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Review article

Review on Carbon Sequestration in Salt Rock Caverns: Application, Theory and Potentials in China

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Abstract:
This paper systematically evaluates the technical feasibility, long-term safety, and resource potential of CO_2 storage in salt rock cavern (SRC), especially in China. Research indicates that salt caverns represent a highly promising storage option due to their high storage efficiency, although their long-term containment performance is governed by multi-field coupling mechanisms. The transport of CO_2 within the surrounding rock is jointly dominated by seepage and diffusion. In China, the widespread occurrence of bedded salt rocks containing interlayers of anhydrite, glauberite, and argillaceous materials significantly complicates the permeation-diffusion network, making it a critical factor in sealing integrity assessment. CO_2 injection-induced water–rock interactions exhibit dual effects: mineral dissolution may weaken the surrounding rock and lead to leakage pathways, whereas salt recrystallization and mineral precipitation can enable self-sealing and pore clogging. Additionally, salt precipitation and phase transitions triggered by supercritical CO_2 directly affect injectivity and cavern stability. Preliminary estimates suggest that the storage potential of abandoned SRCs in China known by the authors ranges from approximately 56 to 84 million metric tons of CO_2, though site-specific evaluation remains essential. The actual potential is likely greater. However, the commercialization of this technology still faces core challenges. Future efforts must prioritize the development of risk prevention and control technologies, along with intelligent monitoring systems, to ensure the long-term safety and efficient operation of CO_2 storage in SRCs.

1 Introduction

The zero-carbon economy is the ultimate socioeconomic model built globally to address climate change and achieve the temperature control targets of the Paris Agreement (Massarweh et al., 2024), whose core lies in reducing net greenhouse gas emissions from human activities to zero. This transition is not only an inevitable requirement for environmental governance but also a key driver for innovating energy systems and upgrading industrial technologies. However, achieving net-zero emissions at the full economic scale faces structural challenges, particularly in hard-to-abate industrial sectors and path dependence on fossil energy infrastructure.

Carbon capture and storage (CCS) technology, especially geological carbon sequestration (GCS), can handle emissions from industrial processes, achieve negative emissions of atmospheric carbon dioxide, and even balance supply-demand imbalances of redundant electricity—thereby providing critical physical support for building a sustainable energy-industrial system (Iqbal et al., 2025). Geological sequestration of carbon

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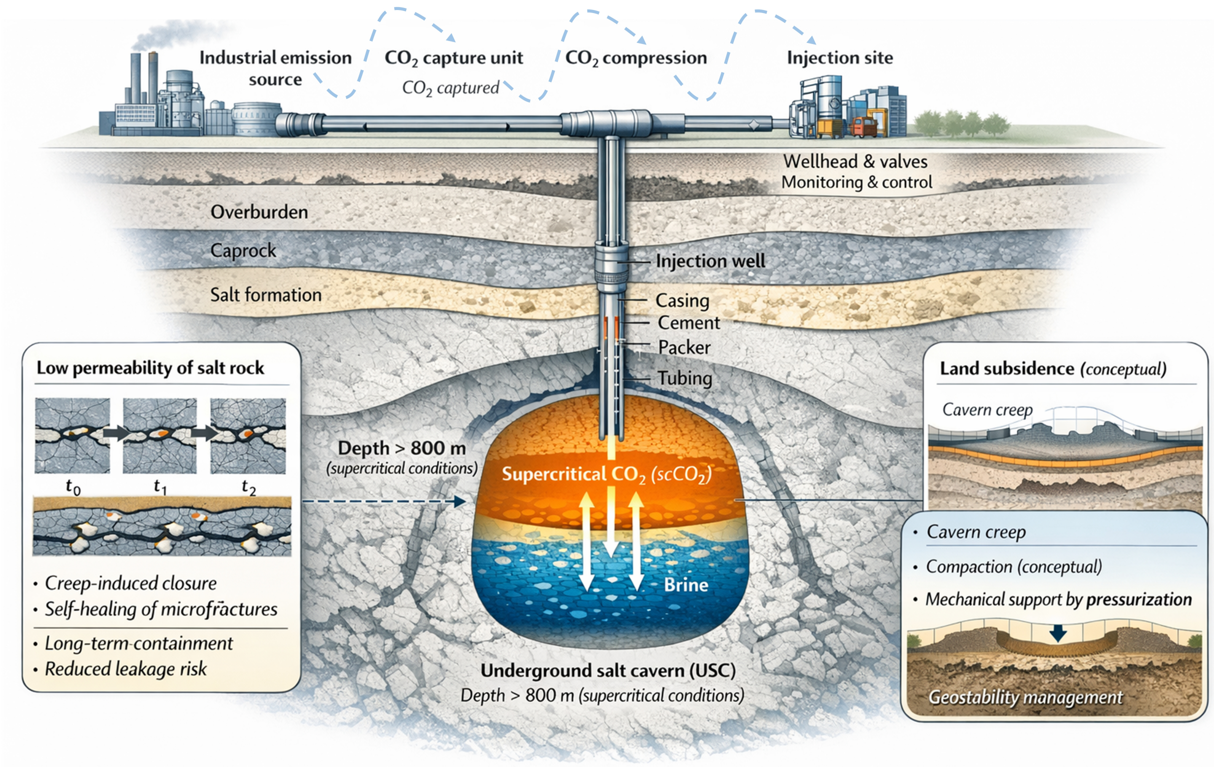

Fig. 1 Schematic diagram of geological carbon sequestration in SRC

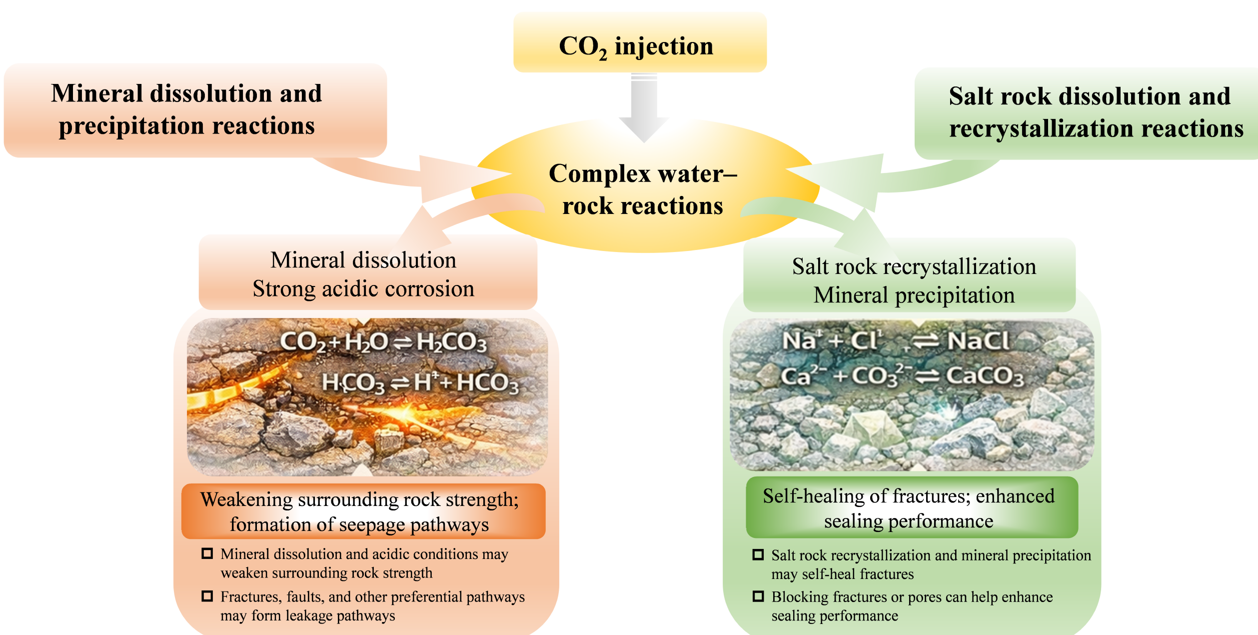

Fig. 2 Schematic diagram of CO_2 transport process in layered SRC

dioxide (CO_2) involves capturing CO_2 from industrial emission sources (such as power plants and chemical factories), transporting it via pipelines or other means, and injecting it into suitable deep underground geological formations (typically at a depth of over 800 meters), where the CO_2 is isolated from the atmosphere in a long-term and safe manner. The current geological formations adopted for GCS are usually porous rock layers (UPRL) (Gidden et al., 2025; Metz et al., 2005), including oil and gas reservoirs (Gidden et al., 2025), deep saline aquifers (Metz et al., 2005), uneconomical coal seams (Asif et al., 2025; Hosseinzadeh et al., 2024), and basalt (Yin et al., 2025; Gislason et al., 2014). In these porous reservoirs, the structural and stratigraphic trapping mechanism by the caprock and the residual trapping mechanism by the capillary pressure of gas-brine interface are expected to seal CO_2 in a couple of years after the initial injection into the formation. And then, the supercritical CO_2 dissolves in formation brine under high pressure, whose density would become larger than that of the surrounding brine (Hanson et al., 2025). The convection effect caused by density difference would drive the CO_2 migrate to the lower part of the formation and spread evenly in the reservoir, which in turn accelerate the dissolution of supercritical CO_2 into brine in decades of years (Bala et al., 2025). Over a period of hundreds of years or even longer, the dissolved CO_2 will react with reservoir rocks to form stable minerals, ensuring long-term storage safety (Wang et al., 2023). Owing to these advantages of good sealing performance and tremendous of potential sequestration capacity, almost all the GCS projects or pilot engineering applications were sited in UPRL (Chen et al., 2022). Among them, owing to the benefits from the CO_2 enhancing oil recovery (EOR), the GCS in oil and gas reservoirs are the most feasible and widely implemented CCUS solutions, contributing to 77% of the world's total carbon capture till now (Rui et al., 2025; Ali et al., 2022). Though much progress of GCS has been achieved in recent years, the total storage capacity of these porous reservoirs were just over 50 million tons (Mt) of CO_2 (IEA., 2025). Thus, more economic and applicable technologies for GCS are required urgently to accelerate the process of building a zero-carbon society.

The SRC was considered as key supplement to conventional porous reservoirs, whose technical feasibility is based on unique geomechanical properties and engineering economics. As in Fig.1, SRCs exhibit excellent sealing performance and mechanical stability. The creep properties of salt rock under stress could effectively close internal micro-fractures and achieve self-healing, granting it excellent containment capacity for injected supercritical CO_2, significantly reducing the long-term risk of leakage. Especially, there are enormous depleted USC after industrial retraction, which would transform decommissioned industrial heritage into valuable storage assets, and significantly reducing the initial investment and construction cycle of carbon storage. Moreover, SRC creep and compaction of karst cave systems are potential sources of land subsidence. By injecting and maintaining CO_2 at a certain pressure, the underground structure can be effectively supported, whose mechanical balance restored, and proactive management of geological stability achieved. This review comprehensively investigates the engineering advances of USC adopted for CCS. In addition, the total quantity and distribution of SRC space in China, as well as the depleted spaces in them. Moreover, the key scientific issues and challenges in GCS in the CUD are elaborated.

2 GCS engineering applications in SRC

Currently, there are no operational CO_2 storage projects in SRCs worldwide. However, many scholars have conducted research on the feasibility of CO_2 storage in SRCs. Grant Charles Mwakipunda et al. reviewed the potential and recent advancements of GCS in SRC, aiming to explore their viability as an option for geological CO_2 storage (Mwakipunda et al., 2024). Soubeyran et al. systematically compared the behavioral differences between CO_2 and CH_4 during storage in SRCs through thermodynamic analysis and experimental studies (Soubeyran et al., 2019). Their research highlighted that CO_2 presents a phase transition risk under typical SRC pressure and temperature conditions due to its critical point lying within this range, necessitating precise control of its thermodynamic state. Furthermore, CO_2 exhibits significantly higher solubility and faster dissolution kinetics in brine compared to CH_4. The authors developed a model describing CO_2 dissolution kinetics in brine and emphasized that mass transfer effects between CO_2 and brine must be considered in the management and simulation of GCS in SRC, to avoid misinterpreting pressure drops caused by dissolution as leakage.

And some scholars have conducted extensive site evaluation studies on potential carbon storage salt rock reservoirs across the globe. For instance, in Brazil, the pre-salt CO_2 storage projects in the Santos and Campos basins represent an indirect application of GCS in SRC and are among the world's largest offshore CCS clusters (Mwakipunda et al., 2024). These projects are situated within world-class offshore oil and gas production areas. The CO_2 is sourced from associated gas (with CO_2 content as high as 10-20%) separated during production from Brazil's pre-salt oil fields, such as Lula and Búzios. Re-injecting the separated CO_2 into the reservoirs helps maintain formation pressure while achieving the dual benefits of CCS and enhanced oil recovery (EOR). These reservoirs lie beneath salt layers up to 2000 meters thick, which act as excellent regional cap rocks, significantly reducing leakage risks (Soubeyran et al., 2019). Since the early 2010s, the injection volumes of CO_2 have steadily increased to 10 million tonnes by 2021, which was designed for a maximum annual storage capacity of 40 to 80 million tonnes by 2030. Furthermore, scholars have proposed utilizing the region's abundant and high-quality subsea salt resources to meet large-scale carbon storage demands. Goulart et al. introduced an integrated subsea SRC hybrid CCS system (Goulart et al., 2020). This system involves separating natural gas and CO_2 on the seabed, storing CO_2 in subsea SRCs, and commercializing the natural gas. Following the API 17N standard (oil and gas industry), they assessed the Technology Readiness Level (TRL) for well engineering, cavern design, subsea layout, flow assurance, and process equipment. The overall system TRL was calculated as 2, indicating a conceptual validation stage, with no insurmountable technical barriers identified. Using COVES 2 software, they simulated the long-term stability of a SRC (50 m height × 150 m diameter). Results proved the structural stability under high-pressure (45 MPa) CO_2 storage conditions. Their study also estimated the region's storage potential: a single cavern could store approximately 3.84 billion standard cubic meters of gas (equivalent to 7.2 million tonnes of CO_2), with 15 caverns having a combined capacity of about 108 million tonnes of CO_2. Costa et al. proposed a CO_2 storage scheme using ultra-deepwater SRCs offshore Brazil, complemented by numerical simulations for experimental cavern design and safety assessment (Costa

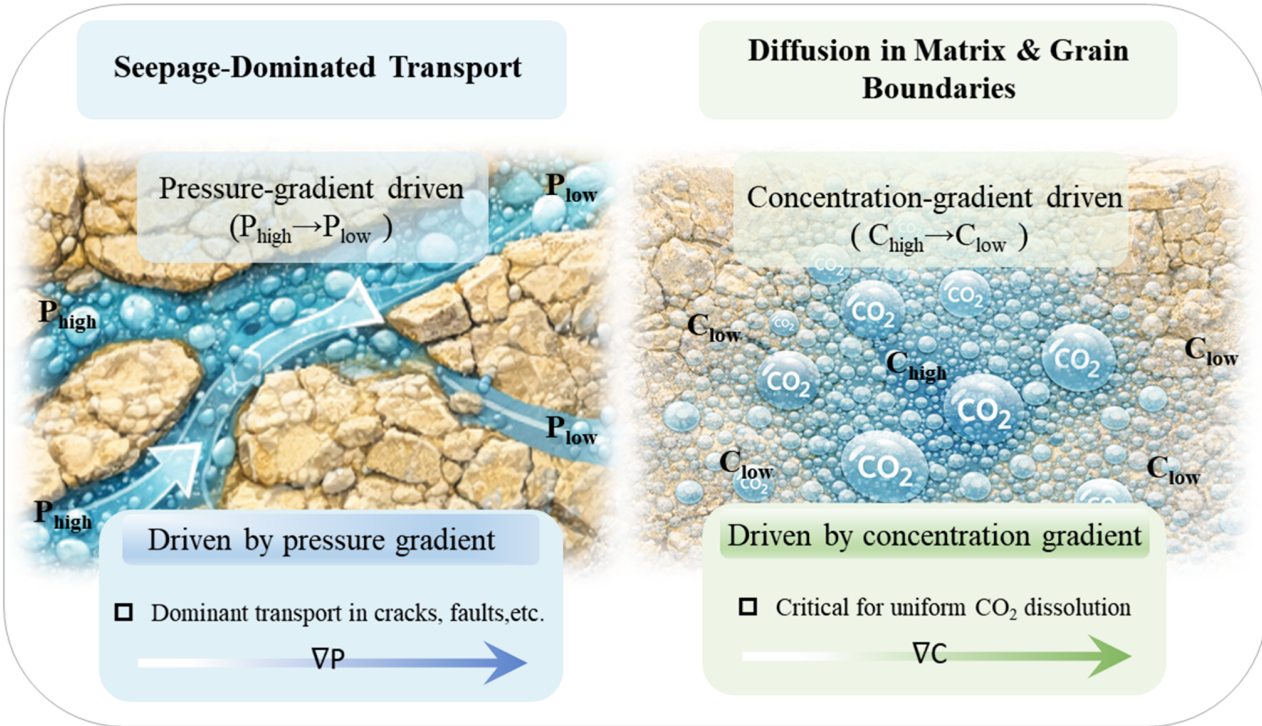

Fig. 3 Schematic diagram of CO_2 reactions and their impacts in layered SRC

et al., 2020). The site is located in a salt dome within the Santos Basin, approximately 10 km from major pre-salt oil fields. The designed cylindrical cavern has dimensions of 17 m in diameter and 48 m in height, with a volume of about 11,000 m³. The SALGAZ software was used to predict cavern shape and the solution mining construction process, alongside evaluations of cavern stability and wellbore integrity.

In addition, Al-Kindi comprehensively assessed the feasibility of carbon storage in underground salt mines in Omen (Al-Kindi et al., 2025). Results indicated that the widespread internal carbonate interlayers would potentially act as leakage pathways, connecting to the edges of the salt body or the surface. Additionally, accurately assessing cavern geometry, geochemistry, and injectivity presents significant challenges, making this option more expensive, complex, and higher-risk compared to other carbon storage opportunities in Oman. Pajonpai et al. investigated the feasibility and safety of GCS in the Maha Sarakham salt formation in northeastern Thailand (Pajonpai et al., 2022). Using geomechanical modeling by finite element methods over a 600-year timeframe, they calculated optimal shapes (spherical, cylindrical, teardrop, bulb-shaped, pear-shaped) for permanent CO_2 storage caverns and assessed their long-term stability. The study found bulb-shaped caverns to be the most stable for GCS, though it assumed homogeneous salt rock and did not account for the impact of interlayers (e.g., gypsum) on stability. Popescu et al. studied the technical feasibility and implementation of GCS in SRCs within dissolved salt mines, focusing on evaluating the structural stability and storage potential of decommissioned caverns in the Târgu Ocna mining area, Romania (Popescu et al., 2021). Through topographic surveys, sonar scanning, and numerical simulations (e.g., FLAC3D), they analyzed cavern geometry, volume, and long-term stability, recommending three existing caverns suitable for GCS. The research concluded that SRC storage offers high efficiency and good safety, representing a viable CCS technology that could facilitate regulatory implementation, technological innovation, and regional energy transition. Dusseault et al. argued that the underground salt formations worldwide were suitable sites for GCS, using Canada's Lotsberg Salt Dome as a case study (Dusseault et al., 2001). The region is adjacent to a Canadian province with significant CO_2 emissions and lacks other suitable geological storage options (e.g., deep saline aquifers), making salt solution caverns a valuable alternative. Their analysis covered salt rock permeability, creep characteristics, mechanical properties, and CO_2 storage capacity in SRCs (Bachu et al., 2005).

Liu et al., based on the geological conditions of the Pingdingshan salt mine in Henan, China, used FLAC3D software to simulate the long-term stability of a pear-shaped cavern (400,000 m³) in bedded salt rock storing supercritical CO_2 (Liu et al., 2023a). They found that over a 100-year operational period, volume shrinkage rates remained below 30% under all conditions, maximum displacement was less than 5% of the cavern diameter, and the plastic zone volume ratio was controllable, which meets stability requirements. The study identified the operational pressure window as a primary factor affecting stability, noting that narrowing this window (by increasing the minimum pressure) could significantly enhance stability. Luan et al. systematically studied the feasibility of using salt rock formations and abandoned SRCs in the Jialingjiang Formation in China's Sichuan region for CO_2 storage, analyzing storage potential and influencing factors (Luan et al., 2024).

Researchers have also proposed novel cyclic energy storage technologies utilizing SRCs for compressed CO_2. Stepanek et al. conducted a thermodynamic analysis of compressed CO_2 energy storage (CCES) in two sealed cavern systems stabilized with crushed rock (Stepanek et al., 2024). Numerical simulations evaluated over 420 configurations of the compressed CO_2 energy storage process. Results showed that this closed CCES system, employing dual caverns (High-Pressure Cavern, HPC, and Low-Pressure Cavern, LPC) filled with crushed rock for thermal storage and stabilization, could achieve round-trip efficiencies exceeding 60%, generate power exceeding 100 MW, with a maximum electricity generation capacity of approximately 600 MWh. The study emphasized that using CO_2 as the working fluid offers higher efficiency than traditional Compressed Air Energy Storage (CAES) and eliminates the need for above-ground thermal storage facilities. The crushed rock not only stabilizes the cavern's thermodynamic conditions and reduces operational parameter fluctuations but also enables direct underground thermal energy storage, demonstrating significant potential for large-scale renewable energy integration and grid peak shaving.

Liu et al. proposed a novel carbon cycle-based model for CO_2 storage in SRCs, highlighting that such storage could help bridge the spatial and temporal gaps between carbon capture and utilization (Liu et al., 2023b). Their research indicated that effective utilization of the sedimentary space (sediment backfill) can enhance cavern and surrounding rock stability, increase gas storage capacity, and improve brine displacement efficiency. Leveraging CO_2's phase behavior, they established and validated injection-brine displacement pressure equations for seal integrity assessment. Innovatively, they proposed a long-term stability evaluation model and key operational parameters (e.g., injection rate, minimum operating pressure), quantitatively analyzed the impact of dynamic burial depth and pressure changes on storage stability, and provided engineering countermeasures. In summary, many scholars have conducted pilot study on the feasibility and technical pathways of CO_2 storage in SRCs. It's believed that SRCs offer exceptionally high storage efficiency, significantly outperforming other geological reservoirs, and the technology is generally feasible. However, key challenges remain, including ensuring long-term sealing integrity, addressing economic viability, and mitigating the impact of geological impurities. Studies highlighted that CO_2 presented a phase transition risk in SRCs, and its solubility and dissolution kinetics in brine were markedly stronger than those of CH_4. Therefore, mass transfer effects must be accounted for in simulation and management to avoid misinterpreting pressure drops due to dissolution as leakage. Currently, there are no dedicated operational CO_2 storage projects in SRCs globally, although site selection and evaluation efforts are underway in multiple countries. Research in Brazil, Oman, Thailand, Romania, Canada, and China has also assessed local geological suitability, cavern stability, and storage potential. These studies emphasize that optimizing cavern geometry, controlling pressure ranges, and managing interlayers are crucial for ensuring long-term stability. Furthermore, scholars have proposed innovative applications, such as compressed CO_2 energy storage systems based on dual-cavern designs, which can achieve round-trip efficiencies exceeding 60% while integrating energy storage with carbon sequestration. Other studies have developed injection-production-brine displacement coupling models and long-term stability evaluation metrics. Overall, CO_2 storage in SRCs is technologically feasible and offers outstanding efficiency, representing a promising option for large-scale carbon sequestration and coupled energy peak-shaving applications. Nevertheless, further field demonstrations and comprehensive techno-economic validation of full-scale systems are still required.

3 CO_2 transport properties in SRC

During the process of GCS in SRC, the transport characteristics of CO_2 are key mechanics to determine its long-term storage performance and geological sealing integrity. It was widely acknowledged that CO_2 transport in salt formations is a complex, multi-scale, and multi-physics coupled process (Zhang et al., 2022), as illustrated in Fig.2. Advective flow serves as the dominant transport mechanism through pre-existing or stress-induced fractures, faults, or other preferential pathways in the surrounding rock of SRC, driven primarily by pressure gradients. Molecular diffusion, on the other hand, plays a crucial role in dense salt matrices and along grain boundaries, driven by concentration gradients; it is key to ensuring the eventual homogeneous distribution of CO_2 and its dissolution into formation brine (Bérest et al., 2003; Song et al., 2023a). Pure salt rock in its intact state is recognized for its extremely low porosity and permeability (Song et al., 2024) and is regarded as an excellent sealing layer. Diffusion constitutes the predominant transport mechanism within the intact salt matrix, driven by concentration gradients (Peach et al., 1991). The primary diffusion pathways include: salt-grain boundaries, which are common sites for defects and thin brine films, offering preferential channels for molecular diffusion; microscopic brine inclusions trapped within salt crystals, which may interconnect or link to grain boundaries, forming a diffusion network; and crystal-scale defects along with minimal matrix porosity (Song et al., 2025).

However, unlike the high-grade salt domes found in regions such as the Gulf Coast of the United States, the North German Basin, and the Zagros Belt in Iran, subsurface salt resources in countries such as China, Pakistan, and Yemen predominantly occur as bedded salt formations (Chen et al., 2025; Warren , 2016). These interlayered strata mainly consist of anhydrite, glauberite, and argillaceous (clay-rich) interlayers (Song et al., 2024; Zhang et al., 2025a; Li et al., 2024a). The presence of these minerals introduces potential advective-diffusive pathways for GCS projects. For bedded salt formations, the key petrophysical parameters governing CO_2 diffusion and seepage in the main rock types are summarized in Tab.1. The permeability and diffusion coefficient of CO_2 in pure salt rock range from 10^{-16} to 10^{-9} mD (Song et al., 2024; Cosenza et al., 1999; Popp et al., 2001) and 10^{-14} to 10^{-12} m^2/s (NEA., 2025; Bourg et al., 2017), respectively. For mudstone, are 10^{-4} to 10^{-2} mD (Liu et al., 2015a; Aljama et al., 2017) and 10^{-12} to 10^{-10} m^2/s

Tab. 1 CO_2 transport properties in layered salt rock cavern

Rock Type		Role	Average Permeability/(mD)	Diffusion Coefficients/(m^2/s)
Pure salt rock		Caprock	$10^{-6} \sim 10^{-4}$(Cadogan et al., 2015; Chen et al., 2025; Costa et al., 2020)	$10^{-14} \sim 10^{-12}$ (Bérest et al., 2003; NEA., 2025)
		Country rock	$10^{-6} \sim 10^{-4}$ (Cadogan et al., 2015; Chen et al., 2025; Costa et al., 2020)	$10^{-14} \sim 10^{-12}$ (Bérest et al., 2003; NEA., 2025)
Mudstone		Caprock	$10^{-4} \sim 10^{-2}$ (Bourg et al., 2017; Liu et al., 2015a)	$10^{-12} \sim 10^{-10}$ (Yuan et al., 2021; Aljama et al., 2017)
Interlayer of salt rock	Anhydrite	Country rock	$10^{-4} \sim 10^{-1}$	No dataset for unsaturated rock
	Glauberite	Country rock	depends on rock integrity	About $10^{-13} \sim 10^{-10}$ in brine
	Argillaceous	Country rock	(Wang et al., 2015; Liu et al., 2015a)	saturated rock(Cadogan et al., 2015; Li et al., 2018a; Ji et al., 2024)

(Yuan et al., 2021; Aljama et al., 2017). In contrast, the permeability and diffusion coefficient of the interlayers, including anhydrite, glauberite, and argillaceous interlayers range from 10^{-4} to 10^{-1} mD (Song et al., 2024; Liu et al., 2015a) and 10^{-13} to 10^{-10} m^2/s (Cosenza et al., 1999; Popp et al., 2001), respectively. Among these interlayers, the dense, low-porosity crystalline structure of anhydrite limits molecular diffusion. However, under tectonic stress or pressure fluctuations within the cavern, the brittle anhydrite may lead to fracturing, creating preferential flow pathways. Glauberite interlayers are prone to dissolution upon contact with cavern-leaching brines, forming dissolution pores, channels, or grooves. The resulting secondary porosity significantly enhances the connectivity of diffusion pathways, thereby increasing the effective diffusion coefficient. In extreme cases, localized sections of the interlayer may be completely dissolved, creating high-velocity flow channels for fluid migration (NEA., 2025; Bourg et al., 2017). Argillaceous (clay-rich) interlayers, characterized by nano-scale pores and a large specific surface area, provide continuous pathways for molecular diffusion and represent the interlayer type with the highest diffusion risk. Their transport properties depend on clay-mineral content, type, and the degree of compaction (Liu et al., 2015a; Yuan et al., 2021).

Thus, the long-term storage efficacy of CO_2 in SRCs is determined by its transport properties within the surrounding rock, which is inherently a coupled multi-physical process governed by both advection and molecular diffusion. High-purity salt rock, with its extremely low porosity and permeability serves as an excellent seal, where diffusion predominates as the main transport mechanism. However, the presence of interlayers in bedded salt formations significantly alters the transport pathways and rates of CO_2. The resulting advection-diffusion network constitutes a key geological factor in assessing the sealing integrity of CO_2 storage.

4 CO_2 reaction in SRC and its effects

As summarized in Tab.2, five major categories of chemical reactions occur during CO_2 storage in SRCs: dissolution-dissociation, mineral dissolution-precipitation, salt rock dissolution and recrystallization, interfacial extraction and brine evaporation, as well as phase transition reactions. These reactions, which triggered by CO_2 injection exhibit dual effects (as illustrated in Fig.3), collectively govern cavern stability, storage security, and long-term performance.

1) Dissociation-Dissolution Reactions: The dissolution and dissociation of CO_2 tend to create a weakly acidic environment (pH dropping to approximately 3.5–5.5), which serves as the basis for subsequent mineral reactions. The carbonic acid (H_2CO_3) formed from dissolved CO_2 can corrode minerals, increasing local permeability. In argillaceous interlayers, clay minerals may swell under acidic conditions, potentially leading to debonding at the interface with the salt rock and forming possible leakage pathways (Kaszuba et al., 2009). Concurrently, the acidic environment dissolves cementing materials, reducing the compressive strength and elastic modulus of the rock, diminishing its brittleness, and enhancing its plastic deformation capacity (Kaszuba et al., 2009; Lamy-Chappuis et al., 2015).

2) Mineral Dissolution-Precipitation Reactions: Mineral dissolution and precipitation represent the most complex set of reactions, primarily involving the dissolution and reprecipitation of carbonate, silicate, and sulfate minerals in interlayers (Lahiri et al., 2025). Among these, carbonate minerals such as calcite and dolomite dissolve under acidic conditions, releasing Ca^{2+} and Mg^{2+} ions into the brine. This process not only provides the material basis for subsequent carbonate precipitation but may also alter the cavern structure by forming high-permeability pathways such as wormholes and dissolution channels, which can increase permeability by 10- to 100-fold and potentially become pathways for CO_2 leakage, thereby compromising storage integrity (Wang et al., 2022a).

Conversely, in supersaturated zones, carbonate precipitation can occlude pores and fractures, reducing permeability by up to 90% and enhancing the sealing capacity of the CO_2 storage system (Song et al., 2024). However, the dissolution of carbonate minerals also weakens the mechanical properties of the rock, leading to reductions in compressive strength and elastic modulus (Altaf et al., 2025). Furthermore, mineral dissolution degrades the internal structure of the rock, making it more prone to localized deformation and even collapse under mechanical loading.

3) Salt Rock Dissolution and Recrystallization Reactions: Salt rock (primarily NaCl) undergoes dissolution in the presence of water, increasing the concentration of Na^+ and Cl^- ions in the brine. Under suitable conditions, these ions may

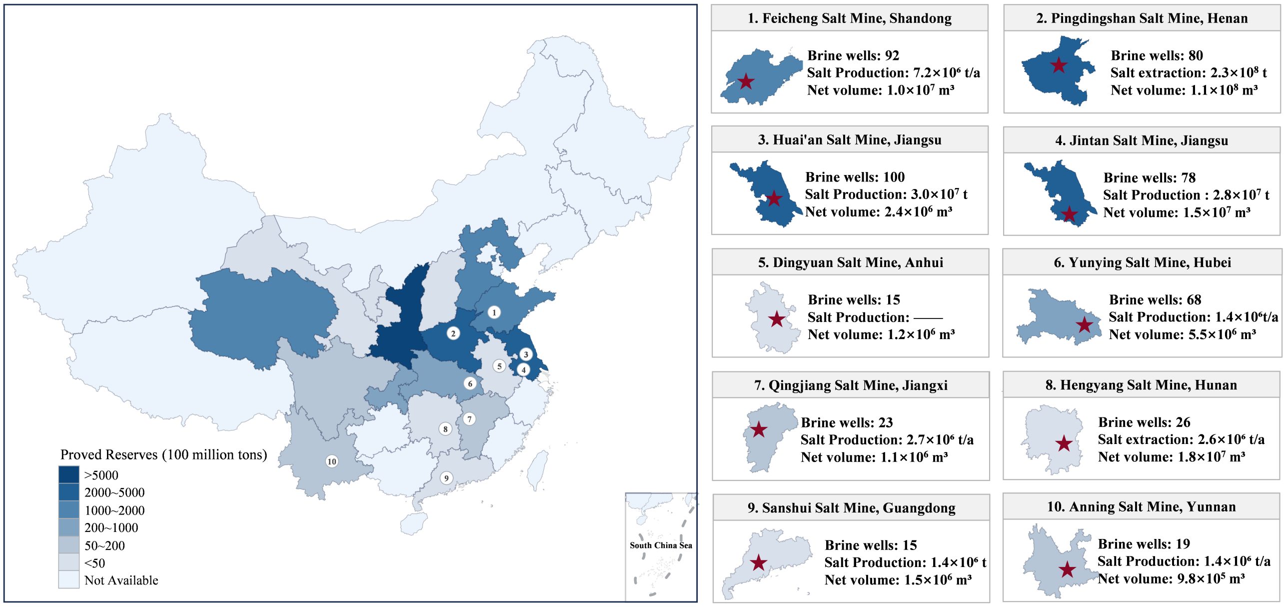

Fig. 4 Schematic diagram of the distribution of proven underground salt mineral resources and abandoned SRCs in China

Tab. 2 Main reactions during GCS in SRC

Reaction Category	Main Reaction Formulas
dissolution-dissociation	$CO_2(g) \rightarrow CO_2(aq)$ $CO_2(aq) + H_2O \rightleftharpoons H_2CO_3$ $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$, $HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$
mineral dissolution-precipitation	$CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^-$ $CaMg(CO_3)_2 + 2CO_2 + 4H_2O \rightleftharpoons Ca^{2+} + Mg^{2+} + 4HCO_3^-$ $NaCa_2Al_5Si_{13}O_{36} \cdot 14H_2O + 8H^+ \rightarrow$ $Al_2Si_2O_5(OH)_4 + 11SiO_2 + Na^+ + 2Ca^{2+} + 3Al^{3+} + 14H_2O$ Montmorillonite → Illite, Kaolinite $CaSO_4 + 2H_2O \rightleftharpoons Ca^{2+} + SO_4^{2-} + 2H_2O$ $Na_2SO_4 \cdot CaSO_4 + H_2O \rightleftharpoons 2Na^+ + Ca^{2+} + 2SO_4^{2-}$
salt rock dissolution and recrystallization	$NaCl(s) \rightleftharpoons Na^+ + Cl^-$
interfacial extraction and brine evaporation	$H_2O(l) \rightarrow H_2O(g) \rightarrow H_2O(CO_2Phase)$
phase transition	$CO_2(sc) \rightarrow CO_2(l)$ $CO_2 + nH_2O \rightarrow CO_2 \cdot nH_2O$

recrystallize to form new salt rock. Fuenkajorn and Phueakphum measured the permeability of fractured salt rock under confining pressures ranging from 0.7 to 20 MPa, investigating the influence of pressure on its self-sealing capacity. Their results indicated that the self-sealing effect strengthened with both increasing pressure and duration; under 20 MPa, the permeability of salt rock could decrease by more than four orders of magnitude within a relatively short period (Fuenkajorn et al., 2011). Li et al. conducted self-sealing experiments on Brazilian splitting-induced fractured salt rock across temperatures of 30–70°C and pressures of 0–10 MPa. Their findings confirmed that the presence of water was essential for recrystallization-driven sealing, and that both rising temperature and pressure promoted the closure of fractures (Li et al., 2024b). Yin et al. performed recrystallization healing experiments on damaged salt rock at 50°C and 12 MPa. The results showed that healed samples exhibited significantly reduced permeability, comparable to that of intact specimens (Yin et al., 2019). Wu et al. carried out three-point bending mode-I fracture tests on salt rock from room temperature up to 700°C and observed that between room temperature and 500°C, the self-sealing capacity improved with increasing temperature (Wu et al., 2024). Chang et al. systematically reviewed the effects of pressure, temperature, moisture, damage extent, and microstructure on the self-sealing behavior of salt rock (Chang et al., 2025).

Thus, while the dissolution of salt rock can alter cavern geometry and threaten stability-potentially leading to cavern collapse in severe cases-changes in pressure and temperature may also drive the recrystallization of Na^+ and Cl^- ions, filling micro-fractures and pores within the salt matrix. This inherent self-sealing capability represents a critical, dual-phase mechanism that must be accounted for in assessing the long-term integrity of CO_2 storage in SRCs.

4) Interfacial Extraction and Brine Evaporation: Under typical SRC conditions (generally P > 7.38 MPa, T > 31.1°C), CO_2 exists in a supercritical state. Supercritical CO_2 exhibits strong water-extraction capability, causing brine to evaporate and the concentrations of Na^+ and Cl^- to rise. When the brine reaches supersaturation, NaCl precipitates and crystallizes-a phenomenon known as salt-precipitation. Experience from existing CO_2 storage projects in saline aquifers has shown that water extraction driven by CO_2 injection leads to salt-precipitation, which in turn reduces reservoir porosity and permeability and impairs CO_2 injectivity. At projects such as Ketzin in Brandenburg, Germany (Baumann et al., 2014), Snøhvit in the Barents Sea, Norway (Grude et al., 2014), and Quest in Alberta, Canada (Smith et al., 2022), salt precipitation has been observed to decrease injection efficiency and increase injection pressure. In the Aquistore CO_2 storage project in Canada, Talman et al. reported wellbore and perforation clogging due to salt deposition (Talman et al., 2020). To mitigate salting-out, Nasiri et al. experimentally investigated intermittent injection of brine and supercritical CO_2 (Nasiri et al., 2025). Their study found that cyclic injection of low-salinity brine together with supercritical CO_2 can effectively reduce salt precipitation and limit permeability impairment. Sun et al. employed low-field nuclear magnetic resonance to monitor the dynamic evolution of fluid saturation and porosity during CO_2 injection (Sun et al., 2025). Their work revealed that salt initially deposits in larger pores, partially or completely blocking preferential flow paths and rendering portions of the pore space inaccessible to flow. Notably, salt aggregation and blockage near the wellbore significantly hinder subsequent CO_2 injection. Using microfluidic experiments, Yan et al. studied brine evaporation and salt precipitation during CO_2 injection in both homogeneous and heterogeneous pore models (Yan et al., 2025). The results illustrated how salt crystallization led to pore clogging: in heterogeneous models, more initial brine was trapped due to irregular pore morphology and larger pore throats, resulting in larger salt crystals. Under intermediate-wet conditions, water evaporation and salt precipitation proceed more slowly, whereas the diameter of the salt crystals was larger in the formation of water-wet conditions.

Analogous to CO_2 storage in saline aquifers, during CO_2 injection into SRCs, the drying effect of CO_2 also acts on residual brine adhering to the cavern walls and floor. This leads to NaCl precipitation and crystallization on the cavern surfaces, the bottom, and within the injection wellbore. While NaCl deposition on the cavern walls and bottom can fill micro-pores and fractures-thereby reducing permeability and potentially enhancing sealing integrity-excessive precipitation may alter the cavern geometry and compromise its mechanical stability, in severe cases even triggering collapse. NaCl crystallization in the wellbore can cause blockage, increasing injection difficulty and reducing CO_2 injection efficiency. Furthermore, localized NaCl precipitation may create pockets of high-salinity brine, altering pore-fluid properties and adding complexity to the coupled thermo-hydro-chemical-mechanical behavior of the system.

5) Phase Transition Reactions: When CO_2 is injected into a SRC, it initially fills the cavity in gaseous form via diffusion. As injection continues, the internal pressure gradually rises. Once temperature and pressure exceed the critical point (critical temperature 31.1°C, critical pressure 7.38 MPa), CO_2 enters the supercritical state. In this regime, CO_2 exhibits distinctive physical properties—low viscosity, high diffusivity, strong solvation capacity, and a density ranging from 0.2 to 0.9 times that of water (Ait Blal et al., 2025). The low viscosity and high diffusivity enable it to penetrate rapidly into fine pores and micro-fractures like a gas, while its substantially higher density compared to the gaseous state increases the volumetric storage capacity within the cavern. During GCS in SRC, changes in temperature and pressure that induce phase transitions would lead to significant volume variations, altering the internal pressure distribution and disrupting the pre-existing mechanical equilibrium of the cavern. For example, when supercritical CO_2 transforms back into the gaseous phase, its volume expands, raising the internal gas pressure. This reduces the effective stress in the surrounding rock and may increase the risk of cavern deformation or even collapse. Moreover, under the low-temperature, high-pressure conditions typical of deep-sea SRCs, CO_2 can combine with water to form solid CO_2 hydrate (Zhang et al., 2025b). Such a phase transition substantially reduces the volume of free CO_2, thereby enhancing both storage capacity and long-term containment security.

Accordingly, GCS in SRCs is a typical multi - physics coupling process, involving strong interactions among mechanics (creep), fluid migration (seepage) and chemical reactions (chemistry). These three processes are mutually coupled and interactively feed back through the material's physical property parameters (such as permeability, porosity, mechanical strength) and field variables (such as stress, pore pressure, chemical concentration).

Seepage - Chemistry: The time - dependent deformation (creep) of salt rock under deviatoric stress will alter its internal structure, such as compaction or generation of microcracks, thereby significantly affecting permeability and porosity. These changes will dominate or modify the seepage paths and diffusion rates of CO_2 and brine, and further influence the spatial location and rate of chemical reactions (e.g., dissolution and precipitation).

Creep - Chemistry: The injection and migration of CO_2 will change the pore pressure distribution in caverns and surrounding rocks. Variations in pore pressure directly affect the effective stress of rocks, thus altering the creep rate and damage evolution. Meanwhile, seepage serves as the main carrier for the transport of reactants (CO_2, H^+) and products (ions), determining the reaction front and intensity of chemical reactions.

Creep - Seepage: Water - rock chemical reactions exhibit a dual - effect. On the one hand, the dissolution of minerals (e.g., salt rock, gypsum, carbonate) will expand pores, form preferential seepage pathways, weaken the mechanical strength of rocks, accelerate creep and even induce damage. On the other hand, the recrystallization of salt or precipitation of secondary minerals (e.g., carbonate, sulfate) will block pores and fractures, reduce permeability, and may cement fractures to enhance mechanical integrity.

Therefore, the long - term behavior of CO_2 storage in salt rock is essentially dominated by the creep-seepage-chemistry coupling mechanism. Establishing an integrated Creep - Seepage - Chemistry (CSC) mathematical model that can characterize the dynamic evolution of permeability/porosity, chemical softening and stress - reaction interaction is an indispensable theoretical tool for quantitatively evaluating storage integrity, optimizing injection schemes and predicting long - term risks.

5 Distribution and GCS potential of underground salt deposits in China

China possesses abundant underground salt mineral resources. According to publicly available data from the National Bureau of Statistics, the proven reserves of underground salt deposits (calculated as NaCl) are approximately 15.54 billion tons, with basic reserves exceeding 200 billion tons and total resources reaching an estimated 130 trillion tons. The distribution of these salt deposits is highly concentrated, forming several major mining bases, including the Huai'an–Lianyungang mining area (Jiangsu Province), the Pingdingshan mining area (Henan Province), the Qianjiang mining area (Hubei Province), the Sichuan–Chongqing mining area (Sichuan Province and Chongqing Municipality), as well as sites in Tai'an (Shandong), Ningjin (Hebei), and Qingjiang (Jiangxi). The theoretical CO_2 storage potential of these formations reaches the scale of trillions of cubic meters, providing a foundation for the large-scale development of SRC storage facilities. Through solution mining technology, artificial caverns can be created by dissolving deep underground salt deposits. Following sealing and stability treatments, these caverns can be repurposed for energy and material storage. Lin et al. established a national evaluation system for the usability of SRC resources through multi-source data integration, classifying them into Grades I, II, and III (Li et al., 2025). Their study indicated that existing SRC resources were most abundant in East and Central China, while Grade II resources in Central, Northwest, and Southwest China hold significant strategic value, accounting for up to 65.4% of the total.

However, the unique geological characteristics of Chinese salt deposits pose considerable challenges for cavern utilization. Unlike the thick salt domes found abroad, China's salt bodies are predominantly bedded, characterized typically by "thin salt layers, numerous interlayers, and high impurity content." Argillaceous (clay-rich) interlayers within bedded salt formations are prone to collapse during cavity construction, severely impacting cavern stability. In regions with complex geological conditions, such as the Longgui Nitrate-Salt Mine in Guangzhou, where saline formations are in direct contact with highly permeable argillaceous conglomerates, the combination of shallow burial depth and hydraulic connectivity increases the risk of engineering geological issues like surface subsidence, posing serious challenges to the safe operation of SRCs.

As shown in Fig.4, the schematic diagram of the distribution of proven underground salt mineral resources and abandoned SRCs in China are reviewed. While most cavities exhibit good sealing integrity after brine extraction, only about 0.2% are currently used for gas storage, leaving a substantial number of old caverns abandoned. These abandoned caverns are concentrated mainly in East, Central, and North China. It was estimated that over 2,000 abandoned SRCs in China meet the basic criteria for storage repurposing. The potential capacity in East and Central China alone exceeds 50 million cubic meters, with an annual addition of about 12.2 million cubic meters of new cavity space. According to the author's incomplete statistics, specific examples include:

I) Jintan Salt Mine (Jiangsu) is a bedded salt formation covering 60.5 km², with proven salt rock reserves of 16.242 billion tons (12.538 billion tons NaCl) (Wang et al., 2022a). By 2019, cumulative effective cavern volume reached about 7 million m³, with an average annual increase of 590,000 m^3.

II) Huai'an Salt Mine (Jiangsu) is characterized by greater burial depth (600–1800 m), vast resources, gentle dip angles, with single salt layers up to 100 m thick (Jiang et al., 2024). After 30 years of solution mining, over 100 cavities have been formed, with a preliminary estimated effective volume of 24.1 million m^3.

III) Yingcheng Yunying Area (Hubei) is proven salt rock reserves of 35.7 billion tons (25 billion tons NaCl) (Zhou et al., 2017). Since 1969, over 150 solution-mined cavities have been created, with an effective volume of 27.2615 million m^3.

IV) Feicheng (Shandong) is the largest well-rock salt production base in China, with proven rock salt reserves of 5.22 billion tons (Yu et al., 2024a). The total underground cavity area exceeds 20 million m², with an annual addition of about 3 million m². Existing 46 caverns have an effective volume of 450,000 m^3.

V) Sanshui Salt Mine (Guangdong) is the only salt mine in Guangdong Province with potential for storage conversion (Yi et al., 2024). After years of mining, 15 old cavities exist with an effective volume of 1.2–1.5 million m^3.

VI) Pingdingshan Salt Mine (Henan) contains 40 old cavities from cumulative salt extraction of 330 billion tons, with an effective volume of 6.87 million m^3 (Li et al., 2015; Zhang et al., 2020).

VII) Zhaoji Salt Mine (Jiangsu) poses proven resources of 135 billion tons, whose salt segment roof at a minimum depth of 1300 m (Wang et al., 2019; Yu et al., 2024b). Existing 19 old cavities have a preliminary estimated effective volume of 8.83 million m^3.

VIII) Hengyang Salt Mine (Hunan) is one of China's extra-large salt deposits, with a total cavity group volume reaching 18 million m^3 (Long et al., 2016; Wang et al., 2024).

Based on theoretical formulas related to geological CO_2 storage, the estimated CO_2 storage potential of the abandoned old salt cavities ranges from approximately 56.3 to 84.5 million metric tons. The accurate value requires detailed assessment according to the geological conditions, engineering parameters, and operational pressure range of each individual cavern. It should be noted that this estimate only includes cavities with clearly documented volumes. Some literature suggested that the actual number of suitable abandoned SRCs nationwide exceeds 2,000, indicating that the total potential is significantly greater than the datasets presented in Fig.4.

6 Conclusions

This study synthesizes existing research to systematically assess its feasibility, long-term security, and the storage potential of abandoned caverns in China, examining multiple dimensions including technical principles, sealing mechanisms, chemical stability, and regional resources. The main conclusions are as follows.

I) GCS in SRC is considered a feasible technology due to its high storage efficiency, significantly surpassing other geological options. While no dedicated operational project exists globally, initiatives such as CO_2 reinjection in Brazil's pre-salt fields have validated the effectiveness of salt rock as a caprock. Related research is expanding from site selection evaluation to innovative applications like integrated energy storage.

II) The long-term storage feasibility of CO_2 in SRCs depends on its transport properties within the surrounding rock, a process inherently governed by the coupled multi-physics of advection and molecular diffusion. However, the transport behavior is more complex in the widely distributed bedded salt formations in China due to the presence of various interlayers. These interlayers significantly alter the transport pathways and rates of CO_2, making the resulting advection-diffusion network a core geological factor in sealing integrity assessments.

III) CO_2 injection triggers a series of brine-rock reactions with dual effects on storage security. The acidic environment can lead to mineral dissolution, potentially creating leakage pathways and weakening the mechanical strength of the surrounding rock. Conversely, salt recrystallization can seal fractures, and mineral precipitation may clog pores. Simultaneously, salt precipitation (salting-out) and phase transitions induced by supercritical CO_2 significantly impact injectivity and cavern pressure balance. Long-term security depends on the coupled outcome of these positive and negative feedback mechanisms.

IV) Based on data from major salt mines, the potential CO_2 storage capacity of identified abandoned SRCs in China is estimated to be approximately 56 to 84 million metric tons. The total national potential of suitable abandoned caverns far exceeds this localized estimate, though the specific capacity requires individual geological and engineering evaluation for each cavern.

V) However, the commercialization of GCS in SRC faces key challenges: 1) The interaction mechanisms between CO_2 and the multi-media environment (oil, water, rock) are complex, involving dynamic phase changes (gas, supercritical, liquid). The difficulty in controlling the multiple physical and chemical processes within the formation can lead to alterations in the geological structure and physicochemical properties, potentially causing mechanical instability of the storage body and CO_2 leakage. There is an urgent need to develop risk prevention and control technologies for CO_2 storage. 2) Furthermore, the migration patterns of CO_2 across the full spatial domain (atmosphere, wellbore, subsurface, and formation) are complex; the entire process (injection, production, transportation) is subject to variable disturbances, and the natural evolution spans a long lifecycle with significant dynamism and uncertainty. 3) It is urgent to clarify the migration and transformation mechanisms of stored CO_2, elucidate the petrophysical responses (acoustic, optical, electrical, seismic) for monitoring, establish a comprehensive monitoring technology system for CO_2 storage migration, and achieve efficient CO_2 monitoring.

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Conflict of interest

The authors declare no competing interest.

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