Marine electromagnetic forward modeling in a resistivity model constrained by seismic and well log data from a field at Campos basin SE-Brazil

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Introduction

Overview

Marine magnetotelluric (MMT) and Controlled Source Electromagnetic (MCSEM) methods are applied to investigate scenarios involving hydrocarbon accumulation in a thin post-salt reservoir from a resistivity model typical of the Campos basin, constrained by well logs and seismic data.

Study area

The Campos basin is located in the Brazilian southeastern margin, being among the most important Brazilian basins in the economic panorama due to the large accumulations of oil.

The Figure on the top right shows public data sets (2D and 3D Seismics, CSEM and well logs) acquired in the area in distinct exploration campaigns. The CSEM data is still a raw data and needs to pass through some processing analysis. However, the great coverage of seismic and well log data available motivates the simulations of EM common scenarios.

Map location of the study area in Campos basin (SE Brazil). The geophysical data selected covers partially three oil fields, the selected area (brown dashed rectangle) comprises the best coverage of EM and seismic data.
Geological setting

- Campos basin formation and evolution is related to the rupture of the supercontinent Gondwana end Jurassic (South America and Africa).
- The sequential deposition is divided by Winter et al., (2007) in three main sequences: rift, post-rift or transitional and drift.
- The regional schematic section below shows the structural architecture of the basin and the main formations.

*Regional section*  

*Stratigraphical chart (ANP ; Winter et al., 2007)*
Geophysical data set

3D seismic data

The seismic reflection is the highest resolution geophysical method, more especially if the data exhibits good quality and well tie can provide geometry of the bodies at subsurface.

Example of the 3D seismic data available (Post-time migrated up to 8.5s). Bright areas with weak and chaotic reflections are associated with salt bodies and basement.
2D seismic lines

Although, a 3D seismic cube of good quality is available, we used for this study the 2D lines because they are migrated in depth (Post-Stack Depth Domain - PSDM).

2D depth seismic lines are better to create layers for the resistivity model; nevertheless, some structures were compared with the 3D data to ensure reliable interpretation in some complex regions.

Example of 2D dip seismic lines (orthogonal to the coast) are presented; The section L3341 passes through the most interesting area and is used to show seismic interpretations and scenarios of the EM forward modeling tests.

Example of 2D PSDM seismic in-lines from the selected area.
Methodology

Seismic interpretation: workflow

Mapping seismic reflectors
- Seismic attributes
- Structural interpretation
- Well log match

Defining horizons
- Seabed
- Top of Salt
- Basement

Interpreting Succession
- Seawater
- Post-salt
- Salt
- Pre-salt
- Basement

Line L3341: original line

Well logs

Line L3341: structurally interpreted with horizons

Line L3341: final interpretation with main succession
Methodology

Seismic interpretation: attributes

In order to create the resistivity model, the seismic lines were interpreted and divided in depositional succession (post-salt, salt, pre-salt and basement).

During the seismic analyses some attributes were applied in the in-line and cross-lines, in order to facilitate the demarcation of seismic horizons and reflector discontinuities. For these tasks, well log and markers were extensively used.

Figure on bottom right shows the similarity attribute applied to the line 3341. Similarity is a form of "coherency" that expresses how much two or more trace segments look alike (Opendtect)
Methodology

Seismic interpretation

Seismic line L3341 with different color bar to highlight discontinuities of reflector using the seismic attribute. Amplitude volume technique (TecVA) or also known as pseudo-relief.

**TecVA** uses Root Mean Square (RMS) amplitude that is the interval average of the seismic trace envelope¹ and phase shift that gives an idea of relief (Bulhões and Amorim, 2005). This attribute were used to highlight faults, delimit salt bodies and basement.

**TecVA**: RMS amplitude + phase shift

\[
x_{\text{rms}} = \frac{1}{N} \sum_{n=1}^{N} x_n^2
\]

\[
x_n - \text{seismic trace}
\]

\[
N - \text{number of sample}
\]

¹\(E(t) = \sqrt{x(t)^2 + g(t)^2}\)

\(g(t) = \text{Hilbert transform of } x_n\)
Geophysical data set

Well logs

- 33 well logs were used to obtain the average resistivity of each formation/succession in Campos basin.

- Figures below show typical examples of well logs located around the area.
Methodology

Schematic type section (resistivity view)

Constraining interpreted model with resistivity values from well logs

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Seawater ~ 0.3 Ohmm
(Literature). Telford

Post Salt
Range: 0.6 – 2 Ohmm – Mode 0.8 Ohmm

Salt
Range: \(10^2 – 5 \times 10^3\) Ohm
Mode: \(10^3\) Ohm

Pre Salt
Range: 0.8 – 30 Ohm
Mode: \(~10\) Ohm

Basement ~ \(10^2\) Ohm
Ohm
(Analogues in Santos basin wells and Fontes et al. 2009).

EM FWD in Campos basin NE Brazil - Benevides et. al., vEGU 2021
Methodology

EM Forward modeling

Once we have our conceptual resistivity model \( \rho(x,y,z) \), we want to obtain the correspondent CSEM and MT responses.

The fwd modeling is performed using ModEM code (Kelbert et al., 2014)

Solution of EM is obtained discretizing diffusion equation using finite difference technique in a staggered grid (Yee, 1966)

The electric field \( \mathbf{e} \) is found iteratively using a solver (e.g. QMR, BiCG)

Resulting in a linear system

\[
A \mathbf{e} = \mathbf{b}
\]

Source term and/or boundary conditions

\[
(\nabla \times \nabla \times + i\omega\mu\sigma) \mathbf{E} = \mathbf{j}_s
\]

\[
\mathbf{h} = (i\omega\mu\sigma)^{-1}C_m \mathbf{e}
\]

\( C_m \) Model covariance

EM FWD in Campos basin NE Brazil - Benevides et. al., vEGU 2021
**Methodology**

**Setup acquisition**

- 15 MT & CSEM stations are placed on the seafloor
- Station spacing 4 km (similar to the real acquisition CSEM)
- The transmitter (CSEM) is in-line with y direction
- Range frequency
  - MT 0.1 to 10000 s
  - CSEM 10 Hz to 0.1

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Discretized model
Results

MT Forward modeling

From the electric and magnetic fields calculated by FWD modeling we can obtain the apparent resistivity and phase from impedance tensor:

\[ \rho_{ij} = \frac{1}{\omega \mu_0} |Z_{ij}|^2 = \frac{1}{\omega \mu_0} \left| \frac{E_i}{H_j} \right|^2 \]

\[ \phi_{ij} = \arctan \left( \frac{\text{Im} \{Z_{ij}\}}{\text{Re} \{Z_{ij}\}} \right) \]

The curves in the pseudo-section show a smooth geometry associated to L3341; it is important to be aware that we are analyzing pseudo sections of MT curves that show resistivity and phase varying with period, in other words, they are not in the depth domain.

The most important differences between \( Z_{xy} \) and \( Z_{yx} \) pseudo-sections are: \( Z_{xy} \) seems to be more sensitive to vertical resistivity variation, while \( Z_{yx} \) shows lateral discontinuity probably associated with interfaces between resistive salt and conductive post-salt sediments.
Results

CSEM Forward modeling

In the CSEM response is possible to observe a different decay in each side of the transmitter for all components.

Looking at Ey-component, we have slower decay on the left side and a faster decay on the right side of the transmitter, probably reflecting the basement relief, that is resistive allowing better EM field propagation.

The opposite situation is valid on the right side because of the presence of thick conductive sediments that consume the EM fields in higher frequencies.
Methodology

Scenario: Hydrocarbon accumulation

- Anomalies associated with the Maastrichtian reservoir of the Carapebus Fm. (Post-salt play) is now investigated. This play is part of oil field.

- The oil probably migrated through evaporites and upper layers using existent faults and was stratigraphically trapped by shale of the Ubatuba Fm.

- On the right we have two logs (GR and resistivity) showing evidences oil accumulation in sandstones of the Carapebus Fm. in the post-salt succession.

- The oil accumulation is shaped as a thin reservoir and the EM responses effectiveness for detecting thin reservoirs HC-filled is tested comparing environments with and without accumulation.

- This exercise is useful to compare and understand the real data collected in the study area.
Results

Testing EM effectiveness in detecting HC
MT FWD

- Analysis of MT sensitivity to the hydrocarbon presence:
  - Mastrichtian reservoir two different resistivities
    - 10 Ohm.m
    - 50 Ohm.m

The comparison between MT responses without reservoir (w/o reservoir) and with reservoir of 10 Ωm were similar, while little difference is observed when the reservoir has a resistivity of 50 Ωm.
Results

Testing EM effectiveness in detecting HC CSEM FWD

For the CSEM case, there are deviations in several frequencies due to the 50 $\Omega m$ HC reservoir inclusion, and the differences are also observed in other EM components, the target affects mainly frequency between 3 and 0.7 Hz. The sensitivity showed by the EM methods to the resistivity variation can assist in indicating a reservoir HC-filled and/or in the obtaining subsurface images that can be integrated in joint approaches with seismic for getting less ambiguous interpretations in future work using real data set.

- Differences between the two responses $E_{\text{reservoir}} - E_{\text{background}}$ for Ey and Ex-components
References


Acknowledgement

The authors gratefully acknowledge support from Shell Brasil through the ‘Design of a workflow for 3D joint and constrained inversion of multiple geophysical data sets’ project at Observatório Nacional and the strategic importance of the support given by ANP through the R&D levy regulation.