Quantitative Assessment of CO_2 Storage Capacity of Cenozoic Saline Aquifers in the South Yellow Sea Basin

Introduction

Geological carbon dioxide (CO_2) storage in deep saline aquifers has emerged as a promising strategy for mitigating anthropogenic greenhouse gas emissions (IEA, 2019; Bachu et al., 2007). Among various storage options, offshore saline aquifers offer distinct advantages, including the protective cover of seawater that minimizes leakage risks and enhances storage security (Schrag, 2009; Yuan et al., 2025). The pore spaces of these formations can accommodate CO_2 through multiple trapping mechanisms, namely structural, capillary, solubility, and mineral trapping (Emami-Meybodi et al., 2015).

The South Yellow Sea Basin (SYSB), located off the eastern coast of China, represents a prospective region for CO_2 geological storage due to its thick Cenozoic sedimentary succession and proximity to major industrial CO_2 sources in Shandong and Jiangsu Provinces (Huo, 2014). Previous investigations have primarily focused on hydrocarbon exploration within the basin (Chen et al., 2019; Yuan et al., 2018), leaving its CO_2 storage potential largely unassessed.

This study aims to: (1) characterize the geological conditions governing CO_2 storage in the Cenozoic saline aquifers of the SYSB; (2) quantify the theoretical CO_2 storage capacity using the U.S. Department of Energy (USDOE) methodology (USDOE, 2015) coupled with a stratigraphically layered volume model; and (3) identify the most suitable tectonic units for storage based on integrated geological and capacity analyses. The findings will provide a scientific foundation for future offshore CO_2 storage site selection in the region.

Geological Framework of the SYSB

The SYSB is a large Mesozoic-Cenozoic sedimentary basin underlain by pre-Paleozoic basement (Lei et al., 2018). Tectonically, it comprises three primary units: the Northern Depression (Yantai Depression), Central Uplift (Laoshan Uplift), and Southern Depression (Qingdao Depression) (Chen et al., 2019; Yuan et al., 2018). The Cenozoic succession, reaching thicknesses of up to 4000 m in the depocenters, consists from base to top of the Paleocene Funing Formation, Eocene Dainan and Sanduo formations, and Neogene Yancheng Formation (Zhu and Mi, 2010) (Figure 1). Reservoir properties vary significantly with depth. Below 800 m, CO_2 exists in supercritical state —a prerequisite for efficient storage (Bachu, 2003). Sandstone porosity ranges from 9–24% in the target interval (800–3200 m), with secondary pores developed at depths of 2000–3200 m due to organic acid dissolution (Qu, 2004; Shi et al., 2005; Wang, 2018).

Methods

The CO_2 storage capacity was estimated following the USDOE volumetric approach (USDOE, 2015), which calculates the pore volume accessible for CO_2 in an open system. To better account for vertical heterogeneity, we developed a layered calculation model:

$$M_{CO_2} = \sum_{i=1}^{n} (V_i \times \varphi_i \times \rho_i) \times E,$$
$$V_i = A_i \times H_i \times R$$

where M_{CO_2} is the effective storage capacity; V_i, ϕ_i, and ρ_i are the sandstone volume, porosity, and CO_2 density of the i-th calculation unit, respectively; R is the net-to-gross ratio; and E is the storage efficiency factor (0.51%, 2.0%, and 5.5% for P10, P50, and P90 estimates) (USDOE, 2015).

The Cenozoic interval (800–3200 m) was subdivided into 14 200-m-thick units. CO_2 density at in-situ conditions was calculated from formation pressure and geothermal gradients using the method of Bachu (Bachu, 2003). Key input parameters are summarized in Table 1.

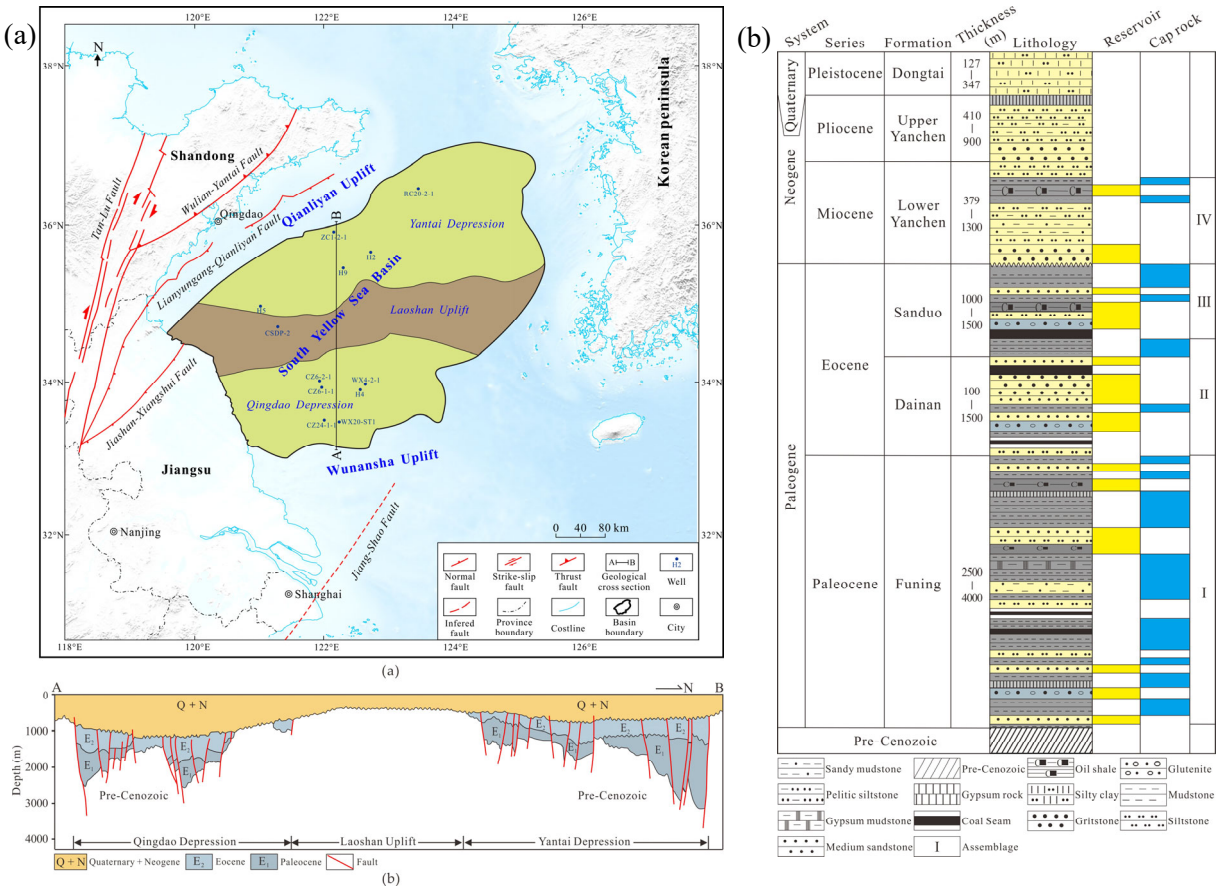

Figure 1 *(a) Stratigraphic column of Cenozoic strata in the South Yellow Sea Basin, showing reservoir–caprock assemblages (modified from Yuan et al., 2023); (b) Stratigraphic column of Cenozoic strata in the South Yellow Sea Basin.*

Geological Suitability for CO_2 Storage

The SYSB exhibits several favorable geological attributes for CO_2 storage. Tectonic stability is evidenced by generally weak fault activity and seismicity, particularly in the Yantai Depression, where only two earthquakes >6.0 magnitude have been recorded historically (Li et al., 2018; USGS, accessed 2022). The thermal regime is classified as a "warm basin" with an average geothermal gradient of 2.93°C/100 m and terrestrial heat flow of 63.5 mW/m² (International Heat Flow Commission, accessed 2019) —conditions conducive to CO_2 storage. Furthermore, four distinct reservoir–caprock assemblages are recognized (Funing, Dainan–Lower Sanduo, Sanduo, and Lower Yancheng formations), each comprising thick sandstone reservoirs overlain by competent mudstone caprocks (Zhu and Mi, 2010; Qu, 2004) (Figure 1).

CO_2 Storage Capacity

The estimated CO_2 storage capacity of the SYSB ranges from 39.59 Gt (P10) to 426.94 Gt (P90), with a mean value of 155.25 Gt (P50). This vast capacity could accommodate the CO_2 emissions of Shandong and Jiangsu Provinces for approximately 89 years at current emission levels (Shan et al., 2020; Guan et al., 2021).

Comparative Assessment of Storage Units

A unit-by-unit comparison reveals that the Yantai Depression is the most promising area for CO_2 storage for three reasons. First, it has a lower geothermal gradient (2.4°C/100 m vs. 2.7°C/100 m in the Qingdao Depression), which enhances CO_2 density and storage efficiency. Second, it exhibits weaker seismic activity, reducing the risk of caprock failure. Third, it possesses approximately double the storage capacity of the Qingdao Depression at the P50 level (99 Gt vs. 46.83 Gt). Conversely, the Laoshan Uplift is unsuitable because its Cenozoic succession is too thin (<800 m) to achieve supercritical CO_2 conditions.

Conclusions

The SYSB possesses favorable geological conditions for CO_2 storage, including weak tectonic activity, moderate geothermal gradients, and four well-developed reservoir–caprock assemblages. The total CO_2 storage capacity of Cenozoic saline aquifers is 39.59–426.94 Gt (mean 155.25 Gt), sufficient to offset regional emissions for nearly nine decades. The Yantai Depression emerges as the optimum storage target, offering superior stability and double the capacity of the Qingdao Depression, whereas the Laoshan Uplift is unfit for storage. This case study provides a reproducible assessment framework applicable to other offshore basins with comparable geological settings.

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