3D CSEM over Frigg – dealing with cultural noise.

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Introduction

Recently, the marine Controlled Source Electromagnetic technique (mCSEM) has been used as an exploration tool in ranking and de-risking deep offshore prospects. The technique has found success as it is often a more direct determination of fluid-type via the resistivity measurement than seismic methods which rely on AVA information. A natural extension of the application of mCSEM is monitoring and appraisal of existing discoveries due to its sensitivity to fluid-type.

This extension makes a great deal of sense as EM methods are somewhat low-resolution and not very sensitive to geometry (Bhuiyan, 2009) and are often combined with seismic and well information to constrain the geometry and physical properties and are readily available for recent discoveries or fields under production. This is not always the case for exploration targets with perhaps uncertainty in the background resistivity structure. Presented here is the possibly innovative application of the mCSEM technique to a field at the end of its production life in an effort to locate bypassed reserves, along with the technical difficulties encountered in such projects.

Towards the end of production at Frigg, remaining free-gas pockets were observed with what was thought to be several GSm^3 of reserve remaining based on history matching and the original estimations made with earlier seismic data. For a full description of the Frigg field see Heritier et al 1979. The intention of using CSEM on the Frigg field was to locate and possibly quantify any remaining gas left un-produced or trapped in small structural closures referred to as 'attics' at the top of the reservoir. CSEM was demonstrated via 3D detailed feasibility to be more sensitive to saturation via the resistivity measurement than seismic techniques despite its lower resolution and inherent ambiguities. The lower resolution was considered in relation to the minimum target size requirement and the ambiguity was thought to be manageable given the wealth of information on Frigg regarding the depth control and formation resistivities from seismic and well data.

3D Feasibility Modeling

Initial testing of the CSEM concept for application to the Frigg problem took the form of detailed 3D feasibility modeling for a number of scenarios summarized in Figure 1. These 3D feasibilities considered four classes of scenario: two 10 km² targets to the north of the central area representing a group of 'attics' of stranded gas at 10 and 20m thickness (Models 1 and 2) and two centered on the top-centre structure at the site of production with gas-water contacts (GWC's) at 1830 and 1850m (Models 3 and 4) all at the top Frigg main reservoir level (see Figure 1 for cross-sections).

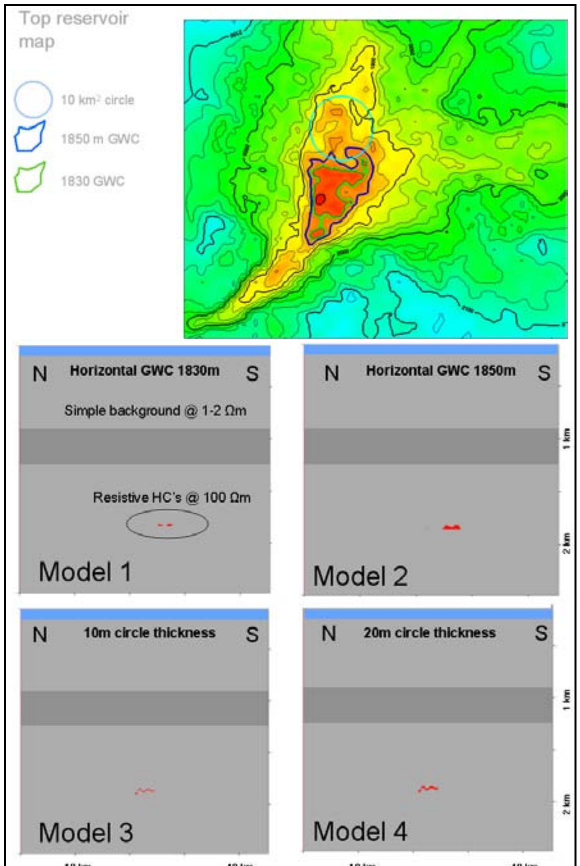

Figure 1: 3D CSEM feasibility scenario map views (top) with N-S central cross-sections of the four classes of models tested (bottom).

Figure 2 details the results of the feasibility in normalized amplitude/offset maps (3800m offset) at 0.2 Hz – the initial feasibility base frequency. A number of target sensitivities were tried to reflect different saturations with 100 Ωm, the lowest shown here. All feasibility scenarios produced what was thought to be significant (detectable) responses above 15-20% NMVO (Normalized Magnitude vs. Offset) except for the Model 1 GWC @ 100 Ωm due mostly to its lateral extent. These results from the 3D CSEM feasibility provided the confidence to move forward with an acquisition.

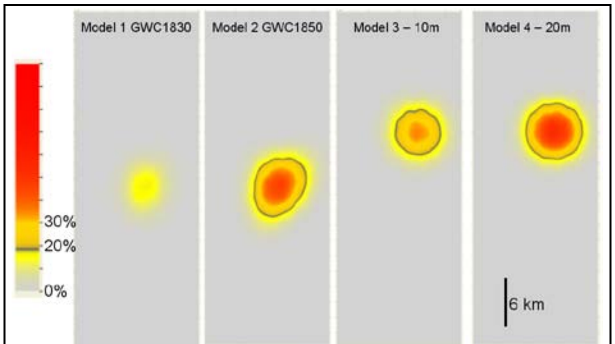

Figure 2: 3D CSEM feasibility results for the four scenarios displayed in map view normalised amplitudes @ 0.2Hz @ 3800m offset. Grey mark on colorbar is approx. 18%

The Acquisition

The 3D CSEM acquisition was designed to provide uniform and redundant coverage of the zone of interest with north-south tow-lines and approximately 1 km spacing of 106 receivers; however modifications were required to avoid a number of seabed pipelines and some wellheads in the area. The pipelines were of particular concern as being metallic, were expected to produce significant interference with the electromagnetic technique. A compromise plan was devised considering the pipelines and uniform coverage which appears in Figure 3. Transmission frequencies were chosen as 0.2 Hz base and 0.4, 0.6, 1.0 and 1.2 Hz higher harmonics in a custom waveform that was selected to specifically interrogate targets at the Frigg level by 1D modeling (see Mittet and Schaug-Pettersen, 2008). The 1D modeling demonstrated that in the shallow water of approximately 100m, the 0.2 Hz base frequency would be largely free from air-wave interference for the target under consideration.

The acquisition was completed late September 2009, with data quality considered good and excellent S/N due to a higher power transmitter current (1,250 Amps). Receiver data were considered good quality for the shallow water deployment of approximately 100m where currents and wave action can perturb the seabed instruments.

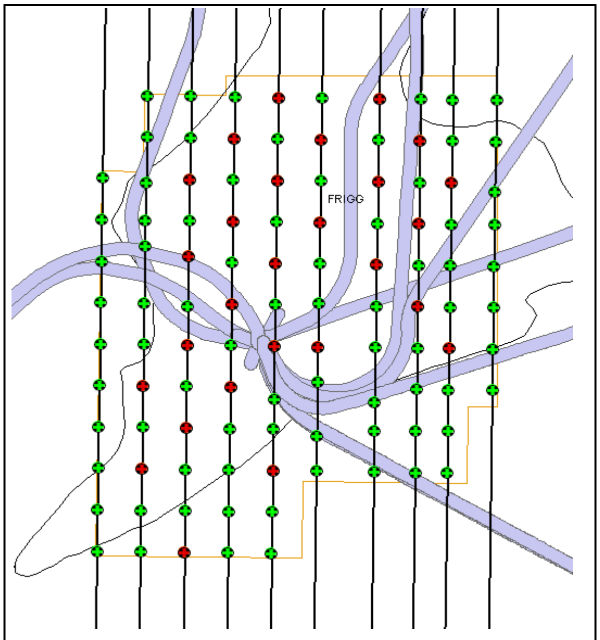

Figure 3: 3D CSEM acquisition plan with north-south tow-lines, and receivers marked in green. Red receivers are equipped with Ez vertical sensors. Seabed pipelines are shown in violet. An approximate field outline is in black.

Processing and cultural contamination

There were however large amounts of data contaminated by pipeline interference as illustrated in Figure 3 and 4. The worst affected data were in areas with tow-lines parallel to pipeline direction resulting in maximum coupling between the horizontal electromagnetic dipole of the transmission antenna, the pipeline and the in-line component of the receiver. Data affected by this type of interference are unpredictable and appear to have little usable sub-surface signal for use in analysis and inversion. Consequently, significant amounts of data were edited with a possibly detrimental impact on the information content of the survey.

However, these edits turned out not to compromise the ability of the technique to examine the areas of interest due to the inherent high redundancy of the 3D survey. This is because a full constellation of receivers were deployed during transmitter towing and an abundance of azimuthal (off-towline) data were acquired out to 10 km of offset. These azimuthal data can and often are at a higher angle to the pipelines where in-line data are affected and hence do not couple as strongly to the pipelines and thus are less affected by this type of interference. Sufficient coverage for the acquisition after these edits is demonstrated in Figure 5 with common-midpoint (CMP) positions plotted for data remaining after editing at an offset of 5 km (0.6 Hz harmonic), an offset at which the 3D feasibility demonstrated sensitivity at the Frigg level. Note that the data coverage over the central and northern areas of interest (reference Figure 1) is little affected by these edits as azimuthal data is included. This determination was eventually supported by the post project forward (post-mortem) 3D modeling demonstrating sufficient coverage for our targets (following section) after editing.

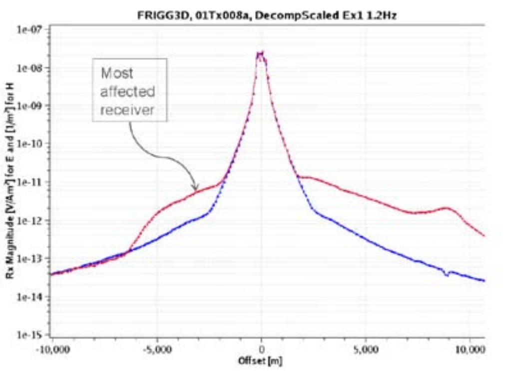

Figure 4: An example of the extreme pipeline interference (red) compared to an unaffected receiver (blue) in in-line electric field.

Interpretation and Inversion

Interrogation of these data took the form of qualitative analysis of the normalized amplitude and phase difference maps at various offsets, along with detailed 1D, 2.5D and 3D constrained and unconstrained inversion.

Great care was taken to include 2D inversion of the Marine Magnetotelluric (MMT) acquired during non-transmission times to aid the construction of appropriate 3D background resistivity and inversion start models as these data are sensitive to large-scale horizontal background resistivity changes at a greater depth of investigation than CSEM. Note that the start model for unconstrained and constrained inversion was checked against the well log and seismic data with excellent correlation to the large scale features.

The 3D inversion effort was divided into two phases with the first involving unconstrained inversion to explore the data solution space without the bias of constraint; and the second application of the plentiful information derived from seismic depth surfaces and detailed well resistivity log data.

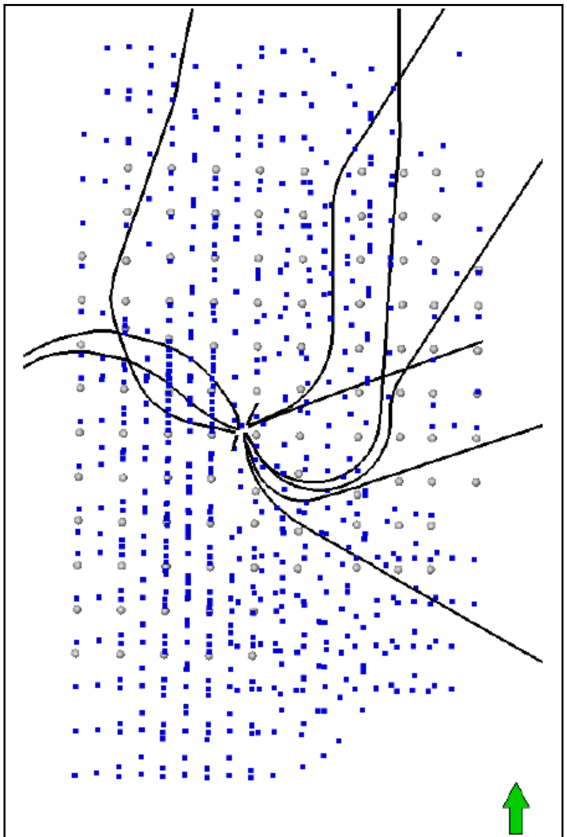

Figure 5: Data coverage @ 5 km offset for the 0.6 Hz harmonic – azimuthal (cross-line) and in-line data displayed in blue. Receivers as grey circles. Pipelines in black with green arrow indicating north direction.

Post Acquisition Modeling

As mentioned earlier, confirmation that the acquisition maintained the required coverage to assess our area and depth of interest after pipeline interference edits was obtained using additional forward 3D feasibility modeling including these data edits. An example of the results of one such scenario modeled for the 1850 GWC @ 500 Ωm appears in Figure 6 with clearly sufficient coverage at this location for this target in the in-line data. Note that the azimuthal data is not considered in this display and offers additional coverage at the shorter offsets and shallower levels lost to editing in the in-line direction.

Conclusion

A comprehensive 3D CSEM dataset has been acquired over the depleted Frigg field in what is thought to be one of the first applications of the technique to assess remaining or stranded gas.

Large amounts of cultural interference with the electromagnetic technique were encountered caused by the network of existing sea-bed pipelines in the area. The strongest coupling of electromagnetic energy between the transmitter/pipeline/receiver corrupting the sub-surface signal was observed when the transmitter tow-line and the transmitter itself paralleled the pipeline. Editing of these data was required for analysis and inversion with sufficient information surviving due to the inherent redundancy of the 3D acquisition and in particular abundant azimuthal (off-towline) information.

Post acquisition 3D modeling confirmed that the survey retained sufficient coverage in the in-line direction to interrogate our structures of interest. Azimuthal data provided additional coverage and above target information.

Acknowledgments

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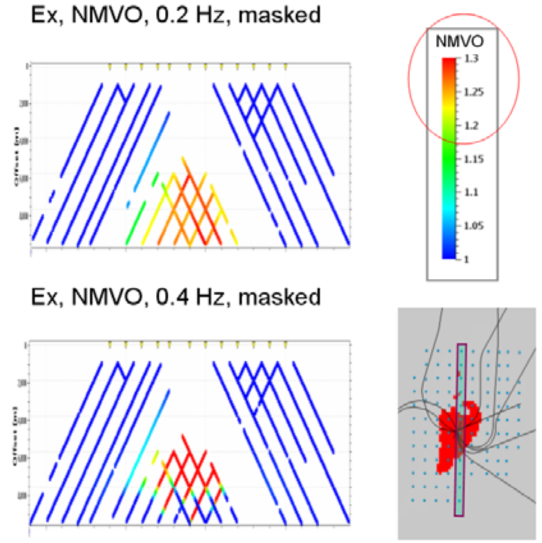

Figure 6: Pseudosections of forward modeled 3D data (left for two frequencies) from the line displayed for the 1850 GWC @ 500Ωm. This model includes data edits forced by pipeline interference showing that sufficient coverage remains in the in-line data for examination of this structure. Response is above 30%.

EDITED REFERENCES

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