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ANALYSIS OF THE VERTICAL-VERTICAL CONTROLLED SOURCE ELECTROMAGNETIC METHOD APPLIED TO RESERVOIR MONITORING

ANÁLISE DO MÉTODO ELETROMAGNÉTICO DE FONTE CONTROLADA VERTICAL-VERTICAL APLICADO AO MONITORAMENTO DE RESERVATÓRIOS

ANÁLISIS DEL MÉTODO ELECTROMAGNÉTICO DE FUENTE CONTROLADA VERTICAL-VERTICAL APLICADO A LA MONITORIZACIÓN DE YACIMIENTOS

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ABSTRACT
Geophysical prospecting in the marine environment has reduced the uncertainties and ambiguities encountered in oil and gas prospecting, mainly due to technological and operational advances. In addition to presenting an increasingly shorter acquisition time and higher resolution, they provide a more significant amount of information and knowledge about the geological environment of interest. In acquiring data in different geological environments, the ideal would be to use different geophysical methodologies to obtain the most considerable amount of information contained in the data and provide full knowledge about the sedimentary environment under study. Thus, controlled-source electromagnetic methods, which measure the decay of fields (electric and magnetic) or map electrical resistivity contrasts, minimise the uncertainties and ambiguities encountered by conventional seismic methods. The vertical-vertical controlled-source electromagnetic method (VVCSEM) is a controlled-source electromagnetic technique differentiated from seabed logging by the Tx-Rx vertical configurations and acquisition mode and time domain rather than the frequency domain. Its primary use is hydrocarbon reservoir monitoring. The present manuscript presents the results of the geological modelling performed at Marlim Field, Campos Basin - Brazil and the data analysis from the VVCSEM three-dimensional electromagnetic multiphysics modelling applied to the Marlim model. Despite the geological complexity of the Marlim Field, the VVCSEM was able to distinguish the thin hydrocarbon reservoir even in the face of large saline and highly resistive structures at the shortest offsets.

Keywords: Electromagnetic Modelling. Reservoir Monitoring. Transient Electromagnetic Method.

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RESUMO

A prospecção geofísica em ambiente marinho reduziu as incertezas e ambiguidades encontradas na prospecção de petróleo e gás, principalmente devido aos avanços tecnológicos e operacionais. Além de apresentar tempos de aquisição cada vez mais curtos e maior resolução, proporciona uma quantidade mais significativa de informações e conhecimento sobre o ambiente geológico de interesse. Na aquisição de dados em diferentes ambientes geológicos, o ideal seria utilizar diferentes metodologias geofísicas para obter a maior quantidade possível de informações contidas nos dados e fornecer um conhecimento completo sobre o ambiente sedimentar em estudo. Assim, os métodos eletromagnéticos de fonte controlada, que medem o decaimento dos campos (elétrico e magnético) ou mapeiam contrastes de resistividade elétrica, minimizam as incertezas e ambiguidades encontradas pelos métodos sísmicos convencionais. O método eletromagnético de fonte controlada vertical-vertical (VVCSEM) é uma técnica eletromagnética de fonte controlada que se diferencia da perfilagem de fundo marinho pelas configurações verticais de transmissão e recepção, pelo modo de aquisição e pelo domínio do tempo, em vez do domínio da frequência. Sua principal aplicação é o monitoramento de reservatórios de hidrocarbonetos. O presente manuscrito apresenta os resultados da modelagem geológica realizada no Campo de Marlim, Bacia de Campos - Brasil, e a análise de dados da modelagem multifísica eletromagnética tridimensional VVCSEM aplicada ao modelo de Marlim. Apesar da complexidade geológica do Campo de Marlim, o VVCSEM foi capaz de distinguir o reservatório de hidrocarbonetos delgado mesmo na presença de grandes estruturas salinas e altamente resistivas nos menores offsets.

Palavras-chave: Modelagem Eletromagnética. Monitoramento de Reservatórios. Método Eletromagnético Transiente.

RESUMEN

La prospección geofísica en el medio marino ha reducido las incertidumbres y ambigüedades presentes en la prospección de petróleo y gas, principalmente gracias a los avances tecnológicos y operativos. Además de ofrecer tiempos de adquisición cada vez más cortos y una mayor resolución, proporciona una mayor cantidad de información y conocimiento sobre el entorno geológico de interés. Al adquirir datos en diferentes entornos geológicos, lo ideal sería utilizar distintas metodologías geofísicas para obtener la mayor cantidad de información posible y comprender a fondo el entorno sedimentario en estudio. Así, los métodos electromagnéticos de fuente controlada, que miden la atenuación de campos (eléctricos y magnéticos) o mapean los contrastes de resistividad eléctrica, minimizan las incertidumbres y ambigüedades de los métodos sísmicos convencionales. El método electromagnético de fuente controlada vertical-vertical (VVCSEM) es una técnica electromagnética de fuente controlada que se diferencia del registro sísmico de fondo marino por sus configuraciones verticales de transmisión y recepción, su modo de adquisición y el dominio del tiempo en lugar del dominio de la frecuencia. Su principal aplicación es la monitorización de yacimientos de hidrocarburos. El presente manuscrito expone los resultados del modelado geológico realizado en el Campo Marlim, Cuenca de Campos (Brasil), y el análisis de datos del modelado electromagnético multifísico tridimensional VVCSEM aplicado al modelo de Marlim. A pesar de la complejidad geológica del Campo Marlim, el VVCSEM logró identificar el delgado yacimiento de hidrocarburos incluso en presencia de grandes estructuras salinas y de alta resistividad a distancias mínimas.

Palabras clave: Modelado Electromagnético. Monitoreo de Yacimientos. Método Electromagnético Transitorio.

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1 INTRODUCTION

The world energy matrix is increasingly diversified; however, the portion derived from fossil fuels is still significant, and many technologies are directly dependent on it. Consequently, prospecting and exploration activities have increased risks as the high demand for oil end products further increases exploration challenges.

The cause and consequence reaction between demand and risks occur, among other factors, because the exploration of obvious and old plays has become costly, since to maintain/increase production, it has been necessary to inject water, use directional wells and other production-enhancing measures, increase operating costs and generate exploration design returns and even abandon promising fields.

Geophysical prospecting in the marine environment has reduced the uncertainties and ambiguities encountered in oil and gas prospecting, mainly due to technological and operational advances. In addition to presenting an increasingly shorter acquisition time and higher resolution, they provide a more significant amount of information and knowledge about the geological environment of interest.

In acquiring data in different geological environments, the ideal would be to use different geophysical methodologies to obtain the most considerable amount of information contained in the data and provide full knowledge about the sedimentary environment under study. Thus, controlled-source electromagnetic methods (Hoversten *et al.,* 1998), which measure the decay of fields (electric and magnetic) or map electrical resistivity contrasts, minimise the uncertainties and ambiguities encountered by conventional seismic methods.

Established, even after extensive research for direct hydrocarbon indication (DHI), the marine controlled-source electromagnetic method (MCSEM) had its acquisition configuration changed by a Norwegian company aiming to enhance vertical resolution and achieve better differentiation among conductive and resistive structures (Flekkøy et al., 2009; Frafjord et al., 2014; Sainson, 2017). In addition to instrumental adjustments, the approach was renamed the vertical-vertical controlled-source electromagnetic method (VVCSEM) and patented under the term transient electromagnetic prospecting using vertical electric lines (TEMP-VEL) (Helwig et al., 2016).

The VVCSEM technique is a CSEM method that is differentiated from seabed logging (SBL, which is associated with electromagnetic controlled source approaches) by the Tx-Rx configurations and acquisition mode in the time domain rather than the frequency domain. Its primary use is hydrocarbon reservoir monitoring. It is sensitive to changes in the physical

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properties of the geological environment and can be performed in precisely the same coordinate in the case of a time-lapse study (4D).

Due to the source-receptor configuration, both vertical and vertical, the VVCSEM is very sensitive to the contrast between electrical resistivities and has been ideal in flow monitoring and analysis studies in producing fields. Monitoring reservoirs is essential for more meaningful and better use of the fields. As petroleum (meaning oil and gas) is exploited, the contrast in physical properties between the embedding medium and the reservoir itself decreases.

Breaking down exploration barriers and in an attempt to increase production at low costs, many companies have launched themselves into increasingly deep and ultradeepwater. The Marlim field (Campos Basin) is an oilfield with complex geology.

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 MCSEM (Correa and Menezes, 2019; Menezes *et al.,* 2021).

Marlim R3D 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 seismic tie in the Marlim field.

The present manuscript presents the results of the geological modelling performed with the MR3D horizon data to isolate the reservoir from the bedrock and the data analysis from the VVCSEM three-dimensional electromagnetic multiphysics modelling applied to the Marlim model.

Despite the geological complexity of MR3D, the VVCSEM was able, at the shortest offsets, to distinguish the thin hydrocarbon reservoir even in the face of a large saline and highly resistive structure.

1.1 GEOLOGICAL CONTEXT

The Brazilian marginal basins have a fascinating tectonic-sedimentary evolution, with compressive characteristics and small portions of distension characteristics. They directly

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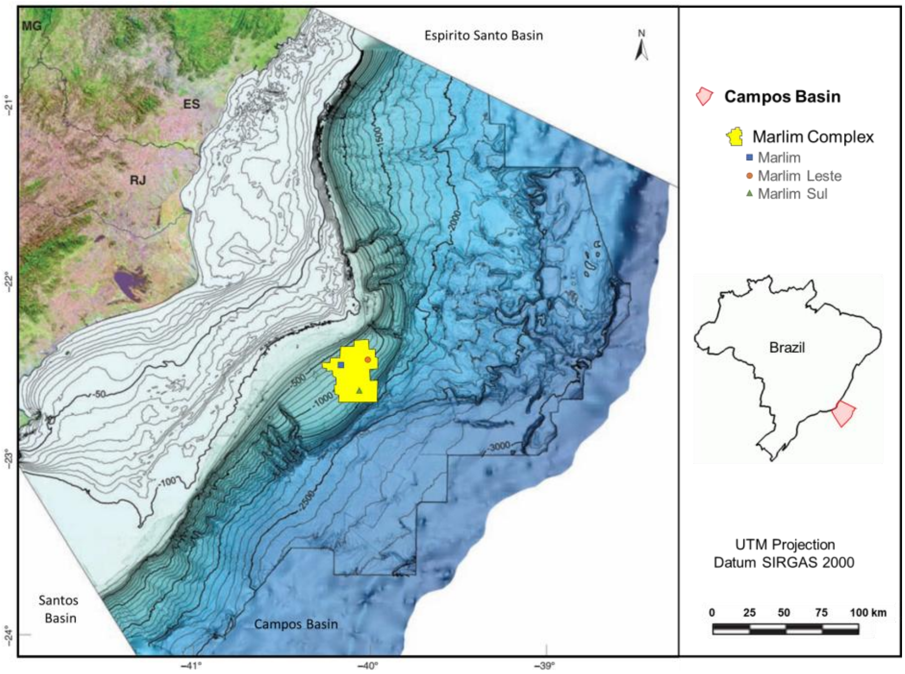
correlate with the African marginal basins, as they share a common origin and evolution. The similarity between these environments can be seen in detail in Scotese (2001).

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 thickness and area of occurrence in the basin (Figueiredo and Mohriak, 1984). Figure 1 shows the location of the Campos Basin and the Marlim Complex (Marlim, Marlim Leste, and Marlim Sul fields) concerning the map of Brazil and the bathymetry of the region.

Figure 1

Location of the Campos Basin (red polygon) and Marlim Complex (yellow polygon). Base map 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 verticalization 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

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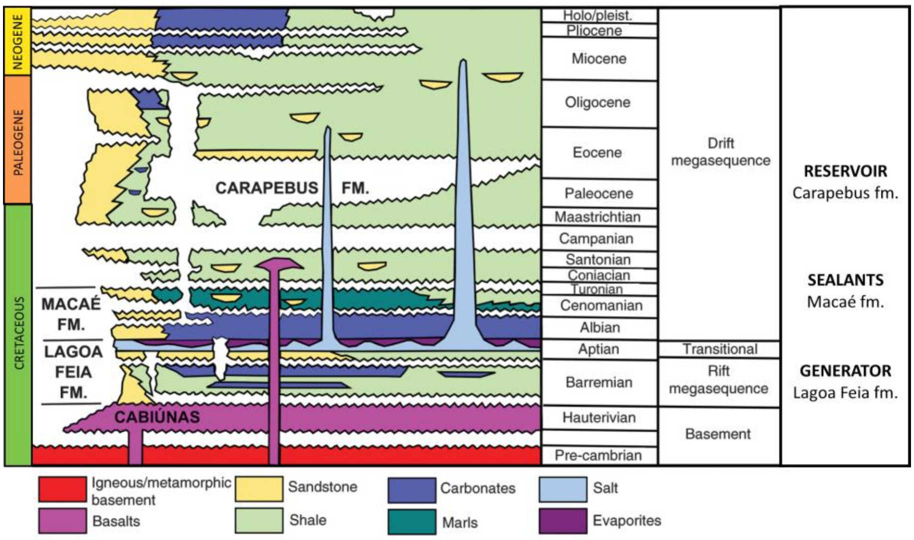
sandy sequences. The basin is dominated by shales intercalated with turbiditic sandstones at greater depths.

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 Figure 2 modified from Guardado *et al.* (2000).

Figure 2

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). The timing of plays formation is directly related to the tectonostratigraphic evolution of the basin (Nascimento *et al.,* 2014).

1.2 THE VVCSEM

The VVCSEM, similar to the MCSEM, measures subsurface electromagnetic fields in a maritime environment. The acquisition system consists of a vertically oriented source (Tx) and receiver (Rx), which are carried by a ship and set up for data collection by cranes.

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A vertical dipole source and a vertical receiver provide various benefits for subsurface resistivity measurements in an offshore acquisition, according to Helwig et al. (2019). However, to fully use the possibilities of this technology, the source-receiver combination must fulfil strict verticality and noise level constraints. The noises that usually contaminate the data come from sea currents and induced polarisation (IP) from the galvanic contact of the source with the ocean floor.

The receivers are vertical tripod antennas produced in nonferrous material and spread across the ocean floor in radial lines (to Tx). The transmitter comprises a direct current (DC) pulse generator, a vertical electric dipole, consisting of two steel electrodes (2500 A each) connected by an extensive copper cable, having one electrode 50 m below the ship and a second electrode on the seabed, and an electrode launcher/recoverer. More instrumental details are available in Barsukov *et al*. (2007), Barsukov *et al*. (2008), and Kjerstad (2010).

Readings and data collection are performed when the source is inoperable (power off), but the stimulation of the just turned-off source continues to stimulate the geological environment. Data acquisition is made in the time domain, in which both the source and the receivers are static. Data reading by the receiver is conducted during source inactivity. The data acquisition process takes approximately 7 h to 12 h.

The vertical-vertical arrangement (Tx and Rx) only causes propagation of the TM mode (the transverse magnetic mode - Hy, Ex, and Ez components) of the EM field. The short offset creates a near zone of the imaging since the usual distance from Rx to Tx is 200 m (followed by multiples). Even though the received signal is weak, the reading is performed only when the source is turned off, and there is a higher sensitivity to electrical resistivity vertical contrast.

The data are acquired in the time domain, with both the source and the receivers remaining stationary. When the source is inactive, the receiver reads the electromagnetic field information. When the source is turned on and the receivers are switched off, no direct waves or airwaves interfere with the measurements, which are intrinsic limitations of SBL acquisitions.

Figure 3 compares the MCSEM and VVCSEM and gives a more detailed description of the approaches. A stationary underwater source (vertical electric dipole - VED) oscillates during on and off periods in the VVCSEM data gathering method (on the right). The pulse is picked up by receivers and distributed on the ocean floor; the source is inactive.

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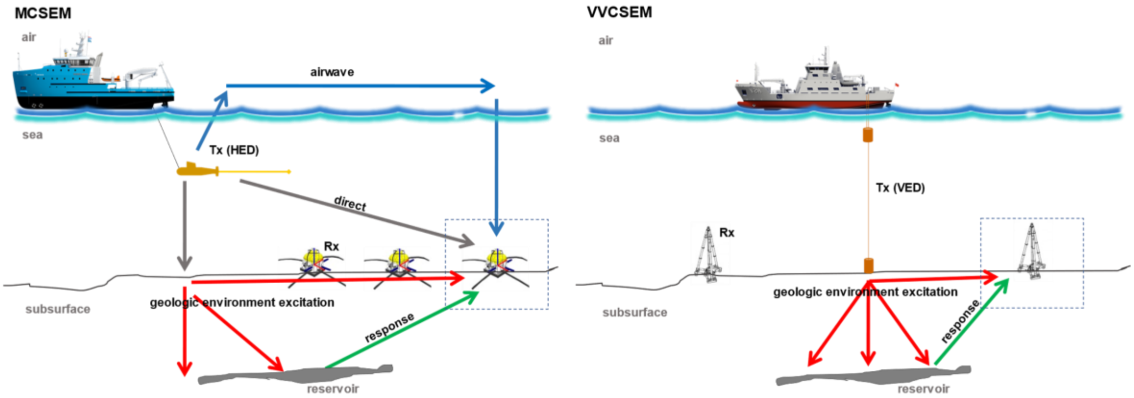
Figure 3

MCSEM and VVCSEM approaches are shown for comparison. The blue line depicts the airwave, the gray line the Tx direct pulse, the red line the geologic environment stimulation by the Tx, and the green line the response of contact with the reservoir and the subsurface



The difficulty in modelling transient approaches is the simulated EM field fading response, its interactions with the subsurface environment, and its physical property contrasts. The acquired data are analysed by comparing the reactions in settings (or models) with no petroleum (NoHC) to the presence of petroleum (HC). The anomaly is primarily determined by the overlying transversal resistivity = (thickness * resistivity) compared to the reservoir's transverse resistivity. For the physics details and mathematics formulation, see Ward and Hohmann (1987); Zhdanov et al. (2006); Ziolkowski and Slob (2019).

2 METHODS

2.1 GEOLOGICAL MODEL

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 geological modeller that was used is an open-source seismic interpretation system for processing (more advanced features require academic or pro licence), visualising and interpreting multivolume seismic, well, and electromagnetic data. The system supports all the tools needed to visualise, analyse, and interpret 2D, 3D and 4D seismic data and enable well seismic ties.

To visualise, map, and isolate the reservoir from its surroundings, the electrical resistivity data (segy) were plotted in inline and crossline profiles, and the reservoir dimensions were verified. Analogous to seismic profiles, the similarity attribute was used to

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distinguish the hydrocarbon reservoir (through the electrical resistivity values) from the sedimentary environment.

The similarity attribute is a coherence attribute, a geometric attribute that provides data on lateral continuity. In this way, changes in electrical resistivity imply that changes in layer properties and contrasts are enhanced. Thus, in this case, the similarity attribute works like a DHI. Further information about DHI and similarity attributes can be found in Nanda (2016a; 2021).

The selection of the volume with the resistivity anomaly (with the neighbourhood) promoted the delimitation and generation of the isolated reservoir body. This measure is necessary because, in VVCSEM, the data are analysed by contrasting the anomaly of the environment with the reservoir and the background (no reservoir). Beyond allowing the insertion of the electrical resistivity distribution of the reservoir in multiphysics modeller.

Figure 4 shows the evolution of the work steps performed in geological modeller for this manuscript. From the top to bottom and from left to right, an inline profile with the Marlim field location, followed by inline and crossline profiles, and the horizon with the distinction of the embedding and the reservoir by the similarity of the electrical resistivity values (horizontal and vertical) and the body isolated.

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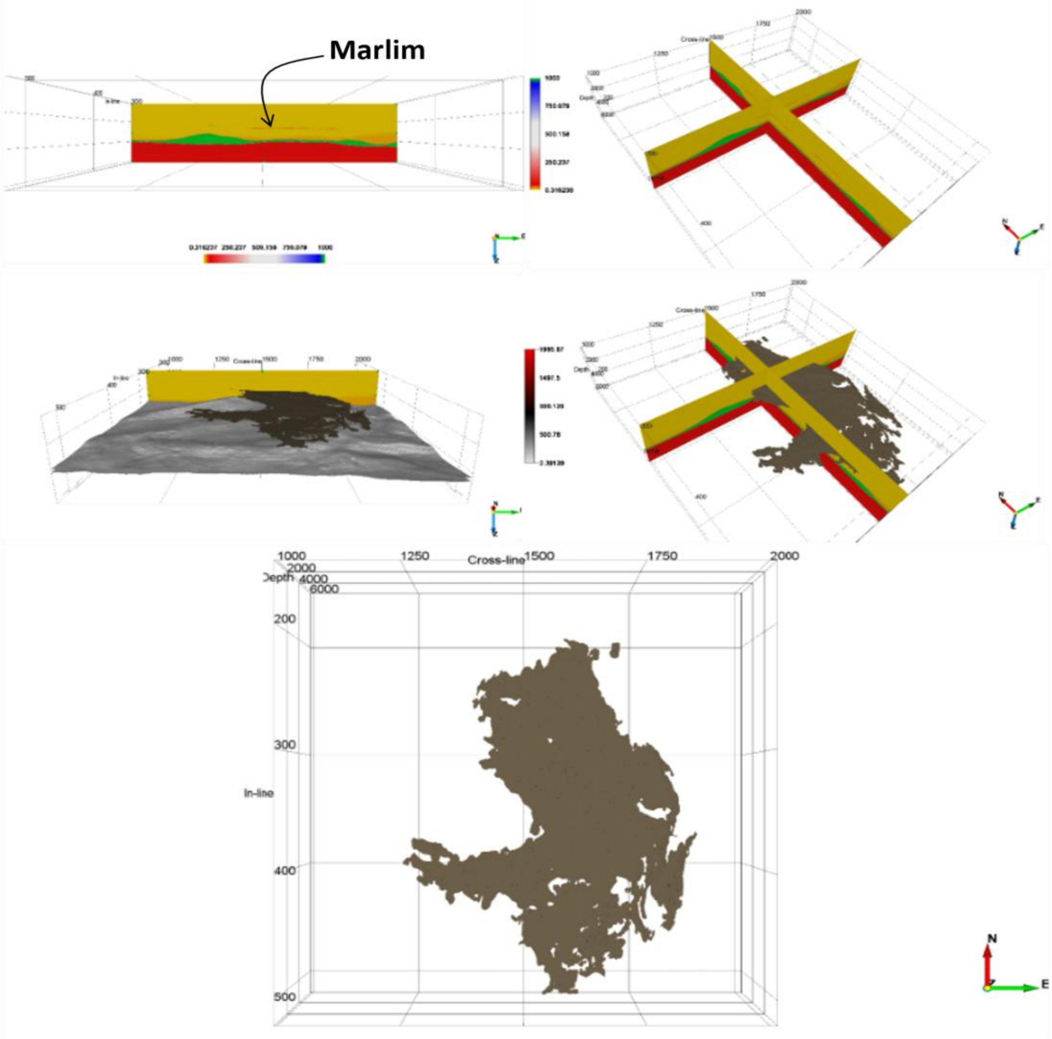
Figure 4

Separation of the Marlim Reservoir for future import



After the geological modelling stage for the reservoir separation, the physical modelling of the three-dimensional Marlim model started to perform the electromagnetic field analysis in the model. The modelling examined the electromagnetic field behavior in the time domain and used a vertical electric dipole (VED) as the Tx to map the absence and resistant structures (hydrocarbon reservoirs).

2.2 MULTIPHYSICS MODEL

Starting from the validation of the VVCSEM response (Souza *et al.,* 2022) and verification of the behaviour in different models and configurations (variation of the seawater column thickness, variation of the reservoir thickness, variation of the reservoir depth,

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variation of the reservoir and sediment electrical resistivity, variation of the source and Tx tilt), performed with a canonical model in multiphysics modeller (COMSOL Multiphysics).

This manuscript aimed to test the VVCSEM on geology that was more realistic found in real-life prospects. Thus, utilising the Marlim-R3D data, forward modelling of the VVCSEM was created.

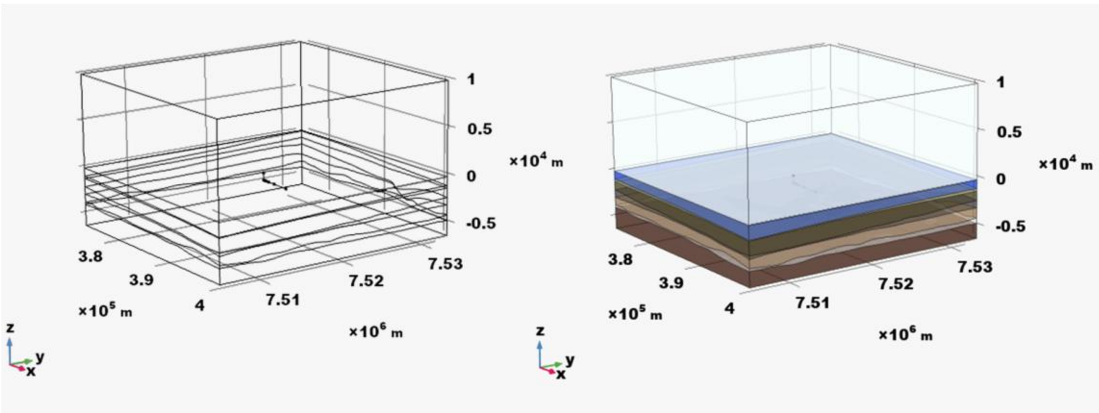
The multiphysics modelling program used includes various scientific and engineering modules for creating realistic models. The modules enhanced the capability of the leading platform and are organised into parts, with electromagnetism being of particular significance in this effort. An academic licence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

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 seismic and tied to well profiles (PSW-01, PSW-02, PSW-03, PSW-04, PSW-05, PSW-06, PSW-07, PSW-08, and PSW-09) were imported into multiphysics modeller.

Figure 5 shows the schematic model of the Marlim-R3D horizons in multiphysics modelling program (MR3DC). For 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 (10 km) with physical characteristics of the air was inserted above the model.

Figure 5

Geometric and physical parameters of the Marlim model in 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

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was later trimmed with the horizon limits. The transmitter (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.

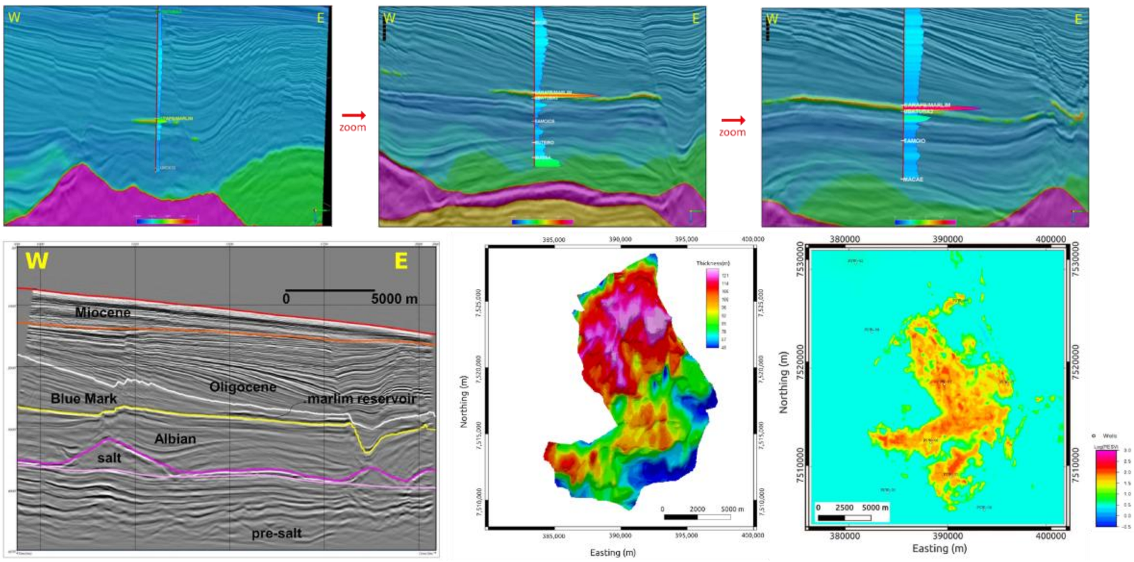
The points reflect the positions of the receivers at 200 m, 400 m, 600 m, 800 m, 1000 m, 2000 m, 3000 m, and 4000 m. Upon completion of the complete model design process, each layer was correlated with its respective physical properties set in the parameters in the materials part.

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).

Figure 6 shows the well seismic tie profile identifying the Marlim Reservoir, the sequence of the sedimentary layers in depth, the thickness variation, and the electrical resistivity distribution at the top of the reservoir.

Figure 6

Identification of the Marlim field through well logging, seismic section interpreted with the marking of each age and its respective depths, thickness and electrical resistivity distribution of the reservoir (adapted from Menezes et al. (2021); Correa and Menezes (2019); Nascimento et al. (2014))



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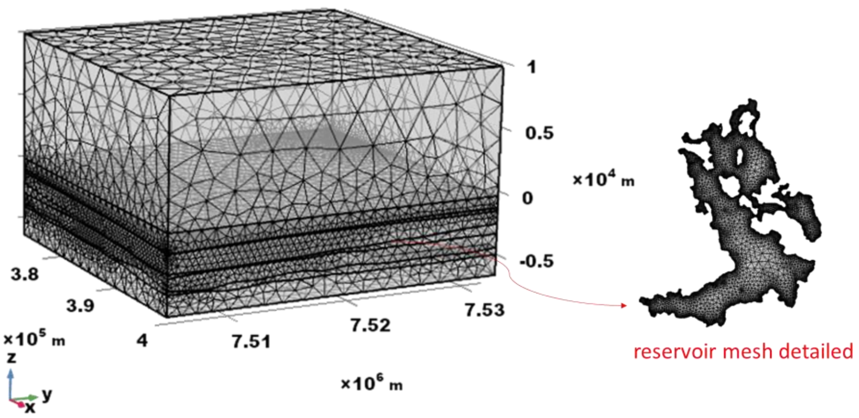
A polygon was inserted around the model (top, bottom, and sides), and absorbing boundaries were imposed around the whole domain (built manually since the scattering boundary condition option is not available in the Magnetics Fields (mf) module).

Because these boundary conditions act as a translucent boundary (shell) for outgoing waves, they are not reflected in the model. However, even though the electromagnetic field propagation occasioned by a VED is structured like a toroid, scattering boundary constraints were included in the VED to avoid contamination in the model.

The mesh has densification in the zones of interest, allowing better refinement and accuracy of the field 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 Figure 7, which illustrates the reservoir mesh in greater detail for improved visualisation. The mesh was created with varying mesh densities. The border region (top, bottom, and sides) is fine-meshed. The air, sea, and sediment regions are extra fine-meshed. The reservoir region and transmitter and receiver surroundings are extremely fine-meshed.

Figure 7

Layered Marlim model and densified mesh



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 electromagnetic field information by the receivers (Rx) happens during times

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of 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 first transient study examines the propagation of electromagnetic waves in the geological formation (background) without a reservoir, 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.

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 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.

3 RESULTS AND DISCUSSIONS

One way of analysing the VVCSEM data is by contrasting the surrounding environment and the anomaly caused by the reservoir rock. The electromagnetic field interaction in the geological environment with the hydrocarbon reservoir is then cross-checked with the response obtained in an area where the absence of hydrocarbons is unavoidable. Thus, in this manuscript, four beacon points were allocated at the ends of the MR3DC.

The beacon marks are point responses and represent the individual result for each study point since the model is anisotropic and has bathymetry with depths ranging from 105 m (beacon mark 1) to 1513 m (beacon mark 3). Figure 8 shows the location of each beacon mark and the respective stratigraphic feature analysed.

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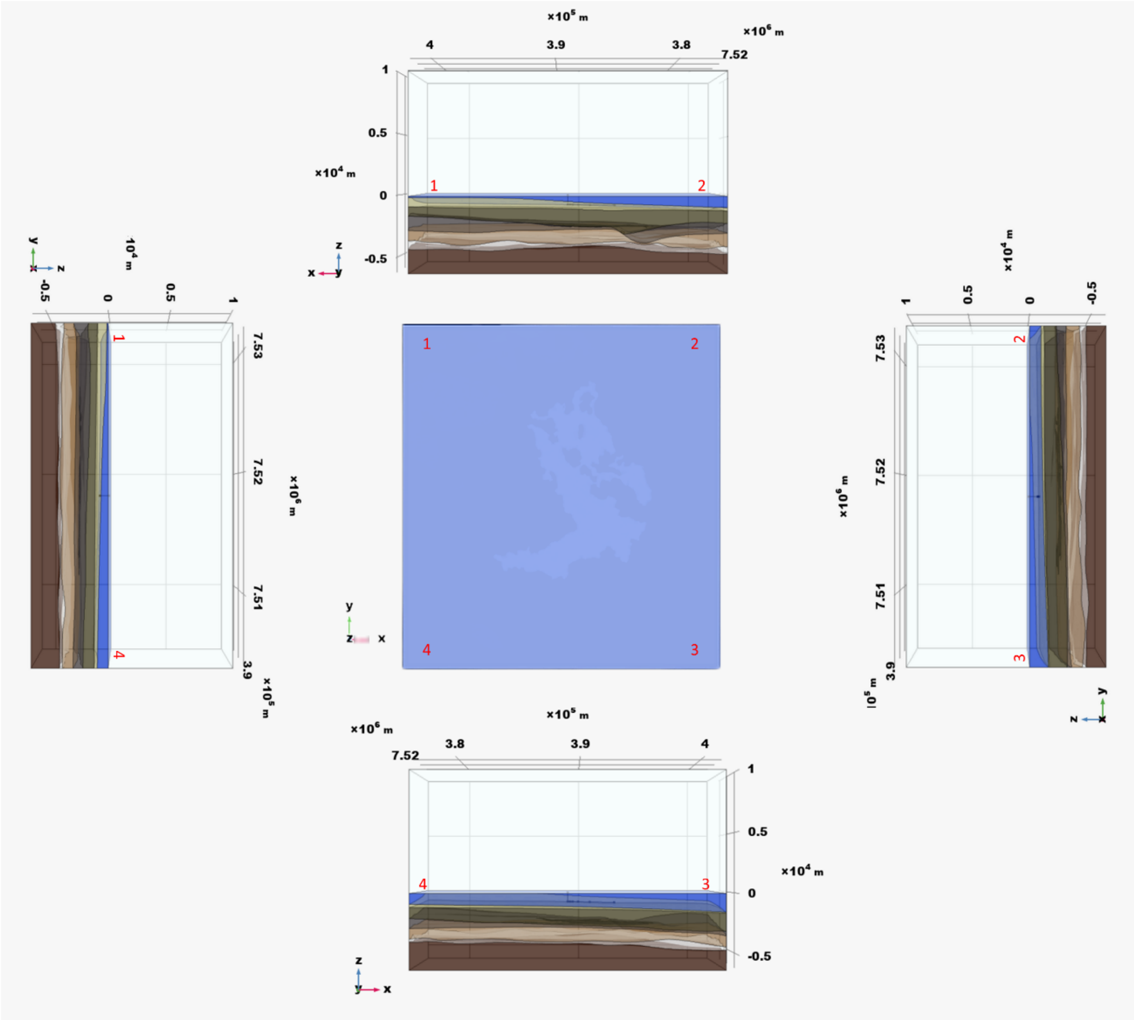
Figure 8

Marlim multiphysics model. The top view is in the middle, and the side views are on each side. Points 1, 2, 3, and 4 represent the locations of the beacon marks



At each beacon, the VVCSEM was simulated for the 200 m displacement. It was able to analyse the data in this manner subsurface geological variations in the results and the effects of Tx size since each beacon is in a different water layer, which consequently changes the length of the VED.

The Tx-Rx separations were arranged at points 1 and 4, starting from left to right, and at points 2 and 3, from right to left in the x-direction. Each point is 1 km from the model margins in the x-direction and the y-direction.

The results obtained at each beacon point can be seen in Figure 9, which shows the modulus of the Ez component (V/m) versus time (s). From top to bottom and from left to right, the response for beacon 1, beacon 2, beacon 3, and beacon 4 is shown.

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Figure 9

VVCSEM response for beacon 1, beacon 2, beacon 3, and beacon 4 with 200 m offset

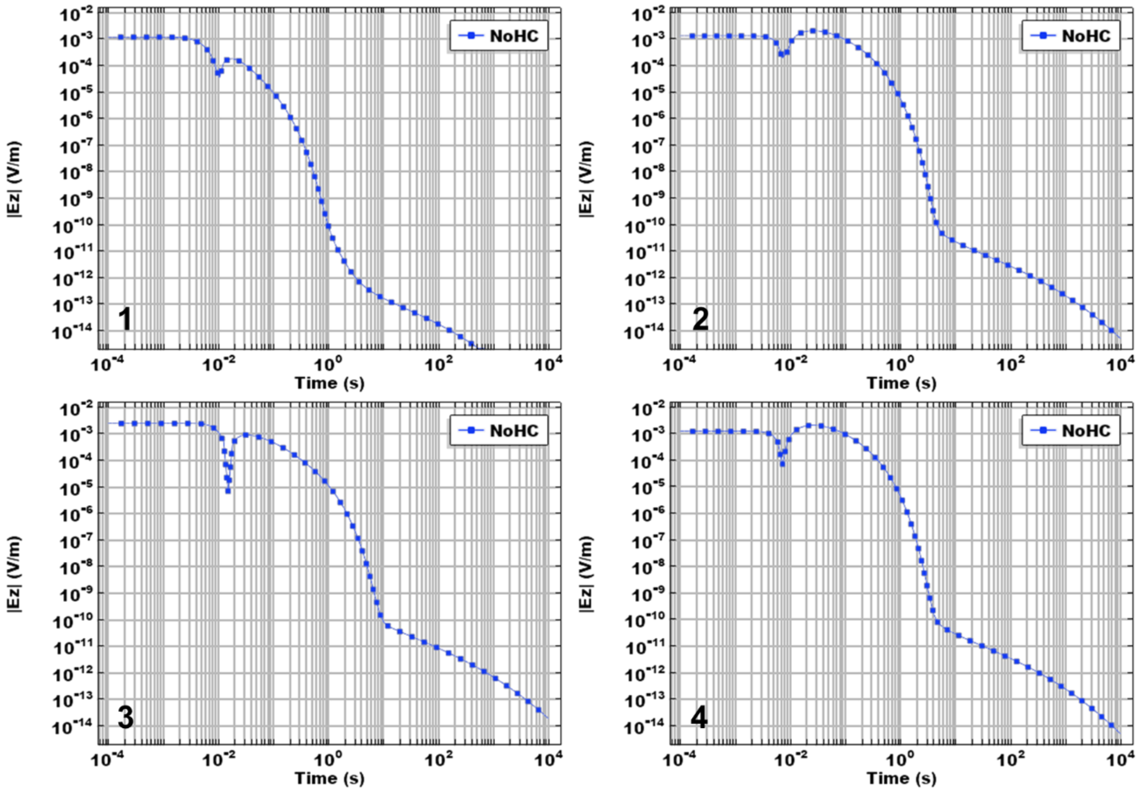

Figure 9 shows that the saline layer promotes strong distortion in the EM field response. In addition to the changes due to bathymetry, each layer's anisotropy and depth and thickness variation interfere directly with the signature VVCSEM. Thus, using the beacons as the background is feasible in 1D computer simulations or with monotone geology, no anisotropy and similar bathymetric coordinates. Thus, a priori geological information is essential, and beacons help understand the geology behind the data.

With the understanding of the background responses, surveys were initiated in the centre of the model, just above the Marlim body. Two campaigns were simulated, the first cutting the hydrocarbon reservoir from W-E and the second from SE-NW. In both campaigns, offsets of 200 m, 400 m, 600 m, 800 m, 1000 m, 2000 m, 3000 m, and 4000 m were used. Figure 10 shows the locations of the campaigns in the MR3DC model.

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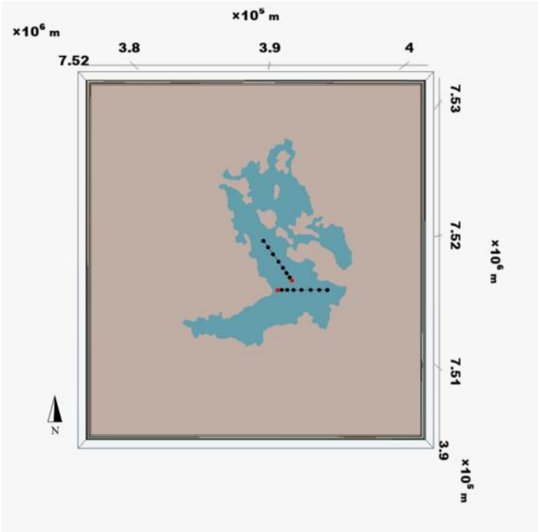
Figure 10

Location of the acquisition profiles. The red circle represents the Tx position, and the black dots represent the Rx positions according to the offset



The campaign conducted from W-E was positioned offshore well above the central part of the hydrocarbon reservoir, and all Tx-Rx arrays analysed were also above the reservoir. Evaluating Figure 11, at first sight, it is noted that the Marlim response is quite subtle compared to the salt structure response present in the model. The curve composed of the blue solid line with squares represents the response of the NoHC environment, and the red solid line with circles represents the HC environment.

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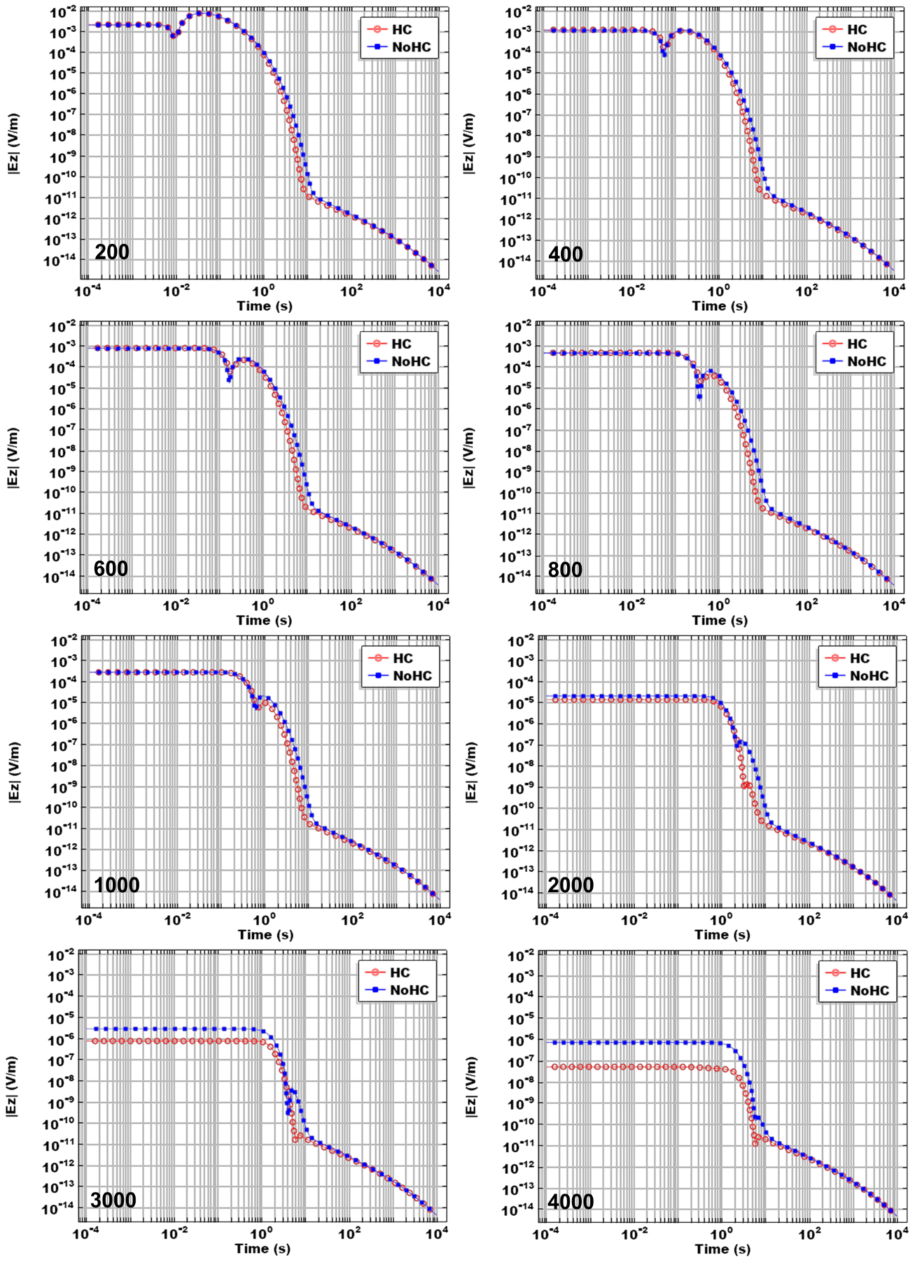
Figure 11

Responses of the VVCSEM in the W-E campaign in the MR3DC model. From left to right and the top to bottom, the red solid line with circles, the curves with hydrocarbons (HC), the blue solid line with squares, and no hydrocarbons with 200 m, 400 m, 600 m, 800 m, 1000 m, 2000 m, 3000 m, and 4000 m Tx-Rx offsets, respectively



It is also possible to note that in the more distant offsets, such as 2000 m, 3000 m, and 4000 m, three distinct behaviours are observed, the first being the notorious loss of resolution due to the source-receiver distance and the second being the effects of bathymetry on the data, as the water sheet increases and consequently increases the length of the VED. The

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third is implications suffered by the field due to the difference in quotas between the Tx and the position of the Rx (lower).

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 the MR3DC geological model and reviewing Figure 6 with the representation of the reservoir thickness variation, one can see that 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.

Comparatively, the curves were plotted using the background and the geological body of interest response. Thus, the curve composed of the blue solid line with squares represents the response of the NoHC environment, and the red solid line with circles represents the HC environment. Figure 12 shows the responses of the SE-NW campaign in the MR3DC model.

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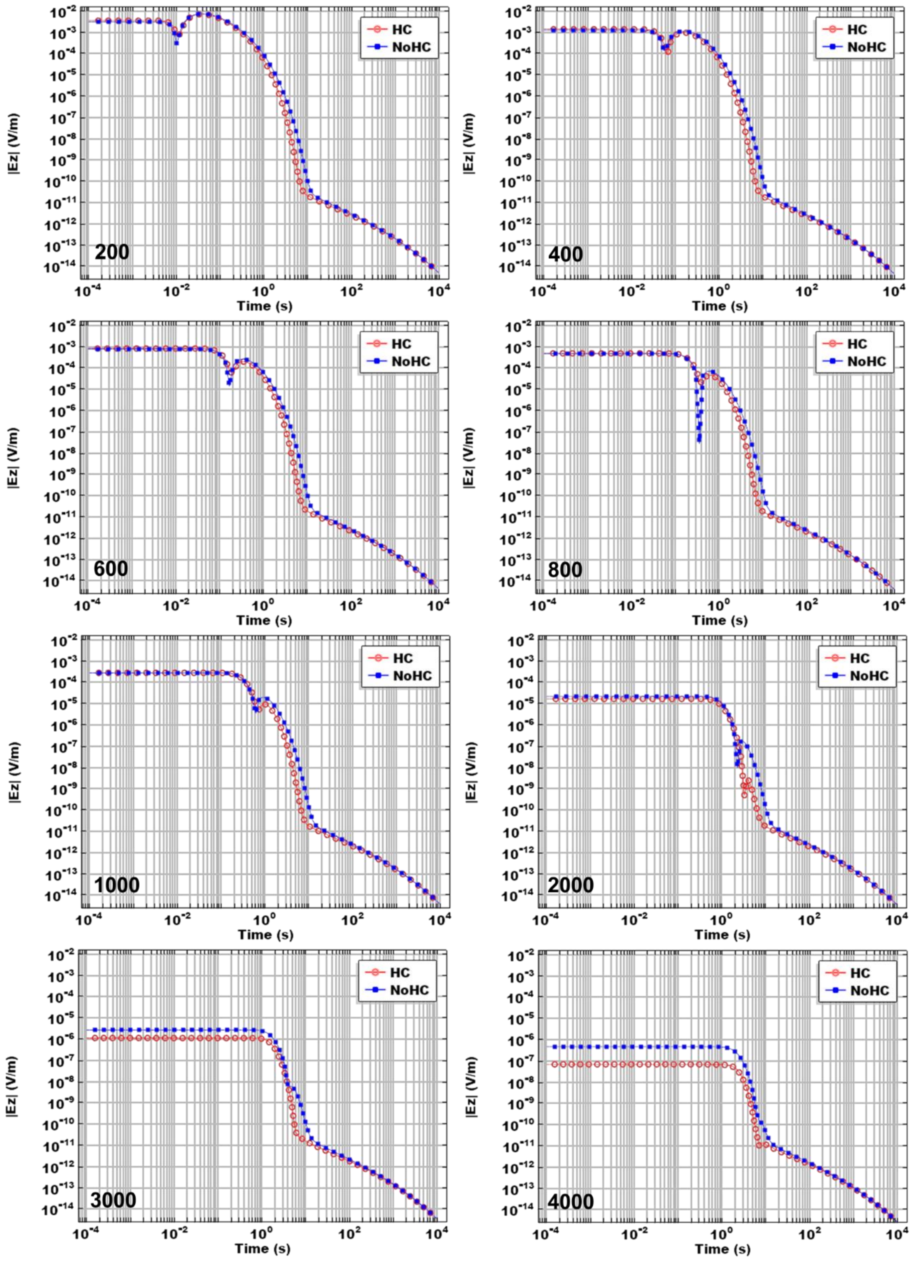
Figure 12

Responses of the VVCSEM in the SE-NW campaign in the MR3DC model. From left to right and the top to bottom, the red solid line with circles, the curves with hydrocarbons (HC), the blue solid line with squares, and no hydrocarbons with 200 m, 400 m, 600 m, 800 m, 1000 m, 2000 m, 3000 m, and 4000 m Tx-Rx offsets, respectively



The campaign performed from SE-NW was also positioned in the offshore portion well above the central part of the hydrocarbon reservoir, and all the analysed Tx-Rx sets were over the reservoir. However, the measurements were taken at a 135° inclination and only at

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the analysis level, which is not common in the offshore acquisition, which usually collects data inline or broadside.

Similar to the set of responses achieved with the W-E survey, the SE-NW survey curves showed discrepant behaviour in the initial times for the 3000 m and 4000 m offsets. Unlike the W-E acquisition, which was oriented from a higher (830 m) to a lower (1034 m) elevation (level), the SE-NW acquisition starts at a lower (805 m) elevation (level). It gradually increases as it moves towards beacon mark 1 (600 m).

4 CONCLUSIONS

The difficulty in modelling a transient method was circumvented with staged modelling, as it allowed better expression of the switch-off response (source switched-off during reading).

The geological and numerical modelling of the VVCSEM applied to the realistic model of Marlim provided good results, especially regarding the use of the beacon marks (points without reservoir) used as background. Comparing the background responses with the reservoir layer response is not always feasible in complex geological and anisotropic environments because each survey point has a different response.

Overall, and even in the face of the geological complexity and exploratory challenges of the Marlim field, the VVCSEM was able to identify the reservoir. The highly resistive saline layer of considerable average thickness promoted substantial distortions in the electromagnetic field, reducing the effects that the reservoir layer would promote if isolated.

With the evolution of the complexity of the developed modelling, it is expected to implement different acquisition designs and evaluate the best approaches to analyse the Marlim and different geological models. A future comparison with conventional MCSEM is also expected.

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