Detecting Hydrocarbon Reservoirs from Marine CSEM in the Santos Basin, Brazil*

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Abstract

The Santos Basin marine Controlled Source Electromagnetic (mCSEM) data were acquired as part of a cooperative project between Petrobras and Schlumberger to assess the integration of deep reading Electromagnetic (EM) technologies into the full cycle of oil field exploration and development. Multi-component electric and magnetic fields data were recorded. All fields at each receiver location were processed and interpreted using an advanced integrated workflow.

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. We show that the mCSEM response of the known reservoirs yields signatures that can be imaged and accurately quantified by new processing and interpretation procedures. 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 (Srnka and Carazzone, 2005; Darnet et al., 2007).

A few hundred commercial mCSEM surveys have been conducted in water depths ranging from 50 to 3,000+ meters and in latitudes ranging from the tropics to the Arctic. In cases where a well has been drilled in the survey area, the reservoir predictions based on the integrated interpretation have been validated. Many improvements have been made to operating practices, survey equipment and delivery of advanced answer products.

The Santos Basin survey was performed as part of a co-operation project between Petrobras and Schlumberger to assess the integration of deep reading Electromagnetic technologies into the full cycle of oil field exploration and development. The mCSEM data were acquired as a feasibility and demonstration study; to provide state of the art data, develop new insights that would lead to novel and cost effective application, establish new integrated interpretation workflows.

mCSEM is proving to be a rewarding tool when applied to real E&P problems, but a great deal of R&D is needed to push its efficiency and reliability in: acquisition hardware, accurate survey engineering, data processing, multidimensional modeling and inversion. Furthermore, the success of mCSEM will depend on the industry embracing integration. The Santos Basin data set was considered ideal to advance data processing, interpretation and integration.

The Santos Basin Survey

The layout 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 survey used a 0.25 and 0.0625 Hz square wave signals 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. Processed multi-component field data at each receiver location were normalized using a ratio method. 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.

Forward multi-component E and H responses were computed for these models incorporating bathymetry and varying sea-water resistivities with water depth. Responses were computed for all frequencies used in the course of the survey.

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 location, 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. The single frequency, narrow offset range data in Figure 3 gives anomalies with broad edges, but spatial resolution is enhanced by imaging with multiple frequencies and offsets. 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 further imaged using a new fast 2.5D inversion method (A. Abubakar et al., 2006). 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 algorithm allows solving the problem for multiple transmitter positions simultaneously and does not confine the sources and receivers to a single plane that is perpendicular to the invariant direction, and thus realistic acquisition geometries can be simulated. The inversion is based on a Gauss-Newton scheme with constrained minimization that enforces physical bounds on the inverted parameters via a nonlinear transformation procedure. The inverted depth images show resistivity anomalies that are consistent with the depth and lateral extent of the known reservoirs 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 and reliable 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 production for reservoir monitoring purposes.

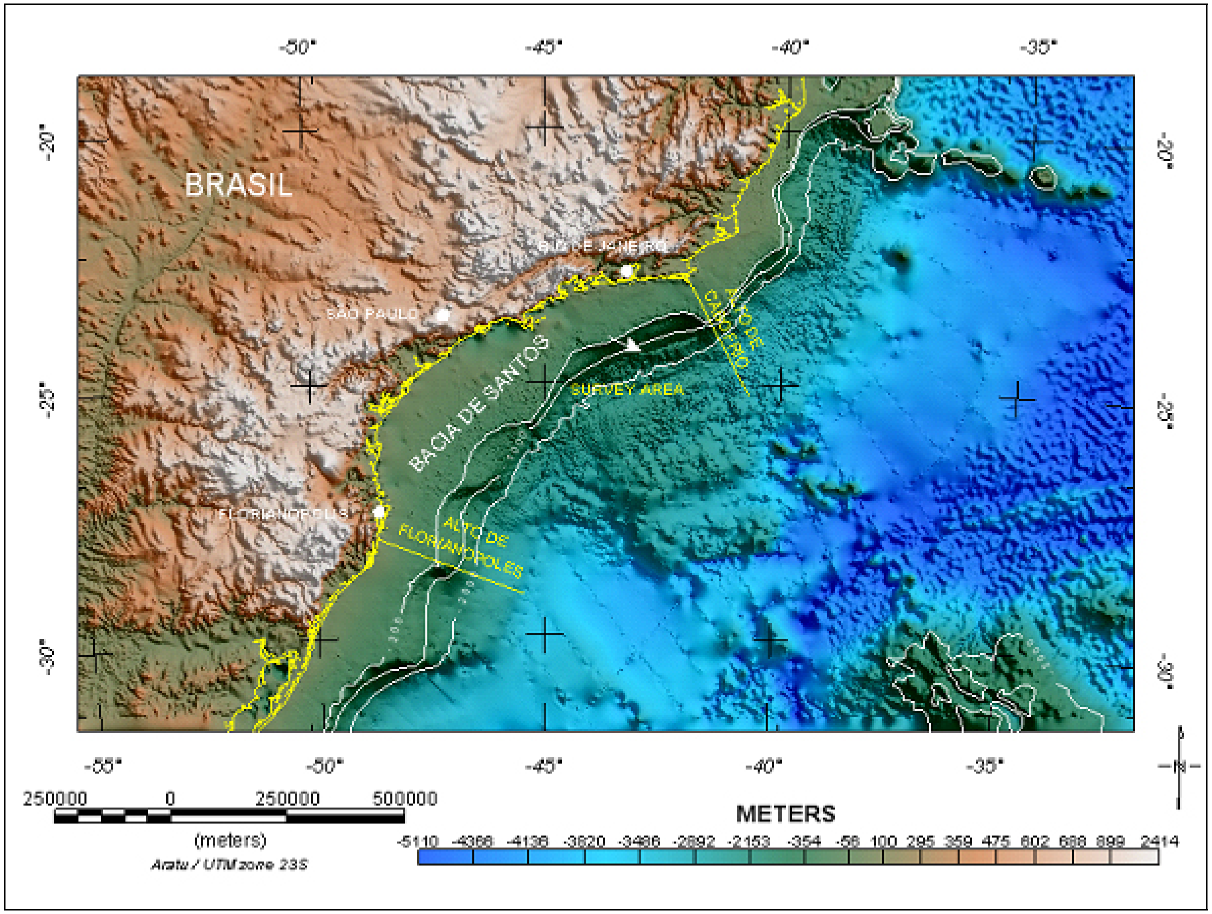

Figure 1. Location of Survey Area.

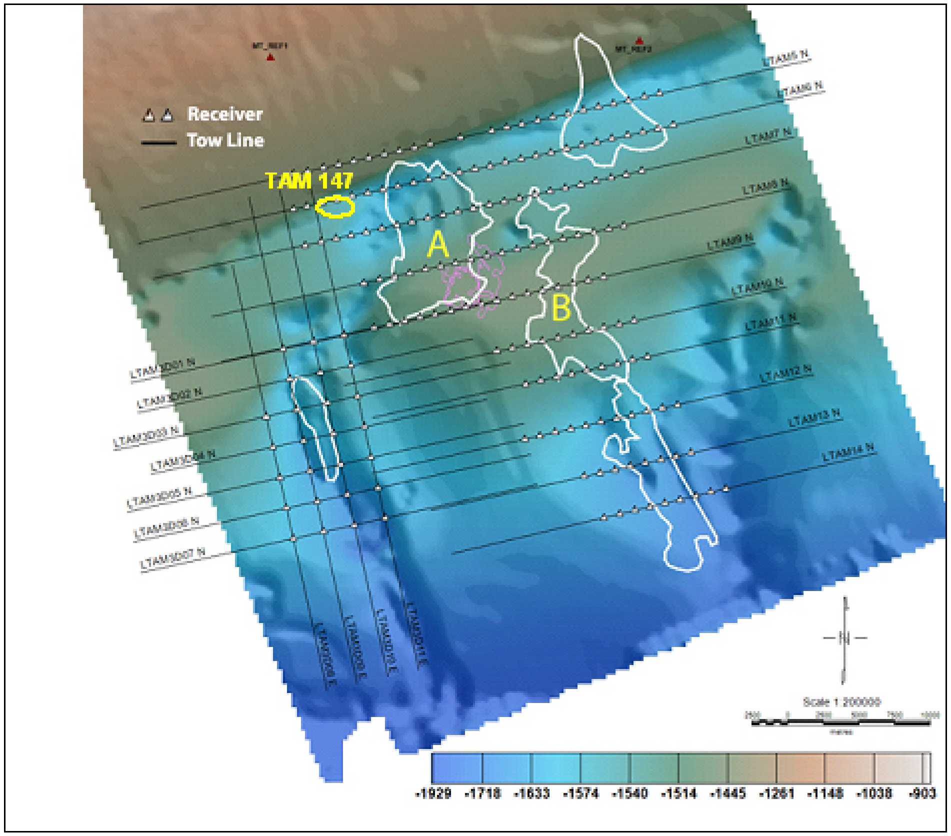

Figure 2. Survey layout.

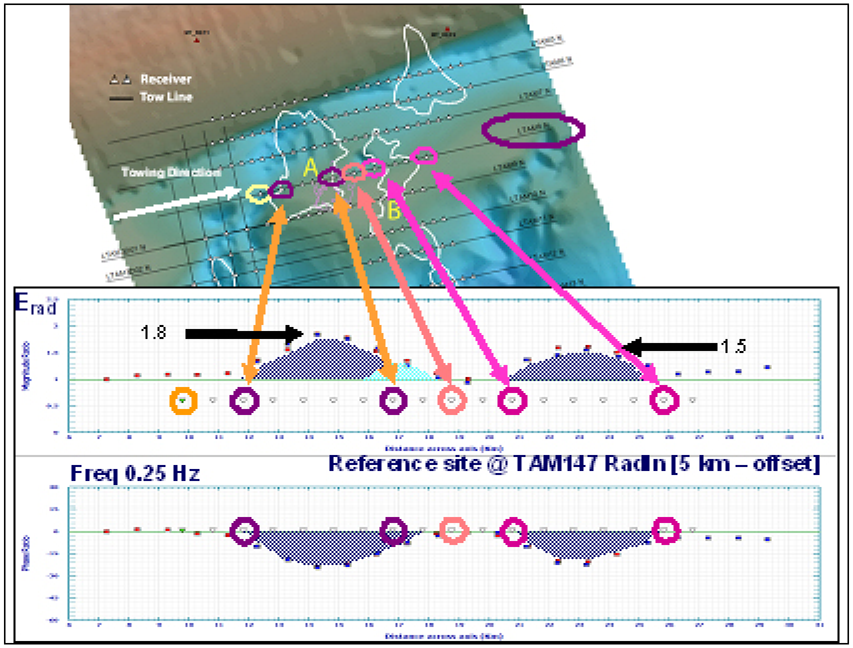

Figure 3. Line LTAM8N normalized mCSEM amplitude (upper) and phase (lower) at 0.25 Hz and 5 km offset.

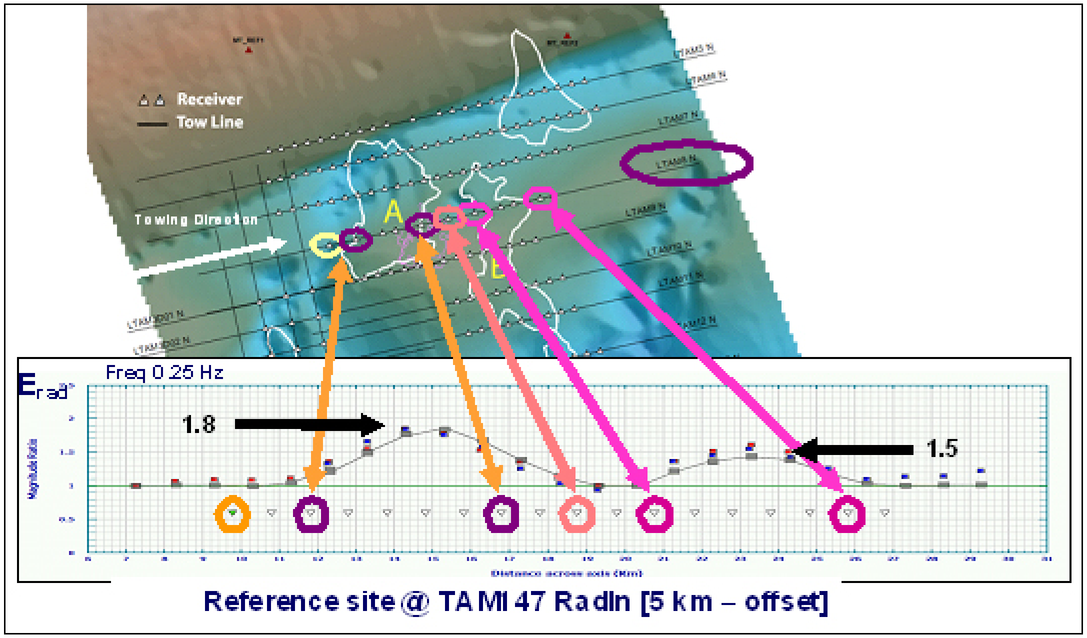

Figure 4. Line LTAM8N normalized mCSEM amplitude at 0.25 Hz and 5 km offset. The dark grey solid line represents the 3D modeled normalized response.

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