

Editorial

Editorial for the Special Issue “Applied Geophysics in Hydrocarbon Exploration, Energy Storage and CCUS”

Paulo T. L. Menezes ^{1,2} 

¹ Departamento de Geologia Aplicada, Faculdade de Geologia/UERJ, Rua São Francisco Xavier, 524, sala 2009, Bloco A, Rio de Janeiro 20550-900, Brazil; paulo.menezes@uerj.br

² PETROBRAS-EXP/PEN/AB, Av. Henrique Valadares 28, 4 andar, Rio de Janeiro 20231-030, Brazil

Since its inception, applied geophysics methods have been crucial in the oil and gas exploration industry. These methods are now employed in all life stages of hydrocarbon reservoirs.

In recent years, advancements in applied geophysics technology have greatly improved our ability to image and understand underground reservoirs. This has reduced exploration costs, improved optimization, and supported efforts to create a more sustainable hydrocarbon industry with less environmental impact. To reduce emissions from the energy industry, companies worldwide are focusing on carbon capture, utilization, and storage (CCUS) projects. Additionally, energy storage in deep reservoirs, such as hydrogen or compressed air, is a key component of current environmental and energy governmental policies.

This Special Issue aims to provide a space for discussing and sharing progress in interpretation workflows and innovations in technology related to hydrocarbon exploration, CCUS applications, and energy storage, all with an eye towards the future.

Our focus in this Special Issue included geophysical method applications from regional exploration to reservoir characterization and monitoring, and carbon and energy storage solutions. We especially welcomed the submission of case studies, reviews, new developments, and the integration of methodologies. We have divided the themes into three sections:

1. Exploration case studies, from regional to local scales.
2. Reservoir characterization and monitoring.
3. Applied geophysics in carbon capture, utilization and storage (CCUS), and energy storage.

As a result, we received an engaged response from the geoscience community, with ten papers covering various important facets of the oil and gas and energy transition industries.

Dell'Aversana [1] presents an integrated deep learning framework that can be widely applied for image analysis and automatic classification in many Earth disciplines, including mineralogy, petrography, paleontology, well-log analysis, and geophysical imaging. When analyzing and classifying images, there are several types of deep learning models available, such as fully connected deep neural networks (FCNNs), convolutional neural networks (CNNs or ConvNet), and residual networks (ResNets). According to Dell'Aversana, all these methods effectively recognize and classify mineral images, with ResNets being the most accurate and precise. He also compared deep learning techniques to other machine learning algorithms, such as random forest, naive Bayes, adaptive boosting, support vector machine, and decision tree. He found that deep neural networks generally perform better in classification. Additionally, he discusses how this deep learning approach can be applied to other types of images and geo-data, making it a versatile and multipurpose methodology for analyzing and automatically classifying multidisciplinary information. This article also serves as a tutorial, providing a detailed explanation of all the key steps in the workflow.

Exploration companies worldwide have widely used marine-controlled source electro-magnetics (CSEM) for exploration purposes. However, due to its perceived value and cost



Citation: Menezes, P.T.L. Editorial for the Special Issue “Applied Geophysics in Hydrocarbon Exploration, Energy Storage and CCUS”. *Minerals* **2023**, *13*, 1335. <https://doi.org/10.3390/min13101335>

Received: 11 October 2023

Accepted: 14 October 2023

Published: 17 October 2023



Copyright: © 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

compared to seismic and the lack of realistic case studies, the industry has yet to show much interest in using it for time-lapse reservoir-monitoring (4D) applications. To increase the value of information and reduce survey costs, Menezes and coauthors [2] propose performing joint operations where seismic and CSEM data are acquired during the same survey and at equivalent spatial densities. Additionally, they propose a new multiphysics ocean-bottom nodes (OBN) concept that shows how CSEM can be a cost-efficient and effective integrator to 4D seismic projects. By performing a feasibility study, Ref. [2] demonstrated that horizontal magnetic field components could be used instead of horizontal electric field components to map the 3D resistivity distribution and 4D fluid change responses in a given reservoir. That would make engineering a new OBN class easier and cheaper, as various miniaturized magnetic fields and seismic sensors are available off-the-shelf or ready to operate.

Estimating rock properties accurately from seismic data is essential in the petroleum industry. Two vital properties are the compressional velocity (V_p) and the quality factor (Q), which measure waves' energy losses as they propagate in the subsurface. These properties are typically obtained from multichannel seismic acquisitions. Santos and coauthors [3] developed a method to estimate Q and V_p using single-channel seismic data by using the windowed discrete Fourier transform for a single seismic trace, then calculating the peak and dominant frequency that changes with time. Their method uses a linear equation to adjust the estimated effective quality factor derived from migrated seismic data. The purpose of this correction is to account for the influence of lower-frequency content from more distant events that may be affecting shorter events. The methodology was applied to the Joetsu Knoll massive gas hydrates (GH) site, an SW-NE anticline structure on the eastern margin of the Sea of Japan. Their outcomes indicate a progressive gas hydrate depletion northward along the dome.

In today's world, finding ways to reduce our carbon footprint and protect the environment is crucial. One way to accomplish this is by recycling or burying carbon dioxide in depleted petroleum reservoirs and shifting our exploration strategies to focus on hydrogen reservoirs. These resources may occur in the same or different reservoirs, so searching for both is more efficient. Meju and Saleh [4] proposed a CSEM-MT workflow for investigating reservoirs within a play-based exploration and production framework. That involves finding the right basin and block, selecting the right prospect, drilling the proper well, and looking for opportunities for sustainability and CO₂ recycling or burial in the appropriate reservoirs. Recent methodological developments integrating 3D CSEM-MT imaging into the appropriate structural constraints are described, along with case studies demonstrating how this can help us understand deep geological processes and the distribution of potential hydrocarbon, geothermal, and hydrogen reservoirs. These advancements could play a critical role in helping us achieve net-zero emissions by 2050.

Menezes and coauthors [5] provide a comprehensive historical overview of the CSEM method in its 20-year usage in the Brazilian continental margin. The authors have shown progress in understanding CSEM resistivity data across various geological scenarios since 2003. Their review presents a roadmap of technical advancements in acquisition design and interpretation techniques. Accordingly, they have shown the expansion of CSEM usage beyond the lead ranking classic use to general applications, including salt imaging, gas hydrates, geohazard mapping, and reservoir characterization and monitoring. Ultimately, Ref. [5] discuss potential upcoming CSEM applications in new energy resources and carbon capture and storage.

Arelaro and coauthors [6] conducted a seafloor 4D gravity feasibility study for monitoring deep-water hydrocarbon reservoirs. They simulated the gravity effect by creating different density and pore pressure distributions using a fluid flow simulator in a realistic model of a turbiditic oil field in Campos Basin, offshore Brazil. These reservoirs are analogs of several other passive-margin turbiditic systems worldwide. Ref. [6] considered four reservoir scenarios with and without seafloor subsidence. Their research indicates that the gravity responses exceeded the acceptable value of 3 μ Gal 12 years after the first base

survey. The maximum gravity anomaly area corresponds to the oil–water substitution in the production zones. A maximum seafloor subsidence of 0.6 cm was calculated, resulting in no detectable gravity effects. Their results support future 4D seafloor gravity acquisitions for monitoring oil production in the deep-water passive-margin turbiditic reservoirs.

Lyrio and Li [7] have developed an innovative approach to map the basement structures of sedimentary basins, which involves integrating surface gravity data, seismic imaging, and well-logging information. Their method depends on a nonlinear inversion algorithm that constructs the shape and depth of the basement from surface gravity data. Using the primal-logarithmic barrier method, Ref. [7] also incorporated depth constraints from wells. In addition, they use seismic data, where available, to image the basement depth, which serves as a reference model for the inversion algorithm. Combining these elements, Ref. [7] can simultaneously define basement structures that fit seismic and gravity data. They successfully applied their new methodology in the Recôncavo Basin, Brazil, a syn-rift onshore mature basin with a strong correlation between oil field distribution and tectonic framework. Their approach has improved the basement definition and highlighted new exploration targets in the studied area.

Accurately predicting the quality and occurrence of source rocks in a sedimentary basin is crucial to evaluating petroleum resources. Analyzing rock samples in a laboratory is the most precise method to obtain their geochemical properties, but rock information is often limited. Moreover, source rocks could be sampled at positions that may not represent the oil kitchens' average organic content and quality. To overcome these challenges, Reis and coauthors [8] propose a seismic interpretation workflow supported by machine learning methods such as random forest, DBSCAN, and NGBoost to automate the source rock characterization methodology from the seismic data. Their technique helps maximize available data, expand information, and reduce data analysis time. Automating the input data quality control, extrapolating laboratory measurements to continuous well logs of geochemical properties, and estimating these properties in 3D volumes of total organic carbon (TOC) can be generated using machine learning techniques. The authors argue that their approach provides more accurate predictions, reduces uncertainties in the characterization of source rocks, and assists in exploratory decision-making. The proposed method was applied to the pre-salt source rocks from Santos Basin (Brazil) and allowed for the quantification of the TOC distribution in the source rocks, improving the interpretation of the main source rock interval based solely on seismic amplitude data.

Jiang and coauthors [9] develop a supervised deep learning method to predict the low-frequency components of the inverted acoustic impedance, combining various seismic and geological attributes that contain low-frequency information, such as relative geological age, interval velocity, and integrated instantaneous amplitude. Based on the results obtained from synthetic and real data, Ref. [9] argue that the proposed method is capable of enhancing the prediction accuracy of low-frequency components, with a significant improvement in the actual data case with a 57.7% increase as compared to the impedance predicted through well-log interpolation.

The Controlled-Source Electromagnetic (CSEM) method is valuable for obtaining information about reservoir fluids and their spatial distribution. It can be utilized in various applications such as storage for carbon dioxide (CO₂), enhanced oil recovery (EOR), geothermal, and lithium exploration. One of the benefits of the CSEM method is its versatility, as it can be tailored to meet specific reservoir objectives by selecting the appropriate components of a multi-component system. Barajas-Olalde and coauthors [10] show the applicability of CSEM in a CO₂ storage site in North Dakota, USA. Their study describes the procedures involved and highlights how surface measurements can achieve log-scale sensitivity when appropriately upscaled. Furthermore, Ref. [10] also evaluate the sensitivity of CSEM in other case studies, such as EOR, geothermal, and lithium exploration applications.

I am grateful to all the authors who submitted their papers to this Special Issue. Additionally, I appreciate the contribution of the reviewers, who helped improve the

quality of the manuscripts and contributed to the success of this Special Issue. Finally, I would like to thank the Minerals editors for their assistance in the publication process.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Dell'Aversana, P. An Integrated Deep Learning Framework for Classification of Mineral Thin Sections and Other Geo-Data, a Tutorial. *Minerals* **2023**, *13*, 584. [[CrossRef](#)]
2. Menezes, P.; Zerilli, A.; Correa, J.; Menor, E.; Ferreira, S.; Labruzzo, T. New Concept Ocean-Bottom Multiphysics (OBMP) Nodes for Reservoir Monitoring. *Minerals* **2023**, *13*, 602. [[CrossRef](#)]
3. Santos, L.A.; Matsumoto, R.; Freitas, F.D.S.; Santos, M.A.C. Geophysical Characterization and Attenuation Correction Applied for Hydrate Bearing Sediments in Japan Sea. *Minerals* **2023**, *13*, 655. [[CrossRef](#)]
4. Meju, M.A.; Saleh, A.S. Using Large-Size Three-Dimensional Marine Electromagnetic Data for the Efficient Combined Investigation of Natural Hydrogen and Hydrocarbon Gas Reservoirs: A Geologically Consistent and Process-Oriented Approach with Implications for Carbon Footprint Reduction. *Minerals* **2023**, *13*, 745. [[CrossRef](#)]
5. Menezes, P.T.L.; Ferreira, S.M.; Correa, J.L.; Menor, E.N. Twenty Years of CSEM Exploration in the Brazilian Continental Margin. *Minerals* **2023**, *13*, 870. [[CrossRef](#)]
6. Arelaro, A.D.; Barbosa, V.C.F.; Oliveira, V.C., Jr.; Menezes, P.T.L. Feasibility of 4D Gravity Monitoring in Deep-Water Turbidites Reservoirs. *Minerals* **2023**, *13*, 907. [[CrossRef](#)]
7. Lyrio, J.C.S.O.; Li, Y. Basement Mapping Using Nonlinear Gravity Inversion with Borehole and Seismic Constraints. *Minerals* **2023**, *13*, 1173. [[CrossRef](#)]
8. Reis, M.A.A.d.A.d.; Damasceno, A.C.; Roriz, C.E.D.; Korenchandler, A.L.; da Silva, A.M.; da Silva Praxedes, E.; Silva, V.G. Source Rock Evaluation from Rock to Seismic Data: An Integrated Machine-Learning-Based Work Flow and Application in the Brazilian Presalt (Santos Basin). *Minerals* **2023**, *13*, 1179. [[CrossRef](#)]
9. Jiang, L.; Castagna, J.P.; Zhang, Z.; Russell, B. Prediction of Reflection Seismic Low-Frequency Components of Acoustic Impedance Using Deep Learning. *Minerals* **2023**, *13*, 1187. [[CrossRef](#)]
10. Barajas-Olalde, C.; Adams, D.C.; Curcio, A.; Davydycheva, S.; Klapperich, R.J.; Martinez, Y.; Paembonan, A.Y.; Peck, W.D.; Strack, K.; Soupios, P. Application of Electromagnetic Methods for Reservoir Monitoring with Emphasis on Carbon Capture, Utilization, and Storage. *Minerals* **2023**, *13*, 1308. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.