Revista ARACÊ
ISSN: 2358-2472

COMPARATIVE PERFORMANCE ANALYSIS OF CONTROLLED-SOURCE ELECTROMAGNETIC METHOD CAMPAIGNS AND SURVEY DESIGN - MARLIM OILFIELD CASE STUDY

ANÁLISE COMPARATIVA DO DESEMPENHO DE CAMPANHAS COM O MÉTODO ELETROMAGNÉTICO DE FONTE CONTROLADA E PROJETO DE LEVANTAMENTOS - ESTUDO DE CASO DO CAMPO PETROLÍFERO DE MARLIM

ANÁLISIS COMPARATIVO DEL RENDIMIENTO DE CAMPAÑAS DE MÉTODOS ELECTROMAGNÉTICOS DE FUENTE CONTROLADA Y DISEÑO DE ESTUDIOS: ESTUDIO DE CASO DEL YACIMIENTO PETROLÍFERO DE MARLIM

https://doi.org/10.56238/arev7n11-302

Submission date: 10/24/2025 **Publication Date:** 11/24/2025

Danusa Mayara de Souza[1], João Carlos Lisboa de Lima[2], Victor Cezar Tocantins de Souza[3], Marcos Welby Correa Silva[4]

ABSTRACT
The controlled-source electromagnetic method (CSEM) has been gaining considerable attention and its main use is the monitoring of hydrocarbon reservoirs, due to its sensitivity in the verification of electrical resistivity contrasts, in addition to being slightly less harmful to marine biota than traditional seismic methods. In this manuscript, a multiphysics modelling of the marine controlled-source electromagnetic method (MCSEM) and the vertical-vertical controlled-source electromagnetic method (VVCSEM) was constructed using a realistic geologic model from the Marlim oilfield, Campos Basin - Brazil. Marlim is an oilfield belonging to the Marlim Complex, located in the Brazilian passive margin, which has large intervals of carbonate rocks that laterally mix with sandy sequences. The basin is dominated by shales intercalated with turbiditic sandstones at greater depths, very similar to the stratigraphic package found in the Potiguar Basin – Brazil. A comparison between the two CSEM methodologies is presented, as well as a survey design proposal. The MCSEM and the VVCSEM methods proved to be efficient in detecting the responses of the hydrocarbon reservoir even in the face of a considerable layer of salt, with VVCSEM achieving a better imaging response in some geological situations in which MCSEM almost did not identify the presence of a reservoir.

Keywords: Reservoir Monitoring. Electromagnetic Method. Multiphysics Modelling. Marlim Oilfield. Frequency Domain.

[1] Dr. in Geophysics. Universidade Federal do Pará. Pará, Brazil. E-mail: danusa@ufpa.br
Orcid: 0000-0003-0114-5394
[2] Dr. of Civil Engineering. Universidade Federal do Pará. Pará, Brazil.
E-mail: joaocarlosliboadelima@hotmail.com Orcid: 0000-0002-1819-0530
[3] Dr. in Geophysics. Universidade Federal do Pará. Pará, Brazil. E-mail: victorcezar@ufpa.br
Orcid: 0000-0003-3318-4486
[4] Dr. in Geophysics. Universidade Federal do Pará. Pará, Brazil. E-mail: welby@ufpa.br
Orcid: 0000-0002-2508-1332

Revista ARACÊ
ISSN: 2358-2472

RESUMO
O método eletromagnético de fonte controlada (CSEM) tem recebido considerável atenção e sua principal aplicação é o monitoramento de reservatórios de hidrocarbonetos, devido à sua sensibilidade na verificação de contrastes de resistividade elétrica, além de ser ligeiramente menos prejudicial à biota marinha do que os métodos sísmicos tradicionais. Neste artigo, foi construída uma modelagem multifísica do método eletromagnético de fonte controlada marinho (MCSEM) e do método eletromagnético de fonte controlada vertical-vertical (VVCSEM) utilizando um modelo geológico realista do campo petrolífero de Marlim, Bacia de Campos - Brasil. Marlim é um campo petrolífero pertencente ao Complexo Marlim, localizado na margem passiva brasileira, que apresenta grandes intervalos de rochas carbonáticas que se misturam lateralmente com sequências arenosas. A bacia é dominada por folhelhos intercalados com arenitos turbidíticos em maiores profundidades, muito semelhante ao pacote estratigráfico encontrado na Bacia Potiguar - Brasil. Uma comparação entre as duas metodologias CSEM é apresentada, bem como uma proposta de projeto de levantamento sísmico. Os métodos MCSEM e VVCSEM demonstraram ser eficientes na detecção das respostas do reservatório de hidrocarbonetos, mesmo na presença de uma camada considerável de sal. O VVCSEM apresentou melhor resposta de imagem em algumas situações geológicas nas quais o MCSEM praticamente não identificou a presença do reservatório.

Palavras-chave: Monitoramento de Reservatório. Método Eletromagnético. Modelagem Multifísica. Campo Petrolífero de Marlim. Domínio da Frequência.

RESUMEN
El método electromagnético de fuente controlada (CSEM) ha cobrado gran relevancia, principalmente para el monitoreo de yacimientos de hidrocarburos, debido a su sensibilidad en la verificación de contrastes de resistividad eléctrica y a que resulta menos dañino para la biota marina que los métodos sísmicos tradicionales. En este trabajo, se presenta un modelo multifísico del método electromagnético de fuente controlada marina (MCSEM) y del método electromagnético de fuente controlada vertical-vertical (VVCSEM), construido a partir de un modelo geológico realista del campo petrolífero Marlim, en la Cuenca de Campos, Brasil. Marlim es un campo petrolífero perteneciente al Complejo Marlim, ubicado en el margen pasivo brasileño, que presenta amplios intervalos de rocas carbonatadas intercaladas lateralmente con secuencias arenosas. La cuenca está dominada por lutitas intercaladas con areniscas turbidíticas a mayor profundidad, muy similar al paquete estratigráfico de la Cuenca Potiguar, también en Brasil. Se presenta una comparación entre las dos metodologías CSEM, así como una propuesta de diseño de prospección. Los métodos MCSEM y VVCSEM demostraron ser eficaces para detectar las respuestas del yacimiento de hidrocarburos incluso ante la presencia de una considerable capa de sal. El método VVCSEM logró una mejor respuesta de imagen en ciertas situaciones geológicas donde el método MCSEM prácticamente no detectó la presencia del yacimiento.

Palabras clave: Monitoreo de Yacimientos. Método Electromagnético. Modelado Multifísico. Campo Petrolífero de Marlim. Dominio de la Frecuencia.

Revista ARACÊ
ISSN: 2358-2472

1 INTRODUCTION

Large reserves that have been discovered and are already in the production phase require reservoir monitoring for more effective and better use of the fields. As the oil (meaning oil and gas) is explored, the contrast in physical properties between the embedding environmental geologic and the reservoir itself decreases. Controlled-source electromagnetic methods (CSEM) are very sensitive to the contrast between electrical resistivities and have been ideal in monitoring and flow analysis studies in producing fields.

This manuscript will focus on the marine controlled-source electromagnetic method (MCSEM), seabed logging (SBL) in question and vertical-vertical controlled-source electromagnetic method (VVCSEM). Both methods use a controlled-source electromagnetic source, i.e., an artificial source for generating the electromagnetic fields. The essential difference between MCSEM and VVCSEM is the mode of operation and the orientation of the source and receivers. In the MCSEM, a horizontal electric dipole (HED) is used and acquired in the frequency domain. In contrast, in the VVCSEM, a vertical electric dipole (VED) is used, and acquisition is performed in the time domain.

A realistic geological model of a study area known as Marlim-R3D (MR3D) (Carvalho and Menezes 2017; Correa and Menezes 2019) was used to test and compare the responses of the two CSEM methodologies. The geological model represented a turbidite reservoir with six stratigraphic horizons and was obtained from the analysis of seismic profiles (2D and 3D) arranged in a parallel and transversal way in the area of interest correlating with the well-to-seismic ties in the region.

The simulations with the CSEM methodologies were built in a multiphysics modeller. For the usual comparison of the responses of the background (NoHC) and the geological model with the reservoir (HC), an isolated three-dimensional body was built with the MR3D data in a geological modeller.

A survey acquisition design of the CSEM data was performed to obtain its responses for different arrangements and azimuths and to compare the responses in MR3D. The curves obtained with the MCSEM and with the VVCSEM offered different perspectives of the resistive layer and proved efficient in monitoring the reservoir.

Revista ARACÊ
ISSN: 2358-2472

2 METHODS

2.1 THE CONTROLLED-SOURCE ELECTROMAGNETIC METHODS (CSEM)

2.1.1 Marine controlled-source electromagnetic methods (MCSEM)

Marine controlled-source electromagnetic methods with a focus on seabed logging (SBL) despite having been proposed in 1980 by Charles Cox and Jean Filloux, it was only in the mid-2000s that a company would undertake the first MCSEM survey using instruments developed by two other companies and was followed by surveys by the third company in 2002. In 2002, three different companies offered MCSEM commercially. In 2004, the last of the three reached considerable capital, and two other prominent new companies bought the other two.

In the following years, until approximately 2007, the market trend continued. A new company acquired 15% of the surveys of the first company that achieved good capital with the methodology. The other two first companies to offer the acquisition service started partnerships in the technology sector. For more details, see Chave and Cox (1982); Constable and Cox (1996); Hoversten *et al.* (1998); MacGregor and Sinha (2000); Eidesmo *et al.* (2002); Elingsrud *et al.* (2002); Kong *et al.* (2002); Johansen *et al.* (2005); Constable and Srnka (2007); Constable and Key (2008); Ziolkowski and Slob (2019).

The commercial fuss around the MCSEM was due to its ability to assist the main points that traditional seismic methods had difficulties. High acoustic contrast in the subsalt, subbasalt and carbonate prospects and problems in imaging structures with subvertical inclination. Complex geological environments generate ambiguity in the interpretation and monitoring of oil flow in fluid injection environments to increase production.

The marine acquisition methodology that uses a controlled-source electromagnetic has received several nomenclatures since it has been used and marketed by several companies. SBL is the most common among them and has become synonymous with MCSEM methods. In this manuscript MCSEM nomenclature will be used.

The MCSEM method came with a significant differential from the usual nonseismic methods, gravimetry and magnetometry, for having a controlled-source. This feature ensured a greater control of offshore operations and gave way to electromagnetic methods (EM) as one of the main and prominent auxiliary methods in seismic campaigns (Constable and Key 2008).

The MCSEM acquisition method has two modes of operation. Both modes use a horizontal electric dipole (HED) source towed behind a ship at a certain depth. In one

Revista ARACÊ
ISSN: 2358-2472

configuration, the receivers are stations positioned at fixed locations on the seabed, while the other configuration uses a coil containing the receiver electrodes. Seabed stations generally measure all magnetic flux components (*Hx*, H_y, and H_z) and the horizontal components of the electric field (E_x, E_y, and E_z), while a streamer measures only the inline component of the electric field. For this reason, the configuration of the seafloor stations was used here. The electric field can be written in terms of the transverse electric (TE) and transverse magnetic (TM) mode fields that diffuse in the upwards and downwards directions.

The MCSEM is an electromagnetic method that operates in the frequency domain and uses a horizontal electric dipole as a source (Tx) that is usually towed to the vicinity of the ocean floor by a ship. Throughout the acquisition, the Tx emits a low-frequency electromagnetic signal (e.g, 0.025 Hz – 1.00 Hz) that spreads toroidally in the surrounding environment, air, sea and sediments.

In current equipment, there are two types of Tx configurations. One where the Tx stays on the surface, positioned using global positioning system (GPS) buoys for greater accuracy, can be towed with up to 4 knots and is efficient at depths of up to 400 m (shallow water). The surface source has a maximum output current of 7200 A and a maximum dipolar moment of 2100 kAm, depending on the geological configuration. In the second type of Tx, the source is towed very close to the ocean floor and can provide an output current of up to 10000 A and operate at depths with water layers up to 4000 m (deep water).

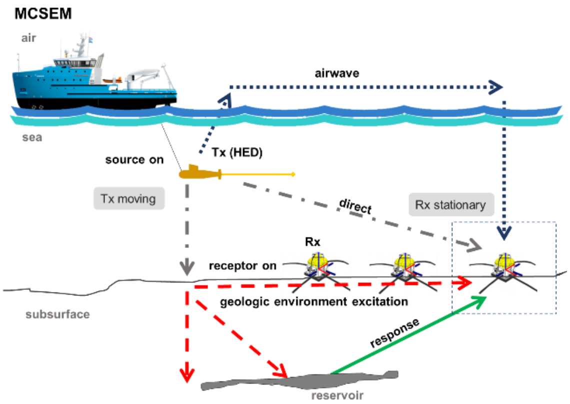
The sources used in MCSEM are of two types instrumentally: magnetic and electrical. Magnetic sources are isolated loops carrying a current known as a magnetic dipole. Electrical sources are usually straight lengths of insulated wire connected with the seabed through low-resistance electrodes and are known as electric dipoles. Magnetic sources are successful in shallow (less than 150 m depth) oil mapping. For deeper hydrocarbons, electrical sources are more efficient. This manuscript will use only electrical sources (electrical dipoles), because of the depth of the target under study.

The receivers (Rx) are launched on the seabed with the aid of cranes and ballasts (cementitious plates or neutral sand). The latter ensures sinking and subsequent floating when uncoupled (remote activation) from the receiving antenna. The Rx is usually composed of four electrical dipoles crossing a central structure and magnetic caps. The source-receiver arrangement favours the detection of resistive layers (hydrocarbons), mainly in deep regions. Fig.1 shows a schematic illustration of the primary responses captured by Rx during an MCSEM acquisition.

Revista ARACÊ
ISSN: 2358-2472

Figure 1

MCSEM data acquisition scheme, in which a submerged source (DEH) is towed by a ship while emitting the pulse picked up by receivers scattered on the ocean floor. The blue dotted line depicts the airwave, the grey dot-dashed line the Tx direct pulse, the red dashed line the geologic environment stimulation by the Tx, and the green solid line the response of contact with the reservoir and the subsurface



The signal emitted by the Tx is picked up by the Rx, both in direct form (Tx-Rx), the so-called direct wave, and in reflected form, airwave and that which travels from the Tx to the sediments and from them to the Rx. Of course, this is a very simplified reflection scheme because even the signal reverberating through the sea, magnetotelluric waves, and currents produced by sea waves, among others, are captured and recorded by the receivers. The data collected are subsequently downloaded, treated and interpreted. The signal will depend on the characteristics of the geological environment under study since it is based on the contrast of electrical resistivity (or its inverse, electrical conductivity) between the surrounding environment and the possible hydrocarbon reservoirs.

2.1.2 Vertical-vertical controlled-source electromagnetic methods (VVCSEM)

In the mid-2000s, offshore research group members decided to invest in EM research and development, the financial resources obtained from consultancies. Furthermore, in 2002, a research group was created focused on studying the MCSEM method, which was chosen because it was on the rise and showed great potential in reservoir monitoring. The problem was in what and how to improve the methodology so that the response would be so good as to reduce the ambiguity and limitations (water layer thickness, rough and irregular bathymetry) that traditional EM methods were already facing.

To improve the MCSEM, an analysis of all registers about the technique was carried out between 2003 and 2004. This resulted in a detailed study of twenty-seven patents and one hundred whitepapers on the methodology, equipment and data acquisition methods filed in several countries.

By systematically analysing the available documentation, the group of scientists and researchers teamed up with engineers (from various specialisations and with extensive experience in marine surveys) to develop a new controlled-source arrangement. The best resolution in the traditional MCSEM data would be obtained by having a vertical source instead of a horizontal source, which was the standard until then. After technical and economic feasibility analysis, transient electromagnetic prospecting with vertical electric lines (TEMP-VEL) was created, and a company was founded in 2004 specifically to commercialise this new arrangement. In the same year, in parallel, transient electromagnetic prospecting with adjusted electric lines (TEMP-AEL) was developed for use in shallow water layers.

TEMP-VEL brought not only the change in the source to vertical but also in the receivers, which were developed to be arranged vertically on the ocean floor, and the acquisition mode changed to the time domain, thus stacking the pulses and strengthening the signal obtained throughout the measurement.

In this manuscript, a treat TEMP-VEL by the nomenclature vertical-vertical controlled-source electromagnetic (VVCSEM), which is more convenient for understanding a method derived from the established MCSEM. The VVCSEM method is, strictly speaking, a CSEM method that is distinguished from the SBL by the vertical source-receiver arrangements and acquisition mode in the time domain instead of the frequency domain.

Similar to the MCSEM, the VVCSEM performs electromagnetic field measurements of the subsurface in a marine environment. The acquisition system is formed by a vertically oriented Tx and Rx, which are transported by a ship and arranged for data collection by cranes.

The transmitter is composed of a direct current (DC) quadratic pulse generator with alternating polarity. The pulse signals an 8-bit (P8 sequence) called the Thue-Morse sequence that changes polarity every P4 (Allouche and Shallit 1999).

The Thue-Morse sequence is peneperiodic and can be exemplified by the binary sequence below; where 0 and 1 compose the sequences P2, P4, and P8 (of interest). Thus, $0 \rightarrow 01$ and $1 \rightarrow 10$, the formation of Thue-Morse follows, replacing the elements of the

Revista ARACÊ
ISSN: 2358-2472

previous one in the subsequent sequence. Therefore, starting from 0, there has 0 → 01 → 0110 (P2) → 01101001 (P4) → 0110100110010110 (P8).

The transmitter has this feature to avoid one of the biggest problems that MCSEM data suffer, the airwaves, and to avoid them being used, in VVCSEM, a function of time at the source. The off-source is mathematically a scaled version of $H(-t)$, for that $H(t)$ is the Heaviside function.

Before the source is switched off, the electric field has an initial value $E(0)$ caused by the current, which is on forever (in principle). However, when t = 0, which is when the source current is switched off, the electric field magnitude immediately jumps to a lower value, and due to attenuation in the Earth, this is followed by a drop to zero, with the magnitude of the jump and the exact shape of the decay curve depending on the electric conductivity structure below the source and receiver.

The source function is a scaled version of the Heaviside function $H(t)$. The electric field in the receiver due to the source is initially zero. When the source current is switched on, there is an immediate jump in the field followed by further increases in magnitude, tending to the final value $E(0)$. The shutdown response E_- and the activation response E_+ are related so that

$$E_+(t) = -E_-(t) + E(0) \qquad (1)$$

which is the switch-on response, the switch-off response, plus a constant known from the initial switch-off value. The constant can be difficult to determine if the data are noisy. One solution to this is to use a long period square wave as a function of the source time.

In addition to the pulse generator, the Tx is also composed of a vertical electric dipole (5000 A), consisting of two steel electrodes (2500 A each) connected by a long copper cable, with one electrode 50 m below the water surface and the second electrode on the seabed. An A-frame electrode launcher/retrieval crane positions the electrodes carefully, minimising the transmitter's cable slope.

The challenge in measuring the vertical rather than the horizontal component of the EM field is the small amplitude of the signal since, at end times, the horizontal response of a horizontal dipole is 2-3 orders of magnitude more potent than the vertical response of a vertical dipole. Therefore, the tilt angles of the transmitter and receiver must be kept as small as possible, a challenge that motivated the design of a tripod antenna where verticality is

Revista ARACÊ
ISSN: 2358-2472

achieved through the action of gravity. The dependence of measured transmitter data and receiver positions can also be used to control pitch effects.

Each receiver consists of a vertical tripod antenna made of nonferrous material. They have an upper unit with electrodes, a lower unit with electronics (batteries, data storage, and recording unit), and a neutral sand ballast (they promote weight for the descent of the Rx and are decoupled at the end of the data acquisition). A buoybell promotes a better vertical alignment through the balance between the weight of the bell (heavy structure whose shape resembles a bell with concavity downwards) and the buoyancy force of the buoy (spherical structure resembling a sea buoy that lies inside the bell).

Different receiver lengths were used throughout the instrumental and operational tests, ranging from 5 m - 18 m for the rigid tripod and 30 m - 60 m for the flexible cable receivers. As there is no physical connection to the sea surface, data are downloaded after retrieval from the receiver station on deck or via cables connected to the receiver base. A remotely operated vehicle (ROV) spreads and connects/disconnects the crane hooks and the optical fibre (receiving the data in real time).

The receivers have four pairs of Pb/PbCl electrodes and a sampling frequency of 1000 Hz with 24-bit resolution used for the measurements. The long receivers (flexible cable) have a higher signal level than the tripod; however, strong sea currents carry noise from electrical discharges and cause small slopes/tilts. The tripod has low noise and less pitch but a low signal level compared to the long cable receiver. Currently and most commonly, tripod antenna receivers are used due to operational advantages.

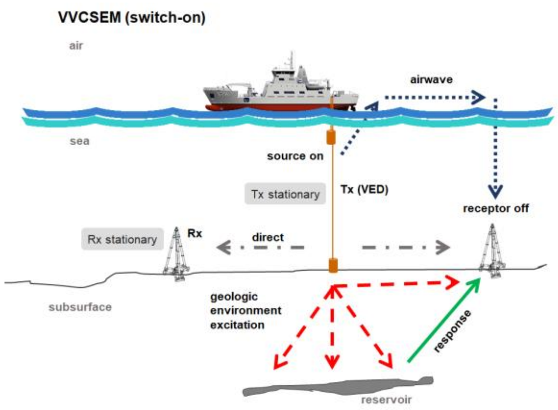
The Rx records electric field measurements, navigation data, source data, and status data. More detailed instrumental information can be found in Barsukov *et al.* (2007); Barsukov *et al.* (2008); Kjerstad (2010), which are the patents for TEMP-VEL, TEMP-AEL, and the receivers, respectively.

The data acquisition is made in the time domain, where both the source and the receivers remain static. The reading of the EM field information by the receiver is done during periods of inactivity of the source. The source is turned on when the receivers are off; thus, the measurements do not suffer interference from direct and airwaves, which are inherent drawbacks of SBL acquisitions. Fig.2 shows a larger illustration of the method.

Revista ARACÊ
ISSN: 2358-2472

Figure 2

Scheme of VVCSEM data acquisition, in which a stationary submerged source (DEH) oscillates between on and off periods, the pulse being captured by the receivers, scattered on the ocean bottom, in the moments of inactivity of the source. The blue dotted line depicts the airwave, the grey dot-dashed line the Tx direct pulse, the red dashed line the geologic environment stimulation by the Tx, and the green solid line the response of contact with the reservoir and the subsurface



For analysis of the collected data, a comparison is made of the responses in environments (or models) with no hydrocarbons (NoHC) $E_0(t)$ and compared with the presence of hydrocarbons (HC) $E_{HC}(t)$; thus, the anomalous vertical field is:

$$E_A = E_0(t) - E_{HC}(t) \qquad (2)$$

and the contrast

$$S = 1 - \frac{E_{HC}(t)}{E_0(t)}. \qquad (3)$$

The contrast is as important as the anomaly itself. The anomaly is determined mainly by the overburden's transverse resistivity = (thickness * resistivity) compared to the reservoir's transverse resistivity. For more physics details and mathematics formulation, see Ward and Hohmann (1987); Zhdanov *et al.* (2006); Ziolkowski and Slob (2019).

The difference between the NoHC responses and a one-dimensional HC reservoir is relatively constant over a radius of approximately 2000 m if the reservoir is more profound than 1000 m. At very short offsets (less than 100 m), small Rx movements generate uncertainties and induced polarisation (IP) effects. In some cases, they can dominate the measurements, while at larger offsets (more than 1000 m), three-dimensional and tilt effects become more significant. Between these limits, the optimal offset between the vertical-vertical (Tx and Rx) arrangement is generally 250 m - 1500 m. The characteristic short offset gives rise to near zone imaging, and the Tx-Rx configuration causes only the transverse magnetic mode (TM components H_y, E_x, and E_z) of the EM field to propagate.

2.2 MARLIM OILFIELD

2.2.1 Geological context

The Brazilian marginal basins have a fascinating tectonic-sedimentary evolution, with compressive characteristics and small portions of distension characteristics. They correlate with the African marginal basins, as they share a common origin and evolution. The similarity between these environments can be seen in detail in Scotese (2001).

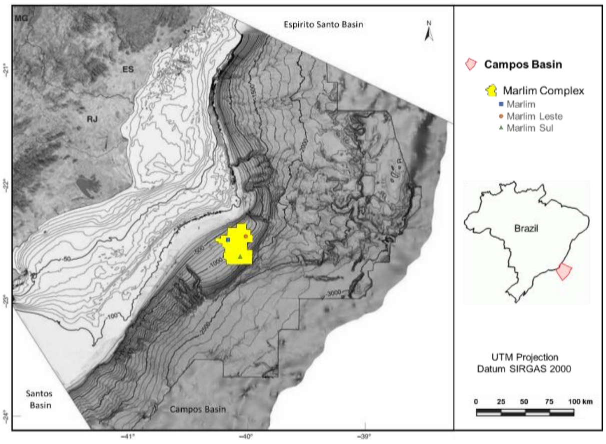
The Campos Basin, the southern segment in the southeastern portion of Brazil, is a Meso-Cenozoic basin of the distal margin, with a perceptible diachronic rupture phenomenon and formation of lacustrine depocentres in the Eocretaceous of the rift section.

The eastern margin still comprises the restricted marine section, well characterised by the evaporite package (such as halite and anhydrite), which is very important in the basin's thickness and area of occurrence (Figueiredo and Mohriak 1984). Fig.3 shows the location of the Campos Basin and the Marlim Complex (Marlim, Marlim Leste, and Marlim Sul oilfields) concerning Brazil's map and the region's bathymetry.

Revista ARACÊ
ISSN: 2358-2472

Figure 3

Location of the Campos Basin (red polygon) and Marlim Complex (yellow polygon). Base map adapted from Schreiner et al. (2014), shapefile from GeoANP, and georeferenced in QGIS



The region of the Campos Basin where the Marlim Field is located has a challenging bathymetry from the perspective of collecting data with vertical dipoles since it is difficult to maintain the verticalisation of the source, and there is, in many cases, a significant difference in elevation between the source and the receivers depending on the offset.

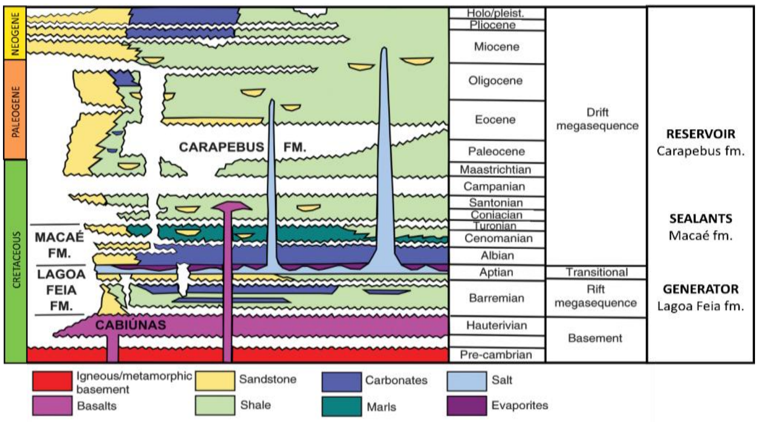
Marlim is an oilfield belonging to the Marlim Complex, located in the Campos Basin (Brazilian passive margin), which has large intervals of carbonate rocks that laterally mix with sandy sequences. The basin is dominated by shales intercalated with turbiditic sandstones at greater depths, very similar to the stratigraphic package found in the Potiguar Basin – Brazil (Brazilian equatorial margin).

The main formations of the Marlim Field are Emboré, Ubatuba, Carapebus, Macaé, Lagoa Feia, and Cabiúnas (Castro and Picolini 2015). The stratigraphic, tectonic and magnetism charts can be seen in Fig.4 modified from Guardado *et al.* (2000).

Revista ARACÊ
ISSN: 2358-2472

Figure 4

Stratigraphic, tectonic and magnetism chart of the Campos Basin with clipping in the zones of interest (modified from Guardado et al. 2000)



The Marlim oil system is formed by lacustrine shales and marls of the Lagoa Feia Formation (generator); turbidite/lacustrine-deltaic sandstones of the Carapebus Formation (reservoir); lacustrine shales of the Carapebus and Emboré Formations and some transcurrent faults in positive flower structure due to the gravitational movement of the salt layer, just below the Blue Mark (maximum flooding surface in the basin) in the Macaé Formation (sealants/pitfalls). The timing of plays formation is directly related to the tectonostratigraphic evolution of the basin (Nascimento *et al.* 2014).

Given the geological complexity and exploratory challenges of the Marlim field, the realistic Marlim R3D (MR3D) model was developed and made available for testing various electromagnetic methodologies, such as CSEM (Correa and Menezes 2019; Menezes *et al.* 2021).

MR3D is an open-source realistic geoelectric model designed for MCSEM simulations of postsalt turbidite reservoirs in the Brazilian offshore margin. The MR3D model is available on the Zenodo platform with a mesh size of 100 x 100 x 20 m extended to a volume of 56 x 51 x 6 km and can be accessed at Carvalho and Menezes (2017). The dataset with the geoelectrical information (vertical and horizontal electrical resistivity) was built by a well-to-seismic tie in the Marlim oilfield. For more information about the interpretation process, see Martínez *et al.* (2021).

Revista ARACÊ
ISSN: 2358-2472

2.3 MULTIPHYSICS MODELLING

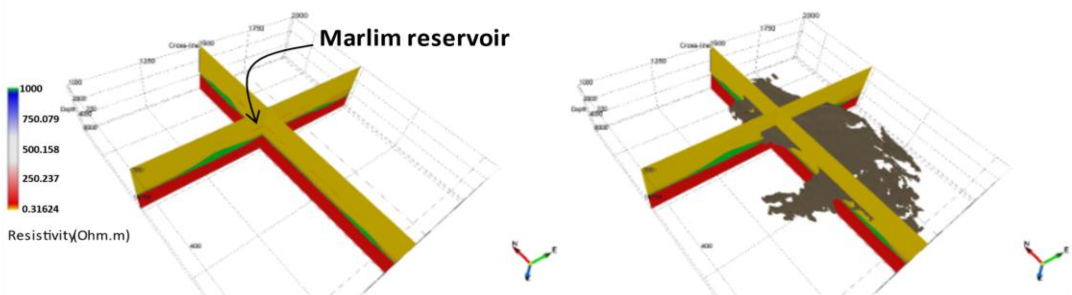
This manuscript aimed to test the CSEM on geology that was more realistic than that found in real-life prospects. Thus, a multiphysics modeller was created by utilising the MR3D data, forward modelling of the MCSEM and VVCSEM, and a survey design.

The multiphysics modelling program (COMSOL Multiphysics) includes various scientific and engineering modules for creating realistic models. The modules enhanced the capability of the leading platform and are organised into parts, with electromagnetism being of particular significance in this effort. An academic licence was used to make the models used in this manuscript.

The first step in using the MR3D model was to import the horizontal and vertical electrical resistivity (segy) and the sedimentary horizons into a geological modeller (OpendTect). The volume selection with the resistivity anomaly (with the neighbourhood) promoted the delimitation and generation of the isolated reservoir body through the direct hydrocarbon identification (DHI) feature. This measure is necessary because MR3D has no horizon delimiting the reservoir, only the enclosing layers (Oligocene). Fig.5 shows the reservoir isolation process performed in the geological modeller for this manuscript.

Figure 5

Construction of the Marlim Reservoir body from the horizons and electrical resistivity distribution (vertical and horizontal). Isolated reservoir outside the electrical resistivity distribution colour bar for emphasis



Beginning with model building, the horizons (xyz): sea_bottom-mr3d, miocene-mr3d, oligocene-mr3d, top_of_marlim_reservoir-mr3d, blue_mark-mr3d, top_of_salt-mr3d, and base_of_salt-mr3d of the bedded features of the sediment package sampled by well-to-seismic ties with borehole profiles (PSW-01, PSW-02, PSW-03, PSW-04, PSW-05, PSW-06,

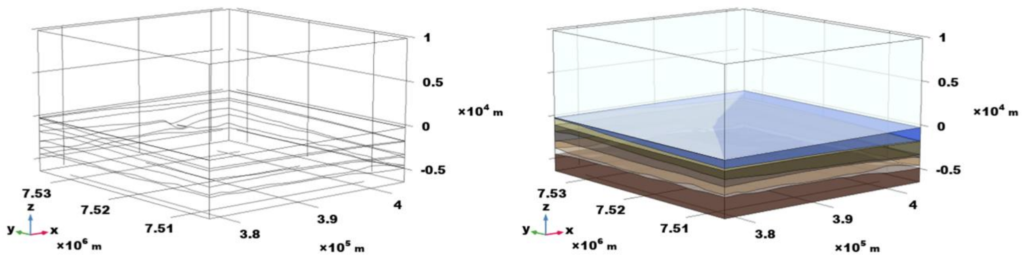
Revista ARACÊ
ISSN: 2358-2472

PSW-07, PSW-08, and PSW-09) were imported into a multiphysics modeller. CSEM methodologies do not distinguish extremely thin reservoirs, so a cut was used in parts of the reservoir with thicknesses of less than ten meters.

The schematic model of the MR3D horizons in the multiphysics modelling program is shown in Fig. 6. To construct the layers as a volume, an interpolation was performed so that the horizons themselves enclosed the top and bottom of each stratum. For a better realistic response, a layer (10000 m) with physical characteristics of the air was inserted above the model.

Figure 6

Geometric and physical parameters of the Marlim model in the multiphysics modeller



In the construction of the model, in addition to importing and interpolating the horizons, the horizons had to be converted into solids and interposed in a larger enclosing block, which was later trimmed with the horizon limits. To simplify the nomenclature, the Marlim model built in the multiphysics modeller will be called MR3DC.

The MR3DC has a realistic multiphysics representation of the layers, from top to bottom, air ($1x10^{-8}$ Ohm.m), sea (0.33 Ohm.m), Miocene - Emboré fm. (1, 1, 2 Ohm.m), Oligocene - Carapebus fm. (1.4, 1.4, 2.86 Ohm.m), Marlim Reservoir (electrical resistivity varies vertically and horizontally between 90 Ohm.m and 140 Ohm.m), Oligocene - Blue Mark (1.4, 1.4, 2.86 Ohm.m), Albian (salt layer) - Macaé fm. (1000 Ohm.m), and the last layer in the presalt region (53 Ohm.m). The electrical resistivity distribution in the air, sea, salt, and basement layers is isotropic. In the other layers, it follows the horizontal, horizontal, and vertical (x,y,z) data matrix for each geographic coordinate of the sedimentary package.

A polygon was inserted around the model (top, bottom, and sides), and absorbing boundaries were imposed around the whole domain (scattering boundary condition).

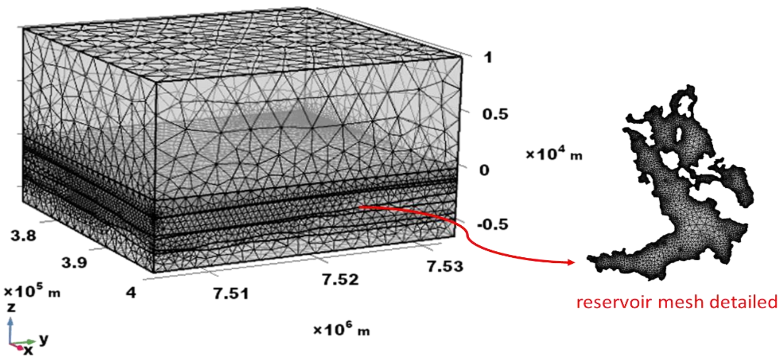
Revista ARACÊ
ISSN: 2358-2472

Because these boundary conditions act as a translucent boundary (shell) for outgoing waves, they are not reflected in the model.

The mesh densifies the zones of interest, allowing better refinement and accuracy of the oilfield response. The tetrahedral mesh utilised has densification in the areas of most significance, namely, around the source, receiver, and reservoir (where present), as seen in Fig.7, which illustrates the reservoir mesh in greater detail for improved visualisation. The mesh was created with varying mesh densities. The border (boundary) region (top, bottom, and sides) is fine-meshed and the air, sea, and sediment regions are extra fine-meshed. The reservoir region, transmitters, and receiver surroundings are extremely fine-meshed.

Figure 7

Layered Marlim model and densified mesh



For the MCSEM modelling, the radio frequency (RF) module and interface in the electromagnetic wave - frequency domain (emw) were used. For the VVCSEM, the alternating and direct current (AC/DC) module, electromagnetic interface fields, magnetic fields and electric fields (mef) were used, and two different studies were used, the first with step stationery to calculate the energisation of the geological environment by Tx (switch-on). The second with a time-dependent step to calculate the response of the medium after the source was turned off (switch-off).

The switch-off step was subdivided into two others, one with the model without a reservoir and the other with the reservoir. The AC/DC and RF interfaces formulate and solve the differential form of Maxwell's equations, along with the initial and boundary conditions. The equations are solved using the finite element method with numerically stable edge and element discretisation in combination with state-of-the-art algorithms for preconditioning and solution of the resulting systems of sparse equations.

Revista ARACÊ
ISSN: 2358-2472

After selecting the study type, mesh, and model, the simulation begins by calculating the source solution and then the unconnected source response, as previously indicated. After the datasets are set up, the results are shown after this phase is completed.

The finite element methods used to calculate the solution are similar to the finite integration technique (Clemens and Weiland 2001). However, they are based on variational principles, and their formulation must be done only in a domain below the ground surface. Thus, the formulations described in Ward and Hohmann (1987); Zhdanov *et al.* (2006) were considered. Initially, a canonical model was used to validate the CSEM response in the multiphysics modeller.

3 RESULTS AND DISCUSSIONS

3.1 MCSEM RESPONSE

As mentioned earlier, the modelling started with validating the methods in a canonical model. The MCSEM response for the canonical model was very similar to that obtained in the benchmark manuscript of Constable and Weiss (2006). The upper region computational domain represents air. At a frequency as low as 1 Hz, some numerical stabilisation is required in this domain so that an artificial electrical resistivity of 1000 Ohm. m is specified.

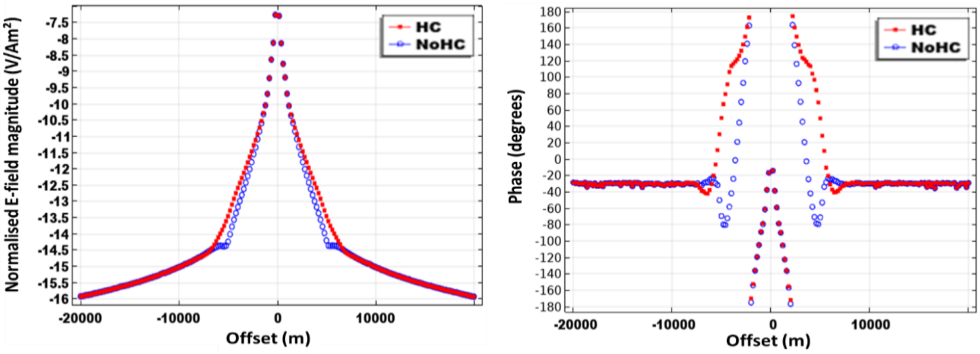
A 100 m deep ocean water domain with an electrical resistivity of 0.33 Ohm.m was specified below the midplane of the domain. Below the air and with an electrical resistivity of 1 Ohm.m was specified for the subsurface (rock). Embedded in the rock at an average depth of 250 m is a block-shaped hydrocarbon reservoir 100 m deep and 4 km by 4 km wide. The conductivity of the hydrocarbon layer is 100 Ohm.m.

The transmitter was modelled as a 1 Hz, short amplitude 10 kA, and AC power line segment (horizontal electric dipole antenna) towed 150 m above the sea bottom (in the x-direction). A receiver array was inserted into the ocean floor to measure the electromagnetic field at various distances from the transmitter. When measuring at a sufficiently large distance, some of the transmitted energy is reflected/guided by the resistive reservoir and results in a higher received signal than if no reservoir was present. The MCSEM response for the canonical model can be seen in Fig.8.

Revista ARACÊ
ISSN: 2358-2472

Figure 8

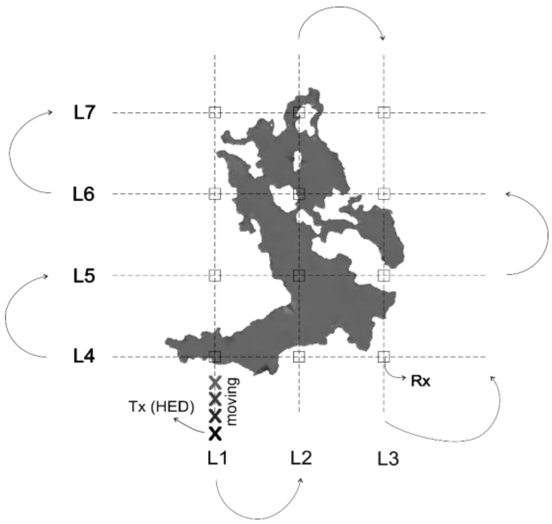
MCSEM response for the canonical model. The red dotted line represents the response to hydrocarbons (HC), and the blue dotted line with circles represents the absence of hydrocarbons (NoHC)



In the realistic MR3DC model, the MCSEM campaign was performed with inline and broadside profiles, following the L1, L2, L3, L4, L5, L6, and L7 lines. The Rx position was inserted to simulate an acquisition scheme to display data intowing and out-toing. Fig.9 displays the MCSEM survey design scheme in MR3DC.

Figure 9

MCSEM survey design scheme in MR3DC. Exaggerated scale for better illustration of the Tx-Rx offset. The crosses symbolise the positions of the Tx (towed by a ship), and the squares symbolise the position of the Rx



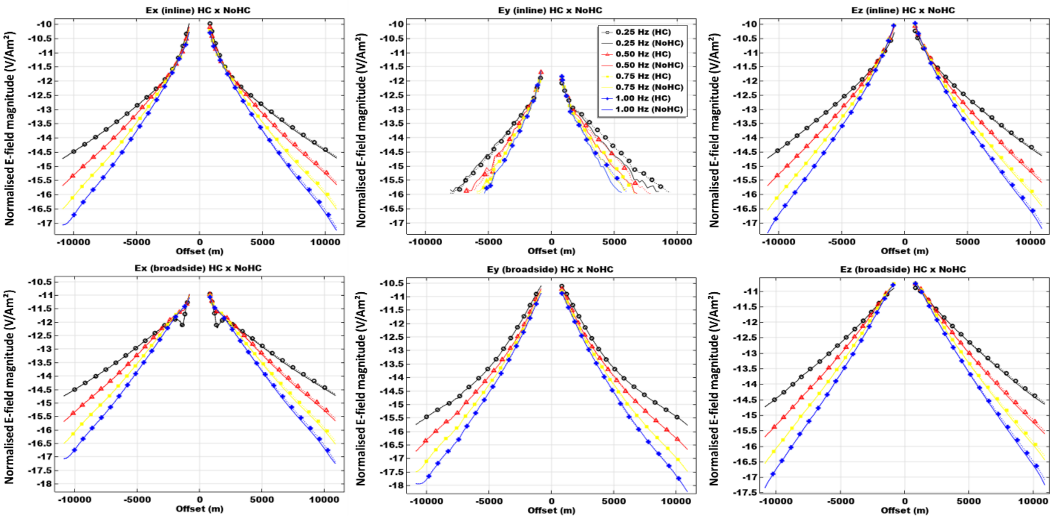
The acquisition lines (L1-L4) are 10 km long each, and the result will be displayed graphically using plot group 1D. The response for the E_x, E_y, and E_z field components inline

Revista ARACÊ
ISSN: 2358-2472

and broadside in the presence and absence of the hydrocarbon reservoir was verified. The present manuscript will display the MCSEM response taken at the central position in the MR3DC model, at the centre of the HED and with W–E oriented measurement lines. Fig.10 displays the MCSEM response measured at L5 for the MR3DC.

Figure 10

MCSEM response for MR3DC at the L5 position. The black dotted line with circles represents 0.25 Hz with hydrocarbons; the black solid line represents 0.25 Hz without hydrocarbons, the red dotted line with triangles represents 0.50 Hz with hydrocarbons, the red solid line represents 0.50 Hz without hydrocarbons, the yellow dotted line with points represents 0.75 Hz with hydrocarbons, the yellow solid line represents 0.75 Hz without hydrocarbons. The blue dotted line with squares represents 1.00 Hz with hydrocarbons; the blue solid line represents 1.00 Hz without hydrocarbons



The MCSEM result on MR3DC shows the reservoir response to be relatively weak due to the thick and highly resistive salt layer in the Albian. The responses of the E_x, E_y, and E_z components are very similar in the inline and broadside, except for the curves presented in E_y (inline), where the difference between the background (NoHC) and reservoir (HC) curves is more significant but distorted.

Due to the position of the Tx at the time of acquisition, the left side of the receivers is above a geological environment where the reservoir is not present, and the right side of the receivers is above. Thus, and as expected, the curves presented in Fig.10 show the identification of the Marlim only on the right side.

3.2 VCSEM RESPONSE

The VVCSEM response and verification of the behaviour in different models and configurations are performed with a canonical model in a multiphysics modeller. The validation of the response of the VVCSEM modelling behaved very similarly to the response presented in the manuscript of Holten *et al.* (2009); Helwig *et al.* (2019), these being the benchmarks of this work, as they are the first and most recent work published by the creators of the prospecting methodology and patent holders, respectively. The canonical model used in validating the VVCSEM response was the same as the one used in the MCSEM modelling.

The first transient study examines the propagation of electromagnetic waves in the geological formation without a reservoir (background), and the second in a geological environment with a reservoir, because in the analysis of collected data, a connection is made between the responses in environments where hydrocarbons are absent (NoHC) and compared to the response in an environment where hydrocarbons are present (HC). The disparity is just as significant as the oddity itself.

The study utilised in this publication was constructed in phases. First, the source's response (switch-on) was estimated in the stationary regime, with the field variables changing as a function of the injected current rather than over time (5000 A). The stationary research was carried out independently, and the response of the source excitation in half-space was saved for further use.

Then, in the transient domain, two investigations were conducted. Because the reading of the Rx's electromagnetic field information happens during the inactivity of the source in the field survey, the source response collected in the prior stationary research is the input signal in these (Tx).

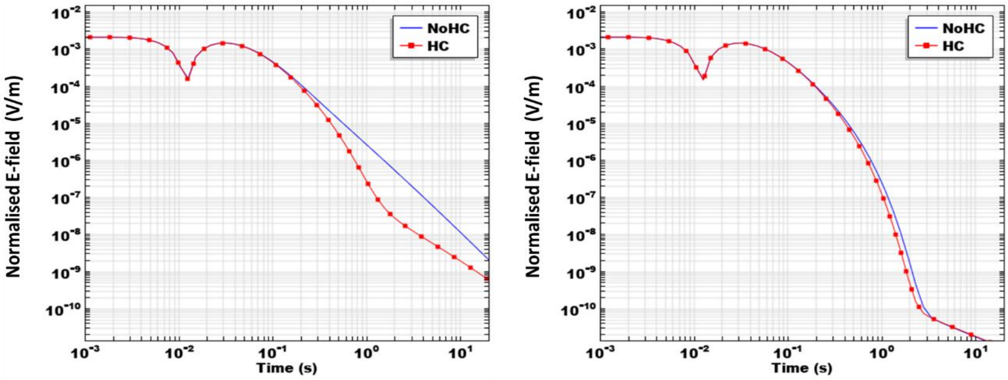
The transmitter, a vertical electric dipole (VED), was built as a line segment (z-oriented polyline) with its top (first point) 50 m below sea level and its bottom (second and final point) in touch with the seafloor. On the seabed, the receivers were built as a polyline.

The results can be displayed graphically, with the curve built using the plot group 1D option. The model's response without the reservoir layer (NoHC) is combined with the response of the field with the resistive structure present (HC) to examine the difference between the background line and the anomalous line. The VVCSEM response for the canonical model can be seen in Fig.11. As Marlim has a very considerable salt layer, a salt layer below the reservoir layers was also simulated in the canonical model to elucidate the signature in the following data presented.

Revista ARACÊ
ISSN: 2358-2472

Figure 11

VVCSEM response for the canonical model. The red dotted line represents the response to hydrocarbons (HC), and the blue solid line represents the absence of hydrocarbons (NoHC)



Unlike the MCSEM response, the VVCSEM response exhibits the curve representing the environment's response with a reservoir (HC) below the curve of the environment without the reservoir (NoHC). This signature has the same characteristics as the other transient methods since a lousy conductor (resistive) tends to promote a faster electromagnetic field decay. Thus, the presence of the reservoir is perceptible when the HC curve is compared with the background curve.

Already foreseeing the marked signature in the curves of both the background and the environment with hydrocarbons, a highly resistive layer was inserted in the simulation in the layers below the reservoir. The response (right side of Fig.11) shows intense deformation in the curves, as expected. It is also noted that depending on the size and resistivity of the reservoir, in the presence of the salt structure, it may not be imaged by the method.

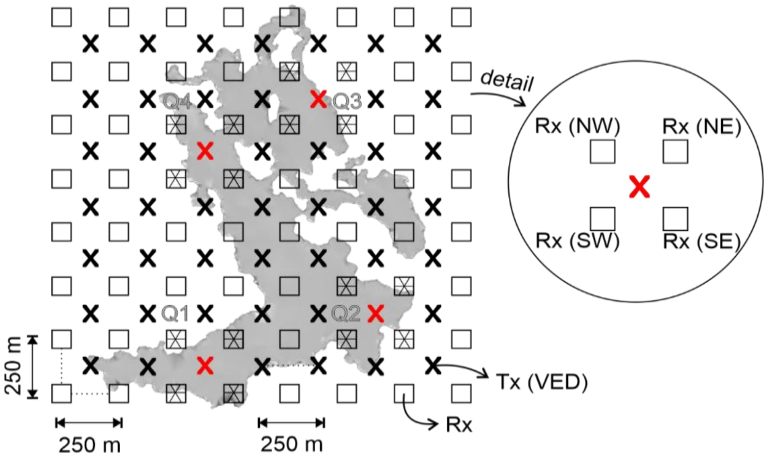
Starting from validating the VVCSEM response with the canonical model, modelling was performed with the same physical settings for the solution of the field in the MR3DC model (described in topic 3.2 Multiphysics modelling).

In the modelling with MR3D, the VVCSEM campaign was performed with profiles with point readings of Tx. The position of the Rx obeyed the 250 m offset between the source receiver, and for each Tx reading point, the four radial Rx was triggered. Fig.12 shows the VVCSEM survey design scheme used in this manuscript, emphasising that only one Tx was triggered at a time.

Revista ARACÊ
ISSN: 2358-2472

Figure 12

VVCSEM survey design scheme in MR3DC. Scale exaggerated for better illustration of Tx-Rx offset. The crosses symbolise the position of the Tx, the red ones being the Tx in use. Squares symbolise the position of the Rx, and squares with bin spider diagram are the Rx in use. Q1-Q4 are the quadrants into which the survey was subdivided



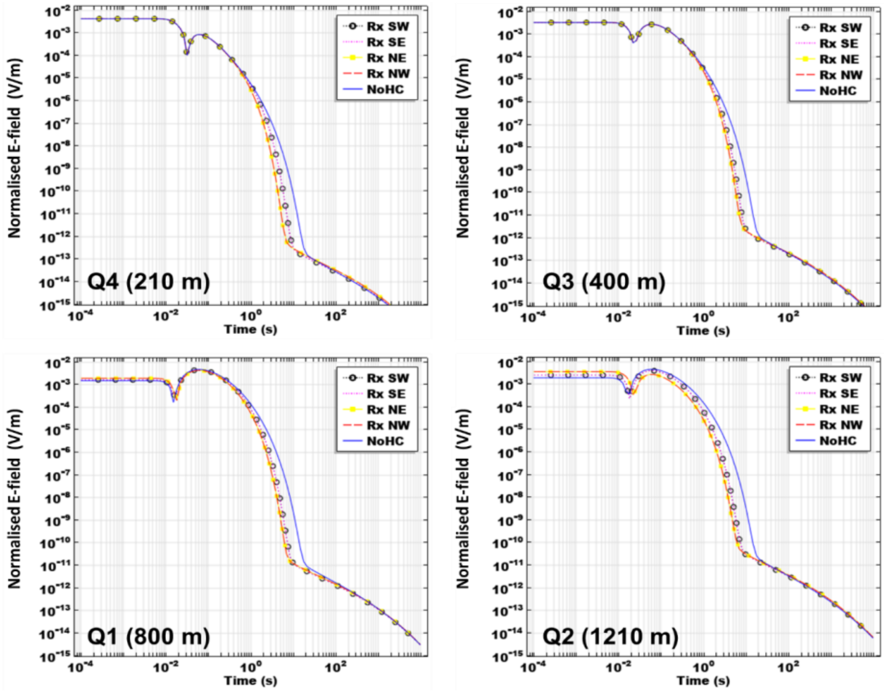
As the campaign sampled several points outside of Marlim, the VVCSEM response in each quadrant where the reading was taken above the reservoir will be shown here. Each quadrant was named Q1, Q2, Q3, and Q4 from left to right and bottom to top. The Marlim model has a bathymetric range of 105 m to 1513 m, so the length of the VED was variable at each reading point so that Q1 is 800 m, Q2 is 1210 m, Q3 is 400 m, and Q4 is 210 m.

Comparatively, the curves were plotted using the background (NoHC) and the geological body (HC) of interest response. Thus, the curve composed of the blue solid line represents the background response, the black dotted line with circles represents the Rx in the S-W position concerning the Tx position, and the red dotted line represents the Rx in the S-E position. The yellow solid line with squares represents the Rx in the N-E position, and the red dashed line represents the Rx in the N-W position. Fig.13 shows the responses of the quadrants in the MR3DC model.

Revista ARACÊ
ISSN: 2358-2472

Figure 13

VVCSEM response for MR3DC in each quadrant. Starting from left to right and bottom to top (counter clockwise), the responses of Q1, Q2, Q3, and Q4 are exposed



As expected, the VVCSEM response in the MR3DC model is very similar to that in the canonical model with the insertion of the saline layer. The particularity of the Marlim is that it is anisotropic; each measurement point reflects a different organisation of the geological environment (bathymetry, thickness, depth, and physical property of each stratum).

Fig. 13, at first sight, shows that the Marlim response is quite subtle compared to the salt structure response present in the model, mainly when compared with the response for the canonical model. Analysing the responses in the different quadrants, it is also possible to notice the effects of bathymetry on the data as the water layer increases, increasing the length of the VED. The influence of the altimetric quota difference between the Tx and the position of the Rx (lower) is also noted.

It is interesting to note that the behaviour of the curves marked by the presence (HC) and absence (NoHC) of the reservoir is very similar in the short offsets, which does not happen with the larger offset, where there is an apparent discrepancy in the initial times, probably due to the distortions caused by the Marlim presence.

Looking at geological information, the particularities of Marlim also influence the EM field measurements. The reservoir layer's thickness and its electrical resistivity values interfere directly and proportionally with the signature present in the data. As expected, the lower the resistivity and thickness are, the lower the contribution of the presence of the oil layer in the HC curves. Clarifying that the thickness of the reservoir decreases in the N–S direction.

4 CONCLUSIONS

Marlim presents a very complex geology, and the multiphysics model is a good alternative for simulations with different electromagnetic methodologies. The presence of the thick layer throughout the model is a real challenge from the electromagnetic point of view because the extremely high electrical resistivity causes substantial distortions in the field and causes a very sharp anomaly in the curves of both the MCSEM and the VVCSEM.

The analysed methods, MCSEM and VVCSEM, were competent in identifying the resistive anomalies coming from the hydrocarbon reservoirs, even if weak. This efficiency can be observed in the results disclosed in the references and by the modelling presented here.

The proposed survey design proved effective in imaging the reservoir in different offsets, configurations, and directions. The optimisation of surveys can be the difference, among other things, in the success or failure of a prospect. Unnecessary costs with exploratory logistics, combined with the generation of data with low accuracy, are a very unpleasant recipe.

The use of MCSEM and VVCSEM in reservoir monitoring is interesting, as the methodologies are sensitive enough to detect variations in the electrical resistivity during a time-lapse. Attention should be given to the injection of saline water to increase the pressure and enhance oilfield production because its presence in the reservoir's pores will bring intense ambiguity to the results.

Carrying out inverse modelling of the data collected in Marlim is a significant step, and advances in this direction are expected soon.

ACKNOWLEDGMENTS

The authors are grateful to the Geophysical Faculty and Postgraduate Programme in Geophysics of UFPA for the infrastructure, to the Research Support and Development Foundation (FADESP) and Petrobras for making available the COMSOL academic licence to

UFPA, to Leandro Moreira for suggested alternatives for the way of importing horizons as volumes in the multiphysics modeller. The first author thanks Higher Education Personnel Improvement Coordination (CAPES) and National Council for Scientific and Technological Development (CNPq) for providing the scholarship. At the time of submission, a statement should be made in a letter to the Editor-in-Chief that all coauthors approve the final version of the review paper as being of acceptable quality before it is submitted to Surveys in Geophysics for peer review and eventual publication.

REFERENCES

Allouche, J., & Shallit, J. (1999). The ubiquitous Prouhet-Thue-Morse sequence. In C. Ding, T. Helleseth, & H. Niederreiter (Eds.), Sequences and their applications (pp. 1–16). Springer London. https://doi.org/10.1007/978-1-4471-0551-0_1

Barsukov, P., Fainberg, E. B., & Singer, B. (2007). A method for hydrocarbon reservoir mapping and apparatus for use when performing the method (Patent No. WO2007/053025). World Intellectual Property Organization. PCT/NO2006/000372.

Barsukov, P. O., Fainberg, E. B., & Singer, B. (2008). A method for mapping hydrocarbon reservoirs in shallow waters and also apparatus for use practising the method (Patent No. WO2008/066389). World Intellectual Property Organization. PCT/NO2007/000416.

Carvalho, B. R., & Menezes, P. T. (2017). Marlim R3D: A realistic model for CSEM simulations—Phase 1: Model building. Brazilian Journal of Geology, 47(4), 633–644. https://doi.org/10.1590/2317-4889201720170088

Castro, R. D., & Picolini, J. P. (2015). Principais aspectos da geologia regional da Bacia de Campos. In R. O. Kowsmann (Ed.), Geologia e geomorfologia (Habitats, Vol. 1, pp. 1–12). Elsevier. https://doi.org/10.1016/B978-85-352-6937-6.50008-2

Chave, A. D., & Cox, C. S. (1982). Controlled electromagnetic sources for measuring electrical conductivity beneath the oceans: 1. Forward problem and model study. Journal of Geophysical Research, 87(B7), 5327–5338. https://doi.org/10.1029/JB087iB07p05327

Clemens, M., & Weiland, T. (2001). Discrete electromagnetism with the finite integration technique. Journal of Electromagnetic Waves and Applications, 15(1), 79–80. https://doi.org/10.1163/156939301X00661

Constable, S. C., & Cox, C. S. (1996). Marine controlled source electromagnetic sounding—II: The PEGASUS experiment. Journal of Geophysical Research, 101(B3), 5519–5530.

Constable, S., & Key, K. (2008). Marine electromagnetic methods for hydrocarbon exploration Part B: Marine CSEM methods and instruments [Course notes]. SEG Continuing Education Shortcourse.

Constable, S., & Srnka, L. J. (2007). An introduction to marine controlled-source electromagnetic methods for hydrocarbon exploration. Geophysics, 72(2), WA3–WA12.

Constable, S., & Weiss, C. J. (2006). Mapping thin resistors and hydrocarbons with marine EM methods: Insights from 1D modeling. Geophysics, 71(2), G43–G51. https://doi.org/10.1190/1.2187748

Correa, J. L., & Menezes, P. T. (2019). Marlim R3D: A realistic model for controlled-source electromagnetic simulations—Phase 2: The controlled-source electromagnetic data set. Geophysics, 84(5), E293–E299. https://doi.org/10.1190/geo2018-0452.1

Eidesmo, T., Ellingsrud, S., MacGregor, L. M., Constable, S., Sinha, M. C., Johansen, S. E., Kong, F. N., & Westerdahl, H. (2002). Sea Bed Logging (CSEM), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas. First Break, 20(3), 144–152.

Ellingsrud, S., Eidesmo, T., Johansen, S. E., Sinha, M. C., MacGregor, L. M., & Constable, S. (2002). Remote sensing of hydrocarbon layers by Sea Bed Logging (CSEM): Results from a cruise offshore Angola. The Leading Edge, 21(10), 972–982.

Figueiredo, A. M. F., & Mohriak, W. U. A. (1984). Tectônica salífera e as acumulações de petróleo da Bacia de Campos. In Anais do 33º Congresso Brasileiro de Geologia (pp. 1380–1394). Sociedade Brasileira de Geologia.

Guardado, L. R., Spadini, A. R., Brandão, J. S. L., & Mello, M. R. (2000). Petroleum system of the Campos Basin, Brazil. In M. R. Mello & B. J. Katz (Eds.), Petroleum systems of South Atlantic margins (AAPG Memoir 73, pp. 317–324). American Association of Petroleum Geologists.

Helwig, S. L., Wood, W., & Gloux, B. (2019). Vertical-vertical controlled-source electromagnetic instrumentation and acquisition. Geophysical Prospecting, 67(6), 1582–1594. https://doi.org/10.1111/1365-2478.12771

Holten, T., Flekkøy, E. G., Singer, B., Blixt, E. M., Hanssen, A., & Måløy, K. J. (2009). Vertical source vertical receiver, electromagnetic technique for offshore hydrocarbon exploration. First Break, 27(5). https://doi.org/10.3997/1365-2397.27.1299.28934

Hoversten, M. G., Morrison, H. F., & Constable, S. C. (1998). Marine EM for petroleum exploration, Part II: Numerical analysis of subsalt resolution. Geophysics, 63(3), 826–840.

Johansen, S. E., Amundsen, H. E. F., Røsten, T., Ellingsrud, S., Eidesmo, T., & Bhuiyan, A. H. (2005). Subsurface hydrocarbons detected by electromagnetic sounding. First Break, 23(3), 31–36.

Kjerstad, J. (2010). Device for a vertical electromagnetic field component receiver (Patent No. WO2010/041959). World Intellectual Property Organization. PCT/NO2009/000352.

Kong, F. N., Westerdahl, H., Ellingsrud, S., Eidesmo, T., & Johansen, S. E. (2002, May 13). SeaBed Logging: A possible direct hydrocarbon indicator for deep sea prospects using EM energy. Oil & Gas Journal.

MacGregor, L. M., & Sinha, M. C. (2000). Use of marine controlled source electromagnetic sounding for sub-basalt exploration. Geophysical Prospecting, 48(6), 1091–1106. https://doi.org/10.1046/j.1365-2478.2000.00227.x

Martínez, G. C., Hanson, G., Tariq, H. H., der Toorn, J. V., Souza, J. A., van der Molen, M., Okprekyi, O., Dandapani, R., & Shah, Z. A. (2021). Chapter 9—Well-to-seismic tie. In E.

Onajite (Ed.), Applied techniques to integrated oil and gas reservoir characterization (pp. 249–271). Elsevier. https://doi.org/10.1016/B978-0-12-817236-0.00009-1

Menezes, P. T., Correa, J. L., Alvim, L. M., Vianna, A. R., & Sansonowski, R. C. (2021). Time-lapse CSEM monitoring: Correlating the anomalous transverse resistance with SoPhiH maps. Energies, 14(21), Article 7159. https://doi.org/10.3390/en14217159

Nascimento, T. M., Menezes, P. T., & Braga, I. L. (2014). High-resolution acoustic impedance inversion to characterize turbidites at Marlim Field, Campos Basin, Brazil. Interpretation, 2(3), T143–T153. https://doi.org/10.1190/INT-2013-0137.1

Schreiner, S., Souza, M. B. F. M., Migliorelli, J. P., Figueiredo, J. R. A. G., Pacheco, C. E. P., Vasconcelos, S. C., & Silva, F. T. (2014). Mapa batimétrico da Bacia de Campos. In R. O. Kowsmann (Ed.), Geologia e geomorfologia (Habitats, Vol. 1, pp. 67–70). Elsevier. https://doi.org/10.1016/B978-85-352-6937-6.50011-2

Scotese, C. R. (2001). Atlas of Earth history. PALEOMAP Project, University of Texas at Arlington.

Ward, S. H., & Hohmann, G. W. (1987). Electromagnetic theory for geophysical applications. In M. N. Nabighian (Ed.), Electromagnetic methods in applied geophysics—Theory (Vol. 1, pp. 130–311). Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560802631.ch4

Zhdanov, M. S., Lee, S. K., & Yoshioka, K. (2006). Integral equation method for 3D modeling of electromagnetic fields in complex structures with inhomogeneous background conductivity. Geophysics, 71(6), G333–G345. https://doi.org/10.1190/1.2358403

Ziolkowski, A., & Slob, E. (2019). Introduction to controlled-source electromagnetic methods. Cambridge University Press.