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Heterogeneity-assisted carbon dioxide storage in marine sediments

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HIGHLIGHTS

- CO_2 storage in heterogeneous marine sediments in investigated for the first time.
- CO_2 storage is possible in shallower marine sediments than previously found.
- Physical and operational thresholds for secure CO_2 storage are presented.

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ABSTRACT

Global climate change is a pressing problem caused by the accumulation of anthropogenic greenhouse gas emissions in the atmosphere. Carbon dioxide (CO_2) capture and storage is a promising component of a portfolio of options to stabilize atmospheric CO_2 concentrations. Meaningful capture and storage requires the permanent isolation of enormous amounts of CO_2 away from the atmosphere. We investigate the effectiveness of heterogeneity-induced trapping mechanism, in potential synergy with a self-sealing gravitational trapping mechanism, for secure CO_2 storage in marine sediments. We conduct the first comprehensive study on heterogeneous marine sediments with various thicknesses at various ocean depths. Prior studies of gravitational trapping have assumed homogeneous (deep-sea) sediments, but numerous studies suggest reservoir heterogeneity may enhance CO_2 trapping. Heterogeneity can deter the upward migration of CO_2 and prevent leakage through the seafloor into the seawater. Using geostatistically-based Monte Carlo simulations of CO_2 transport in heterogeneous sediment, we show that strong spatial variability in permeability is a dominant physical mechanism for secure CO_2 storage in marine sediments below 1.2 km water depth (less than half of the depth needed for the gravitational trapping). We identify thresholds for sediment thickness, mean permeability and porosity, and their relationships to meaningful injection rates. Our results for the U.S. Gulf of Mexico suggest that heterogeneity-assisted trapping has a greater areal extent with more than three times the CO_2 storage capacity for secure offshore CO_2 storage than with gravitational trapping. These characteristics offer CO_2 storage opportunities that are closer to coasts, more accessible, and likely to be less costly.

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1. Introduction

Carbon dioxide (CO_2) capture and storage (CCS) can help stabilizing greenhouse gas concentrations in the atmosphere and mitigate global climate change [1–7]. Multiple approaches have been proposed for the long-term storage of anthropogenic CO_2 emissions, including injection into deep geologic formations (e.g., depleted oil and gas reservoirs, coalbeds, saline formations, shale [8–16]), deep ocean waters [17,18], and storage via chemical transformations [19,20]. However, each of these options has drawbacks. In onshore geologic formations, CO_2 is buoyant and can leak from the reservoir through an overlying impervious formation [21,22], and overpressure due to CO_2 injection may fracture the overlying caprock or induce seismicity [23,24].

Deep ocean waters may be acidified by CO_2, with concomitant impacts on marine ecosystems, and the CO_2 is prone to mixing with ocean currents and may be ultimately released to the atmosphere [25]. Further, industrial demand for chemical transformations is ~200 $MtCO_2$ per year, which is roughly 175 times less than the amount of CO_2 that was emitted from energy use worldwide in 2013 [22]. Offshore geologic formations could also be used for CO_2 storage, which may be beneficial because they are not beneath onshore populations, cannot negatively affect underground sources of drinking water [26], and regulatory considerations and ownership issues may be more easily reconciled than for onshore locations [27]. In fact, several offshore CO_2 storage projects are underway, including CO_2ReMoVe [28], SUCCESS [29], QICS [30], and NLECI [31], and NCIP [32]. Most of these projects are implemented in aquifers under shallow seas and, as in onshore geologic formations, there are hazards that arise from overpressure and the buoyancy of emplaced CO_2, such as, CO_2 interaction with seawater.

We revisit in detail a more promising option for CO_2 storage: emplacement in deep marine sediments [33–35]. CO_2 storage in deep marine sediments has the advantages of geologic storage and deep ocean storage [33]. For example, CO_2 storage in marine sediments can benefit from continuous subsea pressure management and potential chemical transformations through the formation of CO_2 hydrates [34]. While the costs are likely to be higher, CO_2 storage in marine sediments could be more tenable than other options for CO_2 storage, especially when risks are considered. We note that the cost evaluation and cost comparison to onshore CO_2 storage are outside the scope of our work.

At sufficient ocean depths, the pressure is high enough and the temperature is low enough for liquid CO_2 ($CO_{2(l)}$) to be more dense than the surrounding less compressible seawater [36]. If CO_2 was injected above the seafloor, it would sink and form a lake of gravitationally stable $CO_{2(l)}$ on the seafloor. But if CO_2 was injected into the sediments below the seafloor, the emplaced $CO_{2(l)}$ would descend deeper into the sediment. As it descends, the increase in temperature due to the geothermal gradient would cause the density of the $CO_{2(l)}$ to pronouncedly decrease. At the neutral buoyancy depth (NBD) into the sediments, the $CO_{2(l)}$ would stop descending because its density becomes equal to the density of the surrounding pore fluid, and thus the $CO_{2(l)}$ isolates itself within the sediment pores. Gravitational trapping occurs in the "negative buoyancy zone" [33] in marine sediments, located between the seafloor and the NBD, where the emplaced CO_2 is more dense than the pore fluid. This gravitational trapping exists at water depths $>\sim 2.5$ km and sediments within several hundred meters beneath the seafloor [37]. Also, if CO_2 were injected beneath the NBD, it would ascend until it reaches the NBD, where it would then be gravitationally trapped.

Despite the advantages of CO_2 storage in marine sediments, the suitability of this option is poorly understood, and thus the global storage capacity, while potentially enormous, is highly uncertain [35,38]. Prior studies of CO_2 storage via gravitational trapping have assumed *homogeneous* sediments [33,35], but experimental, numerical, and field studies suggest that reservoir permeability heterogeneity may enhance CO_2 trapping by hindering the upward migration of buoyant CO_2 [39]. As such, models that incorporate permeability heterogeneity more accurately account for CO_2 fate and transport in the reservoir [40,41].

In this work, we perform reservoir simulations of CO_2 injection and its interaction with sediment pore water, based on fluid and sediment data from four sites in the U.S. Gulf of Mexico (GOM), shown in Fig. 1(a). The marine sediments at these sites are sufficiently thick and permeable for CO_2 storage. The sediment porosity and permeability have variable degrees of heterogeneity and anisotropy, which reflect the original and post-depositional processes [42–44]. We incorporate these heterogeneities and anisotropies at the reservoir level into our models, where we explicitly model solubility and gravitational trapping processes. Given the various temperatures and pressures in the marine sediments, and the uncertainty in fluid flow parameters, we develop and implement a statistical framework to quantify the uncertainty in CO_2 storage capacity and leakage into the seawater during the heterogeneity-assisted trapping of CO_2 in marine sediments. To best of our knowledge, this work is the first numerical simulation study on CO_2 sequestration in heterogeneous marine sediments.

We find a large CO_2 storage potential due to heterogeneity-induced trapping, which is also effective in combination with gravitational trapping for physico-gravitational trapping (PGT). Marine sediment reservoirs must also accommodate sufficient CO_2 injection rates, which under homogeneous permeability conditions also requires that the sediments be thick and permeable, but such characters are uncommon in most deep-water settings [34,35]. We further show that these constraints can be relaxed through heterogeneity-induced trapping, such that marine sediments in much shallower seas can be viable CO_2 storage options.

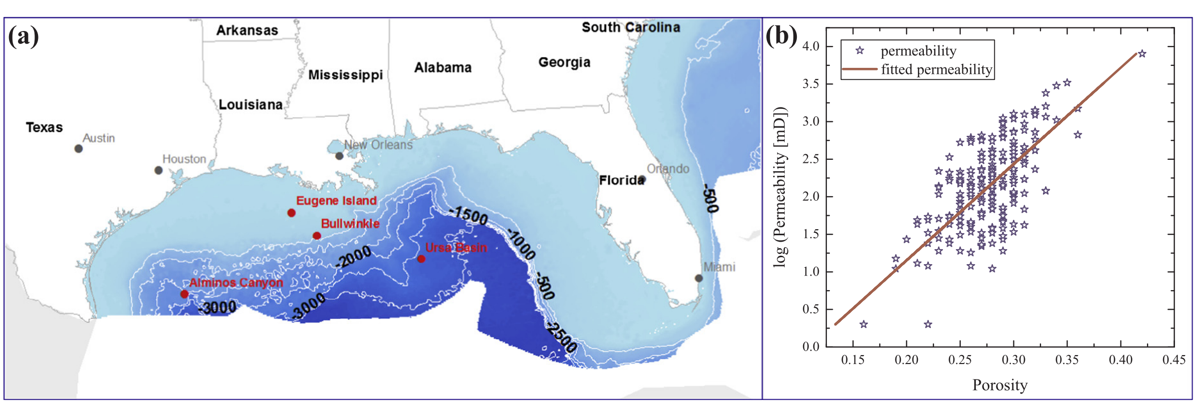

Fig. 1. Data from the Gulf of Mexico (GOM) within the U.S. Exclusive Economic Zone. (a) Site locations in the Gulf of Mexico (GOM), (b) Permeability-porosity correlations.

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