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Multidimensional Modeling and Inversion of Marine CSEM Data Acquired with an Expanded Frequency Spectrum

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Summary

In this paper we show how marine CSEM data interpretation can be improved if the data are acquired with an expanded frequency spectrum. Especially in case of targets located in a wide range of depth, both high and low frequency data can provide useful information for identifying different prospects with variable size and depth. We discuss a CSEM application to a real data set recently acquired in deep water offshore Nigeria using two central frequency values: 0.05Hz and 0.25Hz. Both frequencies, together with higher frequency harmonics (0.75Hz and 1.25Hz), have been used for multi-frequency and multi-dimensional modelling and inversion with excellent results.

Introduction

A marine Controlled Source Electromagnetic survey (marine CSEM) was recently conducted in offshore Nigeria with the main goal of evaluating the prospectivity of the exploration block. The possible exploration targets were individuated in a wide range of depth, from few hundreds meters below sea floor down to the maximum investigation capabilities of the CSEM methodology (Eidesmo et Al, 2002, Greer et Al., 2003, Srnka et Al., 2005, Dell'Aversana, 2005). An accurate feasibility study was performed by Eni E&P in order to optimize the survey layout and, at the same time, the cost/benefit ratio.

Also low frequencies (0.05Hz) were included together with more standard values (0.25Hz). The result was an expanded frequency spectrum that, considering also the first three harmonics, consisted of almost three decades. In this paper we describe synthetically the main steps of the entire work-flow, from acquisition to the final interpretation results confirmed by a new well drilled in the block.

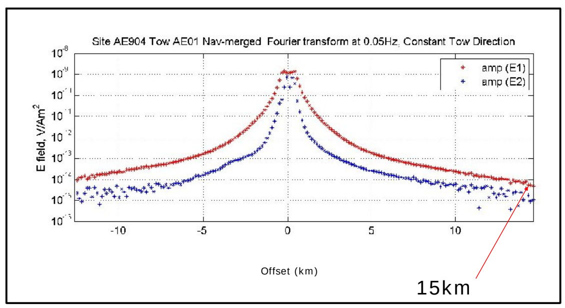

Figure 1: example of low frequency electric data (0.05Hz)

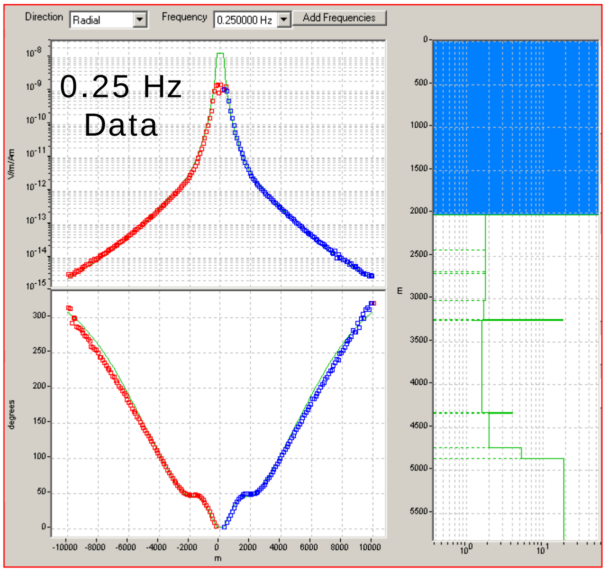

Figure 2: fit of amplitude and phase of 0.25 Hz data (left) and corresponding 1-D resistivity model (right)

Methodology

The comparative analysis of the available resistivity logs together with the seismic data helped in the definition of several hypothetical layered resistivity models that were used for running a full feasibility study. This analysis allowed to optimize the recording parameters and the acquisition layout, and to estimate the theoretical resolution power of the CSEM method in the block.

The study highlighted the importance to use a wide frequency spectrum including also low frequencies (0.05Hz or lower).

This fact is atypical for the standard CSEM surveys that commonly use only one fundamental frequency, generally around 0.25Hz.

Our feasibility analysis strongly indicated that low frequency values and, more in general, a wide frequency spectrum, was required for imaging multiple targets at variable depth.

The data were acquired with operations beginning on February 2006, and ending on March 2006. There were two separate phases: Phase 1 consisted of three CSEM survey lines for a total of 94.5 km, 28 receiver sites, and Phase 2, consisted of 1 towline, 40.6 km in length, and 25 receiver sites.

At the end of the acquisition, several weeks were dedicated to data Q.C., to the optimisation of the calibration factors and of the main processing parameters for transforming the raw data, recorded as time series, into interpretable electric and magnetic fields in the frequency domain.

The main interpretation objectives were set to be:

To produce anomaly maps as observed on the sea floor.

To define accurate resistivity vs. depth models, with particular focus in the prospect areas candidate for the next well to be drilled in the area.

To define a ranking of the exploration risk for all the prospects in the block.

Our interpretation approach was based on few fundamental principles that guided the whole workflow, from data Q.C. to prospect ranking. They can be summarized as following: the CSEM inversion problem is strongly ill posed and ill conditioned; running CSEM data inversion without properly "understanding" the data itself can be misleading; data space and model space must be extensively explored before applying any sophisticated interpretation tool; seismic information and any other independent data, if available, should be used at each step.

The above principles reflect the basic convincement that running directly multi-dimensional inversions without reaching a proper "feeling" with both data and model space can be risky. Using this philosophy, the main steps of our work-flow were:

- Data Q.C.
- Exploration of data space through 1D modeling
- Electromagnetic attributes mapping
- Introduction of seismic constraints and 1D layered model building
- 1D sharp constrained inversion
- Preparation of 3D resistivity models in depth and
- 3D forward modeling
- 2.5-D Free Inversion and 2.5D Constrained Inversion
- Model assessment and resolution analysis
- Inversion results vs. Geological interpretation and AVO seismic anomalies

Fast 1D modelling and 1D inversion, together with the analysis of electromagnetic attributes (Magnitude Vs. Offset, Phase Vs. Offset, Slope of Magnitude Vs. Offset etc) represented a fundamental preparatory work for optimizing the multi-dimensional forward and inverse modelling.

Figures 3 and 4 show respectively an example of the normalized MVO and an example of normalized Slope of MVO that we calculated for many different ranges of offsets and for different frequencies, for both electric and magnetic fields.

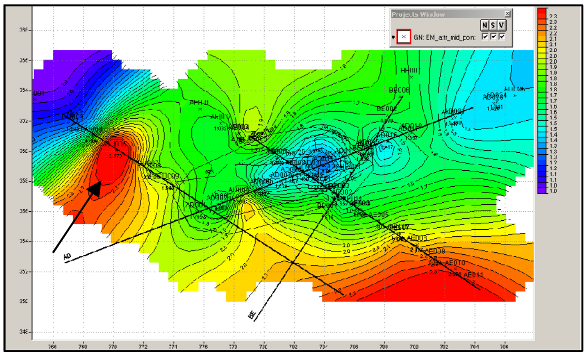

Figure 3: Normalized MVO for the electric field (for an offset of 10km).

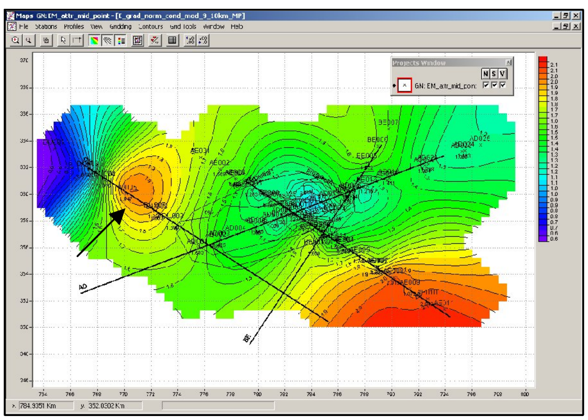

Figure 4: Normalized Slope of MVO for the electric field (for an offset of 10km).

The receiver positions are indicated with the corresponding names. There is an anomalous area (black arrow) around the location of the well previously drilled (the anomaly is represented by red colours in the maps). It can be at least partially explained with the proven presence of gas accumulation in that area. That anomaly decreases towards SE and almost vanishes in correspondence of the central part of the block, where we observe the lowest anomalies (blue and cyan colours in the maps). Instead an area of significantly high MVO anomalies is in the southern part of the block (we remark that also some effect produced by the interpolation algorithm was introduced in the map, such as on the west side of the red anomaly).

The distribution of this anomalous area can change from map to map, depending on the offset range used for the calculation and on the frequency of the data, but in general it is visible at the same receivers with almost equal intensity.

The interpreted seismic horizons were imported into a 3D mesh for building a preliminary 3D resistivity model. Several 3D meshes were tested in order to optimise the calculation times and the accuracy of the modelling results. Each mesh was refined near the main interfaces including the sea floor, in order to improve the accuracy of the forward calculation. A trial and error 3D modelling approach was performed in order to explore the 3D space model before running any optimised inversion. Both low and high frequency data were modelled. The 0.05Hz data set was extremely useful for defining the resistivity of the background and for constraining the deep portion of the model. The 0.25Hz data set and the first three harmonics were used for defining in detail the targets at medium-shallow depth. The acquisition layout conditioned the choice of the inversion strategy. Acquisition was performed along lines, so 2.5D inversion was considered appropriate in this case. A finite difference algorithm was used for the forward calculation and a conjugate gradient optimisation approach was applied for the inversion itself. The horizons derived from the interpretation (in depth) of the seismic data were used as constraints for the inversion and the only free parameter was the conductivity inside the layers. A multi-frequency inversion algorithm was applied. Very variable results were obtained along the different acquisition lines (figure 5 and 7), consistently with the output of the previous interpretation steps based on electromagnetic attribute mapping, 1-D modelling, 1D inversion and 3D modelling.

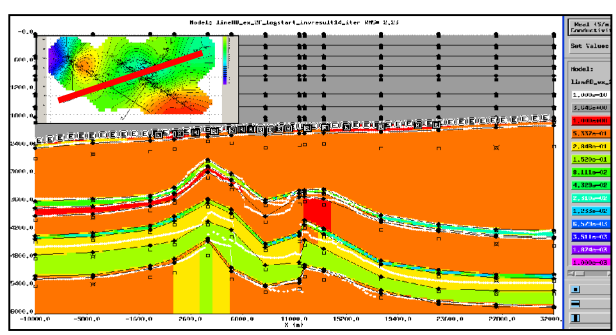

Figure 5: Result of 2.5-D inversion along a SW-NE line

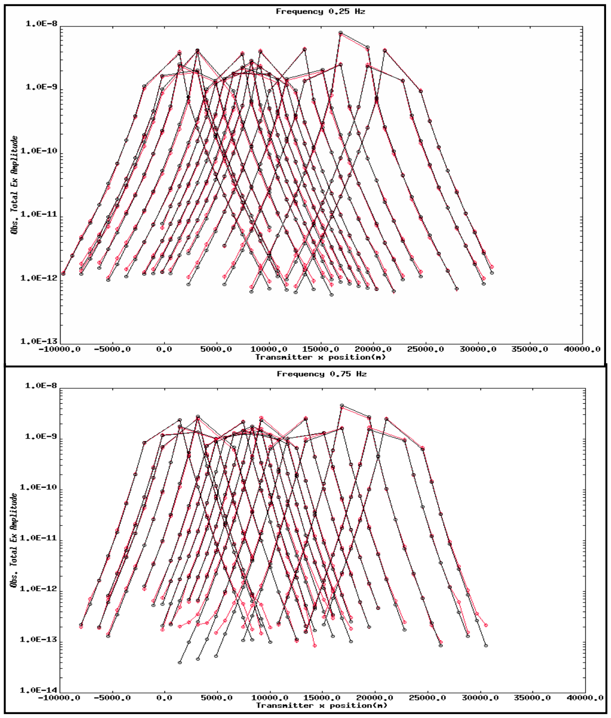

Figure 6: misfit between observed and predicted electric magnitude for the inversion result shown in figure 5 (frequency = 0.25 Hz, upper panel; frequency = 0.75 Hz, lower panel).

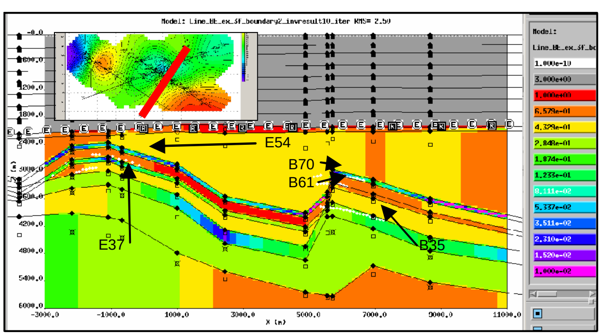

Figure 7: Result of 2.5-D inversion along a NE-SW line

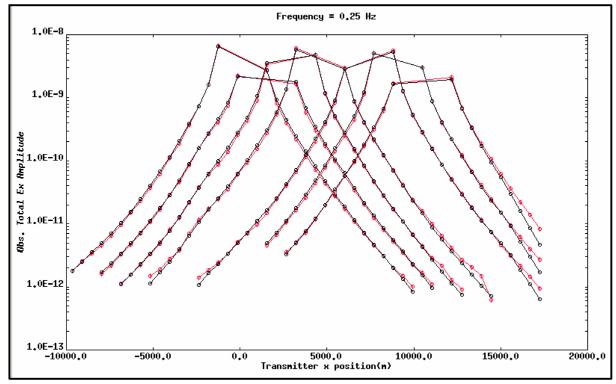

Figure 8: misfit between observed and predicted electric magnitude for the inversion result shown in figure 7 (frequency = 0.25 Hz).

A significant anomaly appeared in the southernmost portion of the block. Figure 7 shows a resistivity section running SW-NE over this part of the block. It shows resistive bodies at different locations and at variable depths. These are fully consistent with the fact that strong anomalies of the electric and the magnetic fields were observed at the sea floor. They could correspond with accumulations of hydrocarbons, but it is not possible to discriminate between oil and gas without using other sources of information.

In summary the whole work flow allowed to define different areas characterized by electric and magnetic anomalies with variable intensity.

The distribution of these anomalies helped in re-defining the ranking of several prospects previously individuated on the basis of seismic data.

Conclusions

Marine CSEM data provided a significant contribution for re-defining the exploration risk in the explored block. The method revealed an evident power of discrimination between areas with different prospectivity.
A sophisticated interpretation approach was applied on an expanded frequency spectrum. Multi-frequency modeling and inversion produced resistivity sections that improved the definition of the exploration risk associated to the different prospects.

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References

Dell'Aversana P., The importance of using geometrical constraints in marine Controlled Source Electromagnetic data inversion, 75th SEG Conf. and Exhib., Houston, 2005.

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

Greer, A., MacGregor L.M., Weaver R., Remote mapping of hydrocarbon extent using marine Active Source EM Sounding, EAGE Conference 2003, Ext. Abstract, N. Z-99

Srnka, J. L., Carazzone, J. J., Eriksen, E. A., Ephron, M. S.; Remote reservoir resistivity mapping-An overview – SEG Conference, [2005], Extended Abstract (EM 3.1).