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Review

Twenty Years of CSEM Exploration in the Brazilian Continental Margin

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Abstract: The controlled source electromagnetic (CSEM) method is frequently used as a risk reduction tool in hydrocarbon exploration. This paper aims to provide a comprehensive historical review of the CSEM method's twenty-year history in the Brazilian continental margin. Since 2003, we have significantly improved our understanding of CSEM resistivity data across various geological scenarios. This review presents a roadmap of the technical advancements in acquisition design and interpretation techniques. As a result, our understanding of the methodology has broadened from traditional to more general use, such as salt imaging, gas hydrates, geohazard mapping, and reservoir characterization. Finally, we indicate the potential upcoming CSEM applications in new energy resources and carbon capture and storage.

Keywords: CSEM exploration; reservoir monitoring; geohazard; energy resources

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1. Introduction

The marine controlled source electromagnetic (CSEM) method is a risk reduction tool used in hydrocarbon exploration [1]. In its most frequently practiced setup, the CSEM operates a towed horizontal electric dipole (HED) source that transmits a low-frequency EM pulse, commonly in the 0.01–10 Hz range, and free-fall ocean bottom node receivers are set on the seafloor (Figure 1). The receivers usually register the two horizontal electric fields and two horizontal magnetic components. During the transmitter's off-time periods, the nodes still register the natural electromagnetic fields, making magnetotelluric (MT) data available as a byproduct of the acquisition.

The marine CSEM has been applied in de-risking deep-water high-cost drilling decisions in many basins worldwide since the beginning of the 2000s, when the first survey was performed in October 2000 at the Girassol Prospect, offshore Angola [2]. Since the early stages, CSEM has been expanded to a broader range of geographic areas, geological environments, and application scenarios.

In Brazil, CSEM's history started 2003, when Petrobras planned and contracted the first multiclient survey in the Brazilian offshore margin in April 2004. Shell and Exxon also acquired these data. Since then, we have achieved impressive numbers, only 20 years after the beginning of CSEM's usage in Brazil.

Forty-seven surveys have been performed along the Brazilian coast, from north to south (Figure 2). These surveys span 19,350 line kilometers of deep towed CSEM data and 5410 receiver deployments. Petrobras plays a leading role in CSEM usage, acquiring almost all of the data shown in Figure 2. Most datasets were acquired by EMGS (80%), while Schlumberger (SLB) was responsible for 20%.

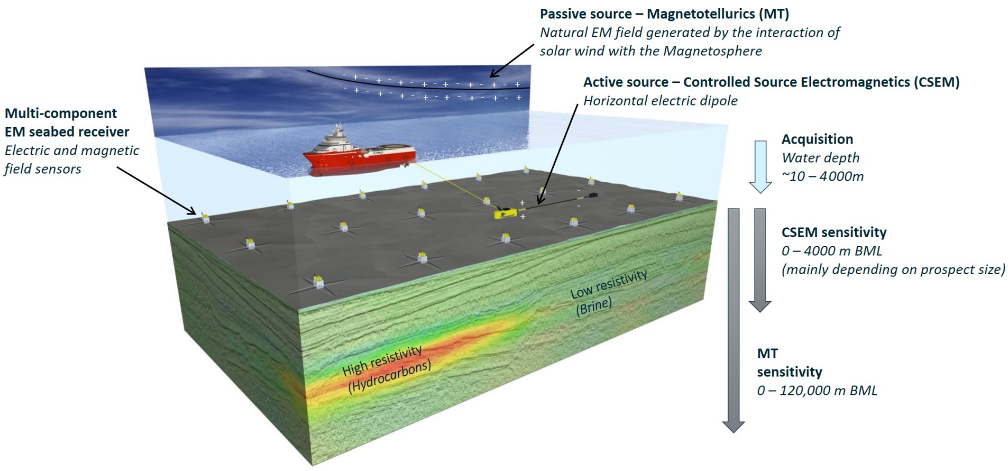


Figure 1. CSEM acquisition scheme and the state-of-art technology sensitivity below mud line (BLM) of the MT (up to 120 km depths) and CSEM (reservoirs up to 4 to 5 km burial) methods. Courtesy of EMGS.

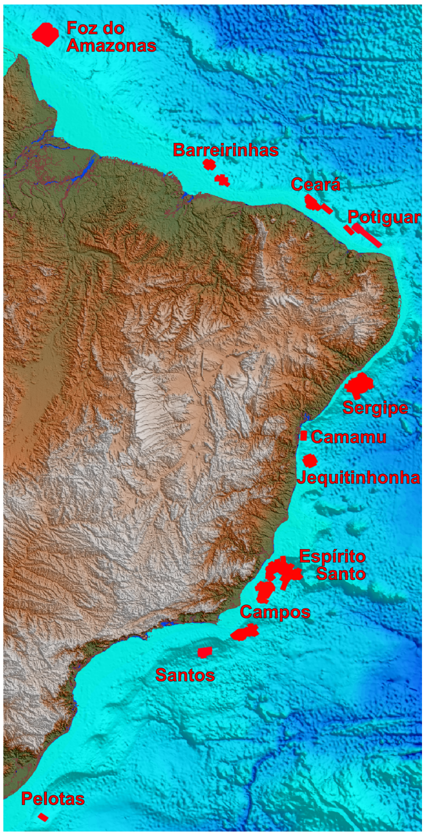


Figure 2. CSEM schematic acquisition map at Brazilian continental margin at several offshore basins (labeled in red). Red polygons indicate the position of the CSEM surveys.

This paper aims to provide a historical review, which is accessible to non-experts, of the CSEM development in the Brazilian continental margin, from the initial period, with the inherent distrust of our asset teams about the usability of the method, until the current period, where CSEM has consolidated itself as a reliable prospective tool for hydrocarbons. We can divide this timeline into three important periods:

- 2003–2010—first steps in CSEM and the consolidation of the methodology;
- 2011–2020—this phase includes the expansion of commercial surveys for exploration and appraisal purposes;

- 2021 and beyond—this includes important information about where we are now. Is CSEM worthwhile? What results have we obtained after 20 years of usage? Finally, we have the opportunity to plan the future, moving from exploration towards monitoring and energetic transition applications.

This review addresses the developments in the acquisition's survey design—most importantly, in the CSEM processing and interpretation schemes, beyond its earlier usage for reservoir de-risking. The idea is to provide a roadmap of the technical advances in acquisition design (Figure 3) and interpretation techniques (Figure 4) over the past twenty years, mainly in understanding how the CSEM resistivity data can effectively contribute to the overall geological knowledge of a given area.

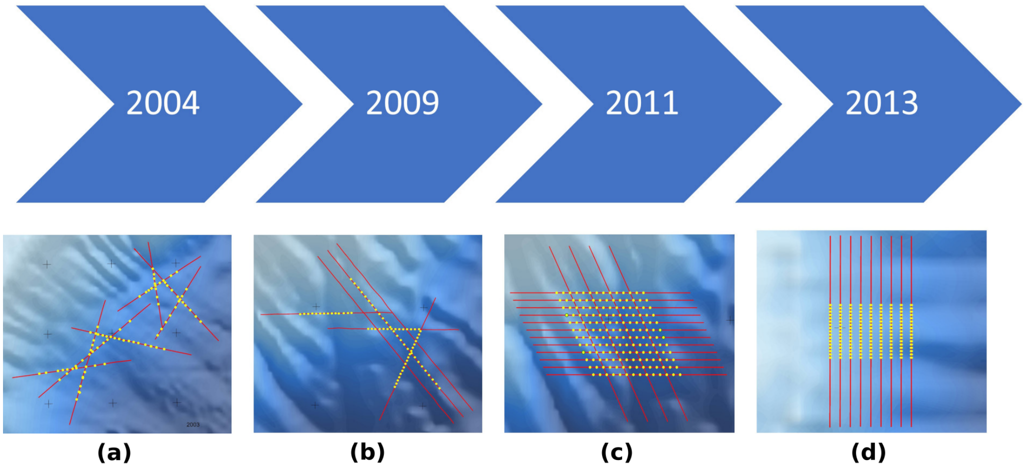


Figure 3. Schematic cartoons (maps out of scale) to illustrate the evolution of the CSEM acquisitions in the Brazilian continental margin. Yellow dots represent the CSEM receivers and red lines indicate the source tow lines. (**a**) 2004 acquisition. 2D regional acquisition with uneven +2 km receiver spacing. (**b**) 2D acquisition with regular 1.5 km receiver spacing; additional source tow lines were collected, simulating a pseudo-3D acquisition. (**c**) Full-azimuth 3D acquisition at the same spot as (**c**), regular grid with 1.5 km receiver spacing. (**d**) High-resolution 3D acquisition (1 × 0.5 km receiver grid).

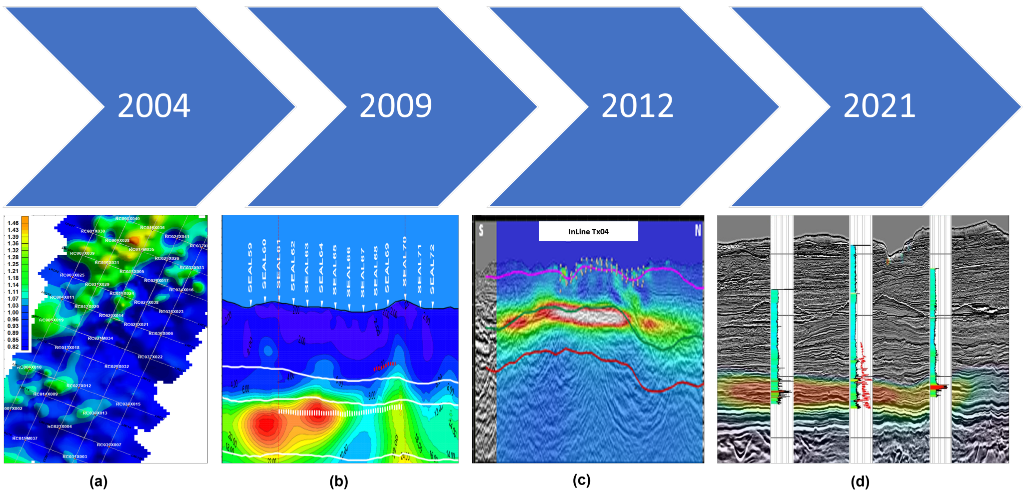


Figure 4. Schematic cartoons (figures out of scale) to illustrate the evolution of CSEM interpretation in Petrobras. (**a**) Normalization map calculated in the data domain. Background values are close to 1 (blue portions in the map); green-to-orange colors represent anomalous spots (areas where the electric field is 15% to 45% higher than the background). (**b**) Output resistivity model from an unconstrained 2D inversion; anomalies are represented by yellow to reddish colors. Three main regional stratigraphic horizons are superimposed on the model. The red dashed line represents a

volcanic layer, and the studied reservoir is shown by the white dashed line. (**c**) Output resistivity model from an unconstrained 3D inversion superimposed on the seismic amplitude attribute; anomalies are represented by yellow to reddish colors. (**d**) Seismic, constrained 3D CSEM inversion results and well-log data integrated into a single interpretation platform.

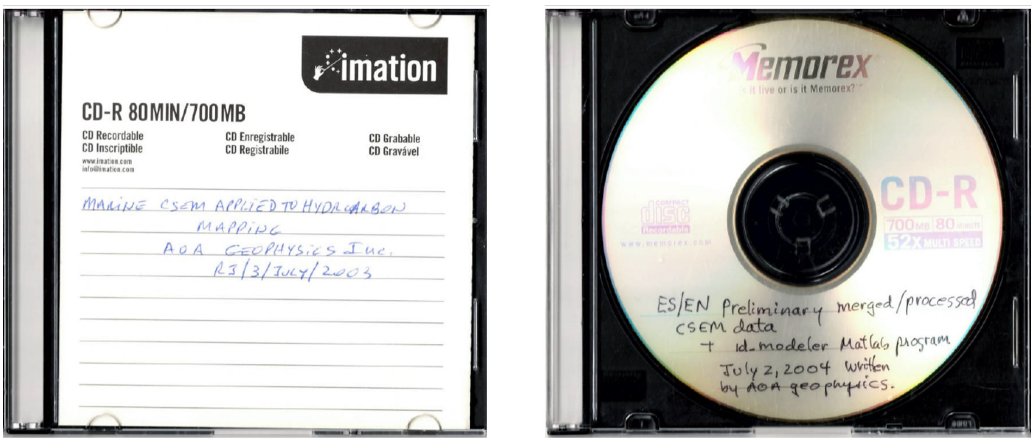
2. The 2003–2010 Period, Consolidation of the Methodology

2.1. First Steps in CSEM

CSEM's history in Petrobras started curiously. By the end of 2002, Ricardo Catellani, a senior consultant with expertise in seismic amplitude versus offset (AVO) analysis and reservoir modeling [3], had read the paper presenting the results of the first CSEM experiment in Angola acquired for Equinor (former Statoil) [2]. Initially skeptical but interested in this new technology, he challenged his colleague, Marco Polo Buonora, a potential-field methods expert, regarding whether this new method was trustworthy and could be applied to the exploration of the Brazilian offshore turbidites.

To respond to this challenge, Buonora carried out research, aimed at comprehending the theoretical principles of electromagnetic methods and reviewing case studies of their use in marine exploration. Then, Buonora scheduled a series of technical visits to the headquarters of the three commercial CSEM service contractors available at that time [4]: EMGS (a descendent of Statoil); OHM Surveys, arising from Southampton University; and Arnold Orange Associates (AOA) Geomarine Operations (AGO, later acquired by Schlumberger [4]).

By July 2003, a group of geophysicists from AOA had visited the Petrobras office in Rio de Janeiro (RJ) to present the CSEM methodology and discuss the parameters of a multiclient survey. To these meetings, Petrobras invited EM experts from Brazilian universities to collaborate in the project and compose a scientific advisory board to help Petrobras staff. A 700 MB CD-ROM-R containing the presentations on CSEM applied to hydrocarbon mapping remains in the Petrobras collection as a register of the first meeting in the Petrobras headquarters, dated 3 July 2003 (Figure 5a).



(a) **(b)**

Figure 5. Digital media used at the beginning of the 2000s to exchange information. (**a**) 700 MB CD-ROM-R (read-only) with CSEM material provided by AOA Geophysics (2003). (**b**) 700 MB CD-ROM-R with the first CSEM data delivered for Petrobras (2004). Courtesy of Petrobras.

As a result, Petrobras agreed to undertake the first multiclient survey in Brazil. The survey comprised approximately 1600 line kilometers acquired along 36 towed lines [5]. The survey was organized into three major areas in the Santos, Campos, and Espirito Santo basins (Figure 2). The CSEM data were acquired using two distinct patterns, two surveys using a sparse 2D layout (receivers with +2 km spacing), in a star-like shape (Figure 3a), and the first regional 3D one employing a 5 km rectangular grid [5].

These three areas were chosen because of the proven reservoirs that could be used to validate and calibrate the responses of the methodology over known targets [5] and undrilled prospects identified by seismic interpretation to be tested [6].

The preliminary CSEM dataset of the multiclient was delivered in CD-ROM-R form by July 2004, together with some Matlab scripts for 1D modeling and data plotting tools (Figure 5b).

At that time, there was no commercial software available, and 2D and 3D imaging processing was rather primitive when compared to seismic [6]. Therefore, the interpretation in the industry was limited in identifying and correlating the CSEM anomalies in the data domain (Figure 4a) with the outline of prospects [5,6].

Buonora et al. (2005) [5] showed that the 2004 CSEM 3D grid data were sensitive to known oil reservoirs in selected areas of the Campos basin. They could identify electric/magnetic field anomalies as small as 20% above the background response using state-of-the-art processing and modeling tools. Finally, they forewarned about the need to push the CSEM technology forward through the development of interpretation workflows based on a novel suite of multidimensional software tools.

Smit et al. (2006) [6] interpreted the 2004 dataset to downgrade an undrilled prospect where seismic amplitude studies were inconclusive. The CSEM receiver collected along the prospect displayed no anomaly in the normalized electric field, indicating that the selected area probably had resistivity similar to the surrounding conductive shales (see Figure 3 of [6]).

Newman et al. (2010) [7] used the regional grid dataset to validate their 3D imaging algorithm. They showed that incorporating electrical anisotropy into 3D inversion produces reliable models with a superior data fit compared to isotropic models.

2.2. Building the House

With increasing confidence in the CSEM method, Petrobras decided, in 2006, to build a strong internal group dedicated to multiphysics methods under Marco Polo Buonora's leadership. To this end, Petrobras hired some EM experts, combined them with new, talented young geologists and geophysicists, and then engaged in intensive investment in the continuous education of all its personnel. Petrobras created in-house EM courses to train the multiphysics group and spread awareness of the EM methods' applicability to the exploration asset teams.

Following this guideline, Petrobras joined some academic EM consortia in the USA, such as Scripps (University of California San Diego) and the Consortium for Electromagnetic Modeling and Inversion (University of Utah), and, more recently, the Electromagnetic Methods Research Consortium (Lamont-Doherty Earth Observatory, Columbia University). In Brazil, Petrobras stimulated the development of EM groups at Universidade Federal do Pará (UFPA), Universidade do Estado do Rio de Janeiro (UERJ), and Observatório Nacional (MCTI-ON).

In 2007, Petrobras established a three-year joint industry project (JIP) with the Schlumberger Brazilian Research Geoscience Center in Rio de Janeiro, Brazil. The main goal of the JIP was to develop an EM interpretation workflow and integrate deep-reading EM tools into the full cycle of hydrocarbon reservoir exploration. The JIP was responsible, among other items, for the first marine magnetotelluric [8,9] and full-azimuth CSEM [10,11] surveys acquired for offshore Brazil.

Other important products of the JIP were the development of a commercial implementation of 2.5D anisotropic inversion as a user-friendly graphical user interface (GUI) [12] and the first results from 3D inversions [11].

The availability of 2.5D inversion as an easy-to-use GUI changed how CSEM was interpreted from the data to the model (Earth) domain. These inversions could be more easily executed by a larger group of non-expert geophysicists and produce more meaningful images to be shared with the asset teams. This approach's major benefit is exporting the recovered resistivity models in the SEG-Y seismic standard format, which can be easily uploaded into any seismic interpretation software. Consequently, it allows qualitative correlations by co-rendering the inverted CSEM 2D Earth models with the depth-converted/migrated seismic data (Figure 4b).

From 2005 to 2009, six commercial surveys were acquired for Petrobras in several basins, all using a 2D layout to investigate leads as imaged by seismic interpretation.

Figure 4b shows the CSEM interpretation of one of these surveys. Acquired in 2009 by SLB in the Sergipe-Alagoas basin, this survey is considered the turning point in Petrobras' high management's acceptance of the CSEM method. To interpret the data, we used the 2.5D inversion to show a resistive anomaly response coinciding with the lateral boundaries of the investigated lead. Nonetheless, the center of the resistive anomaly was above the expected depths given by the seismic AVO anomaly.

Drilled in 2010, the successful wildcat well confirmed the CSEM and seismic forecasts, with the reservoir being hit shallower than expected by the seismic interpretation. The velocity field was then updated using the wildcat well information. Figure 4b displays the co-rendering of the 2009 CSEM anomaly with the 2010 updated depth-converted seismic line, where the low-resolution resistivity anomaly is centered over the top of the reservoir.

3. The 2011–2020 Period, Expansion of the Commercial Surveys

3.1. CSEM for Exploration

The year 2010 ended with a great deal of in-house work for the multiphysics group, performing a huge feasibility study over the Brazilian shelf. This task was named the Varredura (sweep) project. The main idea behind Varredura was to bring a dedicated ship to execute a large multiclient survey over prospects at several basins (Figure 2).

We conducted 2.5D feasibility studies to assess the CSEM effectiveness in distinguishing oil-filled turbiditic reservoirs from the background geology. Our colleagues from the asset teams provided information about the leads: the main stratigraphic horizons, the outline of the leads with their top and base, and resistivity well logs of the nearest well, if available. We analyzed 115 leads; 79 were detectable, and 36 were non-detectable. After a round of analyses based on economic criteria, 56 leads were approved for acquisition.

The Varredura studies were responsible for selecting the target areas and defining all relevant survey parameters, such as the receiver's positioning, sampling frequencies, and source towing directions [13].

EMGS was responsible for Varredura's acquisitions [14]. The surveys started in 2011 in the Barreirinhas basin (Brazilian equatorial margin), followed by the Ceará, Potiguar, Sergipe, Jequitinhonha, Espírito Santo, and Campos basins (Figure 2). The survey designs moved from a 2D to a 3D layout in a similar movement to that which occurred with the seismic method, moving from 2D to 3D seismic acquisitions. At the beginning of the Varredura acquisition, the 3D grids were planned with 1.5 to 2 km receiver spacing (Figure 3c). Nonetheless, with increased confidence in the CSEM method, high-resolution surveys were executed with 500 m receiver spacing, aiming for detailed prospect characterization (Figure 3d) [13].

One of the key lessons that we learned after the start of the CSEM acquisitions was to shift towards using 3D surveys. This type of design provides more information and reduces ambiguity in interpretation. The CSEM vertical resolution is much poorer than the horizontal resolution [15]. To increase the likelihood of a successful drill, we propose imaging the shapes of anomalies along horizons or depth slices and correlating them with the lead's outline [15].

Varredura's CSEM data spanned more than 5000 km^2 coverage and 3103 deployed receivers [14]. Interpreting this massive quantity of data at many distinct basins and leads with different drilling time schedules, and aiming to provide quick answers to allow the asset teams to make drilling decisions, was a great challenge. At this time, 3D inversions were already available [16], but the task was time-consuming, with a single inversion run usually taking several weeks.

To provide quick responses to the asset teams, Petrobras developed a fast interpretation workflow [13] comprising the identification of anomalies via frequency ratio normalization of the CSEM data [17] and then performing constrained 1D CMP inversions [18], followed by high-resolution 2.5D anisotropic polygonal inversions [12]. We applied the workflow in a complex geological setting where the reservoir dipped toward salt domes. An asset team colleague joined the multiphysics group, providing important geological information from the seismic interpretation that helped us to obtain useful information about the local geology. Two successfully drilled wells corroborated the integrated seismic–CSEM interpretation [13].

The multiclient contract included providing the output of unconstrained 3D anisotropic inversions based on a quasi-Newton BFGS optimization algorithm [19] as a by-product (Figure 4c). Petrobras then acquired two commercial 3D inversion suites, Sblwiz (EMGS) and the Petrel^{TM} EM plugin (SLB), and implemented them in a dedicated cluster for the multiphysics group. Since then, Petrobras has been continuously upgrading the capacities of its high-performance computing (HPC) park. Today, we use cluster- and cloud-based solutions to perform our 3D inversions.

Outside the Varredura project, Petrobras acquired, in 2011, the CSEM multiclient dataset collected by SLB [20]. The dataset included more than 250 km of towlines recorded by 136 receivers at five different spots in the Ceará and Potiguar basins (Figure 2). A package with the 3D inversion results of the studied areas (resistivity models, data fits, etc.) was also made available by SLB in their EM plugin at Petrel^{TM}.

3.2. CSEM for "Non-Standard" Exploration Applications

3.2.1. Sub-Salt Imaging

Beyond the standard use of CSEM in de-risking prospects, Petrobras understood that the CSEM data could provide information about the subsurface geology and be used for other purposes within the oil industry. Thus, Petrobras signed a second JIP cooperation agreement with SLB, aiming at several goals, such as sub-salt imaging, reservoir characterization, and the first steps in reservoir monitoring.

One of the aims of the JIP was seismic sub-salt imaging, usually a difficult task, mainly due to complex bodies with steeply dipping flanks of salt domes and large acoustic impedance and velocity contrasts between the high-velocity salt and the lower-velocity sediments beneath. On the other hand, EM fields easily penetrate through resistive (high-velocity) salt with little attenuation, thus providing information on the underlying conductive (low-velocity) sediments [21].

Among the EM methods, MT is the classical method used for sub-salt imaging [22] but also for sub-carbonate [23] and sub-basalt imaging [24,25], which face similar challenges presented by autochthonous and allochthonous salt body zones.

The highly conductive seawater layer attenuates the high-frequency MT fields in deep to ultra-deep waters. Frequencies higher than 0.1 Hz are commonly unusable [21]. A possible approach to overcome this issue is to combine CSEM and MT to interpret using joint-inversion, clearer subsurface images [26,27].

Zerilli et al. (2016) [21] developed an integrated seismic–CSEM two-step interpretation workflow and applied it to a broadband ultra-long offset CSEM research survey acquired over a selected ultra-deepwater area of the Espirito Santo basin [28] (Figure 2).

In the first step, [21] conducted a 3D pixel-based inversion [29] to obtain the first estimates of the geometry and resistivity of an allochthonous salt body, as indicated by previous seismic interpretation conducted by the asset team, and the background resistivity. A priori information about the sedimentary background resistivity was provided by available nearby wells.

In the second step, [21] ran structure-based MT–CSEM joint-inversions [30,31] using the recovered model of the previous step as input. Then, [21] used a start model based on the previous seismic interpretation and constrained the inversion domain to an area enclosing the top of salt and the base of salt horizons. The background resistivity and the top of salt horizon were fixed during the inversion process. This strategy allowed the better recovery of the base of salt horizon, 300 to 700 m shallower than previously interpreted by the asset team.

Interpreting the same broadband dataset, [32] established a resistivity-to-velocity model by calculating the Hacikoylu petrophysical cross-property relationship [33]. They calibrated the Hacikoylu coefficients (a,c) at a well-log scale. Then, they applied them to the regional resistivity models derived from the 3D CSEM inversions to obtain P-wave velocity (Vp) models.

Zerilli et al. (2017) [34] then used the Vp models provided by [32] as a cost-effective starting model for full waveform inversion (FWI), to provide better seismic images in the complex salt environment of the Espírito Santo basin. Moreover, [34] showed that their seismic data alone had insufficient information on the salt geometries and the salt, around-salt, and sub-salt velocity distributions. They concluded that including the knowledge from the CSEM allowed an unambiguous and robust strategy to improve the seismic images, allowing the interpreters to achieve a more accurate seismic interpretation.

3.2.2. Gas Hydrates and Geohazards

Gas hydrates can be an unconventional energy resource [35,36], a potential climate forcer once methane from hydrate deposits is freed into the atmosphere [37]. Nonetheless, they are also a problem as they represent a drilling geohazard [38].

Petrobras supported a CSEM research survey in the Pelotas basin, Southern Brazil (Figure 2), to investigate the origin and distribution of gas hydrate deposits in the basin. The dense 3D survey layout included 132 receivers spaced 1000 m along the source tow and 500 m across the source tow direction. With a 1 to 19 Hz range, the transmitted frequencies were higher than usually acquired for deeper targets.

Tharimela et al. (2019) [39] applied an unconstrained 3D inversion [19] to define the location and extent of the saturated gas hydrates and free gas in the shallow subsurface. The CSEM results were integrated with other near-surface geophysical data, including 2D seismic, sub-bottom profiler, and multibeam bathymetry data, identifying faults, chimneys, and seeps conducting to pockmarks in the seafloor.

As pointed out by [39], some resistivity anomalies revealed an excellent spatial correlation with some of these features. Thus, some seismic features were filled in with free gas and other potential geohazards impacting drilling operations, while others were not. This is a noteworthy contribution of CSEM in solving ambiguities in seismic interpretation.

Additionally, features previously mapped as gas-hydrate-bearing were reinterpreted as residual or low-saturated gas features due to the lack of a significant resistivity response associated with them. Moreover, using Archie's equation, Ref. [39] used the inverted resistivity volume to calculate the saturation volume of the subsurface.

3.2.3. Reservoir Characterization

Other objectives of the second Petrobras–SLB JIP cooperation agreement included developing new techniques for reservoir characterization, aiming to comprehend the reservoir rocks and fluids through accurate multiphysics measurements, to help the asset teams to develop optimal appraisal and production/monitoring plans.

Following this guideline, Miotti et al. (2018) [40] developed a new workflow to perform a petrophysical joint inversion (PJI) of seismic and CSEM data to determine important reservoir properties. The workflow uses seismic, CSEM, and well-log data information to enhance the reservoir's characterization.

The PJI workflow was applied to a deepwater oil field in offshore Brazil in the Sergipe-Alagoas basin, where we had available CSEM data. This approach successfully retrieved an accurate estimate of the reservoir's porosity and saturation from the electric and seismic domains.

The Jubarte experiment (JE) [41–43] was the first attempt to develop an understanding and assess the sensitivity of the CSEM method to water flooding associated with oil production in a complex and heterogeneous deep-water Brazilian turbiditic reservoir. The Jubarte Reservoir was chosen because it hosted the first fully optical deep-water permanent reservoir monitoring (PRM) seismic system installed in Brazil [44].

The JE studies indicate that production effects and associated variations in saturation produce changes in the reservoir's resistivity structure over time. Instead of trying to identify the associated changes in the time-lapse data domain, it was demonstrated that working in the model domain through inversions on each 3D dataset can retrieve reservoir-production-related resistivity differences. The advantage of the latter procedure is to avoid several issues related to receiver positioning and repeatability when working in the data domain, permitting easier and cheaper CSEM time-lapse monitoring.

In 2017, Petrobras embraced and supported the Marlim R3D (MR3D) project [45–47], which produced an open-source realistic Earth modeling project for electromagnetic simulations of the post-salt turbiditic reservoirs of the Brazilian offshore margin.

MR3D provides a realistic anisotropic geoelectric model aiming to be a standard for CSEM studies of the turbiditic reservoirs of the Brazilian continental margin. The MR3D model includes fine-scale stratigraphy and fluid-filled reservoirs whose geometries are based on a detailed 3D seismic interpretation [48]. MR3D also includes a CSEM [46] and an MT [47] dataset.

By using MR3D as a testing scenario in developing its interpretation workflows, Petrobras avoids confidentiality issues for external communications such as papers and conference presentations.

4. 2021 and Beyond

4.1. CSEM for Exploration and Appraisal

By the end of 2020, Petrobras had acquired a new, optimized Gauss–Newton 3D anisotropic inversion commercial code [49], which has several advantages compared to the quasi-Newton (BFGS) inversion code, as it runs faster, provides a higher resolution in defining much-improved and more stable anomaly images positioned at the correct depths, and yields much more accurate resistivity values [50].

Besides better inversion algorithms, by 2021, advanced interpretation software suites were also available, allowing more precise interpretations via correlation with seismic and well-log data, such as the one shown in Figure 4d, where three wells, the wildcat and two appraisals, were successfully drilled along a CSEM anomaly, positioned correctly over the reservoir.

Figure 6 shows the high success rate of the CSEM interpretation at Petrobras, calculated at 44 drilled wells. In the proposed classification, hits indicate true positives and true negatives, while misses indicate false positives and false negatives.

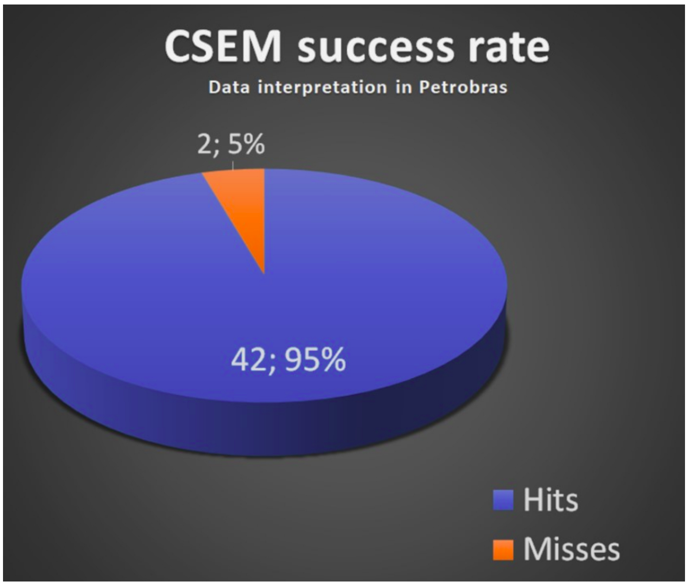


Figure 6. Petrobras CSEM cases at 44 wells and a 95% success rate. Hits (true positives/negatives), misses (false positives/negatives). Results from integrated CSEM–seismic interpretations.

Almost all wells (39) were drilled using the results of the Varredura project, which required the cost of one well to acquire a huge amount of CSEM data over several basins.

Petrobras' success rate of 95% exceeds the published 80% rate [51]. What are the main reasons for this high success rate?

Firstly, we attribute these numbers to the extensive and rigorous feasibility studies described previously in Section 3.1. Non-detectable targets or those with very ambiguous CSEM responses were discarded at once. Some of them occurred because they were too deeply buried to be imaged by the 2010 technology. With upgrades in the acquisition technology, more accurate receivers, more potent sources, and new 3D algorithms, a new 3D feasibility study is planned to reevaluate them.

Secondly, we believe that the in-house training, not only for the geophysicists of the multiphysics group but mainly in exporting the EM culture to the explorationists of the asset teams by allowing them to better understand the physics, advantages, and limitations of the CSEM methodology, allowed a fruitful collaboration between the two groups. As a result, it facilitated an integrated seismic–CSEM interpretation by incorporating all a priori knowledge in every studied area.

Finally, the scientific and technological advances developed in the integrated interpretation workflows must be acknowledged. One of the most recent is the Multiphysics Anomaly Map (MAM) [52], a data fusion solution consisting of a spatial representation of the correlations between anomalies from distinct geophysical methods.

The MAM was applied to CSEM and seismic inversion results from the offshore Sergipe-Alagoas basin. The MAM helped to differentiate between a dry and an oil-bearing channel previously outlined in seismic data. Both channels had the same seismically anomalous response. By applying the MAM, it was possible to resolve the seismic ambiguity. Our results were confirmed by drilling.

Moreover, we may consider the two failures from the drilled wells. The first (Case 1) was a false positive, and the other (Case 2) was a false negative.

Case 1 was an interpretation of the early period, with a 2D star-like shape of the 2007 survey design. CSEM data were interpreted by associating anomalous responses in the data domain with the interpreted reservoir outline and posterior 2D modeling. Nonetheless, we identified a slight anomaly at depth. The well was drilled near the lines, at the best position defined by seismic interpretation, and hit a reservoir with a gas show and filled in with moderately resistive (10–15 ohm.m) freshwater.

Case 2 was a 2012 survey with a small 3D design, with three parallel lines in a complex area with allochthonous salt. The CSEM data were inverted using the BFGS 3D algorithm (unconstrained inversion), which revealed an anomalous body. However, this body was found to be located far above the hydrocarbon reservoir that was discovered in the drilled well. When we performed the statistical analysis, we pinpointed it as a miss in the interpretation. Case 2 is a classic example of a lesson learned. With our state-of-the-art interpretation tools, we could probably position the anomaly correctly at the proper depth [50] and correlate it with seismic anomalies [52].

4.2. Planning for the Future

Figure 7 summarizes Petrobras' thoughts about the usability of the CSEM method through the various phases of a hydrocarbon reservoir's life cycle, from the early stages of exploration to time-lapse studies, including the data acquired for reservoir characterization, which can be used to support geohazard determinations and drilling operations.

CSEM usage for exploration is still very active at Petrobras. We have recently acquired a huge CSEM dataset in the Foz do Amazonas basin (Figure 2) [53]. This dataset is currently being interpreted not only in search for new opportunities but to understand the whole petroleum system in the area, as pointed out by [54].

Beyond exploration and appraisal, we are moving towards reservoir monitoring. Menezes et al. (2021) [55] have shown the ability of CSEM to produce reliable estimates of the SoPhiH maps [56] at a given reservoir. These maps provide knowledge of the remaining oil thickness in the studied reservoir. The reservoir teams frequently use the SoPhiH map as a subsidiary tool to define the best drilling locations for production or injection wells.

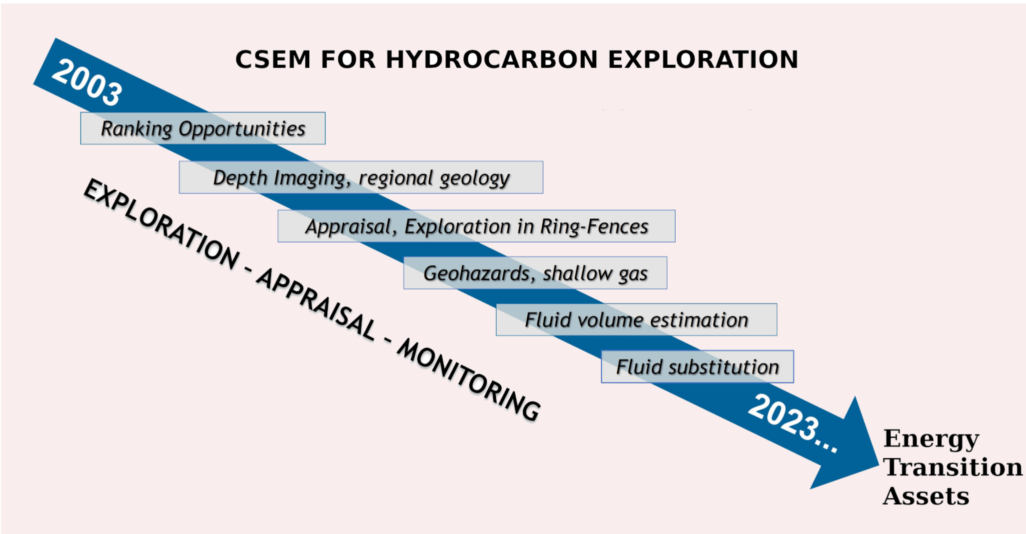


Figure 7. Petrobras' view of CSEM's applicability in the energy market.

Finally, we propose a new concept of ocean-bottom multiphysics nodes (OBMP) designed for reservoir monitoring purposes [15]. The idea is to find a feasible means to increase the demand for CSEM for 4D monitoring programs by increasing the value of information and reducing survey costs by performing joint operations, where seismic and CSEM data are acquired during the same survey at equivalent spatial densities. An important by-product of such joint acquisition is the reduction of the carbon footprint, a challenge for the oil industry. The global deep-water industry is being strengthened and is preparing for the next phase of upgrades. This time, it may be possible for a JIP to build an OBMP reservoir monitoring system that will add substantial value to reservoir management decisions, leading to greater oil recovery, reduced expenses, and improved sustainability for the oil industry.

Regarding the future, the deepening of the climate crisis is driving the world to transition to low-carbon energy sources such as native hydrogen and geothermal resources [57–59]. Another option in reducing the CO_2 concentration in the atmosphere is injecting and storing it in saline aquifers [60], a technique popularly known as carbon capture usage and storage (CCUS).

It is well known that the CSEM method is very sensitive to fluid saturation in rocks. Therefore, CSEM and other EM methods are expected to be prominent in exploring all transition energy assets depicted above. The same is expected in the monitoring phases, as EM acquisitions tend to be cheaper than seismic ones [61].

Similarly to the circle of life, Petrobras has returned 2023 to the beginning. Now, however, the multiphysics group has gained considerable knowledge in EM applications. We expect to achieve the same success with energy transition assets as in hydrocarbon exploration.

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Abbreviations

The following abbreviations are used in this manuscript:

CSEM	Controlled source electromagnetic method
HED	Horizontal electric dipole
EM	Electromagnetic
MT	Magnetotelluric
AVO	Amplitude versus offset
VP	Compressional velocity
FWI	Full waveform inversion
BLM	Below mud line
1/2/2.5/3/4D	One/two/three/four-dimensional
JIP	Joint industry project
GUI	Graphical user interface
CMP	Common midpoint
PJI	Petrophysical joint inversion
JE	Jubarte experiment
MR3D	Marlim Resistivity 3D
BFGS	Broyden–Fletcher–Goldfarb–Shanno algorithm
MAM	Multiphysics anomaly map
PRM	Permanent reservoir monitoring
OBMP	Ocean-bottom multiphysics nodes
CCUS	Carbon capture usage and storage

TLA	Three-letter acronym
LD	Linear dichroism
SoPhiH	Oil saturation (So), porosity (Phi), and thickness (H)
Petrobras	Petroleo Brasileiro S.A
EMGS	Electromagnetic Geoservices
SLB	Schlumberger
AOA	Arnold Orange Associates
AGO	Geomarine Operations
MCTI-ON	Ministério de Ciência, Tecnológia e Inovações—Observatório Nacional
UFPA	Universidade Federal do Pará
UERJ	Universidade do Estado do Rio de Janeiro

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