Summary

A newly developed towed EM system has been tested offshore in the North Sea. In this paper we use modeling and inversion to investigate the ability of the towed EM system to detect and characterize a shallow gas discovery. We show that the measured electric field data are of sufficient quality and signal-to-noise ratio for successful detection and inversion of the high resistivity reservoir area including distinction of some of the shallow gas accumulations above the reservoir. 1D inversion in the frequency domain has been performed on individual common mid points (cmps) along a survey line across the reservoir with robust results. The estimated model from the 1D inversion outside the reservoir is used as the 1D background model in 3D modeling. The imposed 3D resistivity model is based on seismic data and interpreted horizons.

Introduction

An electric dipole current source and an EM streamer were simultaneously towed from one vessel for electric field data acquisition. The objective was to investigate the system performance with respect to detection and characterization of a known hydrocarbon target. Our goal was to collect EM data with sufficiently high quality and signal-to-noise ratio (SNR) to quantitatively characterize the high resistivity target region by means of modeling and inversion.

We present results on 1D inversion and 3D forward modeling on the acquired data. Seismic information in terms of interpreted horizons is used to build an initial 3D resistivity model of the survey site. The 3D model is successively refined by matching the resulting modeled electric field data with the measured data. Finally, we construct a target response in order to enhance the high resistive responses.

Methodology

In-line electric field data resulting from the transient current source was measured in the configuration shown in Fig. 1. The towing depths of the source and the EM streamer were 10m and 100m, respectively. Four offsets were used (1325, 1850, 2025 and 2545 m) and the data were monitored, quality controlled and processed in real time.

![Figure 1 The in-line towing configuration of source and receivers along the survey line.](image-url)
The system was towed along a 12km long survey line crossing the reservoir as shown in the left plot in Fig. 2. The nominal towing speed was 4 knots. A total of 12 runs, each consisting of 48 shots, were conducted on the line. Each shot sequence had a length of 120 s, i.e. 250m, and consisted either of a Pseudo Random Binary Sequence (PRBS) of order 10 and 10 bits/s or a 0.1Hz square wave (SQR) signal.

![Figure 2](image)

**Figure 2** The initial 3D resistivity grid model (left) of the Peon reservoir (dark red) with shallow gas accumulations (blue) in map view. The survey line is crossing the reservoir as indicated by the grey plane. The location of the 35/2-1R well is marked in green. To the right, a seismic cross section along the survey line with the 3D resistivity model overlaid. The main reservoir is shown in red ($250\,\Omega\,m$) and the shallow gas pockets in blue ($100\,\Omega\,m$).

The electric field data were then deconvolved with the transmitted source signal to obtain the frequency response function for each shot point. The transient method using PRBS sequences is described in (Wright et al., 2002, and Wright et al., 2005). The data was then sorted into common midpoint gathers (cmps) with separations of 250m. The advantage of this spatial sampling density is demonstrated below when separating the thin gas accumulations from the main reservoir.

To build the initial 3D resistivity structure of the Peon area, a visualization and model building software was used. A basic velocity model based on the well log data was used to convert the time horizons to depth. A total of five depth horizons were then used to generate the resistivity grid as shown in Fig 2.

1D frequency domain Differential Evolution (DE) inversion (Storn and Price, 1996) was performed at every cmp on the frequency response data along the survey line. All offsets and 16 frequencies in the range 0.1:4.3 Hz were used. The inversion results are shown in Fig. 3.

![Figure 3](image)

**Figure 3** The 1D inversion results plotted together as 2D resistivity cross sections along the survey line for SQR (left) and PRBS data (middle). To the right, the 2D resistivity inversion of SQR data is overlain in color on the seismic cross section.

The reservoir (570-590m) is clearly observed at cmps 20-40 for both data sets, which agrees well with the seismic information. At shallower depths, there is an increase in resistivity above the reservoir,
which could originate from the gas pockets above the reservoir, or could be a response from the reservoir that is influencing the shallower layer as well, or possibly both. However, at cmps 18-20 a spot of increased resistivity can be noted at a depth of ~480m, a feature that has been observed for several different setups of the inversion. This resistivity increase may originate in the leftmost gas pocket, which is not directly overlying the reservoir and is therefore easier to detect. This is supported by the 3D modelling below.

The finite lateral extent of the high resistivity gas field surrounding the survey line causes an underestimation of the resistivity values from 1D inversion (Wright et al., 2009). This is also seen from the 3D modeling discussed below. However, the background resistivity layering consisting of the sea-water, overburden and underburden are accurately estimated with 1D inversion outside the reservoir. The estimated sea-water resistivity also agrees well with the values from in-situ measurements.

In order to separate the high resistive anomaly from the background and airwave parts of the electric field, a target response (TR) is constructed. The frequency response function at every cmp is normalized according to the definition

\[ T(s, h) = 20 \log_{10} \left( \frac{F(s, h)}{F(s_0, h)} \right) \]

where \( F \) is the frequency response function, \( s \) the cmp along the line and \( h \) the product of the frequency and offset. The frequencies are ranging from 0.1-3.1Hz and the offsets are those four given above.

In this case the first cmp is used for normalization. This means that the target response is a measure of the frequency response change in dB along the line. In this case, the lateral termination of the high resistivity region along the survey line can be observed directly from the TR. This is exemplified in Fig. 4 for SQR data as well as for PRBS data. The lateral extent of the anomalies correspond well with the expected target width interpreted from the seismic data.

It can also be concluded that the airwave and sub-bottom contributions to the electric field are fairly constant outside the reservoir region. From the higher frequencies above 2.5Hz it is seen that the primary airwave part is constant along the whole line. Any variations would be revealed in the TR otherwise. Hence, the TR is a powerful definition for the analysis of the electric field data with respect to detection of high resistive sub-bottom anomalies.

\[ \text{Figure 4} \quad \text{Measured normalized frequency response amplitudes, i.e. target responses according to equation (1) along the survey line based on PRBS data (left) and SQR data (right).} \]
To model the structure of the Peon area more accurately the initial 3D-model in Fig. 2 is used. The resulting TR from forward modeling when using a fully parallelized Integral Equation code (Mattsson 2006; Andersson et al. 2007), is presented in Fig. 5. The reservoir resistivity has been decreased to $100\,\Omega\,m$ for a better fit with the measured data.

![Figure 5](attachment:Figure5.png)

**Figure 5** Modeled TR along the survey line using the 3D resistivity model based on seismic data but with a reservoir resistivity of $100\,\Omega\,m$ (left). The right plot shows the TR when the thin overlaying gas pockets have been removed.

The amplitude and shape of the computed TR in the left plot of Fig. 5 agrees well with the measured TR in Fig 4. In particular, the match with the SQR data is really good. The maximum difference between measured SQR data and the computed TR is below 1.2dB. The rms difference is 3.5%.

The effect of removing the shallow gas pockets from the 3D model is visualized in Fig. 5 (right). It is seen that the amplitude below is decreased and that the spatial shape of the TR above is changed. The lateral extent is also shortened when the shallow gas pockets are removed. This indicates that there is a series of high resistivity thin gas pockets on top of the reservoir visible in the measured TR as well as a thin gas accumulation just outside the reservoir. The short distance between each cmp, 250m, the wide bandwidth, the use of TR in the analysis and the 1D inversion results make this conclusion possible.

**Conclusions**

A newly developed towed EM system has been demonstrated over a known hydrocarbon accumulation. Analysis shows sufficient quality and signal-to-noise ratio of the electric field data for successful detection and inversion of the highly resistive reservoir area including distinction of some of the shallow gas accumulations above the reservoir. As expected the 1D inversions result in lower transverse resistance as a compensation for the exaggerated lateral extent.

**References**


