First results from a Brazilian mCSEM calibration campaign

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Abstract

During the past nine years, several operators have gained experience in marine controlled-source electromagnetics (mCSEM) through multiclient and proprietary surveys in all major oil provinces of the deep water offshore Brazil. Most recently, another large multiclient survey has been conducted by EMGS along the Brazilian offshore, a project which Petrobras embraced. The data has been processed and underwent a first pass unconstrained inversion over all the covered survey areas. A range of resistivity anomalies were present over areas of expected and confirmed HC occurrences and on the other hand, pointing out the non-existence of elevated resistive zones in areas where some wells have been proven to be either dry or of non-commercial value.

In this paper, some case studies demonstrate the success of the application of mCSEM for different scenarios in the deep-water Brazilian offshore. Preliminary conclusions on the effectiveness and limitations for a range of the employed survey designs will be discussed.

Introduction

Marine controlled-source electromagentics (mCSEM) is a geophysical method to remotely measure the electrical resistance of subsurface sediments, serving as an up-scaled resistivity well log, which was introduced to hydrocarbon exploration by Eidesmo et al. (2002). The resistivity measurements can be used as additional DHI for prospect de-risking (Ellingsrud et al., 2002), for lead generation and portfolio management on a more regional scale (Fanavoll et al., 2012; Balter & Roth, 2012), or to analyze the volume in-place for appraisal and development purposes (Morten et al., 2012).

In the last nine years, Petrobras has been actively investing in the development of mCSEM. It started to gain experience with the so called Campos Basin mCSEM data set (Buonora et al., 2005), as well as other smaller scale calibration data sets. In 2011, Petrobras embraced the EMGS proposal to acquire a large multiclient mCSEM campaign to establish an analog database across a number of Brazilian offshore basins and to use the experience, gained from a range of different geological settings, to evaluate the most suitable procedures to integrate this method into their exploration workflow.

mCSEM Campaign Overview

The data acquisition started in November 2011 in the Barreirinhas Basin in the Equatorial Margin, followed by acquisition in the Ceara and Potiguar Basins. Data coverage significantly increases towards South as the more active exploration areas like the Sergipe Alagoas and Espirito Santos Basin were approached. This culminated in the acquisition of a 1000 km^2 dense 3D mCSEM survey in the Southern Campos Basin (Figure 1). In total, more than 5000 km^2 of mCSEM data were acquired across all basins.

The survey parameters were determined by prospect type and survey objective, ranging from 500 m for detailed prospect characterization to 2000 m for regional surveys in frontier exploration areas. The majority of the surveys were wide azimuth 3D surveys, with the exception of the surveys in the Espirito Santos Basin. A number of 3D swaths with narrower azimuth coverage were deployed, focusing on the prospects in the sediment column adjacent to the salt.
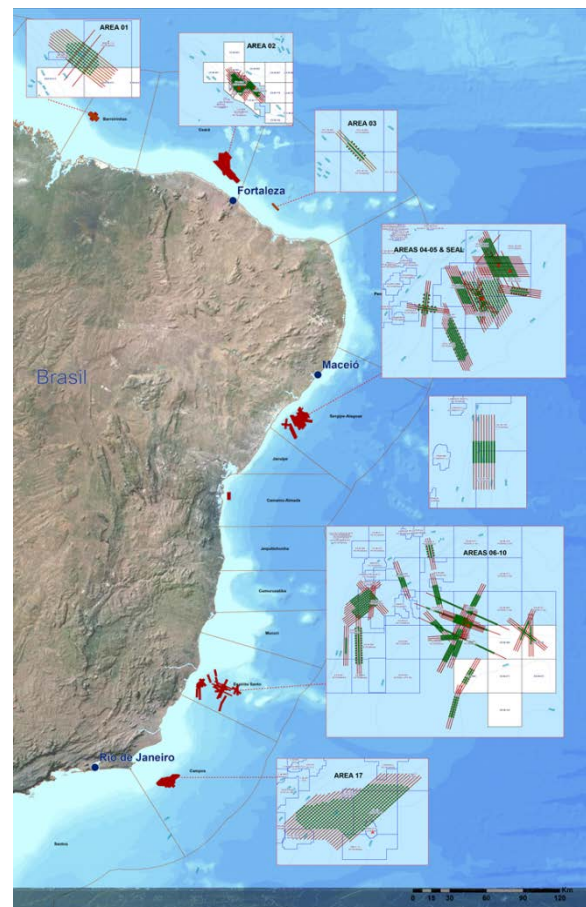

Figure 1: Overview of survey locations and survey layouts of the multi-client mCSEM Campaign

First pass data analysis and well correlation

All the data went through an initial unconstrained anisotropic 3D inversion without incorporation of well log or seismic information to allow for an unbiased evaluation of the resistivity distribution in the area. At this stage, each survey area was considered independently even though surveys were acquired adjacent to each other. For most of the basins, a resistivity contrast was observed at depth which, given the regional extent, is interpreted to be related to a geological interface with a defined lithology change similar to an unconformity. Even though several resistivity models were used as an initial "guess" in the inversion studies and different inversion parameters were chosen, consistent overburden models were reconstructed for the various surveys above this interface. Resistivity differences for the inversion results were observed below this regional interface in response to different inversion parameters and initial models. While the absolute values varied, the relative changes in bulk resistivity across the area were consistent.

Figure 2 shows the average resistivity map extracted from the unconstrained inversion results for all the surveys in the Sergipe Alagoas Basin. The maps are created in a similar fashion as seismic amplitude maps, but to accommodate for the low-frequency character of the mCSEM method and the unconstrained origin of the inversion result, a large averaging window of 1000 m is chosen. The window in the case of the Sergipe Alagoas data set encompasses large parts of the Cretaceous and Campanian interval. The information from the wells which were drilled prior to the acquisition of the mCSEM surveys, the Barra discovery well and 1-BRSA-1013-SES, were not included in the start model to remain true to the unbiased evaluation approach of this initial processing stage.

Increased resistivities are associated with all the recent discovery wells, Barra, Barra-1, Muriu and Moita Bonita. Both, the Moita Bonita well and the Muriu well are located towards the northern edge of a large resistive feature which is covering in excess of 200 square kilometres. The stronger resistivity character of the southern extensions when compared to the Muriu discovery could be either connected to a significant increase in net-pay, and/or have a lithological origin corresponding to a porosity reduction. The Barra-1 well shows a similar relationship between the location of the well and the main anomaly, located further towards south-west. To improve the understanding of these areas, an integration of petro-physical, seismic and mCSEM data is needed to separate lithology effects and reservoir volume changes.

For the well locations of 1-SES-171, 1-SES-173 and 1-BRSA-1013-ESS, low resistivities are observed. For none of these wells, commercial quantities of hydrocarbons were reported. The resistivity variations around well 1-SES-171 are very small, with a slight increase in resistivity further towards south-east of the well location. This could indicate the potential for minor net-pay in this area, but a qualitative comparison with the discovery wells indicates a much smaller contrast to the background of approx. 1 Ωm. Considering the rather large depth window which is investigated in this case, these variations are well within what could be expected for lithology variations and a careful integration of all available data needs to be performed. In the case of 1-SES-173, a pronounced resistive feature is present approximately 2 km towards east and south-east. This resistor is qualitatively comparable with the one which is observed at the Muriu well location. Considering the strength of the resistor and the very distinct fan-like shape, this may indicate some remaining exploration potential for this area despite the results of the recently drilled well.
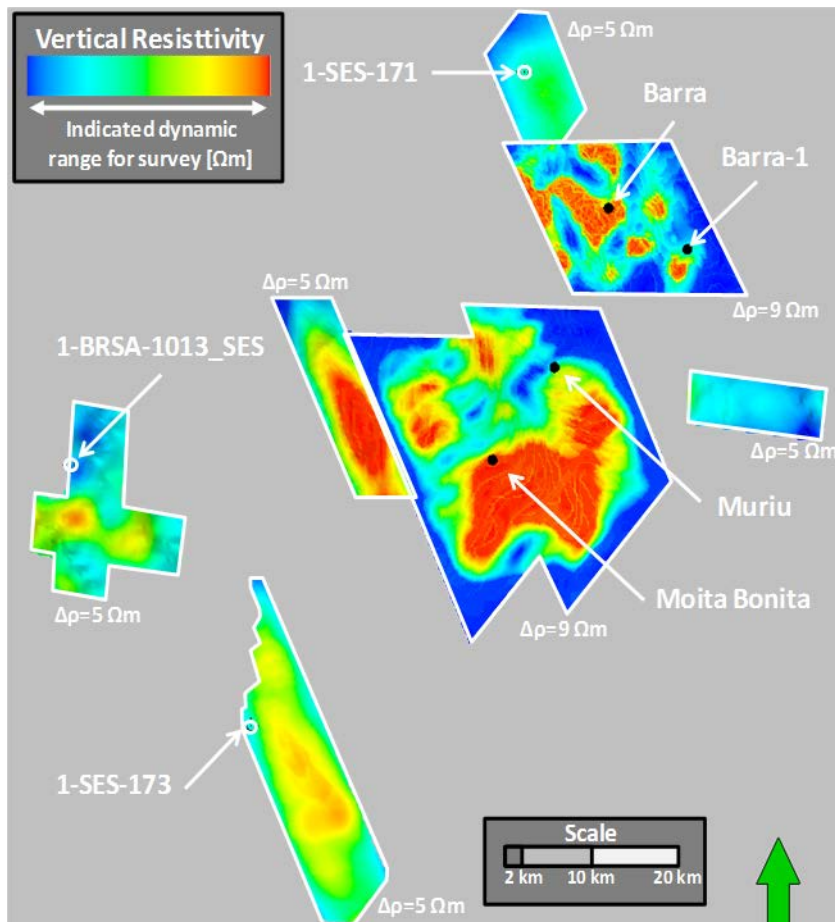

Figure 2:

Results for the surveys in the Sergipe Alagoas Basin. The average resistivity is extracted over a 1000 m window. All surveys are scaled individually, but a uniform color bar is used. The dynamic range for each of the color bars is annotated to each survey.

Figures 3 and 4 are showing two data sets in the Espirito Santos Basin, both being 3D swaths with narrower azimuth content and limited lateral extension. In Figure 3, a resistive feature is associated with well 1-ESS-213A, classified by ANP as a sub-commercial discovery. An additional resistor with a distinct channel like shape is observable towards the north of the well. The lateral extent of the resistive feature at the well location appears rather limited in the unconstrained inversion results, but this could be related to the limited spatial sampling of this type of survey geometry. To obtain a better understanding of the lateral imaging definition of a resistive body for such a survey, several expectation scenarios should be tested. Similar tests need to be performed for the resistor further towards north. Even though both of the features seems to be well defined, the variation of resistivities at this depth interval is low, which may indicate a low net-

pay thickness and/or hydrocarbon saturation. As the survey does not provide a regional view of the area, it is difficult to evaluate if such resistivity variations as observed here are a common occurrence for the area, suggesting a strong lithology component in the response, or if the background variations are minor, emphasizing the hydrocarbon case for the responses. A review of the well data, in combination with a careful integration of seismic data may allow differentiating between these two scenarios if a sufficiently detailed regional resistivity model can be derived.

Figure 4 shows the survey results across the Malombe gas discovery. The discovery well is associated with a defined resistor, but as with the previously mentioned survey, limited lateral extension of the survey challenges the ability to confidently define the lateral extent of the resistor. At the current stage, the potential for the resistor extending beyond the limits of the survey cannot be excluded. Well 1-BRSA-736D-ESS, reported as a dry well, is situated in the area of low resistivities within the mCSEM survey area. This is a similar observation as done before for the Sergipe Alagoas data set.
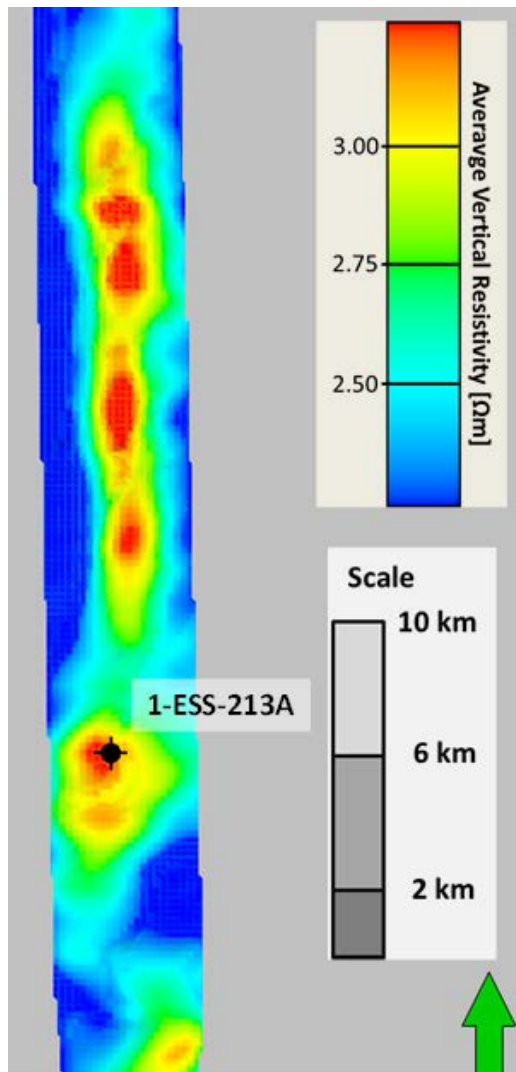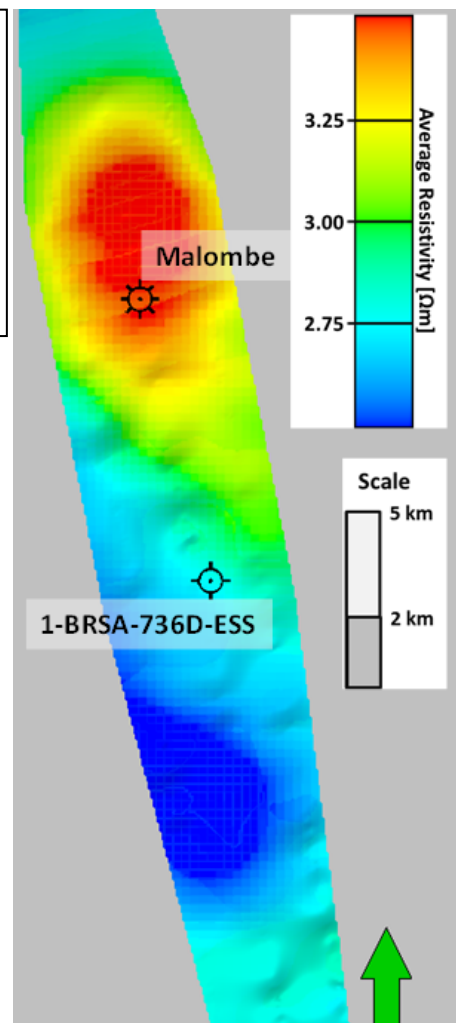

Figure 3:

Results for a survey in the Espirito Santos Basin. The average resistivity is extracted over a 1000 m window. The well is reported as a non-commercial discovery.

Figure 4:

Results for survey over the Malombe gas discovery. The average resistivity is extracted over a 1500 m window. The well towards south is reported as dry.

The consistency in the results of the analyzed wells with the observations in the CSEM data is encouraging. All the hydrocarbon discoveries are associated with elevated resistivities, while this observation cannot be made for any of the wells where no commercial discoveries were reported. This absence of false negatives suggests that in the surveyed and analyzed basins even results from a very early stage of the processing can be used to review a drilling portfolio.

Survey layout discussion

A first pass evaluation of the deployed survey layouts indicates some potential for improvements for future surveys. The interpretation, and in some cases even the processing of the narrower azimuth surveys is strongly affected by the limited spatial sampling, requiring additional input from seismic to provide a regional context. The limited spatial sampling can potentially compromise the independent character of the measurement by relying on the accuracy of the seismic interpretation. Some of these challenges were already introduced in Figure 3 and Figure 4 where the lateral extension of the proven discoveries is difficult to evaluate from the mCSEM results alone.

Figure 5 illustrates this challenge for a different survey where the highest resistivities are not located in the centre of the survey, as originally anticipated, but towards the northern and southern edge. These features are dominating the response at this depth interval, therefore, the confidence in their interpretation will determine what level of resistivity can be considered as anomalous and potentially linked to hydrocarbon saturation. For this purpose, a regional resistivity model will be needed and mainly based on seismic. The lack of lateral definition of these features will challenge the ability for correlation analysis, and the very limited survey area without features under investigation (present anomalies and prospect area) severely limits the calibration points for such a regional model. In the salt areas of the Espirito Santos Basin, these effects got even more amplified due to significant side sweep effects from salt structures which were not covered by the survey layout. The 3D-effects cannot be confidently reconstructed in an unconstrained mCSEM-inversion and consequently, the information on the salt geometry and resistivity properties has to come from seismic and well log data.

Figure 6 illustrates some of the advantages of a more regional style survey when compared to a narrow, very targeted survey. The Moita Bonita discovery was covered by a crossing swath survey which is focused at the immediate area of interest, while an additional regional style 3D survey was acquired to evaluate the whole area. Both of the surveys show a defined resistivity increase in the location of the discovery well, extending further towards south. While the crossing 3D swaths indicate a closure of the resistive feature towards the southern end of the survey, and generally gives the impression of being a well localized feature, the regional survey indicates that it is part of a larger complex. Towards north-west of the Moita Bonita well, the regional survey shows an additional well defined resistive feature which is not indicated by the

3D swath. The swath only shows as a narrow northwards extension of the resistor away from the Moita Bonita well, providing a very different impression of the upside potential in this direction. The slight imaging differences between the 3D swath and the regional survey could be either related to the different sampling of this area by the two surveys as the regional survey was acquired with a coarser receiver spacing and a tow-line orientation, oblique to this narrow resistive band, while the swath was oriented parallel to the feature and had tighter spacing.

Conclusions

The first results from the mCSEM calibration campaign are very encouraging with respect to the applicability of the method to the Brazilian offshore basins, and indicate that the general geology in the post-salt section is very suitable for the application of mCSEM. Resistive features, coinciding with discovery wells, are imaged to a depth of
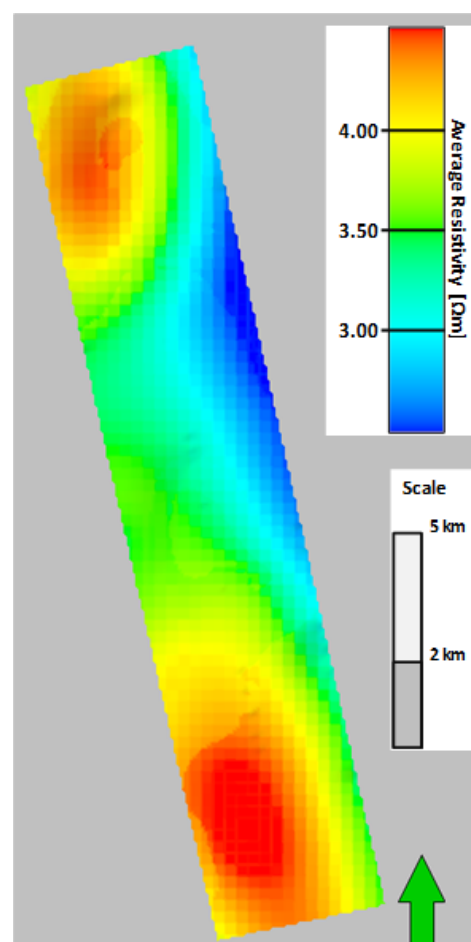

Figure 5:

Results for a survey in the Espirito Santos Basin. The average resistivity was extracted over a 1000 m window. The survey is dominated by resistive features towards northern and southern end of the survey area.

up to 3km burial. Currently, only the recently drilled wells in the survey areas are analyzed for consistency with the mCSEM results. Each of the seven evaluated discovery wells is associated with areas of increased resistivity. Furthermore, five wells, reported as dry or non-commercial volumes of hydrocarbons, are drilled in areas which do not show elevated resistivity in a regional context. This indicates that even results from an early processing stage which are presented here can be used as a guide to review drilling priorities or prospect potential.

An initial review of the surveys indicate some benefits of a more regional approach for exploration surveys beyond the larger picture character. Laterally narrow survey layouts across prospects make the interpretation of the mCSEM data dependent on additional data from seismic and well logs to provide the regional context, thereby compromising the independent character of the mCSEM measurements. Further work on this large data volume is required to thoroughly explain all the observed features and to calibrate the mCSEM data against all the available wells. In addition, PetroBras will be working on updating and developing workflows to incorporate the mCSEM data in an efficient manner into their existing exploration workflows.

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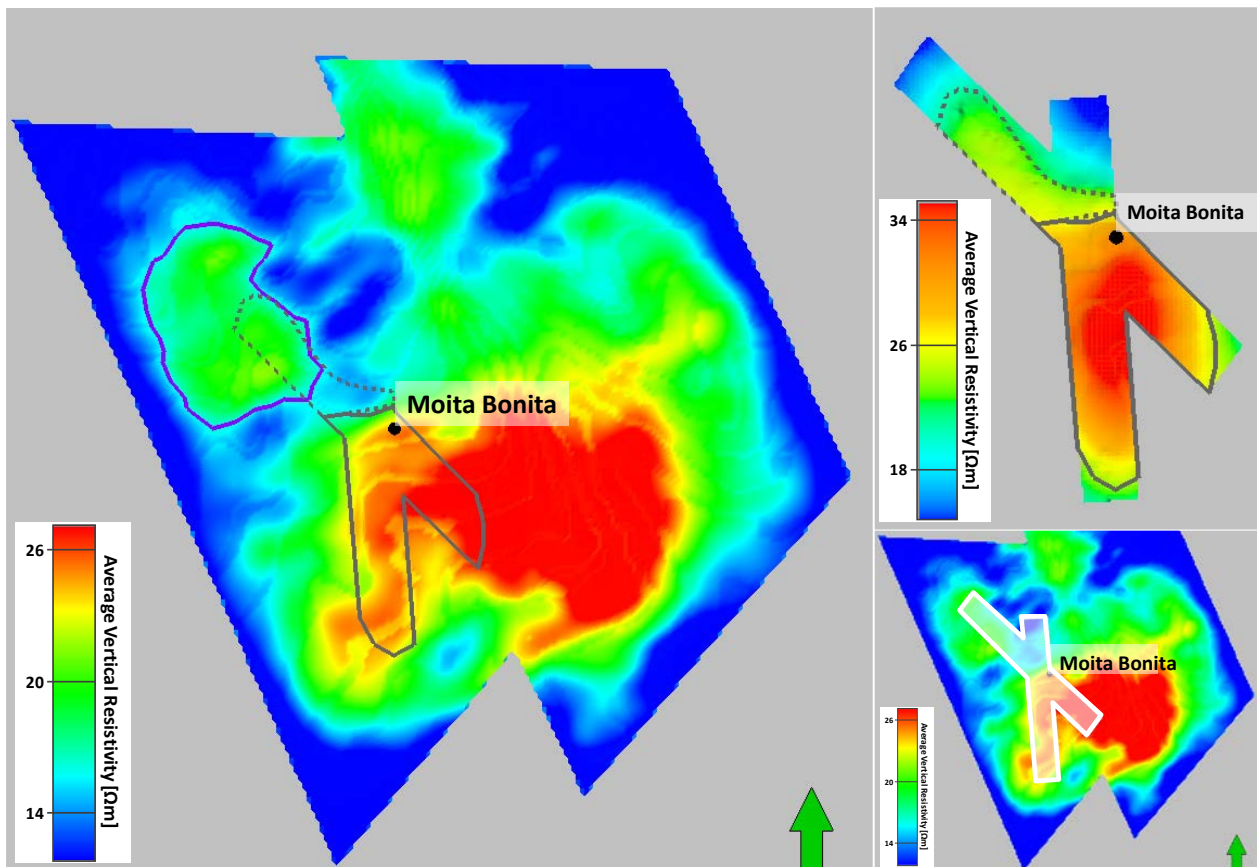

Figure 6:   Comparison of the spatial definition of resistive features for a 3D swath, targeting the immediate vicinity of the Moita Bonita area and a regional survey. The average resistivity is extracted over the same 1000 m window for both data sets. The grey outlines show resistive features which were derived from the 3D swath (upper right). The location of the 3D swath is given in the lower right image. Purple indicates an additional resistor, identified in the regional data set (left image), crossing into the area of the 3D swath.

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