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Editorial

Offshore Carbon Capture, Utilization, and Storage

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Climate change, resulting from human-caused CO_2 and other greenhouse gas emissions, is an urgent problem that demands immediate action from everyone. The need to decrease emissions has sparked a renewed emphasis on developing and utilizing offshore Carbon Capture, Utilization, and Storage (CCUS) technologies. While these technologies offer potential solutions to mitigate greenhouse gas emissions, many challenges must be addressed to ensure successful implementation.

One of the key technical challenges associated with offshore CCUS is the development of reliable and cost-effective capture and storage technologies. Current CCUS technologies have shown promise in capturing CO_2 emissions from industrial sources, but the scalability and efficiency of these technologies remain a concern. Additionally, the long-term storage of captured CO_2 poses significant challenges, including the risk of leakage and the potential impact on marine ecosystems.

In addition to technical challenges, non-technical hurdles must be overcome to deploy offshore CCUS successfully. Public acceptance of CCUS technologies is crucial for widespread adoption, and building trust and understanding among stakeholders is essential. Furthermore, the regulatory framework for offshore CCUS must be strengthened to address issues related to liability, safety, and environmental protection.

Despite these challenges, the offshore CCUS industry has made significant progress in recent years. Pilot projects and demonstrations have provided valuable insights into the feasibility and effectiveness of CCUS technologies in offshore environments. Collaborative efforts between governments, industry, and research institutions have helped drive innovation and improve the overall efficiency of CCUS systems.

This special edition explores important aspects of offshore carbon capture, utilization, and storage. The distinguishing features of distinct geological CO_2 storage reservoirs are expansive area coverage, thick sedimentary layers, and optimal depths. Nonetheless, the complexity of these reservoirs makes it difficult to accurately estimate CO_2 storage capacity, select suitable storage locations, and regulate injection pressures. Therefore, it is crucial to conduct comprehensive fundamental studies on each designated storage reservoir to reduce risks and improve sustainability.

Assessment of Geological CO_2 Storage Space:

To assess the viability of enhancing oil recovery (EOR) through the injection of CO_2 into the siliciclastic reservoirs of the Ankleshwar formation in India, Vishal et al. (2024) utilized a model-based post-stack seismic inversion methodology to acquire high-resolution acoustic impedance data for the estimation of porosity. This research examines the Hazad formation and reveals spatial disparities in effective porosity, as well as offers estimations for pore pressure and fracture gradient in the Gandhar field by utilizing well-log data, geological information, and drilling events. The resulting analytical plots offer significant insights that can inform the formulation of future field development strategies and explore the practicality of CO_2 sequestration.

To optimize the injection of CO_2, the initial components and behavior of the hydrocarbon system must be accurately determined. Eigbe et al. (2024) devised a multidimensional approach encompassing data validation analysis, assessment of site suitability for CO_2 storage, and compositional simulation of hydrocarbon components. The latter utilizes the Peng-Robinson Equation of State (EOS) for modeling fluid flow in porous media and estimating the necessary number of phases and components to describe the system. This research validates that volumetric behavior predictions are derivative of compositional behavior predictions, crucial to reservoir initialization and data quality assurance.

To evaluate the suitability of carbon sequestration in the lower section of the Shimentan Formation within the Upper Cretaceous of the Qiantang Sag, Feng et al. (2024) integrated seismic interpretation and drilling data, along with a comprehensive analysis of cores and thin sections. This study uncovered the vertical variability characteristics of the strata and has assessed the geological conditions conducive to carbon dioxide sequestration in various stratigraphic sections. Taking into

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account the unique characteristics of the source and sink regions, the study indicates a significant correlation between the carbon emission sources in the Yangtze River Delta and the potential carbon dioxide sequestration area in the Qiantang Sag.

Solve offshore in situ problems:

To ascertain the retrograde vaporization effect of condensate triggered by diverse gas injection media in fractured gas condensate reservoirs, Zhang et al. (2024) conducted a comprehensive analysis. The study focuses on the retrograde vaporization of condensate, examining its response to various gas injection media across varying reservoir properties and injection times. The findings indicate that the component exchange between the injected gas and condensate leads to significant retrograde vaporization of condensate within the formation. This research offers valuable insights and effective guidance for the design of gas injection development plans and the dynamic tracking and adjustments required for fractured gas condensate reservoirs.

To acquire an understanding of the fundamental geological context, potential, and underlying mechanisms of the mineralization of CO_2 within the basalts of the Leizhou Peninsula, Jiang et al. (2024) conducted an in-depth analysis of the mineralization processes linked to CO_2 sequestration at two prospective sites. The study encompassed a comprehensive suite of analyses, including petrography, rock geochemistry, the petrophysical properties of basalts, and groundwater hydrochemistry. Numerical simulation outcomes indicate that the basalt properties and hydrogeological conditions prevalent in the Leizhou Peninsula render it an optimal location for CO_2 carbonation and subsequent successful sequestration within the rock strata.

To observe the displacement of CO_2 within a deep saline aquifer, Wu et al. (2024b) introduced a mechanistic model. Drawing upon the specific geological features of saline aquifers found in an offshore sedimentary basin in China, this model simulates the movement of CO_2 over 100 years, taking into account various geological variations, including permeability, dip angle, thickness, and salinity. Furthermore, it evaluates the potential impact of injection rate and well configuration. The findings of this study serve as valuable references for the site selection and well-deployment strategies for CO_2 sequestration in saline aquifers, and it also aids in determining a safe distance from potential leakage sites.

The special issue also includes multiple assessments of potential hazards and introduces innovative methods to track CO_2 migration in subsurface layers and detect any leaks.

Risk assessment:

To formulate scenarios for potential leakage in Offshore Carbon Dioxide Geological Storage (OCGS), Liu et al. (2024b) introduced a novel methodology encompassing four crucial stages: the establishment of an interactive matrix, the evaluation of risk matrices, the performance of cause-effect analysis, and the development of scenarios. Applying this methodology to the Pearl River Estuary Basin in China, two leakage risk scenarios were effectively developed, along with corresponding mitigation strategies. This research significantly contributes to the sustainable development and safe operation of OCGS projects and offers potential for further enhancement and broader implementation across diverse geographical settings and project specifications.

Innovative techniques:

To effectively monitor and estimate carbon sequestration throughout the entirety of the seabed carbon sequestration procedure, Xiong et al. (2024) conducted a review of offshore CCUS safety monitoring strategies. These strategies encompass 1) a comprehensive understanding of the marine environment surrounding the carbon sequestration space; 2) the utilization of innovative offshore platforms; 3) the expanded deployment of ocean observation networks; and 4) Investment in the infrastructure necessary for carbon sequestration safety sensing. Furthermore, the research underscores that the selection of monitoring technology must adhere to the principles of local adaptability, taking into account the specific characteristics of carbon sequestration plant sites, and evaluating potential environmental risks and geological safety concerns.

Concerning seismic monitoring, a notable challenge lies in the typical 3D seismic approach. Liu et al. (2024a) introduced a novel Hcable (Harrow-like cable system) technology tailored for offshore CCS monitoring. This technology incorporates high-frequency sources with a dominant frequency exceeding 100 Hz, utilizing a harrow-like configuration to achieve a reduced bin size of 6.25 m×3.125 m. A case study has showcased the capability of the Hcable to produce a 3D high-resolution image, effectively mapping a gas chimney structure and an MTD, which serve as analogs for potential leakage pathways and storage units. The precise characterization of these features validates the promising potential of Hcable as a tool for monitoring subsurface structures within CCS projects.

A potential high-resolution technique for quantitatively assessing the status of sequestered CO_2 resides in the application of full-waveform inversion (FWI) to time-lapse seismic data. Nonetheless, the practical deployment of FWI is significantly hampered by the well-documented cycle-skipping challenge. To detect alterations in subsurface properties resulting from CO_2 injection and to address this challenge, Wang et al. (2024) introduced a novel time-lapse FWI approach utilizing cross-correlation-based dynamic time warping (CDTW). This method integrates the merits of cross-correlation and dynamic time warping, and it is employed in the automated estimation of discrepancies between seismic signals simulated using the baseline/initial model and those acquired. By comparing the inverted baseline and monitor models, this approach facilitates the retrieval of induced subsurface property changes, surpassing the performance of traditional dynamic time-warping methods.

To examine the practicality of time-lapse seismic monitoring during the sequestration of CO_2 in anisotropic formations, Wu et al. (2024a) formulated a rock physics model. This model incorporates various factors, such as formation pressure, pore aspect ratio, fractures, heterogeneous fluid distribution, and the anisotropy stemming from a horizontal layering of rock strata or mineral alignment. Utilizing the specific conditions of the operational area, the model establishes a correlation between elastic and reservoir parameters, and further derives the reflection coefficient from the anisotropic exact reflection coefficient equation. This approach enables the forward modeling of the influence of reservoir parameters on seismic recordings, thereby enhancing the accuracy and reliability of seismic monitoring during CO_2 storage operations.

To rigorously analyze the capacity of controlled source electromagnetic (CSEM) in monitoring the migratory patterns of sequestered CO_2 plumes, Qiu et al. (2024) developed a model for the calculation of corresponding electric field response characteristic curves. This model comprehensively takes into account a diverse array of potential scenarios for the migration and diffusion of offshore CO_2 storage, encompassing varying burial depths, lateral extension diffusion, vertical extension diffusion, numerous combinations of lateral intervals, as well as diverse electric field components. This study underscores the potential of CSEM in monitoring the migratory behavior of CO_2 plumes in offshore saltwater reservoirs, thereby providing a foundational basis for the monitoring and evaluation of CO_2 transport during storage processes.

In a situation involving the leakage of gas beneath the sea, Cao et al. (2024) employed machine-learning techniques to detect and differentiate bubble clusters. Utilizing the Dual-Tree Complex Wavelet Transform technique, the research precisely extracts the image features of multi-beam forward-looking sonar and effectively classifies underwater gas leakages with varying flow rates. The study attains remarkable classification accuracy in a pool-based gas leakage experiment, thereby showcasing the promising potential in predicting the flow rate of gas leakages.

To overcome the technical and non-technical challenges associated with offshore CCUS, it is crucial to continue investing in research and development. Furthermore, updating policies and regulations is essential to support the adoption of CCUS technologies and encourage investments in carbon capture and storage infrastructure. By working together effectively and leveraging the expertise of various stakeholders, we can make significant reductions in greenhouse gas emissions, thus paving the way for a more sustainable future for generations to come.

It is expected that compiling these papers covering various aspects of offshore carbon capture, utilization, and storage will provide a valuable overview of the relevant problem domain.

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