Advances in marine Controlled Source Electromagnetic: The Santos Basin Project - Brazil

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Summary

The Santos Basin marine Controlled Source Electromagnetic (***mCSEM***) data were acquired as part of a co-operation project between Petrobras and Schlumberger to evaluate the integration of deep reading Electromagnetic (***EM***) technologies into the full cycle of oil field exploration and development.

The main objectives of the survey were to calibrate ***mCSEM*** over known reservoirs, quantify the anomalies associated with those reservoirs with the expectation that new prospective location(s) could be found.

Data interpretation was carried out integrating well-log resistivities and model geometries derived from seismic using advanced multi-dimensional fully anisotropic modeling and inversion technology. We show that the ***mCSEM*** response of the known reservoirs yields signatures that can be imaged and accurately quantified.

A further initiative was to advance the state of the art in integrated interpretation and establish guidelines toward the development of an industry standard workflow unavailable at present.

Introduction

In recent years ***mCSEM*** has driven the attention of an increasing number of operators due to its sensitivity to map resistive structures (such as hydrocarbon reservoirs) beneath the ocean bottom, and successful case studies have been reported (*Ellingsrud et al., 2002; Costello, 2006; Moser et al. ,2006; Srnka et al., 2006; Darnet et al., 2007; MacGregor et al., 2007; Buonora et al., 2008; Carazzone et al., 2008; Monk et al.,2008; Price et al., 2008; Tyagi et al., 2008*).

Numerous industry ***mCSEM*** surveys have been conducted in waters depth ranging from 50 to 3,000+ meters and in latitudes ranging from the tropics to the Artic. In cases where a well has been drilled in the survey area, the reservoir predictions based on the integrated interpretation have been validated.

The Santos Basin ***mCSEM*** data were acquired as a feasibility and calibration study to provide state of the art data that would lead to a realistic view of the technique's strengths and limitations when applied offshore Brazil; to develop new insights toward the development of novel and cost effective applications and the establishment of new integrated interpretation paradigms.

mCSEM is proving to be a rewarding tool when applied to real E&P problems, but a great deal of R&E is needed to push its efficiency and reliability and deploy new ways to acquire, process and interpret.

The Santos Basin project

The lay-out of the Santos Basin ***mCSEM*** survey is shown in ***Figures 1-2***. One hundred and eighty ***mCSEM*** receivers spaced approx. 1 km apart, were deployed along tow lines crossing known reservoirs in the area. The source waveform was designed to transmit a range of frequencies, chosen on the basis of pre-survey modeling to optimize sensitivity of the resulting data to the structures of interest. Fundamental transmission frequencies of 0.25 and 0.0625 Hz were used that are also rich in odd harmonics like 0.75, 1.25, 1.75 and 0.1875, 0.3125 and 0.4375 Hz. Data at each receiver location was processed using an advanced workflow based on: instantaneous dipole length, instantaneous dipole moment, instantaneous dipole altitude, instantaneous feather angle and instantaneous dip. Data processing resulted in high-quality amplitude and phase data to a source-receiver offset of 15 km. For the highest frequencies maximum ranges of 5-6 km are typical.

Data interpretation proceeded in stages. Processed multi-component field data at each receiver location were normalized using modeled reference background fields. The reference background fields were computed by combining the detailed layering from available borehole measurements into reduced geoelectric sections representative of what is resolved using the ***mCSEM*** method and constrained by seismic depth model(s). The objective was to build model(s) using a number of layers necessary to give the same ***mCSEM*** response as a full-layer model(s) derived from well-logs. In order to determine where the boundaries had to be placed, both the cumulative resistance and cumulative conductance coupled with stratigraphy were calculated from the well-logs. This allowed not only to make clear where the layer breaks are but also to determine the resistivities and the anisotropies of the layers.

Multi-component E and H responses were computed for these models using fast multi-dimensional fully anisotropic finite-difference frequency domain approaches that incorporate bathymetry and varying sea-water resistivities with water depth *(Abubakar et al., 2006; Zaslavsky et al., 2006*). Responses were computed for all frequencies and components used in the course of the survey.

Processed multi-component field data at each receiver location were also normalized by the fields measured at a chosen reference receiver(s).

Figure 3 shows the stacked normalized amplitude and phase centered on 5 km offset for the fundamental frequency 0.25 Hz for tow line *LTAM8N*. The stacked responses are normalized for the radial horizontal electric fields by the field measured at the reference receiver TAM147 (***Figure 2)***. The choice of the reference receiver is to have the same background resistivity at the reference location and the measurement receiver locations, with the only differences occurring in the possible anomalous features. The normalized fields clearly show two distinct areas of anomalies centered above two known reservoirs (A and B), reservoir A showing a maximum anomaly of about 1.8, reservoir B showing a maximum anomaly of about 1.5. Detailed 3D modeling was carried out based on blocked well-log resistivities and model geometries derived from seismic incorporating the reservoir data.

Figure 4 shows the match between the processed and stacked normalized real data and the modeled normalized response.

Selected tow lines were interpreted using a new fast 2.5D inversion method (*Li et al., 2008*). The forward solution uses an optimal grid technique based on an anisotropic material averaging formula to upscale fine structure to a coarser computational grid. The inversion is accomplished via a constrained Gauss-Newton technique where the model parameters are forced to lie within upper and lower bounds via a nonlinear transformation procedure. To improve the conditioning of the inversion problem, we use different model-structural constraints. Particular geometric shapes are assumed in parametric solutions, requiring a priori information. The model parameterization used here is based on interfaces known from seismic interpretation in depth. Receiver footprint which can appear in output models from inversion of real data with imperfect timing and calibration are reduced by weighting of the shallow subsurface.

Figure 5 shows the 2.5D anisotropic inversion results superimposed on seismic data for line *LTAM10N*. The inversion is constrained based on the seismic interpretation in depth with the resistivity distribution provided from the well-log data base and reconnaissance modeling. The inverted vertical resistivity depth image shows a marked resistivity anomaly that is consistent with the depth and lateral extent of the known reservoir and closely tie the well-log and seismic data.

Conclusions

We show that the ***mCSEM*** response of hydrocarbon reservoirs known to be present in the Santos Basin yield anomalies that can be clearly imaged and there are evident correlations between the anomalies and the reservoirs.

We show that the application of a new workflow based on true geometry processing, fast, reliable and fully anisotropic multi-dimensional modeling and inversion, advanced integrated interpretation increase our ability to find and delineate hydrocarbon, understand the entire ***EM*** response and increase our confidence about the resistivity at the reservoir(s) level.

There are numerous aspects that must be considered to further develop ***mCSEM*** for successful hydrocarbon exploration. One critical need will be the establishment of advanced interpretation paradigms embedded within industry-standard applications. This will become apparent as more companies start to bring ***mCSEM*** into more complex settings and potentially into development and production for reservoir appraisal and monitoring purposes.

Acknowledgements

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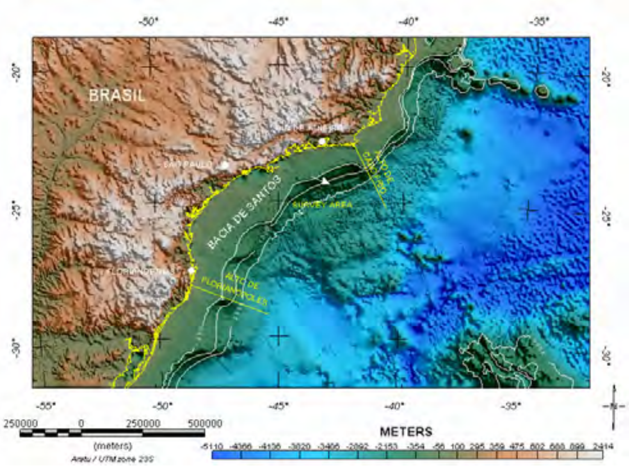

Fig 1. Location of Survey Area

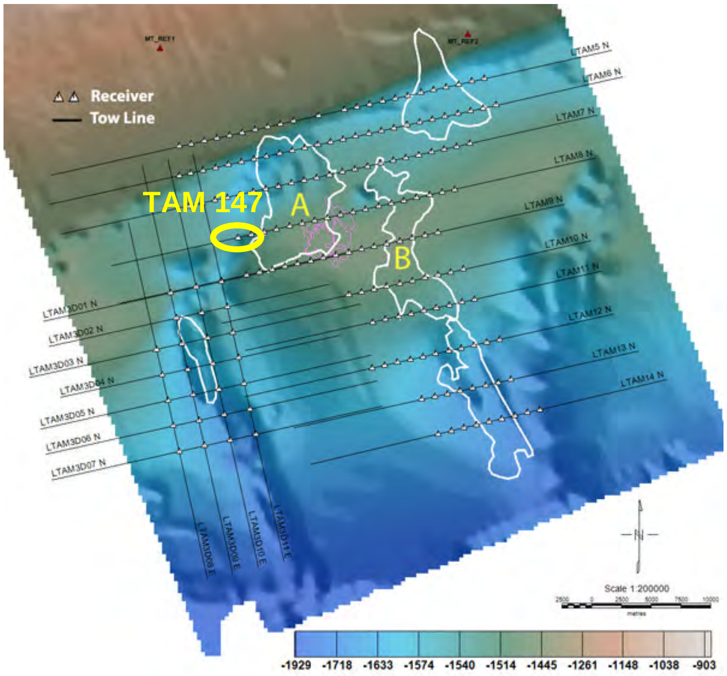

Fig 2. Survey lay-out

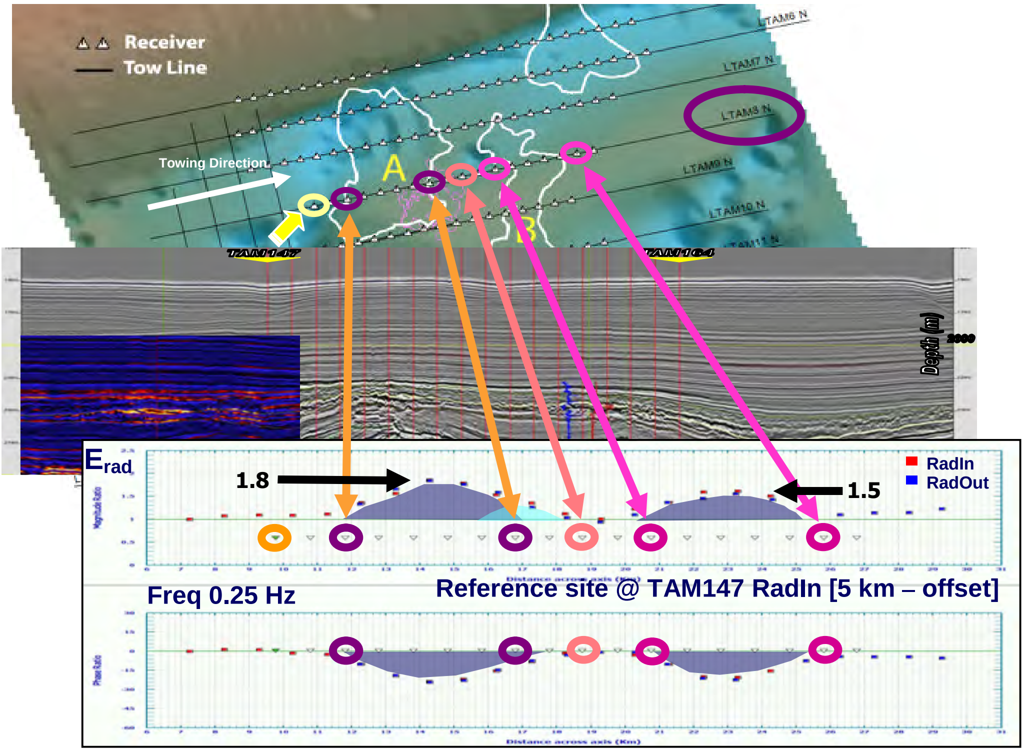

Fig 3. Line *LTAM8N* normalized ***mCSEM*** amplitude (upper) and phase (lower) at 0.25 Hz and 5 km offset.

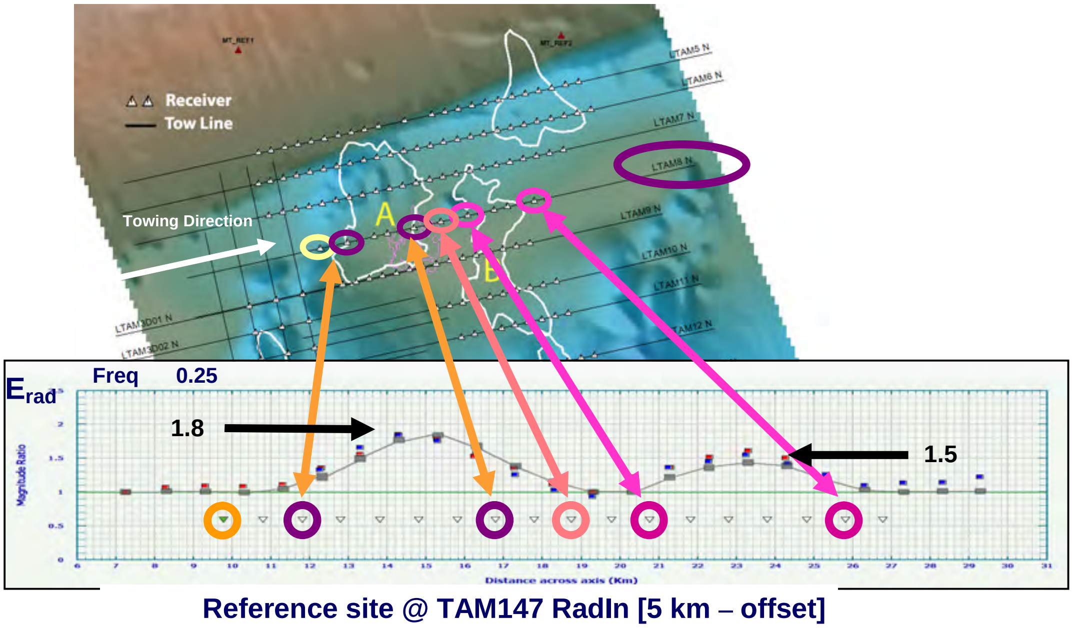

Fig 4. Line *LTAM8N* normalized ***mCSEM*** amplitude at 0.25 Hz and 5 km offset. The dark grey solid line represents the 3D modeled normalized response.

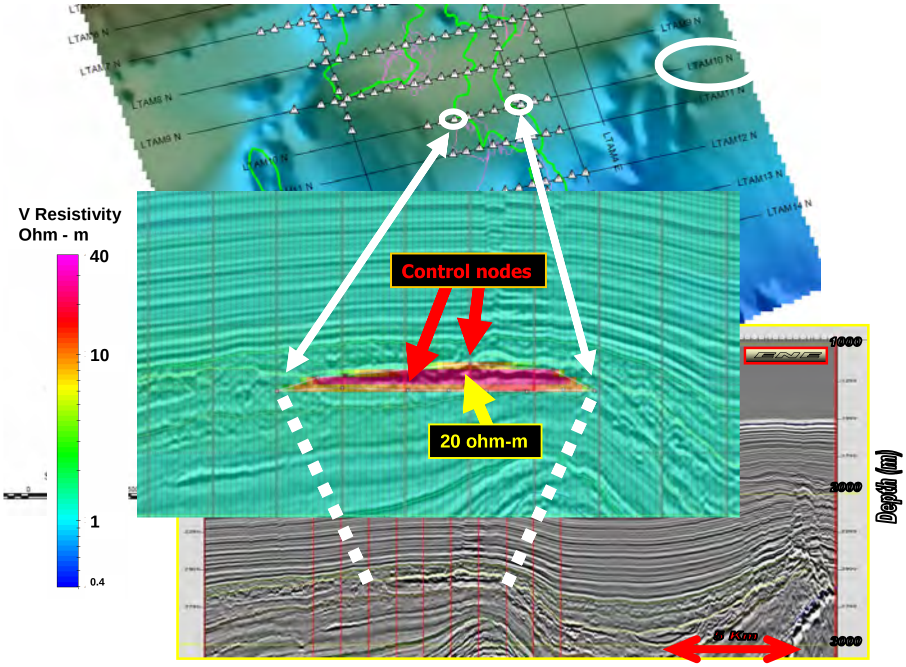

Fig 5. Line *LTAM10N* resistivity section from 2.5D anisotropic constrained inversion. Vertical resistivity. The resistivity anomaly (red) is consistent with the depth and lateral extent of the known reservoir and closely tie the well-log and seismic data.

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