Multi-Transient EM Repeatability Experiment over North Sea Harding Field

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Summary

We present results of a multi-transient electromagnetic repeatability experiment conducted over the North Sea Harding field in 2007 and 2008. The segment of the field under investigation had produced 3.9 MMbbls of oil during this time. Processing of the data included deconvolution for the measured source current and removal of the magnetotelluric noise, which increased the signal-to-noise ratio of the recovered impulse responses by about 20 dB. Without any cross-matching of the two data sets the resulting normalised root mean square difference (NRMSD) between the data sets was 3.9%.

We also generated time-lapse synthetic transient EM data for different states of the reservoir from the initial state in 1996, through predominantly oil production to 2011, and finally through gas production to 2016. Unconstrained 1-D full-waveform Occam inversions of these synthetic data show that Harding should be detectable and its lateral extent should also be well-defined. Resistivity changes caused by hydrocarbon production from initial pre-production state to production of the oil rim in 2011 are discernible as are more significant changes from 2011 to 2016 during a modelled gas blow-down phase.

Introduction

A multi-transient electromagnetic (EM) repeatability experiment was conducted over the North Sea Harding field in 2007 and 2008, as part of a collaborative research project between MTEM Limited (now PGS), BP, and the UK Department of Trade and Industry (now DECC) under project number H0531E. The objectives of the experiment were (1) to determine the repeatability of the multi-transient electromagnetic method (Wright et al., 2002; Wright et al., 2005; Ziolkowski et al. 2007) in a marine environment, and (2) to evaluate the potential of the method for identifying resistive hydrocarbon-saturated reservoir compartments in sub-sea fields in water less than 200 m deep.

We describe the multi-transient EM method for the marine case and the acquisition and processing of the data. Processing included an innovative step, developed within the project, to remove the magnetotelluric noise; this increased the signal-to-noise ratio of the recovered impulse responses by about 20 dB. To understand the results we also generated time-lapse synthetic transient EM data for different states of the reservoir from the initial state in 1996, through predominantly oil production to 2011, and finally through gas production to 2016.

Multi-Transient EM Method

Figure 1 illustrates the setup for acquisition of marine multi-transient EM data. The source is a horizontal electric dipole of length 400 m deployed on the sea floor transmitting a measured current that changes polarity in a transient pseudo-random binary sequence (PRBS). The response is measured by an in-line receiver cable consisting of up to 30 electric bipoles, each of length 200 m. The system provides real time quality control of all the measurements. The measured voltage response at each receiver is deconvolved for the measured input current and divided by the measured source and receiver dipole lengths to recover the earth impulse response. The impulse responses are subsequently inverted for subsurface resistivity.

Field Experiment over Harding Central

Harding is a medium-size field about 1700 m below the sea floor in block 9/23B in the central North Sea about 320 km north-east of Aberdeen. It comprises a high net:gross, high quality, Eocene (Balder) reservoir with a thick gas cap and a thin remaining oil rim. First oil production was in 1996, with gas being re-injected into the reservoir.
Figure 2 shows the positions of the two lines relative to an outline of Harding Central. The 2D line was acquired to tie a well (9/23b-7) across the thickest part of the hydrocarbon reservoir and a second well 9/23A-3 which is outside closure. The line was orientated away from platform infrastructure or operations.

Data Processing

The two data sets were acquired with the same parameters and processed with the same processing flow that included magnetotelluric noise removal to increase the signal-to-noise ratio of each data set by about 20 dB. The elements of the process are illustrated in Figure 3.

The top plot of Figure 3 shows a raw source gather, 250 s in length (vertical axis), offsets (horizontal axis) increasing from 2200 m on the left to 7000 m on the right. The long period MT noise is well correlated from trace to trace; the response to the PRBS decays dramatically from near to far offsets. After deconvolution the noise remains, but the signal has been compressed to impulse responses as shown in the middle plot, 20 s in length. The impulse response is subtracted from the nearest trace to obtain an estimate of the noise and a Wiener filter is found for each subsequent trace to estimate the noise, which is subtracted to reveal the signal, as shown in the lowest plot.

Results from the Field Experiment

The Normalised RMS Difference between the 2007 data $a_i$ and 2008 data $b_i$ is given by

$$NRMSD = \frac{200 \cdot RMS(a_i - b_i)}{RMS(a_i) + RMS(b_i)}.$$
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3-D EM Time-Lapse Modelling Method

To understand the time-lapse EM data over Harding, the reservoir simulation model was converted to input to 3D EM modelling code (Hursan and Zhdanov, 2002).

Figure 6 shows a map of the Harding Central and Harding South fields, the real multi-transient EM survey line in red, and the modelled survey line in black. The modelled line was chosen to be exactly east-west because (a) the reservoir grid was north-south and east-west and it made sense to have the simplest relation between the resistivity model and the reservoir model, and (b) the Pie3D modelling code used (Hursán and Zhdanov, 2006) calculates only one component of the electromagnetic field at a time and we wanted to minimise the computation time.

The Harding reservoir simulation model was converted to input to the Pie3D modelling code by (1) converting to Matlab code, (2) regridding to make a regular grid in x, y and z, (3) converting the porosities and water saturations to resistivities using Archie’s law, and (4) converting the result to input for the Pie3D code. Archie’s law is

\[ \rho_r = a \rho_w \phi^n (1 - \phi)^m \]

in which \( \rho_r \) is the total resistivity of the rock and contained fluid, \( \rho_w \) is the resistivity of the water in the rock, \( \phi \) is the porosity, \( S_w \) is the saturation of the water, and \( n, m, \) and \( a \) are empirical numbers that were given the values 2, 2.02, and 0.845, respectively, based on recommendations by Hacikoylu et al. (2006). The resulting resistivity models are shown in Figure 7.

The gridding is 100 m in x (east-west) and y (north-south), and 6 m in z (vertical). The water column is 110 m thick with a resistivity of 0.3 ohm-m whilst the overburden rock has a relatively uniform background resistivity of 1 ohm-m.

The series of time lapse resistivity cross sections shows oil production starting in 1996, with a thin remaining oil column predicted in 2011. After 2011, the model has been run in “blow-down” mode, where the gas will be produced and replaced by brine. Production would be virtually complete in this segment by 2016.

Figure 7: Snap-shots of Harding Central reservoir resistivity model derived from reservoir simulation saturation plots. The vertical colour scale is linear from 0 (bottom) to 1200 ohm-m (top). Initial state was gas, (1200 ohm-m), overlying oil and brine (0.33 ohm-m).

Time-Lapse Modelling Results

For each snap-shot model transient EM data were simulated with a grounded electric dipole on the sea floor and in-line electric field receivers at 200 m intervals with source-receiver offsets of 2000 to 8000 m; the setup was moved along the line in steps of 400 m. A one-dimensional (1-D) earth model was found to fit the impulse response data of each common mid-point gather using unconstrained full-waveform Occam inversion with a 1 ohm-m half-space starting Earth model. The procedure is described in Ziolkowski et al. (2007). The inversions are displayed side-by-side to give a 2-D section of resistivity beneath the profile line. Figure 8 shows the inversion results for the four snap-shots: initial model; 2009; 2011; 2016. The colour scale is the same for all four results.

The modelling shows that the field should be detectable, although the unconstrained inversion puts the reservoir slightly shallow. The lateral extent of the reservoir is well-defined. Since the 1-D inversion represents the reservoir as a layer with infinite extent in the x- and y-directions, it gives a very low estimate of the resistivity. As production of hydrocarbons proceeds, the amplitude of the reservoir response decreases and the inversion shows progressively lower resistivity from the target. The change from the
initial state to 2009 as oil is produced is clearly observable; the change from 2009 to 2011 is very slight; and the change from 2011 to 2016 is again clearly observable, as the gas is produced.

Figure 9 shows absolute differences in the inversion results between the initial model and 2011, and between 2011 and 2016. These confirm and quantify what can be seen qualitatively in Figure 8.

Figure 9: Absolute differences in inversion results of Figure 7.

Conclusions

We have shown that we are able to obtain excellent, repeatable, MTEM data. The constrained 1D inversion results from the two surveys are consistent and clearly show the Harding reservoir as a resistor, with well-defined edges. The recovered reservoir resistivities of the 1D models are too low, however, due to the 3D nature of the target. We would expect results to improve dramatically with 3D inversion.

The 3D modelling shows that the Harding field should be detectable using the multi-transient EM method, provided the signal-to-noise ratio is adequate. Since amplitude variations of a few per cent need to be detected, the signal-to-noise ratio needs to be better than 100, or greater than 40 dB. 1D inversion of the modelled data shows that the lateral extent of the reservoir is well-defined. Provided the signal-to-noise ratio is adequate, the multi-transient EM method can be used for both exploration and appraisal. This has been confirmed by experiment.

In time-lapse mode the modelling shows that the changes in reservoir resistivity caused by production of hydrocarbons from 1996 to 2011 would be observable, as would the changes caused by the modelled gas production, or “blowdown”, from 2011 to 2016. The gas cap for Harding dominates the picture after the initial oil production. The method has the potential to monitor the production of hydrocarbons.

The changes in resistivity in the two-year period 2009 to 2011 appear to be very small. This is because the rate of oil production is small in this period – about 10,000 bbl per day. The production in the one-year period 2007-2008 between the two EM surveys was even smaller, so the expected changes in resistivity were too small to be detected with a signal-to-noise ratio of 40 dB.

The modelling defines the resolution that is required of the data to achieve the objectives that we have demonstrated. For this particular field the signal-to-noise ratio needs to be better than 40 dB to observe the major changes in production.

Acknowledgments

We thank the Department of Trade and Industry (DECC) for supporting this research, and the Harding partners (BP and Maersk) and PGS for permission to present this paper.
EDITED REFERENCES
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REFERENCES