SUMMARY

We present results of a 3-D time-lapse multi-transient electromagnetic (EM) modelling experiment conducted over the North Sea Harding field. The reservoir model petrophysical parameters of porosity and fluid saturation were converted to resistivity using Archie’s law and the model was regridded for input to Pte3D EM modelling code. Synthetic data were calculated 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 data sets 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

We present results of a 3-D time-lapse multi-transient electromagnetic (EM) modelling experiment conducted over the North Sea Harding field, 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 TP H0531E. The objective of the experiment was to evaluate the potential of the multi-transient electromagnetic method (Wright et al., 2002; Wright et al., 2005; Ziolkowski et al. 2007) for (1) exploration, (2) appraisal, and (3) monitoring of production of sub-sea fields in water less than 200 m deep.

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 1 shows a map of the extent of the Harding Central and Harding South fields, a real multi-transient EM survey line in red, and the modelled survey line in black. The line was acquired to tie 2 wells in the thickest part of the reservoir and one off structure, to the east. 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.

FEASIBILITY

Figure 2 Modelled impulse responses over Harding Central.

It is normal practice to perform a rapid 1-D modelling of the prospect to determine the feasibility of obtaining useful data over the field. The result of this 1-D modelling for
Harding South is shown in Figure 2. The 3-D modelling is the blue line, and the response for a background model of a 1 ohm-m half-space is shown in black. The 1-D modelling shows an apparently easy target for multi-transient EM (500% change above background at the peak), but the 3-D modelling gives a response only 8% bigger than the uniform 1 ohm-m half-space. Its limited lateral extent shows that it is not so easy to detect after all.

3-D EM TIME-LAPSE MODELLING METHOD

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 Pie3D. Archie’s law is

$$\rho_t = \frac{a \rho_w}{\phi^n S_w^m}$$

in which $\rho_t$ 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 taken from along the black modeling line in Figure 1, are shown in Figure 3. 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 cross sections show 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 3](image-url)  
*Figure 3 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 (0.332 ohm-m).*

RESULTS

For each snap-shot model 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 4 shows the inversion results for the four snap-shots: initial model; 2009; 2011; 2016. The colour scale is the same for all four results.

**Figure 4** 1-D unconstrained depth inversion of synthetic data for different time snap-shots. The model reservoir is delineated by the rectangular box.

The modelling shows that the field extent 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 5 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 4.
CONCLUSIONS

The 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.

Furthermore the lateral extent of the field is well-defined, so the method can be used not only for exploration, but also for appraisal.

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 “blow-down”, from 2011 to 2016. The changes in resistivity from 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 method has the potential to monitor production of hydrocarbons.

The gas cap for Harding dominates the picture after the initial oil production.

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.

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REFERENCES