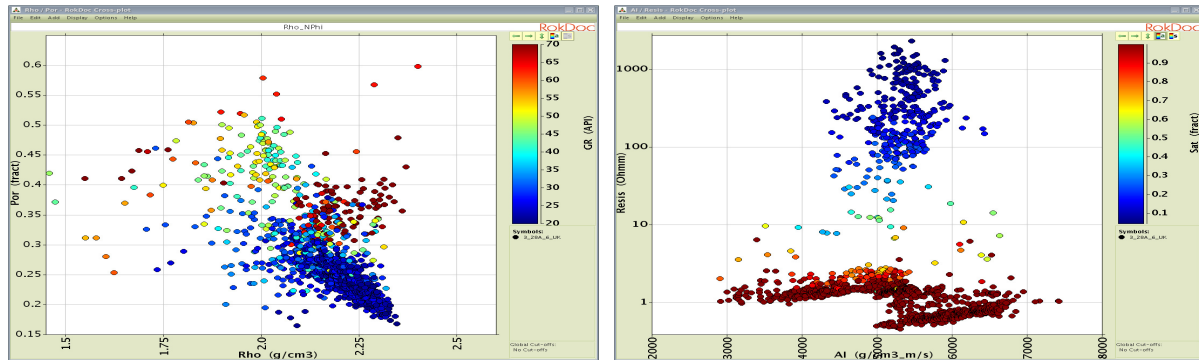


Figure 3 Well log 3/28A-06 rock physics analysis. Left: Density versus Neutron porosity, color coded by GR, displays a clear sand trend (blue) for the reservoir section, whereas the surrounding shales are more dispersed (yellow, green and red circles). Right: AI versus resistivity cross-plot with S_w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

EM Modelling and 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 and Bentley fields. The CSEM data consist of a wide range of offsets, 943 – 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).

By focusing on the seismically constrained sub-surface structures of interest, Bhuiyan et al. (2013) have performed detailed EM modelling and 1D CMP (common-mid-point) inversions along the survey lines. The inverted resistivity models were then stitched together to form a 2D resistivity section. Using the updated reservoir models, a 3D EM forward modelling was also performed. The study demonstrates that the seismically based structural information can help to resolve the ambiguities in the responses between the reservoir and the non-hydrocarbon charged high resistivity adjacent structures (the granite intrusion and Balder Tuff layer). The EM model data indicates that resistive structures can be interpreted even when seismic interpretation is challenging (Figure 2), thus confirming that EM data can complement seismic data in building reservoir models.

In parallel with this study, Key et al. (2014) has conducted 2.5D anisotropic inversions, by adopting a finite element (FE) algorithm, to retrieve a total EM field. 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

At present, there are two major approaches applied to joint seismic and CSEM interpretation with varying degrees of success: (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 (e.g. Medina, et al. 2012); (2) ‘collaborative’ methods that involve the use of petrophysical characteristics to relate the two datasets, e.g., water saturation and porosity have been used to provide a link between resistivity and seismic velocity in porous media (e.g. Du and MacGregor 2010). The ‘cooperative’ method needs input of the ‘boundaries of geological targets’ as hard constraints for the joint inversion. The inversion makes use of the assumption that all these ‘boundaries of geological targets’ must be common boundaries for both seismic and CSEM data, even though the two datasets exhibit very different spatial resolution, and the fact that they are based on measurements of very different physical properties of the subsurface. The key for a ‘collaborative’ joint inversion to be successful relies on the rock physics models forming the link between the rock properties to elastic and electrical properties measured respectively by seismic and CSEM data. However, there is no guarantee that the rock physics models obtained, either numerically or empirically, at well locations are valid away from the well and representative of the entire field.

A novel approach for integration of seismic and EM data is introduced that we call a seismic ‘guided’ EM inversion. It is discussed in detail specifically in the context of Towed Streamer EM and dual-sensor 3D seismic data over the complex geological area of the Bressay and Bentley reservoirs.

The first step is to perform an unconstrained inversion of the EM data. This is useful because it illustrates the inherent sensitivity of the data to subsurface resistivity structure (only the structures required by the data will be present in the inversion result), although its resolution of structural detail is poor. As shown by Key et al. (2014), the unconstrained 2.5D EM anisotropic inversion of the Towed Streamer EM data is able to reveal important geological features. Among the prominent features that the inversion reveals is a conductive and anisotropic overburden, while retrieving an isotropic resistive basement at the depths ~1.5 km. The inversions include no assumptions at all about the background resistivity distribution, or the existence, size and shape of the reservoirs. The anisotropy 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). The Bressay and Bentley reservoirs are located between the base of Balder Tuff and Base Cretaceous Unconformity (BCU). The BCU corresponds to the boundary of the resistive basement.

The seismic guided inversion combines the reliable information given by the 2.5D EM unconstrained inversion and the structural information constrained by seismic (Figure 4). The boundaries between the inter-bedded shales in the overburden were defined by the post-stack dual-sensor seismic data, whereas the resistivity variations within the layers were accommodated by the lower and upper boundaries, i.e. the minimum and maximum average resistivities, as constrained by the previous step of the unconstrained 2.5D inversions (Key et al., 2014). Note the seismic boundaries adopted here are not rigidly held to in the inversion, but rather adopted only for the purpose of ‘guiding’ and to inform the EM inversion that the geological interfaces seen by seismic may also be the potential EM boundaries. We have chosen to perform the inversion using the uncertainty boundaries, by mimic of a global genetic algorithm (GA) joint inversion, derived by Du and MacGregor (2010). In this way, the seismic guided inversion will be able to reliably handle the possible variation of the resistivities in the overburden layers.

In Figure 4, we show an example of applying the seismic guided EM inversion to the EM Line BK006 (Pink line in Figure 1). No other assumptions or a priori information about Bressay and Bentley reservoirs or background resistivities have been made in this inversion, except as described above. The inversion results matched the reservoir depths and geometries and faithfully reflect the resistivity

magnitude by showing a prominent EM anomaly, strikingly coincident with the position of the main target structure as shown by seismic (Figure 2). Similar consistent results were also obtained by inversion of two of the other EM survey lines, BK044 & 045 (Not shown for brevity). As observed in the unconstrained inversion, the seismic guided EM inversion confirms the same degree of anisotropy in the overburden, which persists from line to line, whereas the basement is shown to be isotropic. Hence, both aspects are shown to be true regional geological features.

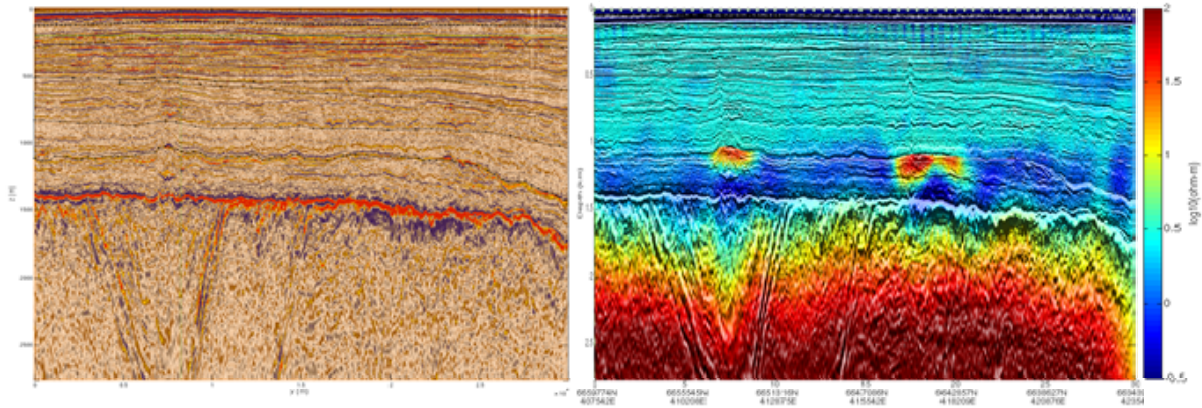


Figure 4 Left panel shows the seismic profile along EM line BK006, where the thin black lines denote the seismic horizons adopted by the seismic guided EM 2.5D inversion. Right panel shows the vertical resistivities of the 2.5D seismic guided EM inversion for the BK006. The starting point of the inversion was a 1 Ω m half-space.

Summary

A novel CSEM and seismic integration method referred to as seismic guided EM inversion has been introduced. The new method has been applied in the inversion of a Towed Streamer EM dataset acquired over a complex geological area of Bressay and Bentley to illuminate the heavy oil reservoirs. We have shown how this approach enables a robust and reliable workflow for integrating CSEM and seismic data. The seismic guided EM inversion introduced here is applicable for exploring complex geological regions, in particular in frontier exploration where CSEM and seismic data co-exist.

Acknowledgements

We acknowledge PGS for allowing us to publish the results. We thank BlueGreen Geophysics for providing the MARE2DEM 2.5 D inversion code for data processing.

References

Bhuiyan, A., Sakariassen, R., Hallanger, O. and McKay, A. [2013] Modelling and interpretation of CSEM data from Bressay, Bentley and Kraken area of East Shetland Platform, North Sea. *75th EAGE Conference and Exhibition*, Expanded Abstract.

Du, Z. and MacGregor, L. [2010] Reservoir characterization from joint inversion of marine CSEM and seismic AVA data using Genetic Algorithms: a case study based on the Luva gas field. *80th SEG Annual Meeting*, Expanded Abstract.

Key, K., Du, Z., Mattsson, J., McKay, A. and Midgley, J. [2014] Anisotropic inversion of towed EM data from Bentley, Bressay and Kraken using parallel adaptive finite elements. *76th EAGE Conference and Exhibition*, Expanded Abstract.

Medina, E., Lovatini, A., Andreasi, F., Re, S. and Snyder, F. [2012] Improving subsalt imaging by incorporating MT data in a 3D earth model building workflow – A case study in Gulf Mexico. *74th EAGE Expanded Abstract*, B033.