MR3D: a realistic model for CSEM simulations–phase II: The CSEM dataset

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SUMMARY

Marlim R3D is an open-source realistic geoelectric model for CSEM simulations of the post-salt turbiditic reservoirs at the Brazilian offshore margin. In the present article, we report the 3D CSEM finite–difference time domain forward study to generate the full-azimuth CSEM dataset for the MR3D earth model. To that end, we fabricated a survey with 45 towlines striking north-south and east-west directions over a total of 500 receivers evenly spaced at 1 km interval along the rugged seafloor of the MR3D. To accurately represent the thin, disconnected and complex geometries of the studied reservoirs, we have built a finely discretized mesh of 100 x 100 x 20 m leading to a large mesh with a total of approximately 90 million cells. We calculated the six electromagnetic field components (Ex, Ey, Ez, Hx, Hy, and Hz) at six frequencies in the 0.125 –1.25 Hz range. A multiplicative noise with a 1 % standard deviation was summed to the data. The whole CSEM dataset, with inline and broadside geometries, is being distributed for research or commercial use, under the Creative Common License, at the Zenodo platform.

INTRODUCTION

MR3D is a project aiming to provide a realistic geoelectric model for the deep-water turbidites reservoirs system of the Brazilian continental margin.

In phase–I, Carvalho and Menezes (2017) presented the workflow on how they have built the earth model and made it freely available for research or commercial use, under the Creative Common License, at the Zenodo platform.

Presently in phase II, we are in the process of completing a suite of a controlled–source electromagnetic (CSEM) finite–difference 3D simulations on the resistive model. Our goal is to produce a full azimuth 3D CSEM dataset that not only mimics current acquisitions patterns but, in most situations, exceeds them.

The MR3D CSEM synthetic dataset can be utilized to support and eventually enhance 3D forward and inversion modeling studies, and also subsurface imaging and characterization techniques using electromagnetic data alone or coupled with other types of geophysical data. The produced CSEM data for a wide frequency range (0.125 to 1.25 Hz) can be used to appraise a priori the effectiveness of a given CSEM interpretation workflow.

Furthermore, the full azimuth survey, with north-south (NS) and east-west (EW) towlines, and a large number of deployed receivers (500 Rx) in the MR3D simulation (Figure 1), when compared to contemporary marine acquisitions, enables the evaluation of alternative acquisitions geometries. Thus, offering parameters for the optimization of the survey designs.

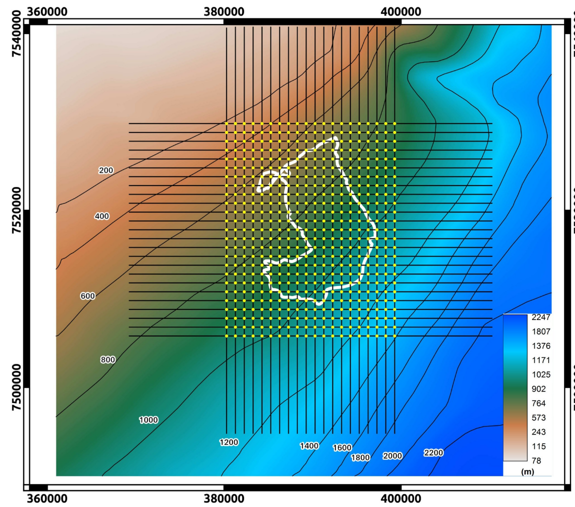

Figure 1: Acquisition geometry superimposed on the bathymetric map of Marllim R3D area. Marlim reservoir outline is shown in the white line. Yellow dots are receiver locations distributed in a 1000 m spacing regular grid. Black lines are source towlines evenly spaced at 1000 m. Source locations are spaced every 100 m along each towline.

The synthetic CSEM data is being made freely available for research or commercial use, under the Creative Common License.

MR3D RESISTIVITY MODEL

In the Brazilian continental margin, sand-rich turbidites constitute the most important post-salt reservoir rocks at several oilfields, and consequently possible targets for mCSEM surveys (e.g. Buonora et al., 2014). These turbidites were deposited in deep-water settings associated with slope and continental rise deposits (Freire et al., 1989).

MR3D is a realistic anisotropic geoelectric model that intends to be a benchmark for mCSEM studies of the Brazilian offshore turbidites reservoirs (Carvalho and Menezes, 2017). The model, based on previous seismic interpretation (Nascimento et al., 2014), includes fine-scale stratigraphy and fluid-filled reservoirs. The core of the model measures 27 km north-south by 24 km east-west by 6 km depth.

The resistivity model has a vertical transverse isotropic (VTI) anisotropy. An anisotropic ratio (Rv/Rv) of 2.5 was applied to the whole sedimentary section, except for the autochthonous salt body which is represented by a 1000 ohm.m isotropic and homogeneous layer.

The simplified VTI model was originated from p-wave seismic velocities (Vp) interpolated along the main stratigraphic

10.1190/segam2018-2997281.1

horizons in the studied area via horizon cube (de Groot et al., 2010). Details about the petrophysical modeling in the development of MR3D resistivity model are given by (Carvalho and Menezes, 2017)

Figure 2 shows the vertical resistivity extracted along a horizon slice at the top of the reservoir. The Marlim reservoir facies (clean sandstones) appears as a high resistivity body embedded in a low-resistivity background (marls and shales). Rather than a single resistivity body, MR3D presents a complex resistivity pattern that represents a genuine challenge for CSEM imaging.

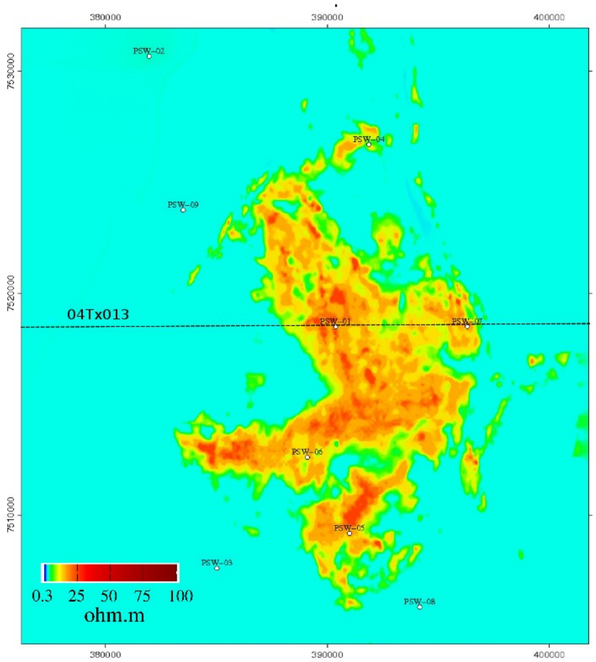

Figure 2: Map of the MR3D vertical resistivity distribution along the Oligocene horizon at the top of reservoir. PSW-01 to PSW-09 are the available wells provided by Carvalho and Menezes (2017). The Marlim turbidites (clean sandstones) are clearly highlighted as high–resistivity bodies. Dashed line 04TX013 is a EW towline.

Figure 3 shows a vertical cross-section of Rv model along the EW towline Tx13. Marlim reservoirs (M in Figure 3) is depicted as thin high-resistive bodies at 2900 m depth.

3D MESH

We conducted the 3D forward modeling using a parallelized version of the fast finite-difference time-domain (FDTD) CSEM modeling algorithm (Maaø, 2007). We utilized two separate models containing the horizontal (Rh) and vertical (Rv) resistivities including the bathymetry with a 100 x 100 m pixel resolution in the depth range 150 – 2200 m (Figure 1) and a 0.32 ohm.m isotropic water layer.

The model comprises a volume of 56 x 51 x 6 km, finely dis-

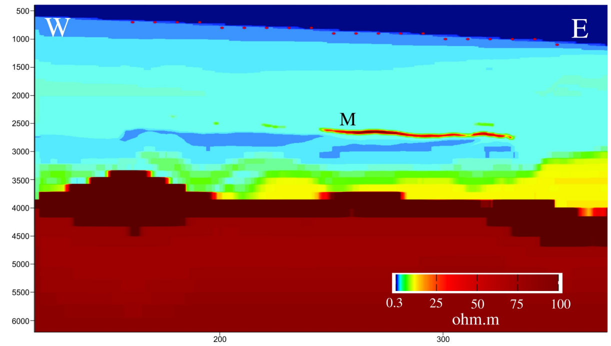

Figure 3: Cross-section of the MR3D vertical resistivity along the EW towline 04Tx013. Marlim oil–prone turbidites (M) appear as thin resistive bodies.

cretized at regular intervals of 100 100 20 m. Such refinement is necessary to properly represent the thin and discontinuous turbidites reservoirs (Figure 3).

The mesh discretization led to an FDTD mesh with a total of∼ 90 million cells (Table 1). The modeling exercises were executed using 62 core processors of our local Intel Xeon E5-2690 v2 @ 3.00GHz cluster (3968 GB memory) with a runtime of ∼ 9 hours each experiment.

MR3D mesh	
cell size - X	100 m
cell size - Y	100 m
cell size - Z	20 m
Number of cells - X	563
Number of cells - Y	511
Number of cells - Z	310
Total number of cells	89.882.950

Table 1: Finite-difference mesh used in the MR3D forward–modeling exercise.

CSEM ACQUISITION GEOMETRY

Full azimuth CSEM data were simulated for a total of 500 receivers located on the irregular seafloor of the MR3D model. For each receiver, sources were located along 45 tow lines having a spacing of 1000 m. Towlines were positioned along 25 EW lines and 20 NS lines for each receiver. Figure 1 shows the receiver positions and towlines superimposed on the bathymetry of the MR3D model.

Each EW towline has a length of 42 km, and each NS towline has a length of 47 km. Both directions are extending 11 km away from the first and last receivers at each towline. Sources positions were spaced at 100 m along each towline for a total of 201 source positions along each towline. The source is a 275 m long horizontal electrical dipole (HED), oriented parallel to the towline. The source parameters of the MR3D experiment are summarized in Table 2.

Source Parameters	
pitch	0^o
feathering	0^o
dipole length	275 m
offset step	100 m
offset range	500 – 11000 m
altitude above sea level	50 m

Table 2: Source acquisition parameters of MR3D experiment.

CSEM DATA

We simulated all the six electromagnetic field components Ex, Ey, Ez, Hx, Hy, and Hz for six source frequencies of 0.125, 0.25, 0.5, 0.75, 1, and 1.25 Hz. We added multiplicative noise with a 1 % standard deviation and settled a 10^{-15} and 10^{-12} ambient noise level for, respectively, the electric and the magnetic fields. The output dataset was generated in the current industry netCDF-based data format (Zach and Frenkel, 2012).

The modeling resulted in high–quality data to a source-receiver offset of 11 km, for the higher frequencies, maximum ranges of 5–6 km are typical (Figure 4).

A standard preliminary step in CSEM interpretation is the use of data normalization to generate pseudo-sections along a chosen line or anomaly maps at fixed constant-offsets. These provide, respectively, to the interpreters a first hint about the existence or not, of a given resistor in depth or area.

There several ways to perform that task(Buonora et al., 2014). We have chosen the normalization by a reference receiver, located in a portion of the model that contains only the background resistivity (i.e., the regional geology surrounding the reservoir). In this procedure, data from each receiver, are divided by the reference receiver data and plotted in pseudo-sections.

We present in Figure 5 the pseudo-section of the normalized MVO inline electric field (Ex) at 0.75 Hz for the 04Tx013 survey line. We used 04Rx251 as the reference receiver (RR in Figure 5). As expected, the high-resistive oil–prone reservoirs show strong anomalous values, up to 50 % above the background.

CONCLUSIONS

MR3D is a realistic geoelectric model for CSEM simulations that aim to be a benchmark model for studies of the post-salt turbiditic reservoirs at the Brazilian offshore margin.

We developed a detailed 3D CSEM finite–difference time domain forward study to generate an official CSEM dataset for the MR3D. To that end, we simulated a full-azimuth survey with 45 towlines striking north-south and east-west directions over a total of 500 receivers evenly spaced at 1 km interval along the rugged seafloor of the MR3D.

To properly represent the thin, discontinuous and complex geometries of the studied reservoirs, we have built a finely discretized mesh of 100 x 100 x 20 m. As a result, we obtained a huge mesh, with a total of approximately 90 million cells.

We modeled all the six electromagnetic field components for six source frequencies in the 0.125 –1.25 Hz range. A multiplicative noise with a 1 % standard deviation was added to the data.

The full CSEM dataset, with inline and broadside data, for the six electromagnetic fields and six frequencies, is being delivered freely usable to the general public on the Zenodo platform.

The MR3D project is being extended to include seismic, gravity and magnetotelluric simulations. All these data will also be publicly available. Hence, our CSEM dataset may, shortly, be evaluated isolated or within multi-physics interpretations schemes.

ACKNOWLEDGEMENTS

We thank Petrobras for its support and permission to publish this paper. We thank Marco Mallman and Mirela Ribas for their assistance to improve our figures. PTLM appreciates the support provided by a research grant from CNPq.

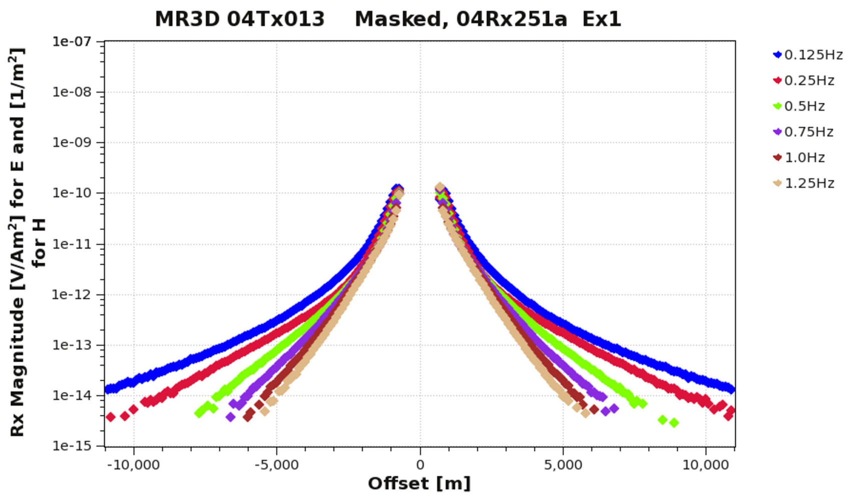

Figure 4: Typical data for the MR3D survey showing the overall good quality of the inline electric field (Ex). Site 04Rx251a along towline 04Tx013.

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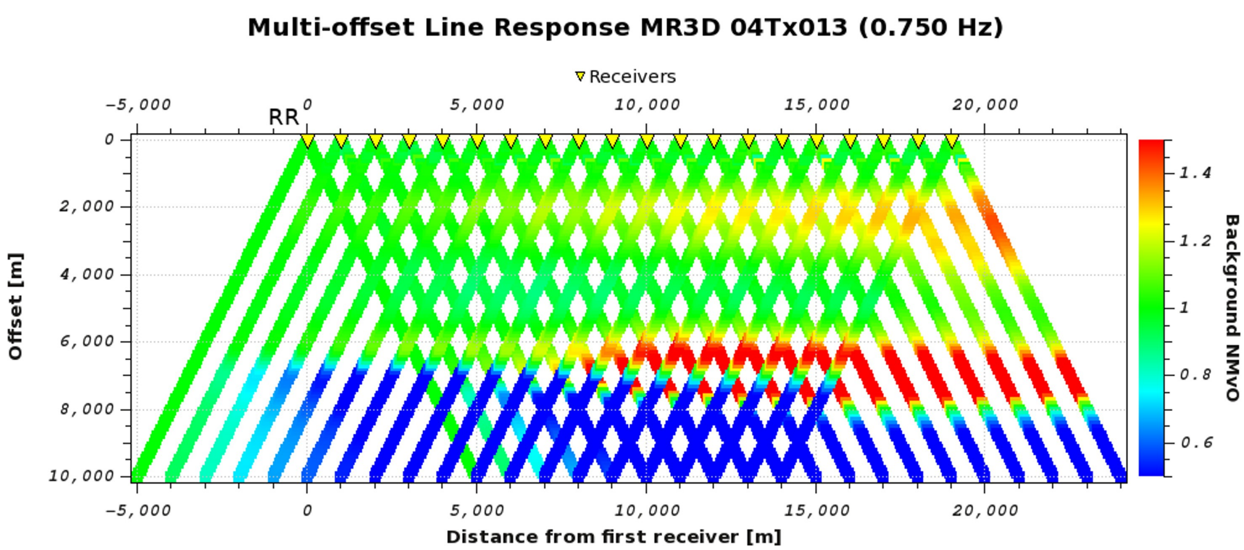

Figure 5: Pseudo-section for the normalized MVO inline electric field (Ex) at 0.75 Hz for the 04Tx013 survey line. Marlim reservoir exhibits anomalous values up to 50% above the background between 6000 - 8000 m offsets. Yellow triangles indicate the positions of the receivers at the seabed. RR is the reference receiver 04Rx251a (Figure 4).

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