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# Time Domain 2D CSEM Inversion with Induced Polarization

Ø. Frafjord (Petromarker), K. Key (Scripps Institution of Oceanography), S. L. Helwig* (Petromarker), A.M. El Kaffas (Petromarker, University of Suez Canal), T. Holten (Petromarker) & K. Eide (Petromarker)

## SUMMARY

Electromagnetic (EM) methods are an accepted tool to reduce offshore hydrocarbon exploration risk. One of the companies offering such a service is the Norwegian geophysical company PetroMarker, which acquires offshore time domain CSEM data with a vertical stationary transmitter and vertical E-field sensors placed on the sea bed.
In many cases a 1D inversion approach will give a good enough understanding of such data. Still, to fully exploit the information inherent in the data set and enhance the resolution of subsurface features it is necessary to account for geometrical effects such as bathymetry and the lateral extension of the resistive features through 2D or 3D inversion.

Recently a new 2D time domain inversion code for CSEM data with induced polarization (IP) capability was developed based on the well-established frequency domain MARE2DEM finite element code. Accounting for induced polarization allows for a wider range of transmitter receiver offsets in a single 2D inversion run. In this paper we show some first examples of this code on synthetic and field data. It is found that a resistivity structure can fast and reliably be recovered, also in the presence of induced polarization.

## Introduction

Over the last decade electromagnetic (EM) methods have become an accepted tool to reduce offshore hydrocarbon exploration risk (Constable, 2010). One of the companies offering such a service is the Norwegian geophysical company PetroMarker, which acquires offshore CSEM data with a vertical stationary transmitter and vertical E-field sensors placed on the sea bed (Holten et. al, 2009, Barsukov et al., 2007). Recent developments of the time domain vertical transmitter – vertical receiver technology has led to a significant increase in the number of active receivers, denser spatial sampling and a wider range of recorded offsets. To utilize the information content inherent in these data sets fast and reliable inversion schemes are necessary.

To enhance the resolution of subsurface features it is necessary to account for geometrical effects such as bathymetry and the lateral extension of the resistive features through 2D or 3D inversion (Holten et al., 2014). In many vertical-vertical surveys, induced polarization (IP) has been shown to affect the late time response of receivers with short transmitter offset. For these cases an accurate estimation of IP parameters is necessary to extract reliable resistivity information at increased depths. Since the IP effect is offset dependent (Holten et al., 2010) a simultaneous inversion scheme for IP parameters from a range of offsets will reduce uncertainty of the IP estimation and increase stability of the inverted resistivity model.

MARE2DEM is a finite element forward and inverse modelling code for electromagnetic geophysics (Key, 2012a). The frequency domain code has been upgraded to handle time domain CSEM data with IP. The code has been tested on both field data and synthetic data containing IP effects, and provides fast and reliable solutions on a range of data sets. In the following work we will present inversion results obtained with MARE2DEM.

## MARE2DEM for Time Domain

We simulated the 2.5D transient responses using a heavily modified version of the MARE2DEM inversion code, which uses unstructured 2D finite elements for the forward responses (Key and Ovall, 2011; Key 2012b). Since MARE2DEM was already parallelized over data frequency, transmitter and receiver subsets, it was straightforward and computationally efficient to add time-domain capabilities by inserting a Fourier transformation module that converted the imaginary component of the frequency domain responses and model sensitivities into time-domain transients; specifically we used the fast cosine and sine transform method with 201 point digital filters as described in Key (2012a). We found that using about 30 to 60 discrete frequencies spanning several decades was sufficient for the time domain transforms. However we soon discovered that this approach suffered from noisy responses at late times (> 1 s); we traced this back to relatively noisy imaginary responses at low frequencies and wavenumbers where the imaginary response is several orders of magnitude lower than the real response. To circumvent this problem, we moved from the direct field formulation of the original MARE2DEM code to a mixed potential formulation that decouples the inductive and galvanic parts of the EM fields. Specifically, we decomposed the electric field using $\vec{E} = i\omega\vec{A} + \nabla V$, where $\vec{A}$ is the magnetic vector potential and $V$ is the electric scalar potential. This formulation is better posed for time domain modeling since at low frequencies the galvanic (i.e., DC) response is fully contained in $V$ while the inductive component required for the transient is entirely contained in $\vec{A}$. Inserting this form of the electric field into Maxwell's equations and taking the Fourier transformation along the 2D model strike direction leads to a coupled set of equations for the vector and scalar potentials in the transverse plane. We solved this equation using 2D vector finite elements for $\vec{A}$ and nodal based finite elements for $V$. We further extended the new code to handle IP effects by inserting the parameterized Cole-Cole model (Pelton et al, 1978). The conductivity σ can be written as (Flekkøy and Hansen, 2015)

$$\sigma(\omega) = \sigma_\infty \left(1 - \frac{\eta}{1 + (i\omega\tau)^c}\right)$$

The changeability η describes the amount of IP, τ is a time constant, c is the frequency exponent, and $\sigma_\infty$ is the conductivity at infinite frequency.

**Inversion with MARE2DEM**

2D inversion of time domain data with IP has been tested on both field data and synthetic data. There are no constraints on resistivity or IP parameters. The variance of the data is estimated, and a random error of 2% (real data) or 3% (synthetic example) of the signal level is added to the variance to represent the systematic errors of the measurements. This total error is compared to the misfit of inversion, and if the inversion reach the point when these are equal in magnitude (RMS =1), the inversion is stopped.

**Synthetic inversion**

We constructed a synthetic resistivity model with 1000m water depth, 30 Ωm and 50m thick reservoir at 3000m depth. Background resistivity and η was set to 1 Ωm and 2% respectively. To simulate a case of a high IP area above a hydrocarbon filled reservoir, the chargeability η is increased to 15% and the time constant τ decreased to 1 in a 500m thick box above the reservoir centred 500m to the right of the reservoir. The full line white rectangle and the dashed rectangle in *Figure 1* show the size of the reservoir and the high IP area respectively. From this model, synthetic data with 3% relative noise was generated. Data below an absolute noise level of 0.5nV/m was not used in the inversion. Simultaneous inversion is carried out for resistivity and all the three IP parameters.

Figure 1 shows the inversion results for resistivity with a misfit of 1.0. The background resistivity value is around 1 Ωm, the same as in the true model. The reservoir is recovered with good lateral and acceptable depth resolution. The average transverse resistivity of this anomaly is 2350 Ωm, close to the real transverse resistivity of 2500 Ωm. The inversion was run on 36 processors for 7 hours.

The chargeability (η) was found to be around 4.5% on average, with just a tiny increase to 5% above the reservoir, see figure 2. This is not in agreement with the model which has a chargeability 1% in the background and 15% in the box above the reservoir. Nevertheless, the inaccuracy in estimating the η distribution is not affecting the capability to resolve the resistive reservoir, which is the primary objective of CSEM surveys. More detailed studies with different weighting rations and inversion approaches are currently carried out to understand if and how the parameters of the Cole-Cole model can be fitted better. One option is for example a hybrid approach where the focus is first on inverting for resistivity while keeping the Cole-Cole parameters constant and focus on the IP part after the relative progress in fitting slows down. Previous experience from 1D inversion has shown that a useful approach is to first estimate c and τ from short offset measurements and only invert on η, to reduce the degrees of freedom. Putting on more constraints to IP and resistivity taken from seismic horizons and a better understanding about the normal strength and distribution of IP around a reservoir, would certainly also help in the inversion.

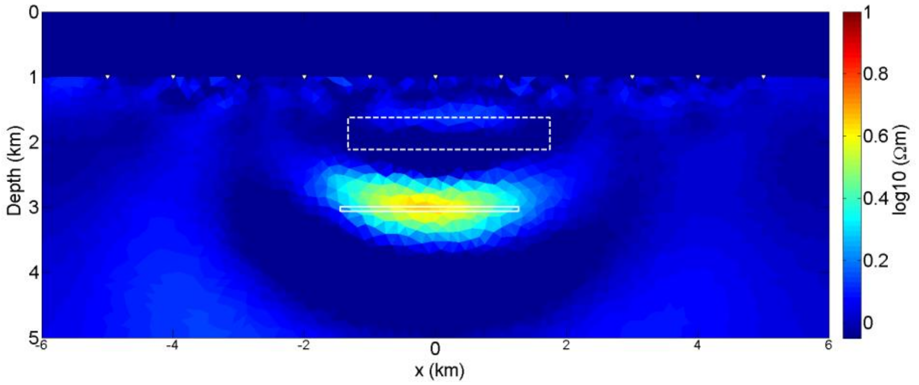


***Figure 1*** *Synthetic inversion result; resistivity ρ.*

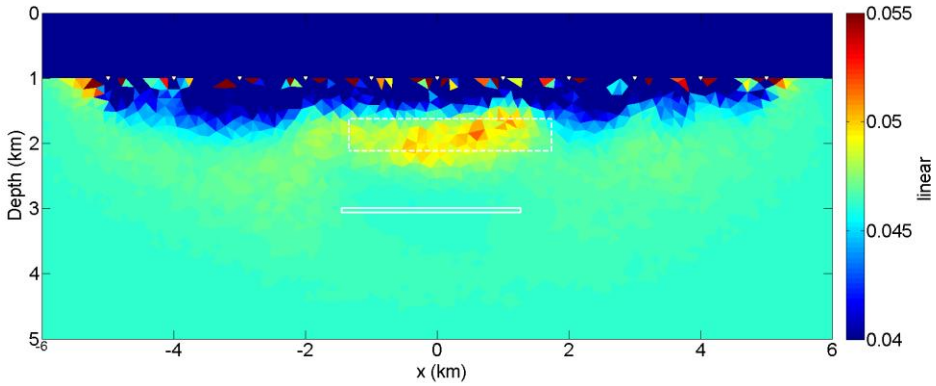


***Figure 2*** *Synthetic inversion result; chargeability η*

**Field data inversion**

Figure 3 shows unconstrained inversion of real data from a North Sea prospect (Kakelborg) surveyed by PetroMarker. This is a case with small IP values. High IP data sets have been successfully inverted with MARE2DEM, but unfortunately show rights for these data sets weren't obtained in time for this abstract. From the inversion results a background resistivity around 1 Ωm down to around 3km and around 6 Ωm below 3km is seen. The inversion result matches previous results (El Kaffas et al., 2013) and give additional information about top basement. A higher resistivity band is seen just above 1000m. Shallow inhomogeneity in resistivity is observed along the profile at 700-800 m depth follow transmitter locations and is believed to be an artefact related to transmitter-receiver offset variation. No sign is seen of an anomaly associated with hydrocarbon accumulations in the prospect reservoir which is located at 1650m depth. The MARE2DEM inversion result shows a low uniform η of around 0.5%, also in agreement with previous results.

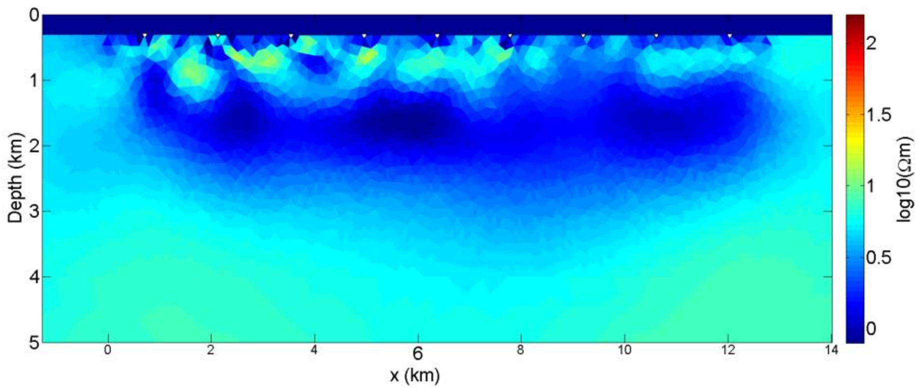


***Figure 3*** *Resistivity inversion result of real data from Kakelborg*

## Conclusions

A new 2D time domain inversion code for CSEM data with IP capability has been developed based on the well-established frequency domain MARE2DEM code. First tests with synthetic and field data show that a resistivity structure can reliably be recovered in the presence of induced polarization. Additional work will need to be done to examine how inversions for Cole-Cole parameters can be done in the most useful way.

The capability of inverting vertical-vertical CSEM in the presence of strong IP allows for the inclusion of a wider range of transmitter receiver offsets in a single 2D inversion run. While long offsets are typically not affected, small offsets react strongly to a polarized subsurface. Without including IP in the inversion these measurement would have to be omitted in the 2D inversion as they would steer the inversion towards unreasonably high conductivity values.

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