# Determining Resistivity from Towed Streamer EM Data Using Unconstrained Inversion - Tie to Well and Discovery Examples

A.J. McKay* (Petroleum Geo-Services), K. Flisnes Bergh (Petroleum Geo-Services) & A.H. Bhuiyan (Petroleum Geo-Services)

## SUMMARY

We show that unconstrained anisotropic 2.5D inversion of Towed Streamer EM data in complex geological settings can produce resistivity models that are consistent with both interpreted log and seismic data, and known discoveries. We consider two cases from recent surveys in the Celtic and Barents Seas offshore Ireland and Norway respectively. In the Celtic Sea case we show an example where we have compared the results of unconstrained inversion to publically available log data. Not only is the overall depth trend recovered, but the main variation of the resistivity is captured as well as, in some intervals, comparable average interval resistivity. For the Barents Sea case we show an example resistivity and anisotropy section from one of eight survey lines that traverse the Skrugard discovery across its short axis (about 2km). While the resistivity section highlights that the sub-surface resistivity is complex, the somewhat simpler anisotropy section reveals an anisotropy anomaly that is co-incident with both the lateral, and depth, extent of Skrugard.

## Introduction

In an exploration setting in areas with a complex geology it is important to be able to interpret the sub-surface resistivity with confidence. We present two brief case studies to show it is possible to recover resistivity depth trends, the average interval resistivity, and interpretable resistivity sections, using unconstrained inversion of Towed Streamer EM data.

For the case studies we use Towed Streamer EM data from surveys in the Celtic and Barents Seas, undertaken in the Irish and Norwegian sectors respectively. Both areas are relatively under-explored, but a working hydrocarbon system is proven, encompass complex geological settings with relatively high and variable background resistivity throughout the sub-surface, and anisotropic sediments.

Firstly, we show a comparison of the results of unconstrained 2.5D finite element inversion to publically available well-log data in the Celtic Sea. Secondly, we consider example resistivity and apparent anisotropy sections (ratio of vertical to horizontal resistivity) over a known discovery in the Barents Sea.

## Survey & Acquisition Details

The acquisition consisted of two main phases, in two different geographic locations; Figure 1 shows the lines acquired in the Irish sector of the Celtic Sea, and Norwegian Sector of the Barents Sea. In both phases the Towed Streamer EM data were acquired simultaneously with seismic data from a single vessel. The seismic data are being processed. In total, the amount of EM data acquired in the Celtic and Barents Sea was about 2800 and 850 line km respectively. The Celtic and Barents Sea surveys were completed in 35 and 12 days respectively.

An important feature of the system that must be considered when modelling and interpreting the data is that a Towed Streamer EM acquisition set-up utilises long source and electric field receiver bi-poles: the source is 800m long while the electric field sensors at the longest offsets are 1100m. For the source waveform we use an Optimized Repeated Sequence (ORS), Mattsson et al (2012). We used the same ORS for the both survey phases, with frequencies in the range from 0.2 Hz to 2 Hz, with a step of 0.2 Hz.

The measured data were Quality Controlled, processed to Towed Streamer EM frequency responses (with estimated uncertainties), and merged with the navigation data, on-board the vessel after the completion of each survey line. For most of the frequencies and offsets the uncertainties are below 1% in both the amplitude and phase.

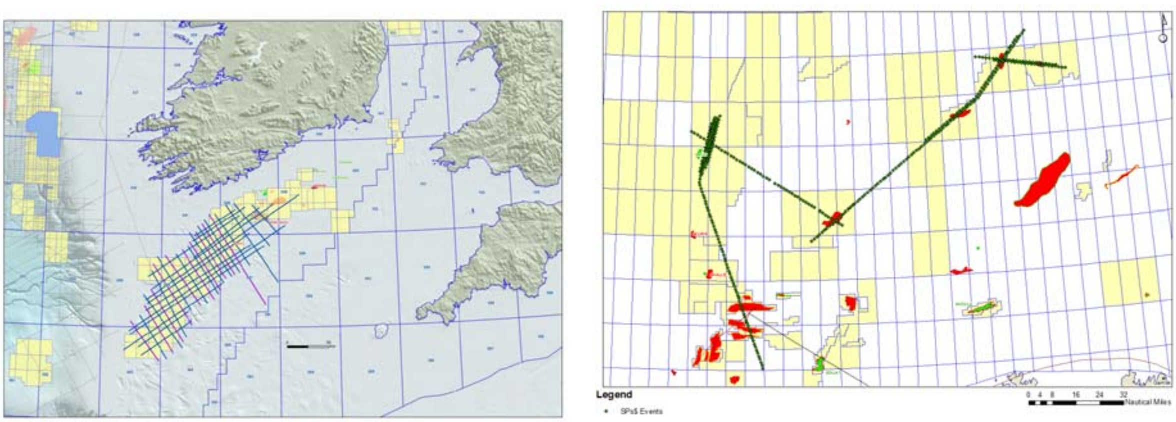


***Figure 1*** *Location and coverage of the Towed Streamer EM data acquired in the Celtic (left) and Barents (right) Seas*

**Inversion Methodology & Performance**

We used regularised unconstrained anisotropic 2.5D inversion to recover the sub-surface resistivity. The inversion code we used was the MARE2DEM code that is available via the Scripps Seafloor Electromagnetic Consortium. The forward modelling kernel of MARE2DEM is based on the adaptive finite element code of Key and Ovall (2011); the inversion scheme is based on smooth “Occam” inversion (Constable et al., 1987) with an additional anisotropy penalty.

The only fixed parameters in the inversion are the water resistivity and water depth. The water depth was fixed on the basis of the measured echo-sounder data. The water resistivity was fixed on the basis of measured seawater resistivity-depth profiles taken daily by the survey guard vessel at different locations throughout both survey areas, and 1D inversion to check that the water resistivity could be recovered by inversion and did not vary between measurement points. However, we have found that examining the inversion residuals from 2.5 D inversion is an effective means of ensuring the effective water resistivity that is chosen as a fixed parameter is appropriate – if the water resistivity is in-correct then biased residuals are evident. In any case the chosen water resistivity is close to the average of the measured values.

For a given model parameterisation two main factors increase the computational burden of inversion. First, the bi-pole source and receivers, and geometry (e.g. orientation), is incorporated in the forward modelling kernel of the inversion. Second, the electric field is sampled densely in space (with a shot-point every 250-300m), and the receiver array moves with the source which means that employing reciprocity does not reduce the computational demand. Nevertheless, for a typical data selection and model parameterisation, consisting of about 10k data points and 20k model parameters, then an inversion iteration takes about 25 minutes when 384 2.60GHz Intel Xeon cores are employed. About 10-20 inversion iterations are usually sufficient to reach the pre-scribed target misfit.

The first pass inversion data selection and parameterisation for both the Celtic and Barents Sea data-sets is similar. The results we show here are based on selection of the five lowest frequencies (0.2:0.2:1 Hz), and 12 offsets in the range 1.5 to 7.5 km. We continue to test the optimum data selection and model parameterization as part of the inversion appraisal workflow (the results of which are not shown here). Nevertheless, we note that the main features recovered are reasonably robust against a change in model parameterisation but are sensitive to data selection – we think the addition of a few higher frequencies (e.g. up to about 2Hz) in (e.g.) the Celtic Sea improves both definition of the overburden resistivity and the overall depth registration of the resistive bodies.

**Well Log Comparison**

We have compared the resistivity we recover from the inversion to the publically available well-log data in the Celtic Sea area. For example, Figure 2 shows the resistivity log from one well, and the pseudo-well log extracted from the unconstrained inversion of a nearby survey profile. The average relative misfit in this case was about 1.5%

Within each geological unit we have up-scaled the log data using the arithmetic and harmonic average to approximate the horizontal and vertical resistivity within each layer. On the log panel in Figure 2 the average horizontal and vertical resistivity is shown by the green and red lines. The green and red-lines on the pseudo-well logs are simply the arithmetic average within the intervals shown.

Examination of Figure 2 reveals that the main depth trends in resistivity are captured: the overall trend is increasing resistivity with depth. Between depths of 0.5 and 2.5km the overall sub-surface resistivity profile has four major features that are, in order of increasing depth, relatively resistive-conductive-resistive-conductive. The resistivity from unconstrained inversion compares favourably to the averaged resistivity in each interval until depths of about 3km, with at least the relative variation captured, and in some cases comparable averages. At depths greater than 3km the “vertical” resistivity appears to be under-estimated in comparison to the up-scaled average. The reason is unknown but assuming the up-scaled log resistivity is representative of reality the deviation could be due to the interplay of reduced sensitivity at depth, and the smooth model/minimum anisotropy regularisation. We intend to investigate this further.

The origin of the obvious resistivity anomaly recovered via inversion at depths of 1500-1700m, and within the Cretaceous Wealdon unit is unknown. However, we note that at this well oil shows were recorded in this interval (e.g. Davies et al., 2012), and in the area it is likely that wells were drilled out-with valid structural traps.

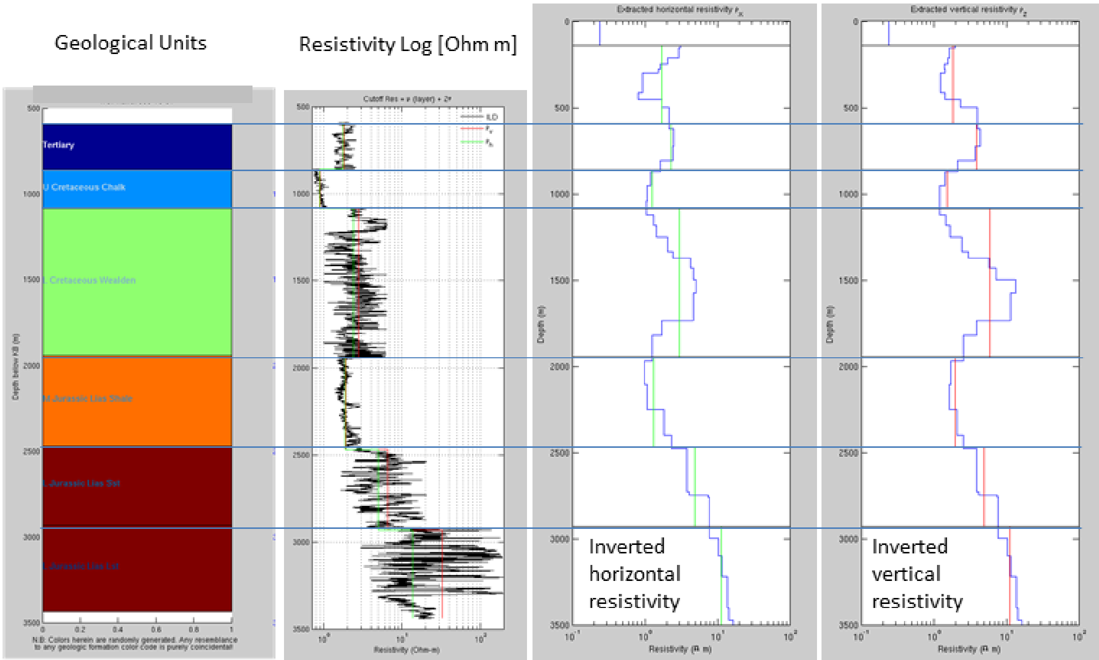


***Figure 2*** *Example comparison between the measured resistivity at one well in the Fastnet Basin and the resistivity recovered via anisotropic inversion.*

**Example Sub-Surface Resistivity in the Barents Sea**

We have inverted all 8 lines of Towed Streamer EM data in the vicinity of Skrugard, the discovery of which was a major milestone in the exploration of the Barents Sea. The average relative misfit in most cases is less than about 3%.

In Figure 3 we show an example result from the inversion in terms of the vertical resistivity, and apparent anisotropy (the ratio of the vertical to horizontal resistivity). The line shown crosses the short axis of Skrugard (about 2km wide) over the surface location of the 722/5-1 appraisal well completed in 2012, and is approximately perpendicular to the geological strike direction. The resistivity sections have been co-rendered with depth stretched (using the velocities from seismic processing) stacked seismic date. The seismic data are from a previous survey in 2011, and the seismic line is about 1km south of the EM line shown.

The vertical resistivity suggests quite a complex resistivity structure in the vicinity of Skrugard. However, the apparent anisotropy indicates that the vertical and horizontal (not shown for brevity) sub-surface resistivity co-vary in space, but there are obvious apparent anisotropy anomalies. The strongest apparent anisotropy is restricted to the precise lateral location of Skrugard, and is remarkably well registered in depth given that we have used unconstrained inversion. At the appraisal well location the top Skrugard reservoir level is 1276 m below mean sea level; the Oil Water Contact is at 1395m. The apparent anisotropy anomaly is between 1200 and 1500 m. There are two additional apparent anisotropy anomalies: the anisotropy anomaly to the west of Skrugard is most likely due to shallow gas, the origin of the near surface anisotropy anomaly is unknown.

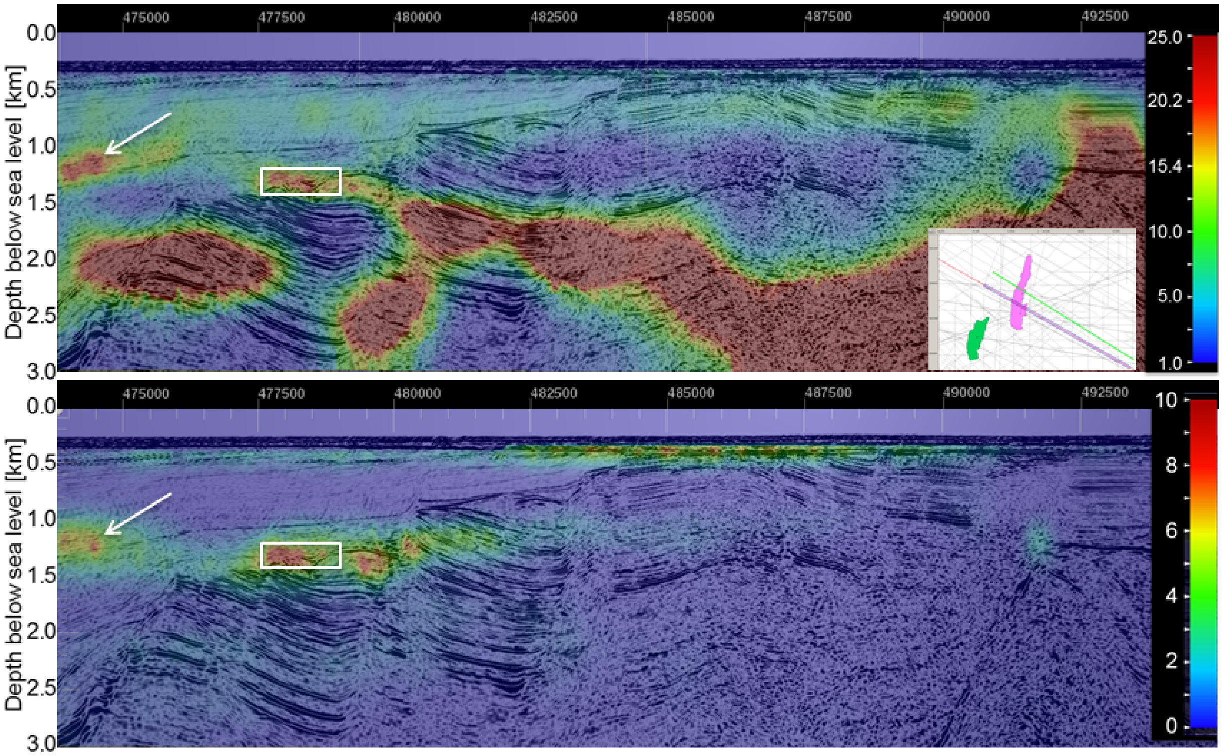


***Figure 3*** *The vertical resistivity (Ohm m) (top) and apparent anisotropy (bottom) section in the Skrugard area overlain on stacked seismic data in depth. The inset map shows the relative position of the EM (green line) and seismic data (red line) shown here. The white box and arrow show the approximate location of Skrugard and region of shallow gas respectively.*

**Summary & Conclusions**

Unconstrained anisotropic 2.5D inversion of Towed Streamer EM data from both the Celtic and Barents Sea produces resistivity models that are consistent with interpreted log and seismic data, and known discoveries in the case of Skrugard. We think that given the density and consistency of Towed Streamer EM data then time spent on unconstrained inversion will produce both "fast-track" results that are robust and interpretable, in addition to providing valuable input information for e.g. parameter value constraints/bounds in a structurally constrained inversion.

**Acknowledgements**

We thank Petroleum-Geo Services (PGS) for permission to publish this work.

**References**

Davies, M., O'Neill, N. and Vernon, R. [2012] *Independent technical evaluation report on licensing option in the Mizzen basin of the Celtic Sea*. Obtained via www. fastnetoilandgas.com.

Constable, S.C., Parker, R.L. and Constable, C.G. [1987] Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data. *Geophysics*, **52**(3), 289-300.

Key, K. and Ovall, J. [2011] A parallel goal-oriented adaptive finite element method for 2.5-D electromagnetic modelling. *Geophys. J. Int*., **186**(1), 137-154.

Mattsson, J., Lindqvist, P., Juhasz, R. and Björnemo, E. [2012] Noise reduction and error analysis for a towed EM System. *82$^{nd}$ SEG Conference & Exhibition*, Extended Abstracts.