CMP Inversion of Marine CSEM Data

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Summary
We introduce a CMP-inversion algorithm for SBL data. The scheme gives promising results for data acquired over a recent discovery in South-East Asia. The main advantage of the method is that it is numerically very efficient. Results are usually available within less than one hour, but we stress that this is not a stand-alone method due to the simplifying assumptions used. Proper 3D modeling is required for model verification in a post-processing step.

Introduction
The application of the method to hydrocarbon exploration, also named Sea Bed Logging (SBL), is described by Eidesmo et al. (2002) and Ellingsrud et al. (2002). The main idea is to use an active source to probe the underground for thin, high resistive layers. Hydrocarbon filled reservoirs typically have a resistivity that is of one to two orders of magnitude higher than a water filled reservoir and the surrounding shale or mudrock. This is sufficient to support a channeled field in the reservoir which will leak energy up to receivers placed on the seabed.
Ideally, inversion of SBL data should be performed with a 3D algorithm that can describe laterally inhomogeneous media. However, 3D inversion is not only a question of methodology; it is also a question of boundary conditions or coverage of measured data. The full potential of 3D inversion can only be realized if data are available on a 2D surface with sufficiently dense sampling. For a standard SBL survey data are normally available only along a 1D line. Processing with a full 3D scheme is possible, but numerically very costly. Also, we can not recover reliable information about the width (with respect to the towline direction) of any resistivity anomaly since data is available along a 1D line only.
A much used way to handle the 1D line data is to assume that the earth is invariant in the direction normal to the towline (2D earth), whereas the electromagnetic fields are 3D. This is often referred to as 2.5 D modeling and inversion. One important benefit is that the processing time is reduced with several orders of magnitude. But inherent is also a first compromise. The resistivity anomaly is assumed infinite in the crossline direction with respect to the towline. This is never the case for the real earth. However, it may be a good approximation, depending on frequency, if the true width is sufficiently large (more than approximately 5 km at 0.25 Hz). If the true width of the real resistivity anomaly is small, good lateral definition is still possible but there is an increased risk of incorrect positioning in depth. An additional problem is that strong seabed bathymetry effects normal to the towline direction may cause inaccuracies in the final results. Used correctly 2.5D inversion of SBL line data is a valuable and important processing tool.
A further reduction in processing time can be obtained by using plane layer modeling and do 1D inversion (Mittet et al., 2004). This involves a second compromise which is that the earth locally has a plane-layer geometry. Direct 1D inversion of SBL data in the source-receiver domain is not a good approach for producing 2D (distance – depth) maps of resistivity anomalies. We borrow from seismic processing and use the CMP-offset transformation. The assumption is that after this transformation the earth is better approximated by a locally plane-layer geometry for each CMP position, but may vary laterally from one CMP location to the next. This is the method discussed in the following. The limitations are larger than for 2.5D inversion. We require a gently varying seabed also in the towline

direction but will still allow for lateral variations in the formation. The method should not be used as a stand alone tool. As a post-processing step we perform a suite of full 3D forward modeling operations to verify the models obtained from the CMP inversion.

Methodology

For line data we rotate and translate our coordinate system such that the x-axis coincide with the towline and with y = 0. Under the plane-layer assumption and with an inline transmitter it is only the x-component of the horizontal electric field and the y-component of the horizontal magnetic field that differs from zero in this coordinate system. The source position is denoted x_s and the receiver position is denoted x_r. The CMP position is $x_c = 1/2\ (x_s + x_r)$ and the half offset is $x_h = 1/2\ (x_s + x_r)$. We seek to minimize the error functional, ε,

$$\varepsilon = \sum_{x_c, x_h, \omega} W(x_c, x_h, \omega)\ (E_x^{Obs}(x_c, x_h, \omega) - E_x^{Mod}(x_c, x_h, \omega))^*\ (E_x^{Obs}(x_c, x_h, \omega) - E_x^{Mod}(x_c, x_h, \omega))$$

$$+ \sum_{x_c, z} \frac{(\nabla \rho(x_c, z))^m}{\alpha^m + (\nabla \rho(x_c, z))^m} \quad , \qquad m \geq 2 \ \text{ and } \ m \ \text{ even,}$$

where E_x^{Obs} (x_c, x_h, ω) is the observed inline electric field in the CMP-offset domain. E_x^{Mod} (x_c, x_h, ω) is the corresponding modeled electric field for the present iteration. The amplitudes of SBL type electro-magnetic data have a strong offset dependence. The purpose of the weighting function $W\ (x_c, x_h, \omega)$ is to equalize the amplitudes of the data-misfit kernel of ε as a function of offset. The dominant offset behavior of W is as the inverse of the inline electric field squared. The resistivity distribution as a function of CMP location and depth, z, is $\rho\ (x_c, z)$. The second sum in the above equation is a regularization term. The regularization term has a smoothing effect, but when correctly tuned, it also allows for a limited number of sharp jumps. Each CMP-offset trace could in principle be inverted independently without the regularization term. However, we seek a global minimum of the above equation where the regularization term will be the glue between the CMP positions. The optimization procedure is a damped least-square or Levenberg-Marquardt scheme.

Results

SBL data has been acquired over a prospect in South-East Asia. Normalized amplitudes as a function of CMP position and offset are shown in Figure 1. The reference receiver used for normalization is located on the left side of Figure 2. The main anomaly has a length of approximately 4 km and is between 8 km to 12 km. The seismic section has a clear flatspot of length 2 km along the towline direction, that is from 10 km to 12 km and at depth 2 km in Figure 2. Already from the normalized amplitude plot in Figure 1 it is clear that the length of the SBL anomaly is larger than the length of the flatspot. Based on the seismic data the prospect was interpreted to be a late Miocene deepwater slope turbidite reservoir sequence deposited upon an unconformity and unconformably overlain by a thick sequence of Late Miocene to Plio-Pleistocene deepwater shales that form the ultimate top-seal. This reservoir stratigraphic interval was thought to be equivalent to intervals found elsewhere in the area where nearby wells penetrated 100-150 m of net sand with good reservoir quality. It was also expected to have low resistivity in the deeper part of the model. The transition zone is visible in the seismic data. There is an undulating surface at 2000–2400 m, below which there is a clear degradation in seismic resolution. The prospect displays a significant seismic amplitude and AVO anomaly. The AVO anomaly shut-off is coincident with the strong flatspot event.

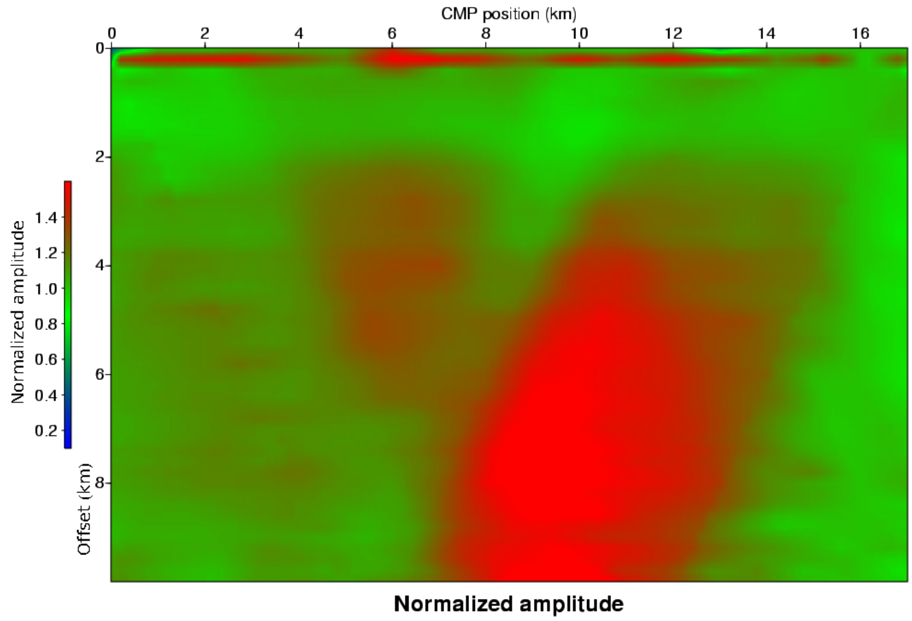

Figure 1. Normalized amplitude as a function of CMP position and offset.

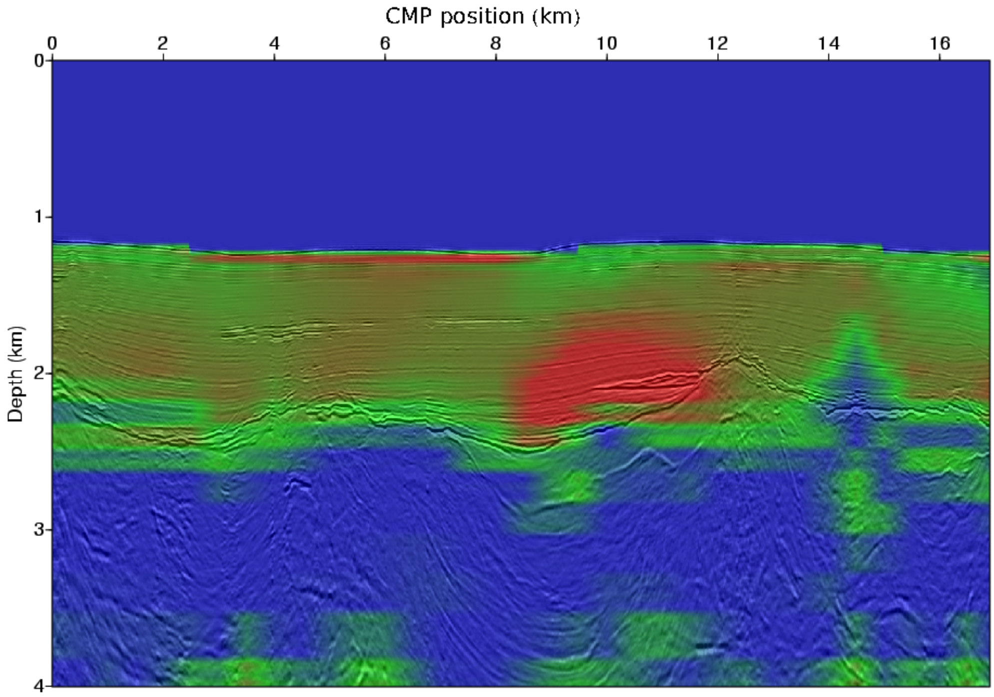

Figure 2. Low resistivity is blue and high resistivity is red.

A result of the CMP inversion is shown in Figure 2. The result is based on using three frequencies at 0.25 Hz, 0.75 Hz and 1.25 Hz. The inverse problem we try to solve is clearly non-unique. The depth of the anomaly may vary slightly with the relative weighting of frequencies and parameterization of the regularization. However, for all tests we find a resistive object at approximately the same position as in Figure 2 and with the same lateral extent. We also systematically recover low resistivity in the deeper parts of the model.

The electromagnetic response from a thin resistive layer is dominated by the transverse resistance, which is the product of layer resistivity with layer thickness. The implication is that the electromagnetic response from a layer of thickness 50 m with resistivity 80 Ohmm is nearly identical to the electromagnetic response of a layer with thickness 400 m with resistivity 10 Ohmm. The red blob in Figure 2 can not be "compressed" more in the depth direction unless additional constraining information is used. This is mostly a result of the Maxwell equations and has little or nothing to do with the inverse scheme used. On the right hand side the termination of the SBL anomaly coincides with the termination of the flatspot, this is not so for the left hand side. Further work is needed to understand the difference in length between the seismic flatspot and the SBL anomaly. The 3D modeling, post-processing, is started. Synthetic and real data are compared with an L2 norm as for the CMP inversion. More data points are needed, but preliminary results indicate small errors for models with reservoir depths of 2 km and reservoir lengths smaller than 4 km.

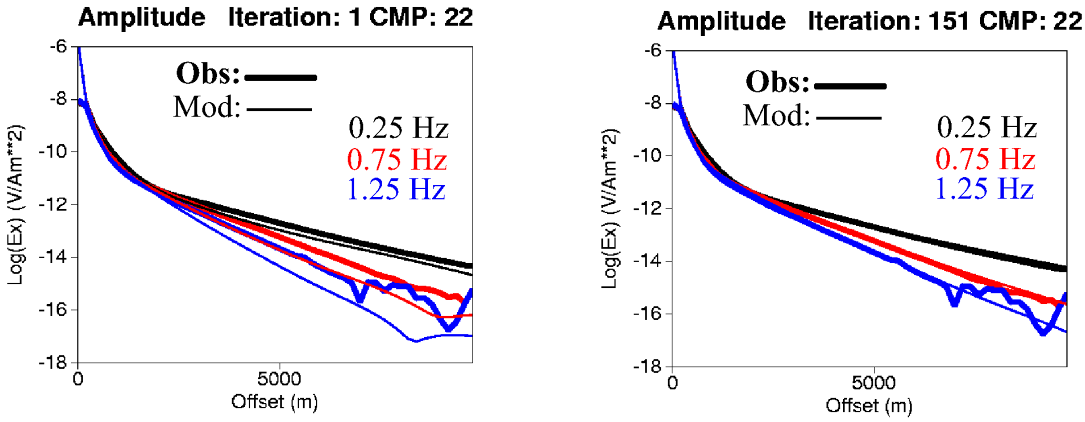

Figure 3. Amplitudes for CMP 22 (10.5 km). Real data: thick line. Modeled data: thin line.

Conclusions

We have demonstrated a CMP-inversion algorithm for SBL data. The scheme gives interesting results for data acquired over a recent discovery in South-East Asia. The main advantage of the method is that it is numerically very efficient. Results are usually available within less than one hour, but we stress that this is not a stand alone method due to the simplifying assumptions. Proper 3D modeling is required for model verification in a post-processing step.

References

Eidesmo, T., S. Ellingsrud, L.M. MacGregor, S. Constable, M.C. Sinha, S. Johansen, F.N. Kong, and H. Westerdahl, 2002, Sea bed logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas: First Break, **20**, 144-152.

Ellingsrud, S., T. Eidesmo, M.C. Sinha, L.M. MacGregor, and S. Constable, 2002, Remote sensing of hydrocarbon layers by Sea Bed Logging (SBL): Results from a cruise offshore Angola: The Leading Edge, **21**, 972-982.

Mittet, R., L. Løseth, and S. Ellingsrud, 2004, Inversion of SBL data acquired in shallow waters: 66th Annual Conference and Exhibition, EAGE